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Editorial

POLISH MARITIME RESEARCH is a scientific journal of worldwide circulation. The journal appears as a quarterly four times a year. The first issue of it was published in September 1994. Its main aim is to present original, innovative scientific ideas and Research & Development achievements in the field of :

Engineering, **Computing & Technology**, **Mechanical Engineering**,

which could find applications in the broad domain of maritime economy. Hence there are published papers which concern methods of the designing, manufacturing and operating processes of such technical objects and devices as : ships, port equipment, ocean engineering units, underwater vehicles and equipment as well as harbour facilities, with accounting for marine environment protection.
The Editors of POLISH MARITIME RESEARCH make also efforts to present problems dealing with education of engineers and scientific and teaching personnel. As a rule, the basic papers are supplemented by information on conferences , important scientific events as well as cooperation in carrying out international scientific research projects.

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Coordinator's message

This is the second part of special issue of the Polish Maritime Research quarterly, as continuation of No S2/2006, focused on presentation of a new idea of cargo and passenger inland ship with wide analyses of European inland waterways transport systems, information on properties of inland water routes which are collected in open database, presentation of environmental problems of specialized power plants and selected problems with inland ship design, production and application of new structural ideas like steel, sandwich panels. Presented papers are based upon research programs carried out within frame of the EU-supported EUREKA project INCOWATRANS – E!3065. Information related to all reports, papers, expertise and other activities carried out within project can be found at link: http://www.oce.pg.gda.pl/oce2/eureka.

Project Coordinator: Krzysztof Rosochowicz, Prof.

Project Eureka E!3065

A New Generation of Environment Friendly Inland & Coastal Ships for Polish East-West Waterways

INCOWATRANS

Chief executor and coordinator of the project :

Gdańsk University of Technology Faculty of Ocean Engineering and Ship Technology

Gdańsk 2007

Photo : Arkadiusz Łabuć

A new generation of inland modular vessels for polish east-west waterways with low depth

Tomasz Łącki*,
Krzysztof Rosochowicz**, Prof.
Joanna Bentkowska***

ABSTRACT

A new generation of inland environmentally friendly ships destined for waterways with critical limited depth is presented. General project concepts are supported by push system idea of standardized, optional equipped hulls for desirable exploitation necessities. A few traditional motor ships and barges are described as the background for comparison.

Keywords : inland shipping, waterways with restricted depth, environment protection, modularized ships.

As a result of long term negligence and unfinished hydrological investment ventures, Polish system of inland waterways diminished step by step and has achieved a condition which is so bad that is impossible to run regular inland shipping. Simultaneously, accepted the Nature 2000 Program indicated environmentally protected corridors along the main rivers, which practically eliminate larger investments. As a result of these conditions, to enable inland shipping to be carried on, it is necessary to create a new generation of inland water ships adapted to slightly correct and controlled parameters of waterways permitted by Bird and Habitat Directives.

From this point of view draught of new inland ships must be sharply restricted to maximum 1m. Breadth and length are the result of existed old locks dimensions and waterway bends.

In the frames of European Eureka Project, "Environmentally friendly inland and coastal ships for Polish East-West Waterways" Σ!3065 INCOWATRANS, we undertook activities to create a family of inland ships with limited dimensions. There are :

- universal general cargo/container motor ship 18/36 TEU (SINE 207)
- traditional bulk barge (2 options) (SINE 208)
- basic barge (pontoon) for multipurpose application of modular functional convertible blocks (container vessel, ro-ro, ferry, house boat, passenger cruiser), push system (SINE 209)
- passenger two-unit luxury vessel [push system (EUREKA II)].

A project consortium was formed by the following participants :

- Technical Universities and Research Institutes :
  - Gdansk University of Technology, Faculty of Ocean Engineering and Ship Technology as coordinator of the whole project with involvement of Faculties of Civil Engineering as well as Architecture
  - Warsaw University of Technology, Institute of Environmental Protection, Faculty of Civil Engineering – environmental problems
  - Wroclaw University of Technology, Faculty of Mechanical Engineering, Institute of Machines Design and Operations (Waterways)
  - Maritime Institute, Gdansk, logistic problems.
- Companies from the small and medium size enterprises sector :
  - Design Office SINUS Ltd., performing design work based on ships conception projects
  - DesArt Ltd., Design Office, optional FEM analysis.
- Foreign Partners – INFERT GmbH – Rostock, (Germany).

The consortium performed the work in two stages.

Definition stage included studies of inland water transportation conditions and possibilities in direction east-west, environmental problems as results of shipping revitalization in the inland running "wild" Polish waterways, studies of existing technical possibilities of ship systems and machinery, analyses of inland harbours and hydrotechnical infrastructure of waterways, new concepts of passenger terminals and first ideas of multimodal inland harbours. The computer information system in the field of waterways technical and shipping conditions were proposed. At the design and testing stage, designs of the ships were carried out and hydromechanical investigations of selected model of ships were performed. Also appropriate calculations of different alternative solutions of ship machinery, propulsion systems and equipment were carried out.

Inland ship during the building processes and operation create some ecological hazards (Fig.1). Therefore a range of different solutions were applied in the designed ships :

- diesel electric, diesel hydraulic or water jet propulsion system
- POD propulsion and steering system
- two propulsion systems
- use of low sulphur content fuels
- use of exhaust gas catalyst
- ballast water and all waste to be discharged only to utilization service station in harbours
- minimizing of fuel margin
- specialized modular container blocks for arranging of passenger cabins, sanitary machinery, power station in the passenger cruiser or house vessel
- use only natural media in the fire fighting systems
- automatic limitation of the oil contents in bilge water
- use of environmental friendly painting materials and other production and repair processes
- use of special ship sewage processes.

* Manager of Design Office „SINUS" Ltd – Gdansk, Poland
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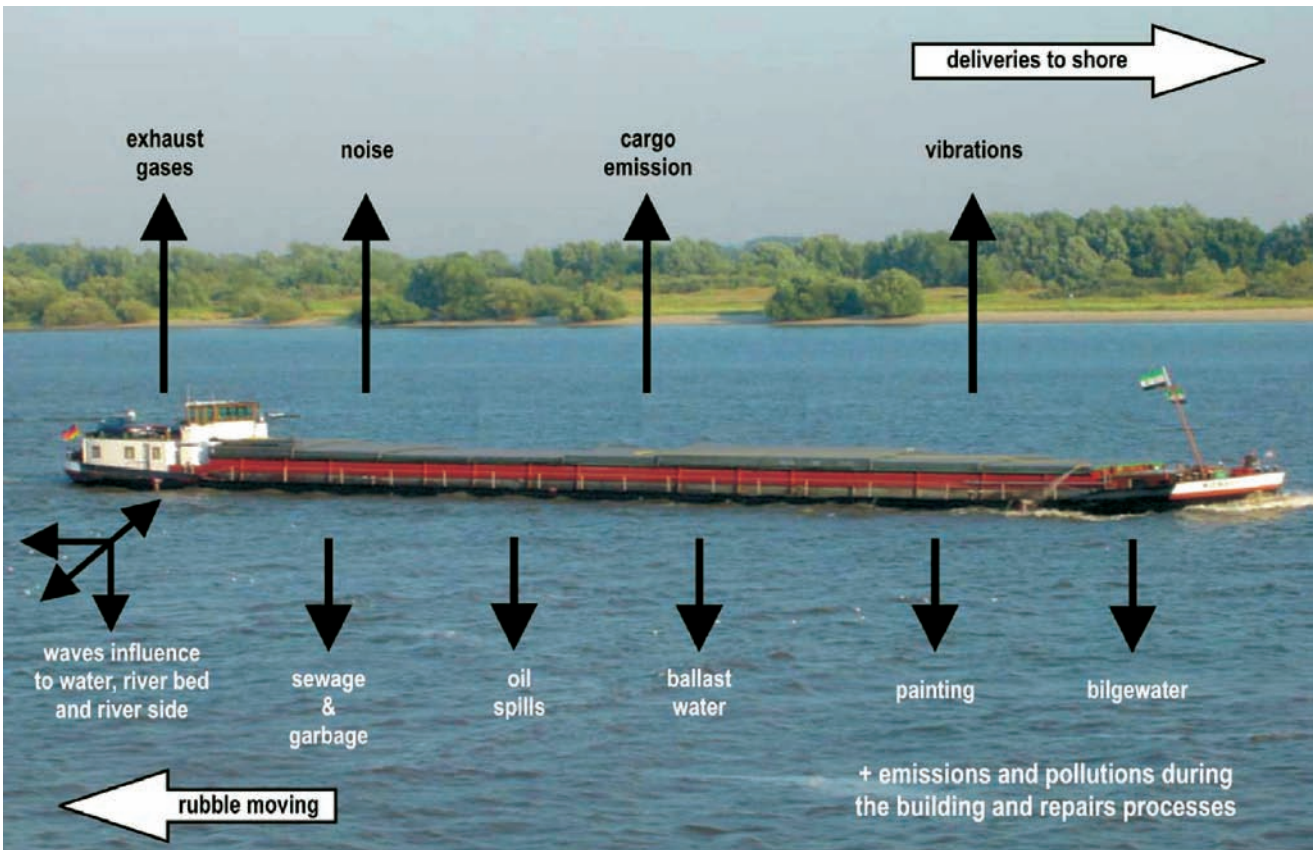


Fig. 1 Ecological hazards created by inland ship

The ships were designed according to Germanischer Lloyd and Polish Register of Shipping regulations. Additionally the vessels fulfil the requirements for class CLEAN DESIGN, what guarantees their harmless for environment.

Diesel-electric propulsion was applied to drive the ships. The propulsion consists of engines and generators Volvo Penta and also Schottel Pump-Jet propellers. This configuration is characterized by :

- ✶ fluent regulation of power consumption and achieved thrust
- ✶ low vibrations and noise
- ✶ very good manoeuvrability
- ✶ effective protection of propeller destruction on shallow water
- ✶ elimination of suction effect on shallow water.

In order to obtain the class CLEAN DESIGN there were applied the following solutions reducing hazardous influence of vessels on environment :

- addition of special substance "Urea" to limit NOx emission
- sewage tanks
- bilge tanks
- oil pollution tanks
- double bottom
- double sides
- ecological coatings for internal and external shell plating.

SINE 207 (inland general cargo/container 18/36 TEU) is adapted to transport 20' or 40' containers in three holds and on the hatch covers. The containers in holds are located in one layer in three rows. The same arrangement is provided for containers on hatch covers. In the holds the ship can transport also general cargo.

SINE 208 (inland general and bulk cargo push tow) consists of pusher tug and barges. The tug was designed in two options with different pull forces. Every of two types of barges, "Barge 1" and "Barge 2", occurs in two option with different high of coamings. Barges are adapted to transport general and heavy cargo (ore) in several arrangements.

SINE 209 (inland multi-purpose vessel) is composed of pusher tug and universal pontoon without own propulsion system. The pontoon is adapted to :

- ♦ carry house containers – the vessel becomes inland passenger ship in STANDARD or LUX version (house boat or cruiser)
- ♦ transport 20' or 40' cargo containers – the ship becomes inland container vessel
- ♦ transport wheeled vehicles – trailers, vans, lorries and cars – the ship becomes inland ferry or inland ro-ro vessel.

The following versions of vessel were designed :

VERSION IA – house boat for 34 passengers and 2 persons of crew
VERSION IB – cruiser for 28 passengers and 4 persons of crew
VERSION II – container vessel for 24 TEU or 6 TEU and 9 FEU
VERSION IIIA – ferry (in two configurations)
VERSION IIIB – ro-ro vessel (in two configurations).

Proposed modular solutions base on application of specialized functional containers. This equipment allows shipowner to change character of universal push tow depending on temporary market requirement and possessed transport orders. The innovation permits Shipowner, even the smallest one, to dispose of considerable transport potential with diversified structure without excessive development of inland fleet. The advantage of the multi-purpose vessel is economic

effectiveness of company. The solution allows operating in different sectors of market and indirectly improves environment protection conditions for inland waterways. Main parameters of the designed ships are given in the Table 1 and 2.

Table 1. *Traditional inland ships designed in the project*

Parameters	Type of ship			
	Coastal cargo/container SINE 207	**Pusher Tug SINE 208**	**Bulk Barge 1 SINE 208**	**Bulk Barge 2 SINE 208**
L_{OA}[m]	56.50	17.30	38.25	56.46
L_{BP} [m]	55.30	15.79	37.24	55.44
B [m]	9.0	9.0	9.0	9.0
T_1 [m]	1.0	1.0	1.0	1.0
T_2 [m]	1.6	1.6	1.6	-
H [m]	3.0	3.0	3.0	3.0
DWT (T_1) [T]	210	-	-	-
DWT (T_2) [T]	510	-	389	557
Holds capacity [m^3]	840	-	-	-
Container capacity	18/36 TEU	-	-	-
Engine power [kW]	620	2x240 or 2x294	-	-
Propulsion power [kW]	-	2x185 or 2x200	-	-
Propulsion system	Pump jet diesel electric	Pump jet diesel electric	-	-
Cruising speed [km/h]	15	15	-	-
Crew	max. 6 persons	6 persons	-	-
Total pull [kN]	-	25.9 or 40.8	-	-
GL-Class	GL ✠ 100A5 ✠ MCY	GL ✠ 100A5 TUG ✠ MC. CLEAN/D	GL ✠ 100A5 ORE. CLEAN/D	GL ✠ 100A5 ORE. CLEAN/D

Table 2. *Modular inland ships designed in the project*

Parameters	Type of ship					
	Basic barge (pontoon) SINE 209	**House boat version**	**Passenger ship version**	**Container version**	**Ferry version**	**Ro-Ro ship version**
L_{OA}[m]	56.55	=	=	=	=	=
L_{BP} [m]	56.0	=	=	=	=	=
B [m]	9.0	=	=	=	=	=
H [m]	1.20					
T [m]		0.7	0.7	0.9	0.9	0.9
Cruising range [days]	-	7	7	7	7	7
Container 20” [TEU]	-	-	-	24	-	-
Container 20”+40“ [TEU]	-	-	-	6 + 9	-	-
Passenger [persons]	-	34	28	-	-	-
Crew [persons]	-	2	4	-	-	-
Engine Power [kW]	-	-	-	-	-	-
Cruising range [days]	-	7	7	7	7	7
PRS class	PRS ✠ sk2 pas/pr/con/ro-ro “Clean Design”					

where :

L_{OA} – Length Over All of a Ship; L_{BP} – Length Between Perpendiculars of a Ship; B – Breadth of a Ship; T – Draft of a Ship; H – Height of a Hull; DWT – Dead Weight Tonnage; GL – Germanischer Lloyd; PRS – Polish Register of Shipping

The Fig. 2 ÷ 8 present general arrangement plans of ships. The ship documentation has been prepared to the level of preliminary design.

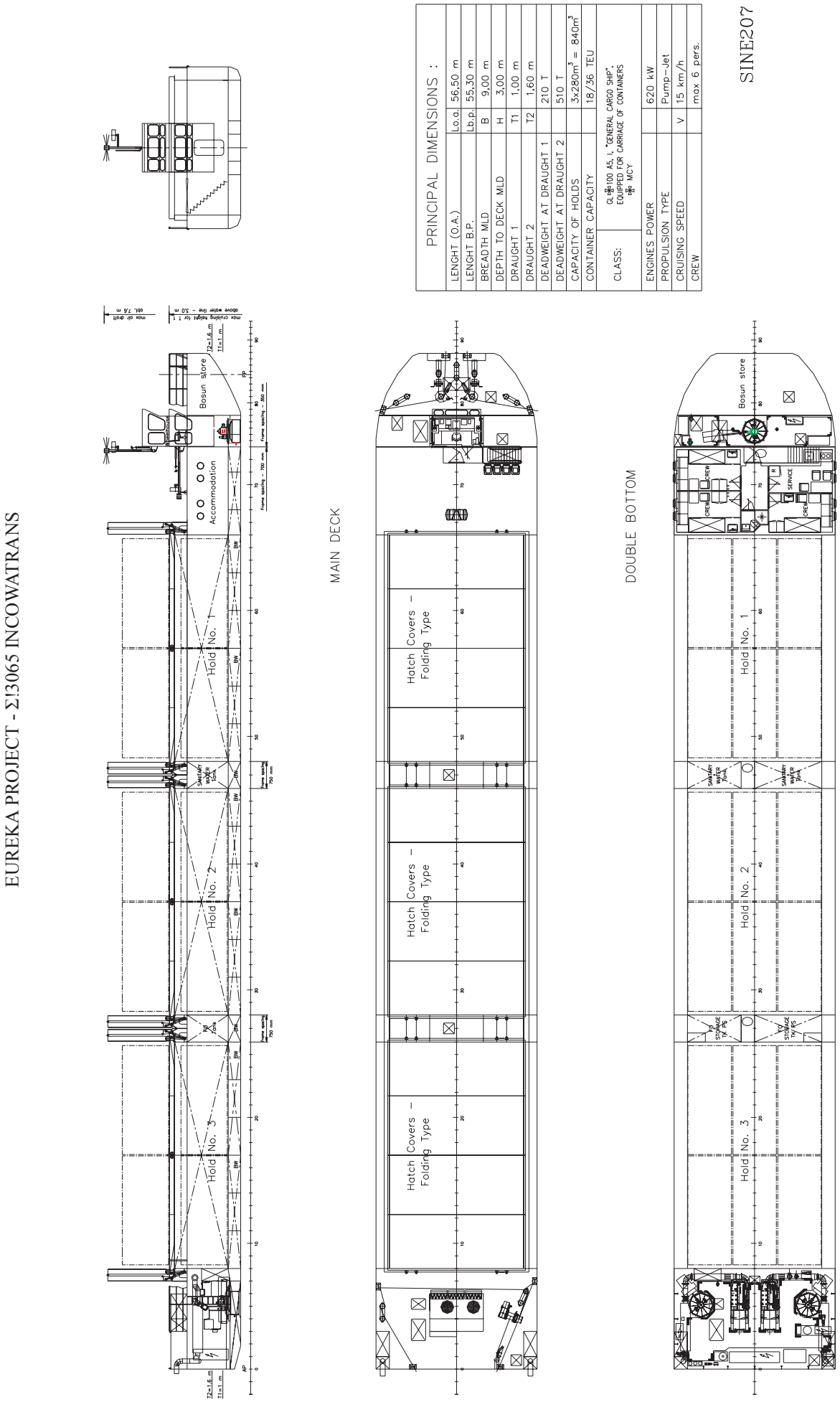
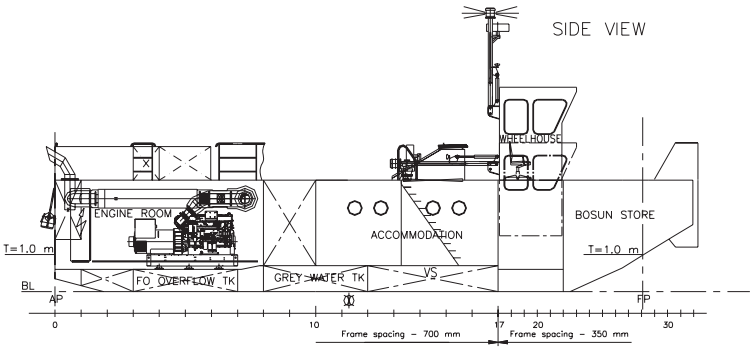
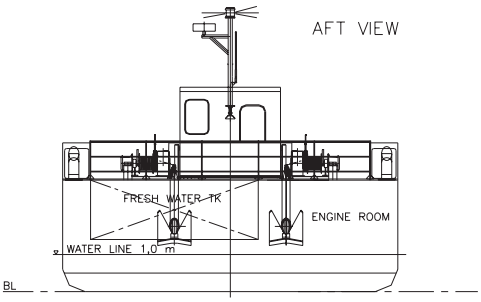
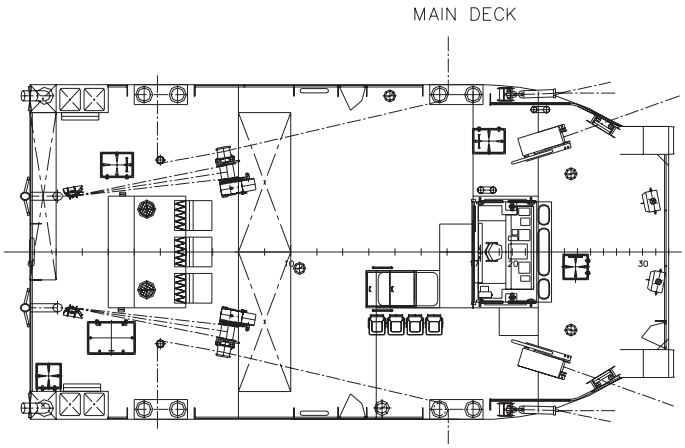


Fig. 2. Inland general cargo / container 18/36 TEU (SINE 207).

EUREKA PROJECT - Σ!3065 INCOWATRANS







PRINCIPAL DIMENSIONS:		
LENGHT (O.A.)	Lo.a.	17,300 m
LENGHT (B.P.)	Lb.p.	15,786 m
BREADTH MLD	B	9,00 m
DEPTH TO DECK MLD	H	3,00 m
DRAUGHT	T	1,00 m
CLASS:	GL ✠100 A5, I, "TUG", ✠ MC CLEAN DESIGN	
DIESEL ELECTRIC POWER		2X240 kWe
PROPULSION TYPE		Pump–Jet SPJ57
PROPULSION POWER		2X185 kW
TOTAL BOLLARD PULL		25,9 kN /2,64 T/
TRIAL SPEED	V	max 15 km/h
CREW		max 6 pers.

SINE208

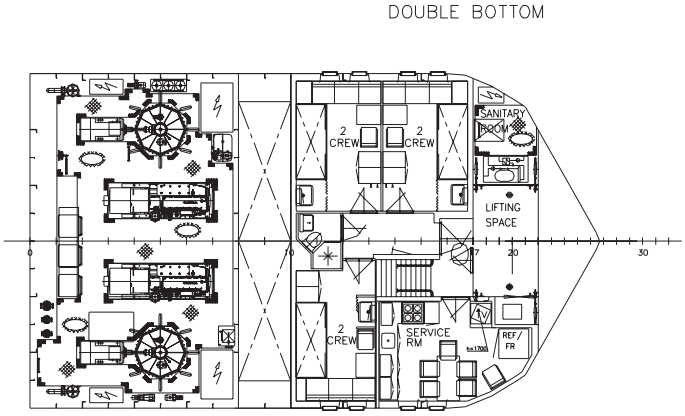


Fig. 3. *Pusher tug – first option (SINE 208).*

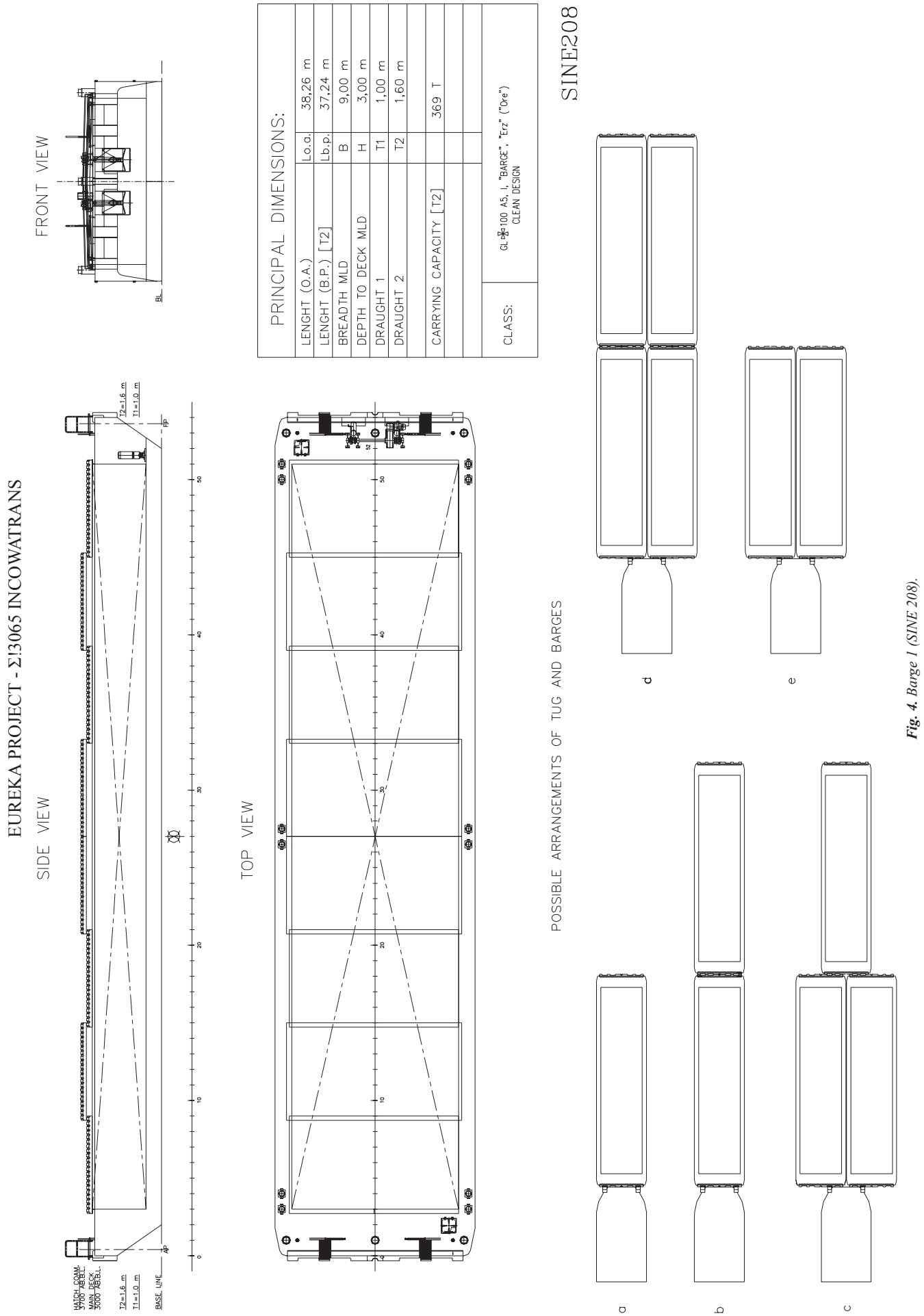


Fig. 4. Barge 1 (SINE 208).

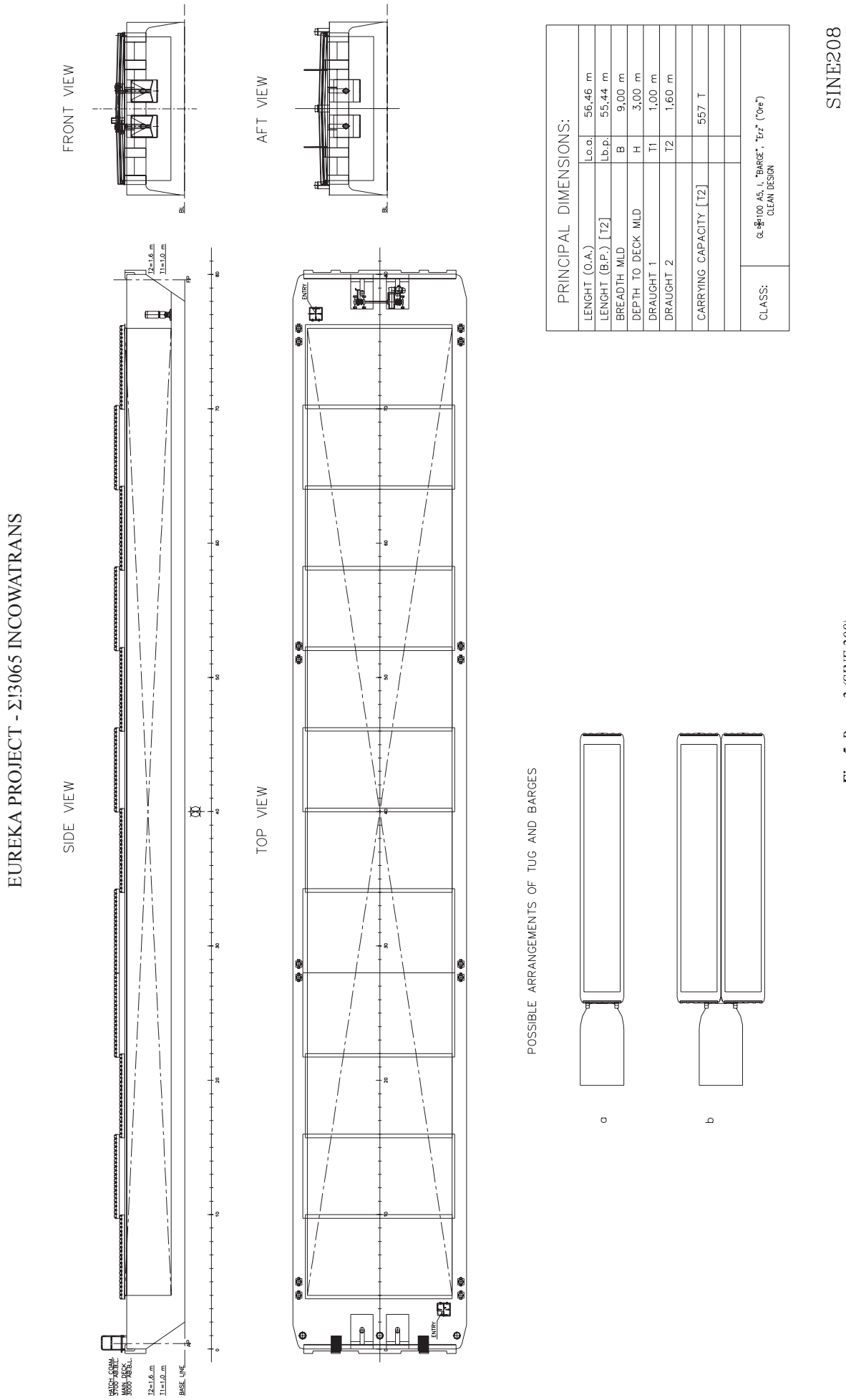


Fig. 5. Barge 2 (SINE 208).

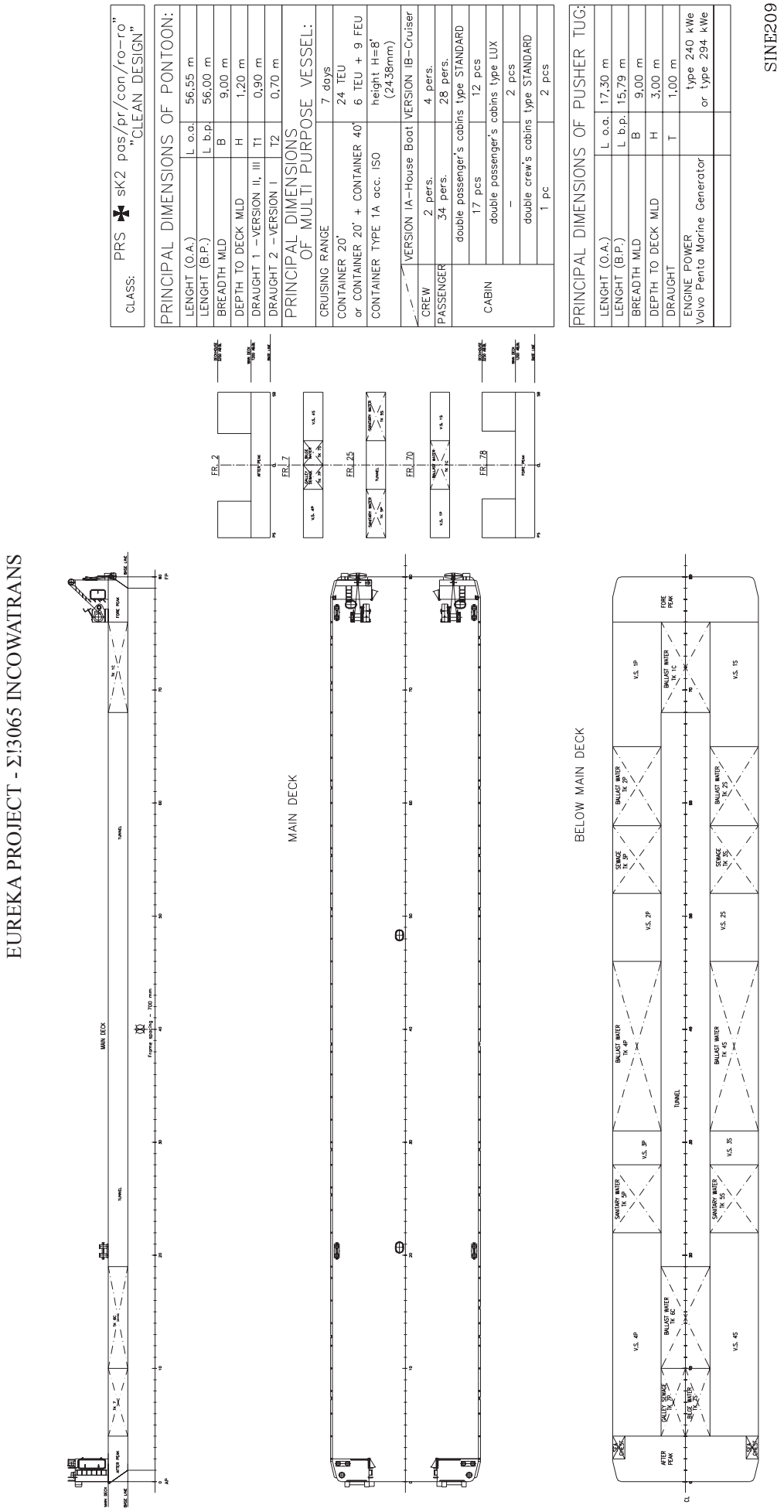


Fig. 6. *Multi-purpose vessel – basic pontoon (SINE 209).*

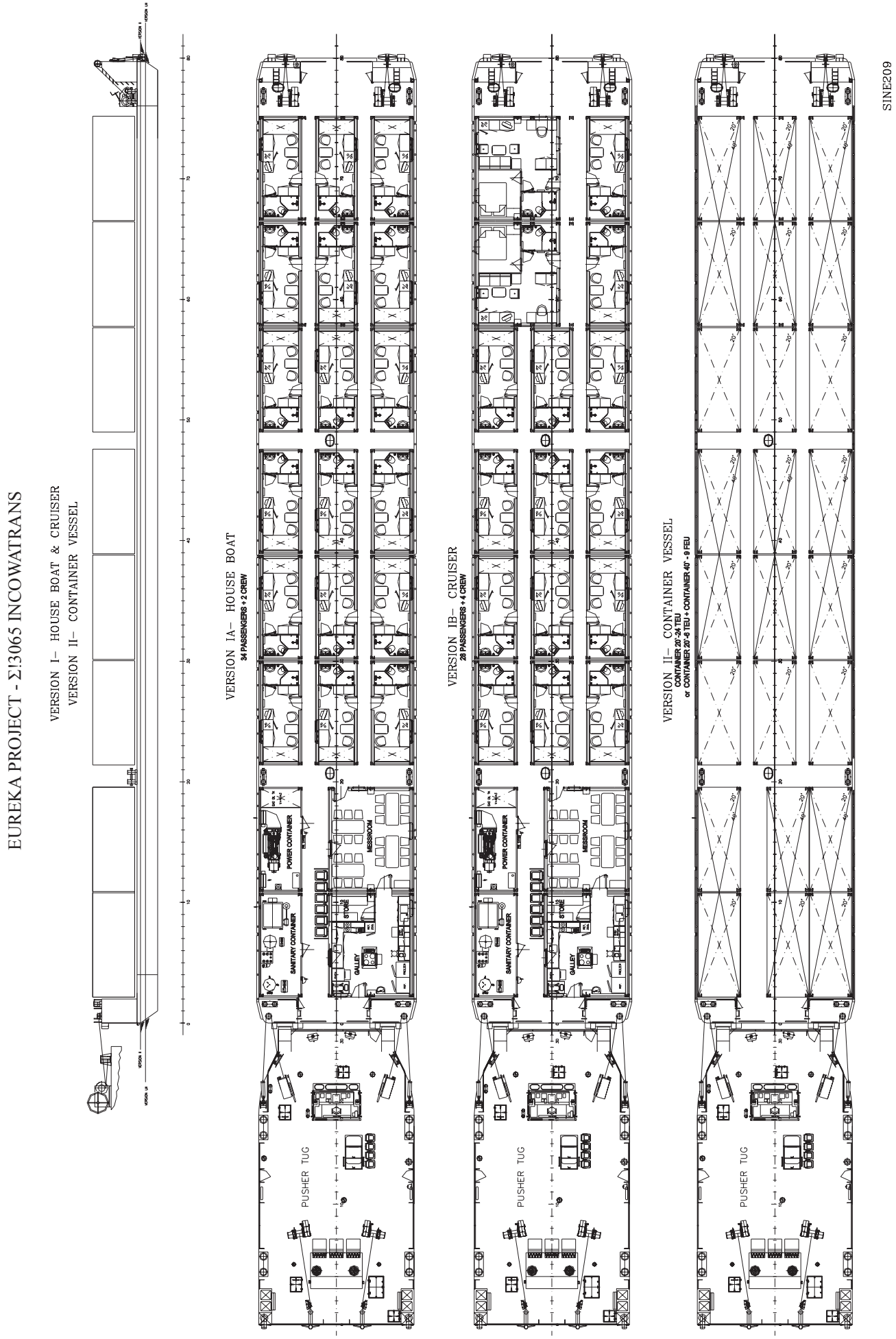


Fig. 7. Multi-purpose vessel – house barge, passenger barge, container vessel (SINE 209).

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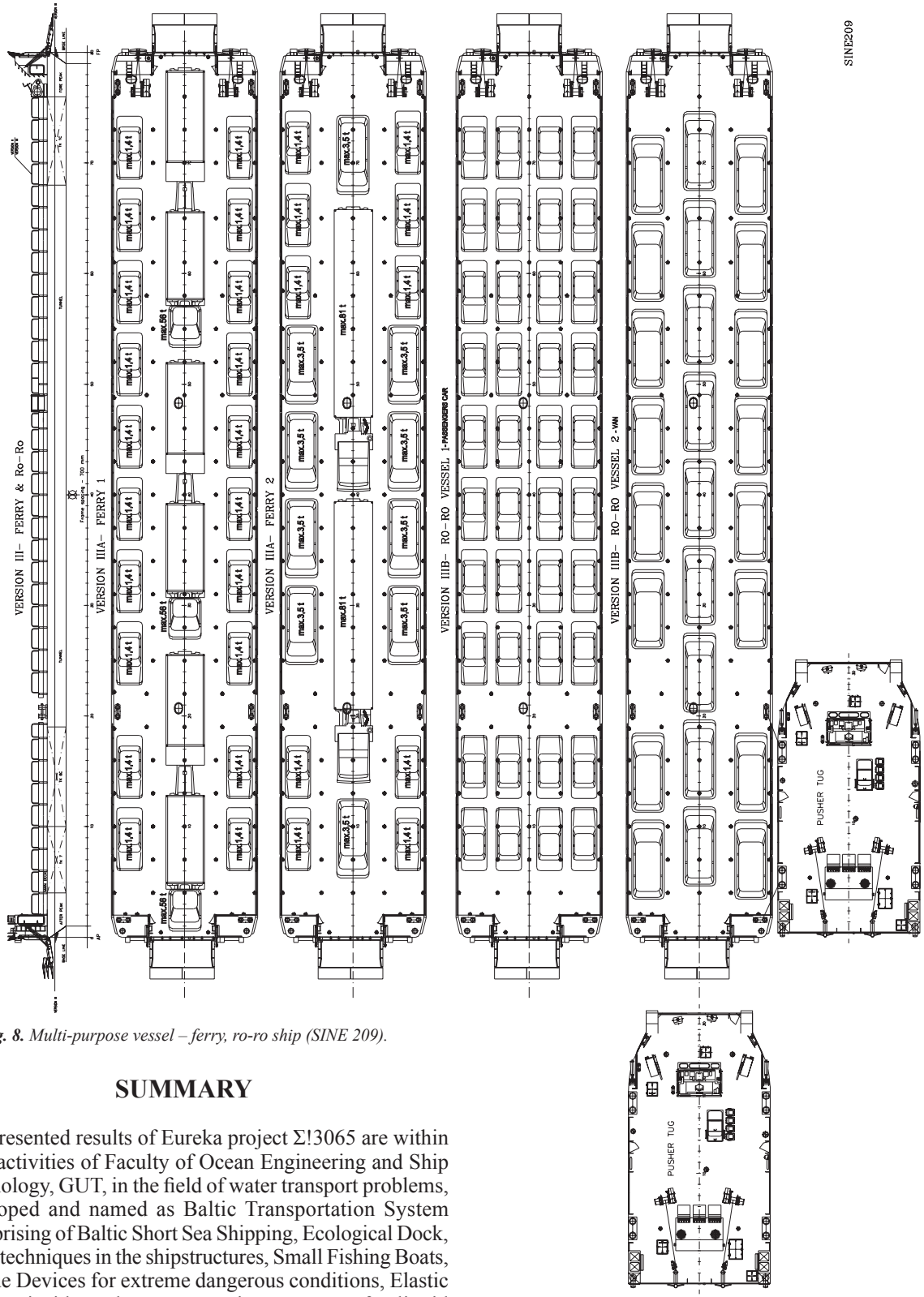

Fig. 8. Multi-purpose vessel – ferry, ro-ro ship (SINE 209).

SUMMARY

- The presented results of Eureka project Σ!3065 are within wide activities of Faculty of Ocean Engineering and Ship Technology, GUT, in the field of water transport problems, developed and named as Baltic Transportation System (comprising of Baltic Short Sea Shipping, Ecological Dock, Laser techniques in the shipstructures, Small Fishing Boats, Rescue Devices for extreme dangerous conditions, Elastic Coating inside tanks as preventive measures for liquid cargos spill and Inland Water Ships).
- The accumulated knowledge in the above described project is published in the 220 reports. Selected results will be presented in the special issue of Polish Maritime Research (December 2006, January 2007).
- The page www.oce.pg.gda.pl/oce2/eureka/inco/inco.htm presents titles of all carried works and reports.
- Realized project of Eureka system sponsored by the Polish Committee Scientific Research concerns facts, problems and solutions important for balanced development of economy, people and technology taking into account environmental protection conditions.
- The designed ships create opportunities for limited revitalization of Polish inland shipping respecting the Nature 2000 limitations and taking into account bad technical conditions of waterways.
- Inland shipping revitalization will create the base for economic and tourist development along the waterways.

BIBLIOGRAPHY

See Appendix

Warenströme in der Binnenschifffahrt der BRD

Boshidar G. Metschkow, Prof.
INFERT GmbH Wiendorf/Deutschland

EINFÜHRUNG

Die Volkswirtschaft der Bundesrepublik Deutschland zählt zu den leistungsstärksten Europas. Das relativ rohstoffarme Land importiert beachtliche Mengen verschiedenartigster Rohstoffe, Materialien und Halbzeuge, welche zu den Produktionsstätten auf dem Land- und dem Wasserwege transportiert werden. Dabei treffen die überseeischen Importe in den Nord- und Ostseehäfen wie Hamburg, Bremen, Kiel, Rostock u. a. ein und werden per Straßenfahrzeug, Eisenbahn oder Binnenschiff der Industrie zugestellt. Ausländische leistungsfähige und geografisch günstig gelegene Häfen wie Rotterdam und Antwerpen sind ein fester Bestandteil dieser komplexen Transportkette. Andererseits zählt Deutschland zu den Ländern mit dem größten Exportvolumen im globalen Maßstab. Industrielle Fertigwaren und andere in Deutschland hergestellte Produkte nehmen den umgekehrten Weg, um zu den Endverbrauchern oder zu den Kooperationspartnern in der ganzen Welt zu gelangen. Die zentrale Lage des Landes hat eine enorme Transportdichte zur Folge, infolgedessen der Verkehr zu einem der größten Energieverbraucher nicht nur in Deutschland, sondern auch in der EU geworden ist. Im Weißen Buch der Europäischen Kommission [1] veröffentlichte Untersuchungsergebnisse belegen den enormen Energieverbrauch des Verkehrs. Rund 30% des Gesamtenergieverbrauchs in der EU entfallen auf den Verkehr, der ca. 71 % des Erdölverbrauchs verzeichnet.

Das ausgebaute Autobahn- und Straßennetz Deutschlands wird als Kreuzungspunkt des europäischen Güterverkehrs zunehmend intensiver belastet und es sind seit längerer Zeit Anzeichen einer Kapazitätsüberbeanspruchung sichtbar. Der flexible Straßenverkehr weist den größten Anteil am Güterverkehr auf, stellt aber zunehmend auch einen Umweltbelastungsfaktor dar, dessen Folgen globale Auswirkungen haben. Das ungünstige Verhältnis zwischen Energieverbrauch und Transportleistung des Straßenverkehrs hat deshalb die Europäische Kommission bewogen, eine Verlagerung des Güterverkehrs auf Wasserstraßen und Schienen zu empfehlen, um der Überlastung der Infrastruktur des Straßennetzes entgegenzuwirken und die Umweltbelastung zu reduzieren [1]. Folgerichtig hat Jaques Barrot, der für Verkehr zuständige Vizepräsident der Kommission unterstrichen, dass die EU sich verstärkt darum bemühen müsse, den Straßen- und Luftverkehr wirksamer und umweltfreundlicher zu gestalten. Das Europäische Parlament hat bereits im Jahre 2005 eine Einigung für die Co-Finanzierung von 30 prioritären Transportprojekten als Bestandteil eines transeuropäischen Wasserwege-Netzwerkes im Zeitraum 2007-2013 erzielt. Die europäische Förderung für diese Projekte kann bis zu 30 % der Realisierungskosten betragen, wobei Machbarkeitsstudien mit bis zu 50 % gefördert werden können [2]. Die Implementierung eines transeuropäischen Managementsystems für die Wasserstraßentransporte (river information service RIS) wird ebenfalls mit bis zu 20 % aus europäischen Fonds unterstützt.

Die Anstrengungen zur Umlenkung der Güterströme von der Straße auf Schiene und Wasserwege erfordern Finanzierungen in Milliardenhöhe, wobei allein die Ausgaben für die Schaffung des transeuropäischen Wasserwege-Netzwerkes im Zeitraum bis 2012 auf etwa 8 G€ geschätzt werden. Ausgaben dieser Größenordnung werden aber durch den wesentlich niedrigeren Energieverbrauch von Binnenschiffen im Vergleich zu Lastautos gerechtfertigt (s. Bild 1).

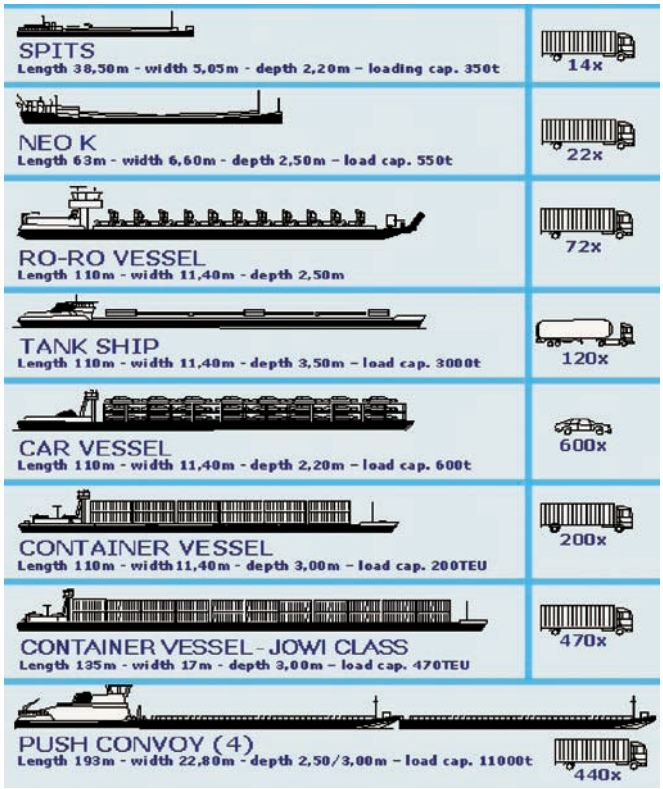

Bild 1. *Gegenüberstellung der Transportleistung von LKW und Binnenschiffen [2].*

Derartige Transportleistungen können allerdings nur die auf den größeren europäischen Strömen (Rhein, Donau, Elbe, Main, Seine, Maas) eingesetzten Binnenschiffe erreichen, aber auch bei begrenzten Wassertiefen sind kleinere Wasserfahrzeuge durchaus in der Lage, effektiver als der Straßentransport zu

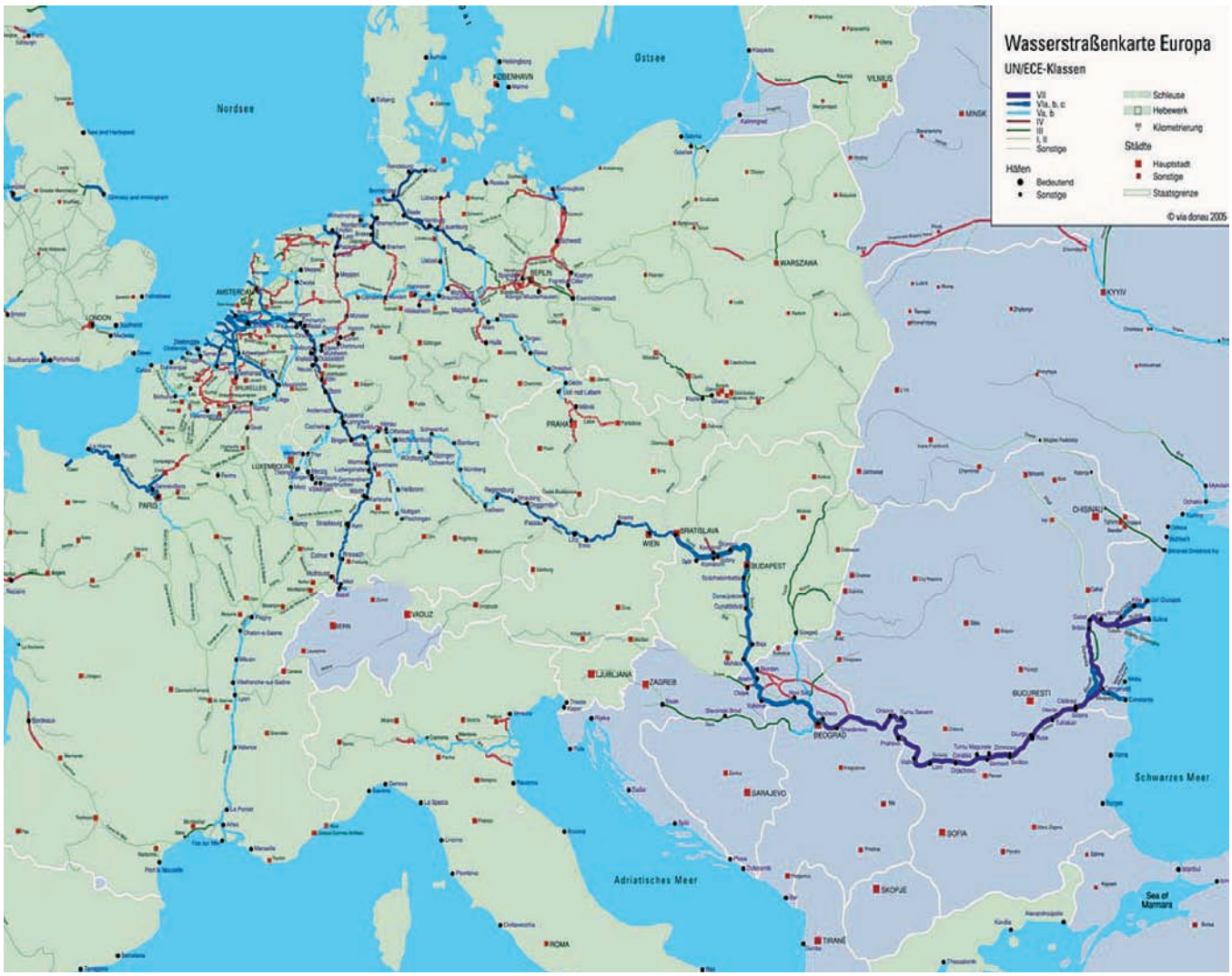

Bild 2. *Übersicht der Binnenwasserstrassen in der Europäischen Union und angrenzender Staaten [3].*

operieren. Die zunehmende Bedeutung des Containerumschlags schafft bei einer sinnvollen Kombination mit dem Schienenetz eine weitere Alternative zum Straßenverkehr. Durch die Erweiterung des Tourismus beginnt auch der Personenverkehr eine beachtliche Rolle bei der Binnenschifffahrt zu spielen und tritt als ein zusätzlicher positiver Faktor in Erscheinung, welcher die Anstrengungen zum Ausbau der Binnenwasserwege begünstigen kann.

DAS WASSERSTRASSENNETZ DEUTSCHLANDS

Sämtliche Belange der Binnenschifffahrt hängen primär vom Zustand des Wasserstraßennetzes ab, welches seinerseits ein wesentlicher Bestandteil der transeuropäischen Güterlogistik ist. Wie aus Bild 2 hervorgeht, verlaufen die meisten Binnenwasserstraßen Europas im Großraum der Nord- und Ostseeküste auf dem Gebiet Deutschlands, Hollands, Belgiens und Frankreichs. Eine echte transeuropäische Binnenwasserstrasse ist die Verbindung Rhein-Main-Donau, welche eine Nordsee-Schwarzes Meer-Achse bildet. Andere leistungsfähige Binnenwasserstraßen sind der Rhein, die Rhone, die Seine, die Elbe, der Po, die Oder und andere Flüsse, die von der Küste tief in das europäische Festland reichen.

Durch die gezielte Nutzung der natürlichen Gegebenheiten hat Deutschland seine Binnenwasserstraßen systematisch ausgebaut und zu einem inländischen Verbundsystem gestaltet. Rückgrat dieses Systems ist der Rhein, der zum größten Teil durch Deutschland fließt und in Bezug auf das Transportaufkommen als die wichtigste europäische Wasserstraße gilt. Die vier großen Flussgebiete (Rhein-, Elbe-, Weser- und Donaugebiet) sowie die Berliner- und Brandenburgisch-Mecklenburgischen Gewässergebiete sind mit zahlreichen Kanälen wie das Westdeutsche Kanalsystem, der Mittellandkanal, der Rhein-Main-Donaukanal, der Elbe-Havel-Oderkanal und anderen Querverbindungen miteinander verbunden. Zwischen den größten Flüssen, den Seehäfen und den Industrie- und Ballungsgebieten ist somit ein intensiver, energieeffizienter und umweltfreundlicher Güterverkehr auf dem Wasserwege möglich. Die Oder verbindet die Berliner- und die Brandenburgisch-Mecklenburgischen Gewässer direkt mit dem Nachbarland Polen und erfüllt eine ähnliche Transportfunktion wie der Rhein, der die Anbindung an die Binnenwasserstraßen in Frankreich, Holland und Belgien ermöglicht. Das deutsche Binnenwasserstraßennetz ist schematisch im Bild 3 gezeigt.

Das deutsche Binnenwasserstraßennetz ist das größte in Europa und die Gesamtlänge aller Wasserwege beläuft sich auf ca. 7476 km. Somit sind nicht nur die an den großen Flüssen liegenden Städte und Produktionsstandorte auf den Wasserwege erreichbar, sondern auch Ortschaften, die relativ weit davon entfernt sind. Mit der netzartigen, flächendeckenden Anbindung des Binnenlandes praktisch an alle wirtschaftlich bedeutenden Zentren sind günstige Bedingungen für die Umlenkung immer größerer Güterströme von der Straße auf die Wasserwege gegeben. Diese Möglichkeiten werden systematisch ausgebaut, wie die nachfolgenden Beispiele belegen.

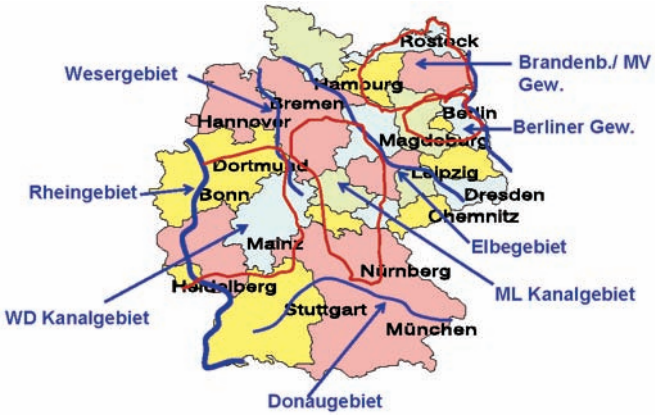

Bild 3. *Deutsches Binnenwasserstraßennetz.*

- ende 2006 wurde die größte Binnenschleuse Deutschlands eröffnet (Uelzen II). Die Schleusenkammern von Uelzen II haben eine Länge von 190 m und sind 12,5 m breit (Investitionsvolumen von 122 M€). Es wird ein Höhenunterschied von 23 m überwunden. Weitere 38 m werden bei Scharnebeck benötigt, um die Schiffe auf Elb-Niveau herunterzubringen [4]
- im Binnenhafen Nürnberg wurden im vergangenen Jahr (2006) insgesamt 31 M€ investiert und den Umsatz von 590 Kt (84.Platz in der Rangliste der Binnenhäfen Deutschlands) auf 11 Mt gesteigert (Verbesserung auf den 4.Platz). Die Bahn investiert in diesem Jahr 35 M€ für den Ausbau des Containerterminals (350.000 Container/ Jahr). Gleichzeitig mit dem Güterumschlag wird auch der Passagierverkehr weiter ausgebaut (allein im Jahre 2006 wurden im Binnenhafen Nürnberg 500 Passagierschiffe abgefertigt) [5]
- der Nord-Ostseekanal wird in den nächsten Jahren für Schiffe bis zu 280 m Länge ausgebaut (derzeit können nur Schiffe bis 235 m Länge die Verbindung zwischen der Nord- und der Ostsee passieren) [6].

Im Bild 4 ist eine moderne Binnenhafenanlage zu sehen, die inmitten eines Industriegebiets mit Anbindung an eine Autobahn lokalisiert ist.

Bild 4. *Deutscher Binnenhafen in einem Industriegebiet.*

Derartige Lösungen sind typisch für viele deutsche Binnenhäfen. Trotz dieser sehr gut ausgebauten Infrastruktur wird ein Großteil der Güterströme nach wie vor auf der Straße abgewickelt. Gerade daraus resultiert das deutlich ausgeprägte Bestreben der Europäischen Kommission zur Veränderung dieser Situation.

GÜTERUMSCHLAG DER DEUTSCHEN BINNENHÄFEN

Ein so stark und flächendeckend ausgebautes Binnenwasserstraßennetz ermöglicht die größten Transportleistungen im europäischen Güterverkehr. Die Leistungsfähigkeit der Binnenschifffahrt kann durch die zwei wichtigsten Kennzahlen – Menge der transportierten Güter (Transportvolumen) in t/Jahr und die Transportleistung charakterisiert werden. Letztere wird als die von den Gütern zurückgelegten Transportstrecken in tkm definiert. Der Güterumschlag kann somit nicht als alleiniges Kriterium angesehen werden, wenn es darum geht, die Leistungsfähigkeit der Binnenschifffahrt einzuschätzen. In der Tabelle 1 ist dieser Sachverhalt deutlich zu sehen.

Tabelle 1. *Leistungsfähigkeit der Binnenschifffahrt in ausgewählten EU-Ländern.*

Land	Transport-volumen Mt	Bewertung Punkte-skala 1 bis 10	Transport-leistung Gtkm	Bewertung Punkte-skala 1 bis 10	Mittelw. Binnen-schifffahrt
Großbrit.	1,56	0,06	0,03	0,005	0,033
Frankreich	58	2,1	7,3	1,15	1,73
Deutschland	271,2	10	63,6	10	10
Österreich	7,9	0,3	7,2	1,13	0,72
Holland	106,8	3,9	0,017	0,003	2,1
Belgien	145,1	5,4	0,002	0,0003	2,9

Anhand der in Tabelle 1 zusammengestellten Werte kann die Bedeutung der Wasserstraßen für die in der Binnenschifffahrt führenden EU-Länder abgelesen werden. Das für die Volkswirtschaft eines relativ kleinen Landes wie Belgien beachtliche Transportvolumen wird auf sehr kurzen Wegen realisiert, wie die Transportleistung in tkm zeigt. In Österreich dagegen halten sich das Transportvolumen und die Transportleistung die Waage und deshalb sind die Wasserstrassen auch wesentlich länger. Österreich hat lediglich 5,4 % des belgischen Transportvolumens aufzuweisen, übertrifft aber die belgische Transportleistung um das 3600-fache. Diese sehr differenzierte, um Größenordnungen streuende Leistungsfähigkeit der Binnenschifffahrt ist ein kennzeichnendes Merkmal für die gesamte Branche. Wenn für den Vergleich der Leistungsfähigkeit die in der letzten Spalte der Tabelle 1 angegebenen nicht gewichteten Mittelwerte herangezogen werden, so ergibt sich eine Rangfolge mit Deutschland als unangefochtenem Spitzenreiter. Die drei Positionen danach werden von Belgien, Holland und Frankreich belegt. Die Leistungsfähigkeit der Binnenschifffahrt tritt noch deutlicher hervor, wenn das Volumen der in Binnen- und Seehäfen Deutschlands umgeschlagenen Güter verglichen wird. Der Güterumschlag deutscher Seehäfen erreichte im Jahre 2006 die Marke von 320 Mt und ist somit lediglich um das 1,26-fache größer als der Umschlag der Binnenhäfen (271,2 Mt). Der Umschlag der Binnenhäfen berücksichtigt nur Güter, die nach oder von Deutschland transportiert worden sind. Somit werden Transitleistungen von und nach Drittländern in dieser Statistik nicht erfasst.

Das Bundesamt für Statistik in Wiesbaden veröffentlicht periodisch jeweils in der Mitte des laufenden Kalenderjahres Übersichten zur Leistung der Binnenschifffahrt im Vorjahr [7]. Bezug nehmend auf die im Vorjahr 2004 erreichte Umschlagsleistung (um ca. 1,4% kleiner als im Jahre 2005), wies das Bundesamt darauf hin, dass für den Transport dieser Gütermenge auf der Straße fast 27 000 LKW-Fahrten täglich erforderlich wären, wenn die Nutzlast der Fahrzeuge 24 Tonnen beträgt. Alle diese Fahrzeuge hintereinander gereiht würden eine Kolonne von ca. 540 km Länge ergeben (ungefähr die Strecke von Berlin nach Frankfurt/Main). Würden stattdessen dafür Eisenbahnwaggons mit einer Tragfähigkeit von 40 Tonnen eingesetzt, würde das deutsche Schienennetz pro Tag

mit zusätzlichen 16200 Güterwaggons belastet. Die Folge wären ca. 9,8 Millionen LKW- oder aber etwa 5,9 Millionen Güterwaggon – Fahrten innerhalb eines einzigen Jahres. Abgesehen von der sowohl von den LKW als auch durch die Bahn verursachten höheren Umweltbelastung durch den CO_2 – Ausstoß, wäre derzeit weder das Straßen- noch das Schienennetz Deutschlands in der Lage, diese Güterströme zu bewältigen. Dagegen stößt die potentielle Durchlassfähigkeit der Wasserstraßen noch nicht auf ihre Grenzen.

Mit den in [7] und [8] enthaltenen Werten lässt sich die Leistungsfähigkeit deutscher Binnenhäfen grafisch verdeutlichen. Die Statistik des Bundesamtes weist die 99 leistungsstärksten Binnenhäfen detailliert aus und fasst weitere 100 kleinere Häfen zu einer gemeinsamen Gruppe zusammen. Wird der arithmetische Mittelwert aller 99 namentlich genannten Binnenhäfen als Bezugsbasis gewählt, so ergibt sich der Umschlagsindex jedes Hafens als Quotient seines Umschlagsvolumens und des Mittelwertes. Im Bild 5 ist eine Übersicht der 20 leistungsstärksten Binnenhäfen angegeben.

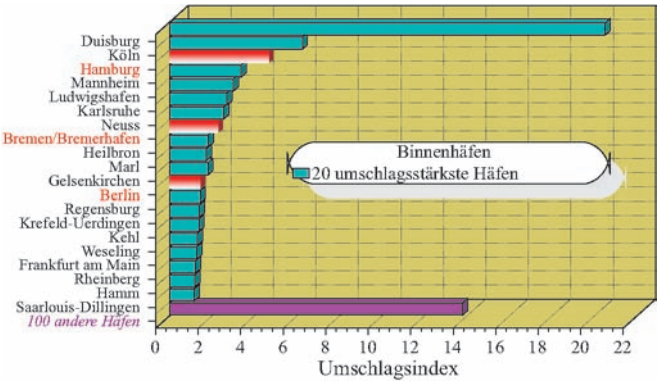

Bild 5. *Die leistungsstärksten deutschen Binnenhäfen.*

Mit großem Abstand wird die im Bild 5 gezeigte Rangliste vom Binnenhafen Duisburg angeführt, dessen Umschlag größer ist als die Summe der nächstfolgenden acht Häfen. Die mit rot-weißer Farbe gekennzeichneten Häfen sind am Gütertransport von oder nach Polen beteiligt. An letzter Stelle ist der summarische Güterumschlag von 100 Häfen angegeben, die in der Statistik nicht differenziert erfasst worden sind. Sie erreichen etwa 70% des Umschlags des Duisburger Hafens.

Diese im Bild 5 gezeigten Werte belegen, dass die leistungsstärksten Binnenhäfen im Rheingebiet liegen. Die Binnenhäfen Hamburg und Bremen/Bremerhafen sind direkt an die gleichnamigen Seehäfen gekoppelt und sind als Drehscheiben des Güterverkehrs von zentraler Bedeutung für die Volkswirtschaft. Eine ähnliche Position haben alle Binnenhäfen im Rheingebiet, deren Anbindung an Antwerpen und Rotterdam den beachtlichen Güterumschlag von und nach Belgien und Holland ermöglicht.

Aus der geografischen Verteilung der Industriezentren und Ballungsgebiete und deren Anbindung am Wasserstraßennetz ergeben sich sehr deutliche Unterschiede im Güterumschlag der deutschen Binnenhäfen. Zwischen den insgesamt acht Wasserstraßengebieten sind signifikante Unterschiede bei der Güterumschlagsleistung feststellbar, wie Bild 6 zeigt.

Bild 6 unterstreicht eindrucksvoll die Dominanz des Rheingebiets beim Güterumschlag deutscher Binnenhäfen. Er ist über 5-fach größer als der Durchschnittswert, der dem Umschlag der Binnenhäfen im Westdeutschen Kanalgebiet entspricht. Am Güterumschlag der im Rhein- und im Donaugebiet liegenden deutschen Binnenhäfen ist die polnische Wirtschaft nicht beteiligt (alle mit rot-weißer Farbe gekennzeichneten Gebiete empfangen Güter von Polen oder versenden Waren nach Polen). Die in unmittelbarer Nähe polnischer Binnenwasserstraßen gelegenen Gebiete, insbesondere die Berliner und die brandenburgisch/mecklenburgischen Gewässer sind für den deutschen Güterumschlag von einer wesentlich kleineren Bedeutung als das führende Rheingebiet.

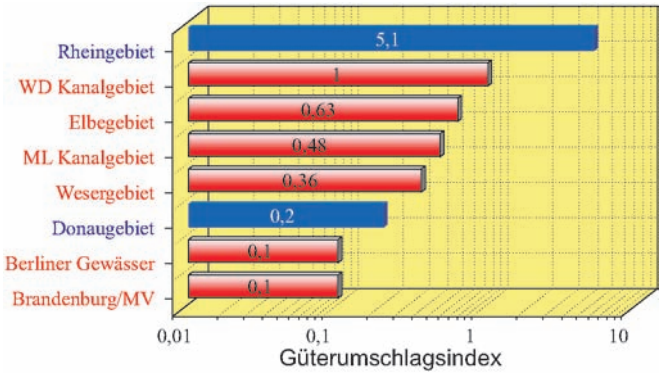

Bild 6. *Der gebietsweise deutsche Güterumschlag.*

Eine prozentuale Differenzierung der auf Binnenwasserstraßen transportierten Güter in Deutschland ist unter Berücksichtigung der Güterspezifik wie im Bild 7 möglich. Die vier dominanten Güterarten mit einem prozentualen Anteil über 10 % sind der Abraum (Steine, Erden), das Erdöl und die Erdgase, die festen mineralischen Brennstoffe (Koks, Stein- und Braunkohle) sowie die Erze einschließlich metallischer Abfälle. Der Löwenanteil des Güterumschlags entfällt folglich auf feste, flüssige oder gasförmige Massengüter.

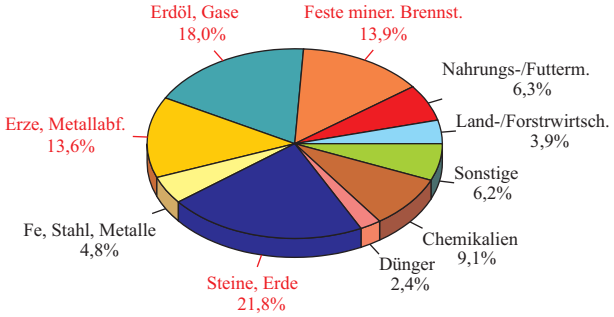

Bild 7. *Struktur des Güterumschlags deutscher Binnenhäfen.*

Der zunehmende Trend eines verstärkten Containereinsatzes wird nicht primär beim Transport von Massengütern, sondern insbesondere bei Nahrungs- und Futtermitteln, Chemikalien, Düngern und sonstigen Waren beobachtet, deren summarischer Anteil über 20% liegt. Eine wesentliche Transportleistung, deren Bedeutung gerade in den letzten Jahren nachdrücklich in den Blickpunkt der Binnenschifffahrt rückt ist der Touristik- und der Passagierverkehr, welcher jedoch noch nicht gesondert ausgewiesen wird.

Der gesamte Güterumschlag deutscher Binnenhäfen (271,2 Kt) setzt sich aus zwei Warenströmen zusammen – Güter, die aus Deutschland ins Ausland mit Binnenschiffen befördert (157,2 Kt) und solche, die zum innerdeutschen Transportvolumen gehören (115 Kt). Allein aus der Dominanz der Binnenhäfen im Rheingebiet resultiert die Spitzenposition der unmittelbaren Nachbarländer Belgien, Holland und Frankreich in der Struktur des deutschen Güterumschlags auf Binnenwasserstraßen. Wenn der Güterumschlag in seine zwei Bestandteile (Empfang und Versand von Gütern) nach Ländern aufgeschlüsselt wird, lassen sich die Größenordnungsdifferenzen besser darstellen, wenn entsprechende Güterumschlagsindizes eingeführt werden. So ergibt sich der Güterumschlagsindex aus dem Quotienten der empfangenen bzw. versandten Gütermenge und dem Mittelwert

der empfangenen bzw. versandten Güter. Die Größenordnungs unterschiede werden dann in einem logarithmischen Maßstab darstellbar. Wegen der Übersichtlichkeit werden bei den nachfolgenden Darstellungen nur die ersten 10 Länder der jeweiligen Rangliste berücksichtigt. Im Bild 8 ist die Rangliste beim Umschlag empfangener und versandter Güter gezeigt.

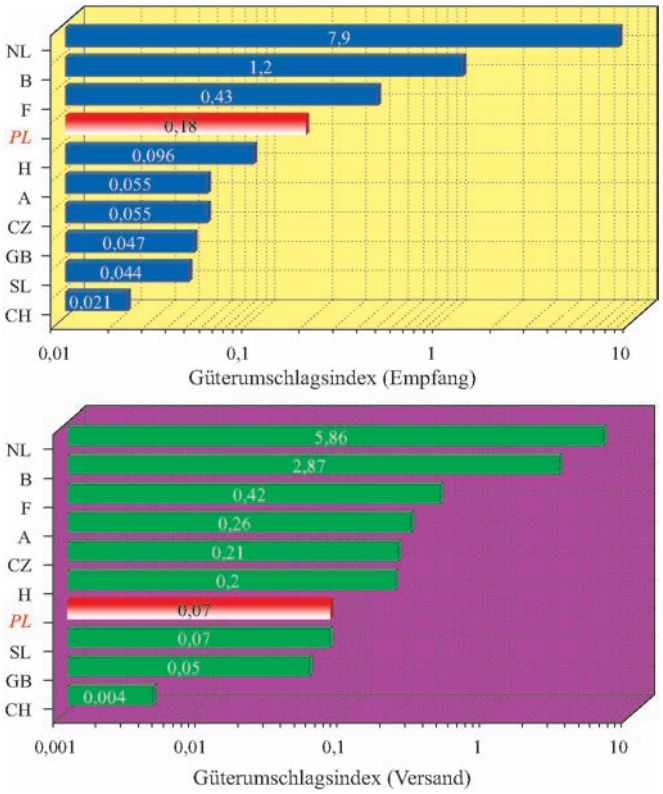

Bild 8. *Rangfolge des Güterumschlags deutscher Binnenhäfen mit dem Ausland.*

Beide Darstellungen im Bild 8 belegen erneut die Ausnahmeposition von Holland und Belgien beim deutschen Güterumschlag auf Binnenwasserstraßen. Schon das drittplazierte Frankreich versendet und empfängt nach bzw. von Deutschland ca. 15- bzw. 13-fach weniger Güter als Holland. Der Anteil Polens ist beim Empfang mehr als 2-fach größer als beim Versand, aber im Vergleich zu Holland ergeben sich in beiden Fällen schon Größenordnungsunterschiede.

GÜTERUMSCHLAG VON UND NACH POLEN

Trotz der geografischen Nähe zu den polnischen Ostseehäfen Szczecin/Swinoujscie, Gdynia, Gdansk und anderen kleineren Seehäfen sowie der von einer leistungsfähigen Binnenwasserstraße (Oder) gebildeten Landesgrenze im Norden hält sich der Güterumschlag zwischen Deutschland und Polen eher in bescheidenen Grenzen, wie die obigen Übersichten zeigen. Die Ursachen dafür sind komplexer und vielfältiger Natur, sie sind teilweise historisch bedingt, stellen aber keinen Gegenstand dieses Berichtes dar, da sie von polnischen Projektteilnehmern untersucht worden sind. Mit der Schaffung eines einheitlichen transeuropäischen Binnenwasserstraßennetz es werden sich einige entscheidende Randbedingungen günstig verändern, welche den Güterumschlag auf Binnenwasserstraßen von und nach Polen beleben können.

Der gesamte polnische Anteil am Güterumschlag deutscher Binnenhäfen, der als die Menge umgeschlagener, aus Polen eintreffender oder nach Polen versandter Güter verstanden wird, beträgt lediglich 0,81 %. Im Rahmen der empfangenen Güter beläuft sich dieser Anteil auf 1,13% und die nach Polen versandten Güter stellen gerade mal 0,3 % der Versandleistung deutscher Binnenhäfen dar. Von den acht Binnenwasserstraß engebieten Deutschlands sind sechs am Güterumschlag mit Polen beteiligt (Bild 9).

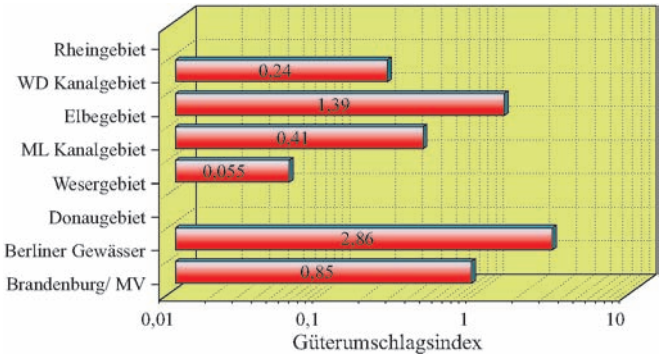

Bild 9. *Güterumschlag deutscher Binnenhäfen von und nach Polen.*

Im Bild 9 ist der Güterumschlagsindex als Quotient des Umschlags des jeweiligen Gebietes und des Mittelwertes des Gesamtgüterumschlags von und nach Polen definiert. Der aus den Berliner Gewässern, dem Elbegebiet und den brandenburgisch/mecklenburgischen Gewässern erzielte Güterumschlag hat die größte Bedeutung für Polen. Die Hauptverkehrsader der Binnenschifffahrt Deutschlands – das Rheingebiet – ist an diesem Umschlag nicht beteiligt und das Wesergebiet sowie das westdeutsche Kanalgebiet zeigen nur eine schwache Präsenz. Grenzüberschreitende Binnenwassertransporte zwischen Deutschland und Polen sind folglich als Anbindung an die geografisch nächst gelegenen Berliner und brandenburgisch/mecklenburgischen Gewässer und an das Elbegebiet zu betrachten, wenn die Problematik des künftigen Ausbaus polnischer Binnenwasserwege und Häfen diskutiert wird. Gleiches gilt sinngemäß auch für die Wasserfahrzeuge, die unter dem Blickwinkel der benachbarten Wasserstraßen mit einer relativ kleinen Tiefe und verhältnismäßig stark schwankendem Wasserpegel zu konzipieren sind.

Empfänger und Versender von Gütern aus und nach Polen sind im wesentlichen Binnenhäfen Deutschlands, die in den geografisch benachbarten Gebieten liegen. Der Spitzenreiter dieser Häfen ist Berlin, gefolgt von Brandenburg und Hamburg. Wie aus Bild 10 ersichtlich, wird der Güterumschlag mit Waren von und nach Polen in Häfen abgewickelt, die – mit Ausnahme von Hamburg und bedingt auch Berlin – keine Spitzenposition in der Rangliste deutscher Binnenhäfen aufweisen (die Ranglistenposition im Güterumschlag deutscher Binnenhäfen ist im Bild 10 in Klammern nach dem Namen des Hafens angegeben). Der Binnenhafen Berlin ist der Spitzenreiter beim Güterumschlag von und nach Polen. Der zweitplazierte Hafen Brandenburg weist im Vergleich mit Berlin einen um etwa ein Drittel kleineren Umschlag auf. Seine Spitzenposition im Güterumschlag mit Polen ist aber wegen der relativ kleinen Umschlagsmenge nicht ausreichend, um ihm einen vorderen Platz in der Rangliste des Gesamtgüterumschlags zu sichern (Brandenburg belegt nur den 68. Platz).

An dieser Stelle muss jedoch vermerkt werden, dass die obige Statistik ausschließlich den deutschen Güterumschlag in Binnenhäfen berücksichtigt und nicht schlechthin als eine Grundlage für die Bewertung des deutsch-polnischen Güterverkehrs auf Binnenwasserstraßen dienen kann. Aussagefähiger ist zweifelsohne ein Datenmaterial, das auch die von polnischen Binnenschiffen realisierten Gütertransporte von und nach Deutschland widerspiegelt.

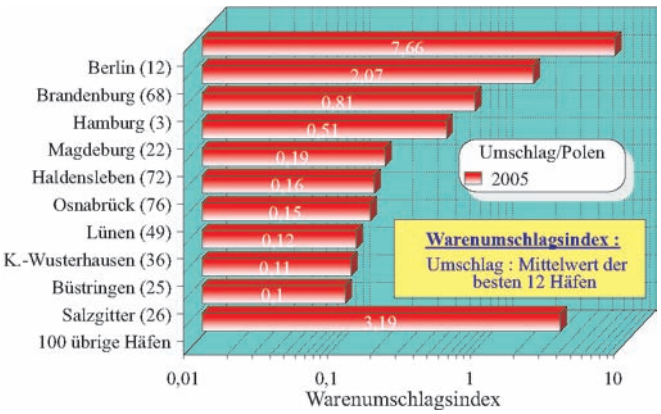

Bild 10. *Rangliste deutscher Binnenhäfen beim Güterumschlag von und nach Polen.*

ZUSAMMENFASSUNG

- In der Bundesrepublik Deutschland werden beachtliche Güterströme auf Binnenwasserstraßen transportiert. Das Rückgrat des Güterumschlags bildet die Binnenschifffahrt im Rheingebiet. Das Rheingebiet wird mit anderen größeren Flüssen wie die Elbe, die Donau, die Weser und die Oder mit einem Netz von Kanälen verbunden. Somit stellt der Gütertransport auf Binnenwasserstrassen ein wichtiges Bindeglied zwischen See – und Landverkehr dar und ist ein integraler Bestandteil des transeuropäischen Verbundsystems.

- Der Gesamtgüterumschlag der Binnenhäfen ist in der BRD vergleichbar mit dem Umschlag der deutschen Nord- und Ostseehäfen. Die Binnenschifffahrt entlastet spürbar die Infrastruktur des Landverkehrs, insbesondere das stark beanspruchte Straßennetz aber auch die Eisenbahn und stößt im Unterschied dazu noch nicht auf ihre Kapazitätsgrenzen. Trotz der noch vorhandenen Kapazitätsreserven wird das Kanalsystem der BRD systematisch erweitert und modernisiert, um die Durchlassfähigkeit weiter zu verbessern.

- Die Transportkette Seehäfen – Eisenbahn – Binnenwasserstrassen wird für den Containerverkehr gezielt ausgebaut, wobei dem Passagierverkehr eine immer deutlich sichtbarere Bedeutung beigemessen wird.

- Der polnische Anteil am Güterumschlag der Binnenhäfen der BRD ist sowohl bezüglich der empfangenen als der versendeten Güter relativ gering und deshalb ausbaufähig.

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Photo : Arkadiusz Łabuć

Current state and prognoses of the structure of cargo transport on Polish and European inland water transport area

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ABSTRACT

The present report was prepared within the framework of research activities carried out in the Maritime Institute in Gdansk, when taking part in the international research project EUREKA E! 3065 INCOWATRANS, the goal of which was working out preliminary designs of new-generation ships for inland and coastal navigation, and preparing technical and economic structure for the revitalisation of inland waterways in Poland, with their further incorporation to the European transportation system. The article aims at analysing the present state and assessing the future potential of cargo routes observed in inland East-West water transport, i.e. between Poland and Western Europe countries.

Keywords : inland water transport, Europe, State, flow of cargo, potential for development.

INTRODUCTION

The use of inland transport in European countries was analysed. Moreover a detailed analysis was performed of the scale and structure, with respect to both directions and types, of the cargo carried by inland transport between Poland and Western European countries. According to the assumptions of the EU transport policy, oriented on shifting some volumes of cargo from road and railway transport to water transport, as well as on sustainable development of the entire transport structure, this is the area in which potential cargo for water transport can be looked for. An attempt was made to assess potential volumes of cargo which could be carried by inland water transport. The scope of the analysis includes cargo transport between voivodeships situated along the E-70 waterway, which links the Western European countries with Russia and Lithuania. On Polish territory this waterway goes from the Oder-Havel Canal to the Hohensaaten lock, then along the lower part of the Oder river through Kostrzyn, along the Warta and Notec Rivers to the Bydgoszcz Canal, and finally along the Brda and lower Vistula Rivers through the Nogat River distributary to the Vistula lagoon.

USE OF INLAND NAVIGATION FOR CARGO TRANSPORT IN EUROPEAN COUNTRIES

In 2004, the inland water navigation in EU countries transported about 408 million tonnes of cargo (65 760 million tonne-kilometres), 48% of which was the domestic transport and 52% was the international transport (percentages calculated with respect to volumes of the shipped cargo). The international transport included transit. To the highest degree the water transport is used in Germany and the Netherlands, contributing to 86% of total cargo carried by domestic and international transport in this sector in all EU member countries in 2004. The share of France and Belgium altogether was equal to 12%, while the combined share of Luxemburg and Austria equalled 1%, and that of all new member countries was also equal to as little as 1%. The highest dynamics in water transport development in that time was observed in Hungary and Luxemburg, increase by 20% and 15% in 2004 compared to 2003, respectively. Average transport increase in EU equalled 13.9% in 2004, when excluding Belgium and Poland. The domestic transport dominates in Poland and Czech, while in the remaining EU countries, except Luxemburg, it is the international transport which dominates.

In the domestic transport almost half of the transported volume is mineral raw materials and semiproducts, and construction materials. Self-propelled barges transported 81% products of this group. Among the non-EU countries and new EU member countries, inland waterways are most intensively used for international transports in Romania and Bulgaria, while remarkable decrease of the use of inland navigation for carrying goods has been observed in Czech in recent years.

General tendencies in the development of EU inland waterway transport in years 2001-2004 are given in Tab. 1.

Tab. 1. *EU inland waterway transport in years 2001–2004 .*

Country	2001	2002	2003	2004	2001	2002	2003	2004
	transport in thousand tonnes				transport in million tonne-kilometres			
Total EU	**395 465**	**382 651**	**357 894**	**407 533**	**58 337**	**58 505**	**54 655**	**65 760**
Belgium	127 870	134 463	137 145	...	7 655	8 073	8 230	...
Czech	1 747	1 569	1 184	1 176	78	80	58	48
Denmark	236 101	231 746	219 999	235 861	64 818	64 166	58 154	63 667
France	68 408	67 092	63 670	67 312	8 294	8 269	8 024	8 420
Luxemburg	11 061	8 568	9 704	11 180	371	281	316	370

Continuation Tab. 1								
Country	2001	2002	2003	2004	2001	2002	2003	2004
	transport in thousand tonnes				transport in million tonne-kilometres			
Hungary	5 897	7 093	6 137	7 356	2 346	3 076	1 517	1 904
Netherlands	328 913	311 507	293 390	319 219	41 793	40 804	39 031	43 092
Austria	11 634	12 316	10 737	9 072	2 557	2 846	2 276	1 747
Poland	...	...	...	7 296	...	...	…	370
Scandinavia	3 234	3 293	2 624	2 725	...	98	94	91

Source: EUROSTAT.

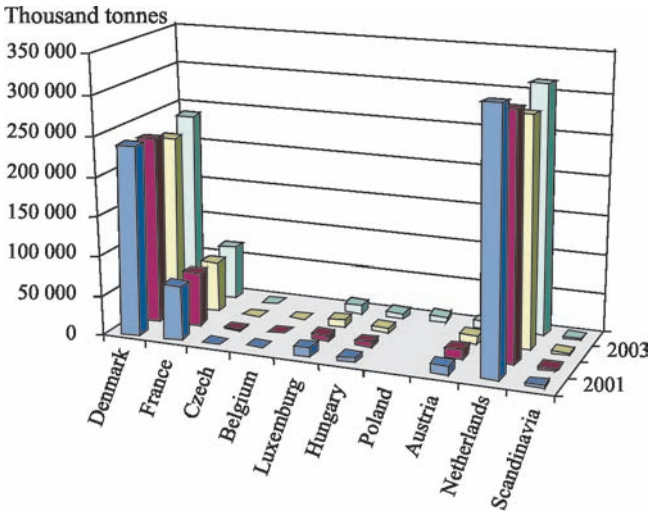

Fig. 1. *Inland waterway transport In EU countries. Source:* ***Tab. 1.***

The directional structure of the inland waterway transport between particular EU countries in 2004 is given in Tab. 2.

Out of the total volume of EU international waterway transports, about 75% takes place between three countries: the Netherlands, Germany and Belgium, and as much as 49% of total international transports in EU takes place between Germany and the Netherlands, while 17% between the Netherlands and Belgium. Using inland waterways, the Netherlands exported 117 million tonnes of cargo in 2004, out of which 110 million tonnes covered their exchange with Germany and Belgium, equalling to 94% of the total volume of the international transports. In inland waterway export, Germany is the main target of almost all transports from EU countries. Out of 95 million tonnes of total export to Germany, 80% is represented by the Netherlands, 14% by Belgium, and 6% by France. Germany is also the biggest cargo exporter using inland water transport.

In the type structure of domestic transports in 2004, nearly half were mineral raw materials, and construction materials and semiproducts, out of which 19% were oil products. At the same time the biggest proportion in the international transports were metals and scrap, contributing in 19% in total volume of the transported cargo. The volumes of transit transports in EU inland water transport in 2004 are given in Tab. 3.

With respect to cargo groups, transit transports are highly diversified in particular countries. In France, it was the cargo falling into group 0 in the NST/R classification, i.e. agricultural products and living animals, which was the biggest proportion (18%) . In Luxemburg the dominating cargo was that belonging to the group 6, i.e. mineral raw materials and semiproducts, and construction materials, and that belonging to group 3, i.e. oil products. Altogether, they amounted to 2/3 of total transport. The oil products were also relatively high proportions in transits in France, Germany, and the Netherlands : 35%, 17% and 15%, respectively.

Tab. 2. *Inland waterway transport between EU counties in 2004 (in thousand tonnes).*

Country of loading	Country of unloading										
	Total	Belgium	Czech	Germany	France	Luxemburg	Hungary	Netherlands	Austria	Poland	Scandinavia
Total	**211 003**	**54 893**	**436**	**94 712**	**12 644**	**1 269**	**1 333**	**40 960**	**4 223**	**316**	**217**
Belgium	22 454	x	2	11 851	5 175	282	50	5 041	52	1	0
Czech	255	16	x	222	-	-	.	17	-	.	-
Germany	48 284	14 700	357	x	1 798	387	381	29 324	998	311	28
France	15 253	3 854	.	5 231	x	208	27	5 933	.	.	.
Luxemburg	281	19	-	181	6	x	-	76	-	.	.
Hungary	1 676	69	-	659	6	23	x	333	585	.	2
Netherlands	117 413	36 110	78	73 947	5 634	370	314	x	957	4	.
Austria	1 411	95	-	440	24	-	526	140	x	.	186
Poland	1 832	24	.	1 773	.	.	.	35	.	x	.
Scandinavia	2 144	7	-	407	1	-	35	62	1 632	-	x

Source: EUROSTAT.

Tab. 3. *Inland waterway transit transports in EU countries, year 2004 (in thousand tonnes).*

Country	Group of loading											
	Total	%	Agricultural products and live animals	Food and feed	Solid fuels	Oil products	Ore and scrap	Metal products	Mineral raw materials and semiproducts, construction materials	Fertilizers	Chemicals	Machines, transport equipment, industrial goods
Total	**93 454**	**x**	**7 874**	**5 866**	**12 637**	**13 953**	**6 932**	**9 659**	**11 294**	**4 063**	**6 461**	**14 715**
%	x	100	8.4	6.3	13.5	14.9	7.4	10.3	12.1	4.3	6.9	15.7
Belgium	4 325	4.6	1 425	295	200	41	301	444	436	727	396	61
Czech	0	0.0	0	0	0	0	0	0	0	0	0	0
Germany	24 175	25.9	2 610	2 150	4 283	4 174	2 008	1 765	3 178	624	538	2 845
France	9 344	10.0	314	375	235	3 285	186	784	1 982	171	710	1 302
Luxemburg	9 650	10.3	1 852	882	3 965	35	1 219	739	666	234	50	8
Hungary	3 146	3.4	83	191	142	65	1 286	598	124	279	86	293
Netherlands	41 454	44.4	1 514	1 558	3 794	6 267	1 892	4 868	4 872	1 921	4 651	10 117
Austria	1 174	1.3	67	4 04	11	87	7	353	29	100	29	86
Poland	68	0.1	1	2	0	0	18	41	4	0	1	1
Scandinavia	119	0.1	8	11	6	0	15	66	3	7	0	3

Source: EUROSTAT.

VOLUMES OF INLAND WATERWAY CARGO TRANSPORT IN POLAND

For many years, Polish inland water navigation has played negligible role in the domestic transport system. In recent years the proportion of inland transport in meeting total transport needs, measured in tonnes, was kept within 0.6 – 0.8%. As well as that, this type of transport contributes to a negligible degree in cargo shipped by Polish foreign trade. Since the early eighties the process of increasing degradation of the role of inland water navigation in cargo transport has been observed. The number of craft belonging to Polish carriers has systematically decreased, and the transport activities have been reduced (Tab. 4). In recent years some fluctuations of the volume of the transported cargo are observed, at the background of a general tendency of keeping them on a low level.

Tab. 4. *Numbers of watercraft and inland waterway cargo transport in Poland, years 1980–2005.*

Items	1980	1990	1995	2000	2001	2002	2003	2004	2005
Inland water transport craft (in numbers)									
– tugs and pushers	425	411	339	245	278	259	259	257	253
– barges	1 570	1 337	737	492	598	582	590	587	574
Transported cargo [1)]									
– thousand tonnes	22 247	9 795	9 306	10 433	10 255	7 729	7 968	8 747	9 607
– millions tkm	2 325	1 034	876	1 173	1 264	1 126	872	1 066	1 277
– average distance of transport (km)	104.5	105.5	94.1	112.4	123.2	145.7	109.4	121.9	132.9

Source: *Transport – results of activity in 2005.*

[1)] Data refer to the transport performed by the craft operated by Polish inland navigation companies (including that being at the disposal of foreign companies during the break in navigation on Polish waterways) and, since 2001, also the transport performed by companies whose basic activity is different than those services.

The main reason for the present situation is continuously worsening quality of Polish inland waterways.

Fig. 2. Polish inland waterways
Source: www.zegluga-bydgoska.com.pl

Over 54% of waterways in Poland are of class I. The waterways of international significance which, according to the European standards should have parameters of class IV, the least, to provide opportunities for operating ships of net deadweight of over 1500 tonnes, are as short as 5.5%. In a total of over 3638 km of navigable waterways, this amounts to about 200 km, represented by three small Vistula river fragments without links, a fragment of the upper Vistula River opened in 2003, and lower fragments of the Odra River. Too small a volume of storage reservoirs and insufficient waterway management are the reasons why even those parameters are not kept. In dry years the river depths drop down considerably below levels required by particular classes, thus making the navigation impossible or extremely difficult. In total volume of cargo carried by Polish inland water transport the majority is done on domestic waterways. Transport of cargo shipped by Polish foreign trade in relations with Western Europe amounts only to 25 – 28% of the total volume (Tab. 5, Fig. 3).

A tendency towards strengthening the position of Polish inland water navigation on the European navigation market has been observed since the ninetieths, when Polish shipping companies started looking for employment on the European market as a result of unfavourable infrastructural conditions of Polish waterways and decreased demand for domestic transport. In two recent years Polish inland navigation has recorded strong increase of coastal transport, which is undoubtedly connected with the accession of Poland to the European Union and opening of transport markets for Polish ship owners, as well as with good quality of services offered by them. In 2005, the volume of outside cargo transported between foreign ports amounted to 2.44 million tonnes, and was nearly 5 times as big as in 2003. The majority of these transports was done between German inland ports (Tab. 6).

Due to a bad state of Polish waterways, which limits transporting distances, domestic transports are mainly of a local nature (Tab. 7). The majority of transports is concentrated on waterways of individual voivodeships, mainly situated along the Oder River. Most cargo is transported on the Lower Oder River, in the Zachodniopomorskie voivodeships.

Tab. 5. *Polish inland waterway cargo transport in domestic and international communication, years 2000–2005 (in thousand tonnes).*

Item	2000	2001	2002	2003	2004	2005
TOTAL – in thousand tonnes - in thousand tkm	**10 433 1 172 772**	**10 255 1 263 596**	**7 729 1 125 784**	**7 968 871 935**	**8 747 1 066 377**	**9 607 1 276 766**
domestic communication	5 025	5 816	4 536	4 959	5 010	4 466
international communication	5 408	4 439	3 193	3 009	3 737	5 141
- export	3 946	3 076	1 936	1 859	1 832	2 086
- import	551	673	444	307	386	588
- transit	421	373	562	353	68	26
- transport of outside cargo between foreign ports	490	317	251	490	1 451	2 441

Source: *Transport – results of activity in 2000–2005*, Central Bureau of Statistics, Warsaw 2000, 2001, 2002, 2003, 2004, 2005.

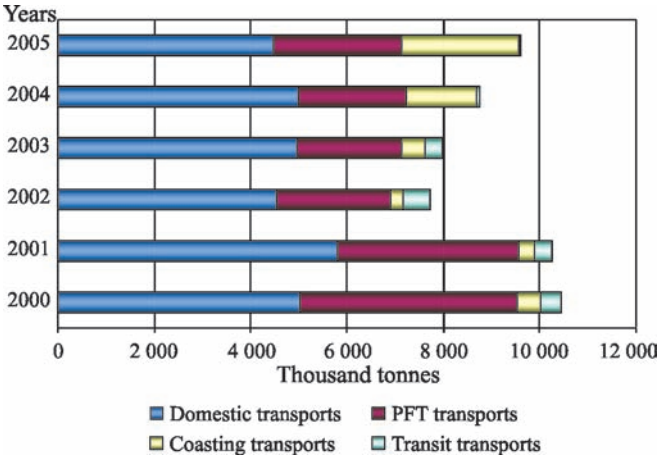

Fig. 3. *Polish inland waterway cargo transport in years 2000–2005. Source:* ***Tab. 5****.*

Tab. 6. *Inland waterway transports of outside cargo between foreign ports.*

Voivodeship or country		Cargo (thousand tonnes)		Transporting work (thousand tkm)	
		2004	2005	2004	2005
Total		**1 451**	**2 441**	**221 965**	**418 461**
Germany	Germany	1 341	2 318	155 722	338 770
Germany	Netherlands	16	19	10 418	12 895
Germany	Belgium	5	12	3 971	9 413
Netherlands	Germany	58	48	32 156	30 052
Netherlands	Netherlands	1	1	242	243
Netherlands	Belgium	2	1	398	257
Belgium	Germany	28	38	19 058	26 285
Belgium	Netherlands	-	3	-	446
Belgium	Belgium	-	1	-	100

Source: Customs Administration Analytical Centre, Warsaw.

Tab. 7. *Domestic inland waterway transports between voivodeships, years 2004–2005 (in thousand tonnes)[a)].*

Voivodeship		Cargo (thousand tonnes)		Transporting work (thousand tonne-kilometres)	
From	**To**	**2004**	**2005**	**2004**	**2005**
Total		**5 010**	**4 466**	**242 758**	**185 410**
Dolnoslaskie	Dolnoslaskie	1 025	1 276	3 939	4 878
Dolnoslaskie	Zachodniopomorskie	30	-	15 682	-
Kujawsko-pomorskie	Kujawsko-pomorskie	-	72	-	255
Lubuskie	Lubuskie	4	4	63	86
Małopolskie	Małopolskie	262	357	6 272	5 089
Mazowieckie	Mazowieckie	4	-	49	-
Mazowieckie	Pomorskie	-	8	-	2 380
Opolskie	Opolskie	827	840	1 788	2 004
Podkarpackie	Podkarpackie	9	-	9	-
Pomorskie	Pomorskie	291	257	6 526	4 638
Pomorskie	Warminsko-mazurskie	19	-	1 035	-
Slaskie	Dolnoslaskie	567	631	109 115	120 457
Slaskie	Slaskie	460	54	460	54
Swietokrzyskie	Swietokrzyskie	53	51	413	367
Warminsko-mazurskie	Pomorskie	-	9	-	596
Warminsko-mazurskie	Warminsko-mazurskie	-	4	-	231
Zachodniopomorskie	Dolnoslaskie	32	-	17 0 53	-
Zachodniopomorskie	Slaskie	21	-	14 879	-
Zachodniopomorskie	Zachodniopomorskie	1 085	889	55 747	39 534

[a)] Only those voivodeships were taken into account in which transports equalled or exceeded 4 thousand tonnes

Source: Customs Administration Analytical Centre, Warsaw.

This cargo is mainly carried between Szczecin/Swinoujscie and Police seaports. Relatively large volumes of cargo is also carried on the Upper Oder River, between Glogow and Kedzierzyn-Kozle, and on the Gliwice canal.

Smaller volumes of cargo are transported on the Upper Vistula River in the Malopolskie voivodeships - on a river part opened for operation in 2003, and on the waterways of the Pomorskie voivodeship in the region of Gdansk and Elblag - on the Vistula River delta fragment. This confirms the above statement about the use of only limited fragments of Polish waterways for transport.

Due to geographic position of Poland, transport links with Western European inland waterways, and the directional structure of the Polish foreign trade, the international transport is, as a tradition, mainly performed with Germany, to which about 98% of cargo is carried (Tab. 8). Cargo transported to the Netherlands, Belgium, and France are of negligible volumes.

The data recorded during two recent years reveal that about 2.0 – 2.5 million tonnes of cargo is carried between Szczecin/Swinoujscie seaports (Zachodniopomorskie voivodeship) and Germany per year. This transport is facilitated by a good system of links between Polish ports situated on the western coast of Poland and the German waterways, and good state of those waterways. At the same time only very limited volumes of cargo are carried to Germany from other voivodeships (on upper and Middle Oder River waterways).

Tab. 8. *Inland waterway cargo export to and import from countries in East-West direction, years 2000–2005 (in thousand tonnes).*

Country/year	2000	2001	2002	2003	2004	2005
Total	**4 497**	**3 749**	**2 380**	**2 166**	**2 218**	**2 674**
- export	**3 946**	**3 076**	**1 936**	**1 859**	**1 832**	**2 086**
- import	**551**	**673**	**444**	**307**	**386**	**588**
Germany	4 422	3 692	2 282	2 129	2 153	2 619
- export	3 889	3 039	1 859	1 827	1 773	2 053
- import	533	653	423	302	380	586
Netherlands	64	41	61	24	39	40
- export	49	30	43	19	35	40
- import	15	11	18	5	4	-
Belgium	9	14	26	13	26	14
- export	6	5	23	13	24	13
- import	3	9	3	-	2	1
France	2	1	11	-	-	-
- export	2	1	11	-	-	-
- import	-	-	-	-	-	-

Source: Customs Administration Analytical Centre, Warsaw.

Tab. 9. *Inland waterway transport in East – West direction, broken into voivodeships and countries situated along E-70 waterway, years 2004–2005.*

Voivodeship or country		Cargo (thousand tonnes)		Transporting work (thousand tkm)	
		2004	2005	2004	2005
Exports - Total		**1 816**	**2 085**	**464 866**	**510 203**
Dolnoslaskie	Germany	30	-	8 588	-
Dolnoslaskie	Netherlands	0	-	572	-
Lubuskie	Germany	37	43	9 634	14 191
Lubuskie	Netherlands	8	1	7 840	694
Lubuskie	Belgium	8	3	7 981	3 113
Opolskie	Germany	2	0	2 568	162
Opolskie	Netherlands	1	2	838	3 205
Opolskie	Belgium	1	-	834	-
Slaskie	Germany	-	0	-	299
Warminsko-mazurskie	Germany	-	0	-	93
Zachodniopomorskie	Germany	1 704	1 989	386 326	442 762
Zachodniopomorskie	Netherlands	25	37	23 376	34 923
Zachodniopomorskie	Belgium	16	10	16 309	10 761
Imports - Total		**386**	**588**	**121 122**	**154 910**
Germany	Dolnoslaskie	1	-	433	-
Germany	Lubuskie	7	6	1 776	3 287
Germany	Opolskie	-	0	-	411
Germany	Zachodniopomorskie	373	580	113 436	149 395
Netherlands	Dolnoslaskie	-	0	-	6
Netherlands	Zachodniopomorskie	4	1	3 982	716
Belgium	Mazowieckie	-	0	-	3
Belgium	Zachodniopomorskie	1	1	1 495	1 092

Source: Customs Administration Analytical Centre, Warsaw.

The cargo which traditionally dominates in the domestic inland waterway transport is bulk cargo (tables 10-11). For instance, in 2005 transports of coal (52%), fertilizers (13%) and minerals (13%) were the biggest proportions in export, while the imported cargo mainly included metal products (71%). Goods transported in smaller volumes include food and feed, construction materials, iron ore and scrap, and non-ferrous ores. Transports of containers, replaceable bodywork and semitrailers (within the framework of intermodal transport) are not used in Polish waterway transport.

POTENTIAL FOR INCREASING VOLUMES OF CARGO FOR INLAND TRANSPORT TO WESTERN EUROPEAN COUNTRIES

It is believed that the inland waterway transport between Poland and Western European countries has not been used so far to the extent which would cover all transport needs. Development and modernisation of Polish waterways, in particular the Oder-Vistula waterway being a component of the E-70 international waterway, would undoubtedly provide opportunities for higher competitiveness of inland navigation.

In the light of EU transport policy, the potential for increasing cargo volumes for East-West river transport should be mainly looked for in road transport. To do this :

- the area of gravitation to the E-70 waterway in Poland is to be defined
- Western European countries gravitating to the E-70 waterway are to be identified
- type of cargo which has been transported by land to selected European countries but which can be transported using inland waterways is to be defined
- the scales of general streams of cargo carried by road transport between Poland and Western European countries are to be analysed
- directional and type structure of cargo streams from the gravitation area to Western European countries are to be analysed
- cargo volumes which can be potentially shipped by Polish foreign trade for inland transport are to be assessed.

It can be assumed that those cargos will gravitate to East-West inland waterway transport which were carried by road transport and directed to or from voivodeships situated along the E-70 waterway part on the territory of Poland, i.e. from the Havel-Oder canal to the Hohensaaten lock, then along the lower part of the Oder River via Kostrzyn, along the Warta and Notec rivers to the Bydgoszcz canal, an finally along the Brda and Lover Vistula Rivers to the Vistula River distributary (Fig. 4). The area gravitating to this transport includes the warminsko-mazurskie, pomorskie, kujawsko-pomorskie, wielkopolskie, lubuskie and zachodnio-pomorskie voivodeships.

The foreign partners include such countries as Germany, the Netherlands, Belgium, France and Russia.

Tab. 10. *Type and directional structure of East-West inland waterway transport, year 2004 (in thousand tonnes).*

Groups of cargo	Export				Import			
	Total	including:			Total	including:		
		Germany	Netherlands	Belgium		Germany	Netherlands	Belgium
Total	**1 832**	**1 773**	**35**	**24**	**386**	**380**	**4**	**2**
Cereals	8	8	–	–	8	8	-	–
Food and feed	3	3	–	–	64	63	1	–
Oil seeds and fruit, fats	47	43	4	–	2	2	–	–
Mineral solid fuels	838	835	2	1	5	5	–	–
including: hard coal and briquettes	827	826	–	1	5	5	–	–
Iron ore, iron and steel scrap, blast-furnace dust	258	257	1	–	5	5	0	–
Non-ferrous ore and scrap	28	14	–	14	15	13	2	–
Metal products	108	77	23	8	217	217	–	–
Cement, lime, other finished construction materials	12	12	–	–	18	17	1	–
Raw an processed minerals	181	181	–	–	32	32	–	–
Natural and artificial fertilisers	286	286	–	–	4	2	–	2
Paper pulp and waste paper	52	52	–	–	0	0	–	–
Finished metal products	9	4	4	1	3	3	–	–
Glass, glassware and ceramics	–	–	–	–	12	12	–	–
Others	2	1	1	0	1	1	–	–

Source: Customs Administration Analytical Centre, Warsaw.

Tab. 11. *Type and directional structure of East-West inland waterway transport, year 2005 (in thousand tonnes).*

Groups of cargo	Export				Import			
	Total	including:			Total	including:		
		Germany	Netherlands	Belgium		Germany	Netherlands	Belgium
Total	**2 086**	**2 033**	**40**	**13**	**588**	**586**	–	**2**
Cereals	34	34	–	–	0	–	–	–
Food and feed	15	14	1	–	46	46	–	–
Oil seeds and fruit, fats	57	50	7	–	4	4	–	–
Mineral solid fuels	1 093	1 073	17	3	–	–	–	–
including: hard coal and briquettes	1 086	1 067	16	3	–	–	–	–
Iron ore, iron and steel scrap, blast-furnace dust	195	192	3	–	12	11	–	1
Non-ferrous ore and scrap	28	20	–	8	24	24	–	–
Metal products	72	62	9	1	420	419	–	1
Cement, lime, other finished construction materials	6	6	–	–	39	39	–	–
Raw and processed minerals	269	269	–	–	15	15	–	–
Natural and artificial fertilisers	274	274	–	–	15	15	–	–
Other chemicals	–	–	–	–	2	2	–	–
Paper pulp and waste paper	38	38	–	–	6	6	–	–
Finished metal products	4	1	2	1	2	2	–	–
Glass, glassware and ceramics	–	–	–	–	–	–	–	–
Others	1	–	1	–	3	3	–	–

Source: Customs Administration Analytical Centre, Warsaw.

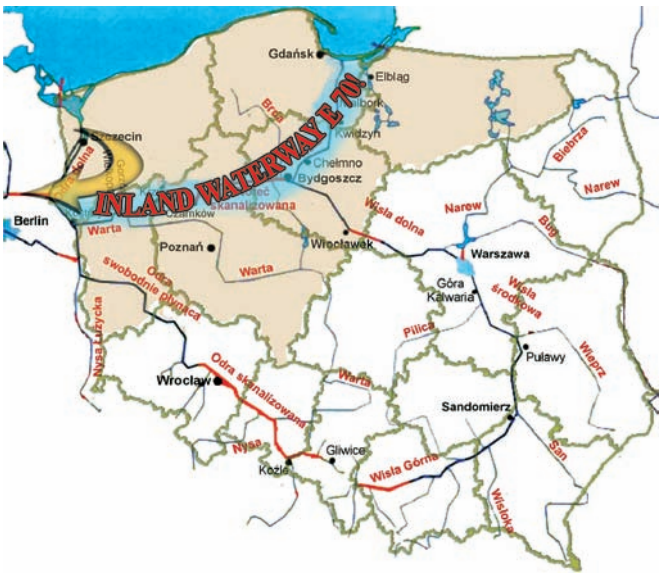

Fig. 4. Area of gravitation to E-70 inland waterway. Source: in-home analysis.

Cargo streams in the road transport are enormous. In recent years the road transport carried 7.6 – 9.6 million tonnes of cargo per year in export and 7.8 – 9.4 million tonnes in import (Tab. 12). The main direction of transport is Germany. This country is the main trade partner for Poland. For instance in 2005, the road transport carried to Germany 42% of total cargo in w export and 46% in import. To France about 1.0 million tonnes of cargo is transported per year both in export and in import. Cargos transported on such long distances, in particular those which could be transported using inland waterways, are especially attractive for inland transport.

Analysing the volumes of cargo transported between the above defined gravity area on the territory of Poland and selected Western European countries reveals that the road transport in these relations carries 3.2 – 3.8 million tonnes in export and 3.2 – 3.4 million tonnes in import (Tab. 13).

For a detailed analysis of cargo streams such cargos were selected, which have been transported by road but can be carried by barges on inland waterways. Selecting those cargos was based on the data on international transports, including statistical information arranged making use of commodity type relations used in Polish customs nomenclature. For selected cargos, a preliminary analysis of cargos transported from or to voivodeships situated along the E-70 waterway in relation with selected Western European countries was done.

The analysis of road transport cargo routes, done using data for two recent years, reveals that 1.9 – 2.6 million tonnes of cargo is transported from the area identified as the inland waterway gravity area to those countries in export, and 1.9 – 2.2 million tonnes in import per year (Tab. 14).

***Tab. 13.** East-West road transports between voivodeships and countries situated along E-70 waterway and France, years 2004 – 2005 (in thousand tonnes).*

Voivodeship	2004		2005	
	export	import	export	import
Total	**3 821.7**	**3 459.9**	**3 192.0**	**3 212.8**
Warminsko-mazurskie	298.2	99.9	267.5	115.2
Pomorskie	390.3	350.7	373.7	370.3
Kujawsko-pomorskie	527.5	357.0	634.9	367.9
Wielkopolskie	1 082.6	1 214.9	1 013.1	1 510.3
Lubuskie	881.5	880.1	594.8	466.2
Zachodniopomorskie	641.6	557.3	308.0	380.2

***Tab. 14.** Type and directional structure of road transport of cargos attractive for inland waterway transport between voivodeships and countries situated along E-70 waterway and France, years 2004–2005 (in thousand tonnes).*

Type of cargo	2004		2005	
	export	import	export	import
Total	**3 822**	**3 460**	**3 192**	**3 213**
Cereals	4	6	56	4
Food[1)]	125	65	46	48
Oil seeds and fruit, fats, feed	6	3	15	1
Salt, sulphur, soil, stones, gypsum materials, lime and cement	41	159	33	117
Metal ores, slag and ash	15	1	0	2
Mineral fuels, mineral oils, products of their distillation, bituminous substances	13	114	19	71
Organic and inorganic chemicals	60	161	40	126
Natural and artificial fertilisers	22	40	42	55
Plastics and their products	138	433	141	397

[1)] Vegetables and some edible roots and bulbs, products of milling industry, malt, starches, products made of cereals, flour, starch, or milk.

***Tab. 12.** Total road transports to countries situated along E-70 waterway and to France, years 2000 – 2005 (in thousand tonnes).*

Country	2000		2001		2002		2003		2004		2005	
	export	import	export	import	export	import	export	import	export	import	export	import
Total	**9 612**	**7 798**	**9 266**	**7 759**	**9 209**	**8 505**	**10 332**	**9 048**	**8 458**	**8 950**	**7 755**	**9 431**
Germany	7 490	5 458	7 055	5 472	6 858	6 024	7 698	6 407	6 112	6 343	5 577	6 839
Netherlands	906	860	904	793	940	835	1 018	866	783	829	650	831
Belgium	429	567	474	585	507	660	598	698	567	689	540	679
France	787	918	833	909	904	986	1 018	1 077	996	1 089	988	1 082

Source: Customs Administration Analytical Centre, Warsaw.

Continuation Tab. 14				
Type of cargo	2004		2005	
	export	import	export	import
Wood and wooden products[2)], wood coal	977	330	594	332
Wood pulp, cellulose, waste paper, paperboards	53	9	20	24
Cotton	0	12	0	11
Products made of stone, gypsum, cement, asbestos, and mica	54	67	34	35
Glass, glassware and ceramics	36	138	26	36
Iron, cast iron, steel and their products	293	414	213	422
Other metals and their products	80	86	68	73
Boilers, machines and installations, tools	101	117	85	84
Furniture, bedding, mattresses	492	21	412	13
Total	2 592	2 233	1 915	1 910
Others	1 230	1 227	1 277	1 303

[2)] Except furniture

Source: Customs Administration Analytical Centre, Warsaw.

Assuming that out of the cargo volumes presented in Table 14 at least 20% of exports and 10% of imports will be shifted to inland waterway transport means that additional cargo potential for this transport in East-West relation amounts to 400-500 thousand tonnes in export (increase by about 20% with respect to the present level) and about 200 thousand tonnes in import (increase by nearly 50%). According to experts' opinions, present conditions of operation of Polish inland navigation do not create limits for servicing this additional mass of cargo, especially taking into account that the majority of cargo is directed from or to voivodeships situated close to the waterways linked with the European inland waterway system.

More intensive development of East-West inland navigation will undoubtedly be possible after the development and modernisation of the E-70 waterway along all its length from the Oder River to Bydgoszcz and further to Elblag, and adapting it to European standards. This goal was assumed in the AGN Agreement expressing pro-ecological transport policy of the European Union. However, the Agreement assumes that all waterways of international significance will be adapted to the technical state of class IV parameters, the least, which in Polish situation cannot be achieved in the nearest years to come. Therefore a problem of utmost importance becomes adapting the inland fleet to the present navigational conditions, assuming that all bottlenecks existing now on this waterway will be removed.

CONCLUSIONS

- It was the accession of Poland to the European Union and opening EU transport markets for Polish carriers which affected most the improved results of Polish owners of inland watercraft in terms of transport activity.
- Traditionally, transports in international communication are mainly performed to or from Germany, amounting to about 98% of all international cargo carried on inland waterways. Due to bad condition of the Odra-Bydgoszcz-Elblag waterway, transport of cargo between the area situated along this waterway and Western Europe is not performed at all.
- According to AGN Agreement, part of the E-70 waterway on the territory of Poland from the Havel-Oder canal to the Hohensaaten lock, then along the lower part of the Oder River through Kostrzyn, along the Warta and Notec rivers to the Bydgoszcz canal, and finally along the Brda and Lower Vistula Rivers to the Vistula River distributary, was included to the European network of inland waterways of international significance and is a condition for the planned activation of East-West inland navigation between Western and Eastern Europe.
- The inland waterway transport is dominated by bulk cargo (coal, fertilisers, minerals in export and metal products in import). Food products and feed, construction materials, iron ore and scrap, and non-ferrous ores are transported in smaller volumes.
- Detailed analysis of the type structure of cargo routes has revealed that the volume of cargo, which is potentially attractive for inland waterway transport but now transported by road in the area of gravity to inland waterways, is on the level of 1.9 – 2.6 million tonnes in export and 1.9 – 2.2 million tonnes in import. The inland water transport will take over 400-500 thousand tonnes in export. According to experts' opinions, the existing conditions of operation of Polish inland navigation do not create limits for servicing this additional mass of cargo, in particular taking into account that the majority of this cargo comes from or is directed to voivodeships situated in the vicinity of the Oder River waterway having direct links with the European inland waterway system.
- Visible improvement of the situation and development of East-West transport via Polish inland waterways is only possible after the development and modernisation of the E-70 waterway along all its length.

The role of inland ports in integration of polish waterways with the european network

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ABSTRACT

This paper includes main conclusions of author's studies within the framework of the EUREKA Project. Present state of inland waterways in Poland, legal regulations, importance of inland navigation in cargo transport and river ports are shortly presented. Most important barriers for the development of polish inland waterways are also described. In August and October 2004 the author participated in two technical trips which aim was to recognize actual state of the inland waterways and ports in northern Poland. Presented photos were made during these cruises.

Keywords : inland waterways, river ports

INTRODUCTION

The presented article is a summary of author's research activities performed in years 2004-2006 within the framework of the EUREKA INCOWATRANS E!3065. Project group on „New generation of environment friendly inland and coastal ships for Polish East-West waterways". The topics analysed by the author were entitled „A study of European fast, multi-modal inland transport systems, with particular attention being paid to river port systems of cargo loading, unloading and storage, and final land transportation in East-West direction - analysis of adaptation of the Lower Vistula waterway to meet the assumed tasks" and „The integration of ecological means of water and railway transport in northern Poland". The present publication includes main conclusions resulting from these analyses.

INLAND WATERWAYS IN POLAND

Poland does not have natural conditions for developing an intensively branched network of waterways. Nevertheless, starting from the thirteenth-fourteenth century, a systematic development of inland navigation was observed. The core of the waterway network is created by the Vistula and Oder Rivers. Due to their meridional location, for centuries they have created separate waterways without any mutual links. A similar geographical position of main natural inland waterways is also observed in the neighbouring countries, for instance the waterway networks created by Elbe, Rhine, Dnieper, and Niemen Rivers. Development of inland navigation in Europe was the reason why in the eighteenth century regular activities were started to create a network of waterways by building artificial water canals linking selected natural navigation routes, and to improve navigational conditions on the already existing navigation routes. Activities of this type were also recorded on the area of the present territory of Poland. A basic system of the waterway network existing in Poland was brought into being in the eighteenth and nineteenth century. The total length of classified waterways in Poland changes, reflecting changes in legal regulations that formulate principles for defining boundaries and classes of inland waters.

The regulation which are in force now and regulate the status of inland waterways in Poland include :

- the act on inland navigation, dated December 21, 2000, (Gov. Reg. and Law Gaz., no. 5, item 43 of January 24, 2001)
- the Water Law act, dated July 18, 2001, (Gov. Reg. and Law Gaz., no. 115, item 1229 of October 11, 2001)
- the Resolution of the Cabinet of Ministers, dated September 11, 2001, changing the resolution on water boundaries, coastal line, near water installations and classes of navigationable inland waters (Gov. Reg. and Law Gaz., no. 106, item 1151 of September 29, 2001)
- the Resolution of the Cabinet of Ministers, dated May 7, 2002, on the classification of inland waterways (Gov. Reg. And Law Gaz., no 77, item 695 of June 18, 2002)

According to the classification in force in Poland :

- total (nominal) length of inland waterways equals 3649.1 km; which means that it has been reduced by 18% in recent years (1977-2002)
- waterways adapted to cargo transport activities are 1720 km long (starting from class II)
- only 4.5% of total length of the waterways belongs to class V (including the Wloclawek Reservoir – 1.5%, class Va and internal seawaters – 3%, class Vb), 1% - to class IV, 11% - to class III, 25% - to class II, and over 50% to class Ia and b. That means that these routes are in practice only available for small recreation vehicles – yachts and kayaks.

The inland waterways in Poland are subject to systematic degradation resulting from: the absence of a strategy for developing inland navigation in Poland, lack of attendance of water navigation routes and hydrotechnical buildings, liquidation of ports and cargo handling equipment, and changing concepts of the use of main water navigation routes in Poland.

Within the framework of the AGN convention (Agreement on main inland waterways of international significance) of 1996, which was not signed by Poland as the only nation in Europe, the territory of our country is crossed by three international waterways :

- E-30 – linking the Baltic Sea with the Danube River in Bratislava (part on Polish territory – the Oder River from Szczecin to the border of Poland)
- E-40 – linking the Baltic Sea with the Dnieper River, via the Vistula River from Gdansk to Warsaw and further along the Bug River to Brzesc
- E-70 – linking the Netherlands with Russia and Latvia via the Oder River from the Oder-Havel Canal to the Warta River mouth, the Oder-Vistula waterway (Warta and Notec

Rivers, Bydgoski Canal) and the Vistula and Nogat, or Szparkawa Rivers to Elblag.

A concept of adapting the Polish waterways to present standard parameters of international navigation routes (class IV and Vb) are rather unrealistic due to poor local hydrological conditions and the resultant huge investment expenditures required. What is more realistic, however, is the reconstruction of those water navigation conditions which were about 40 years ago, i.e. adapt the waterways to class III parameters (according to the classification in force now). As for the above list of international waterways, the only practically realisable action is the revitalisation of the E-70 waterway as a continuous navigation route leading to Russia and Baltic Republics.

PRESENT STATE OF INLAND NAVIGATION

At present, the inland navigation in Poland contributes in about 0,7% to cargo transport and is ranked last, compared to other transportation forms in Poland. 9 million tonnes of cargo transported via waterways per year (average from recent 20 years) places Poland among countries with the lowest contribution of inland water transport in Europe. The transport is mainly executed locally, which results from, among other factors, the present condition of Polish waterways making the planned and regular long-distance navigation very difficult. Transporting cargo over longer distances is executed sporadically and refers to single large-dimension commodities in favourable seasons of the year.

INLAND PORTS IN POLAND

At the beginning of the twentieth century, when the Oder-Vistula connection was a main transportation route, numerous river ports and transportation hubs were located along it. On the Warta River the cargo was shipped in Kostrzyn, Skwierzyna, Miedzychod, Poznan, Lubon, Gorzow, Ujscie, Naklo, Czarnkow, Drezdenko, Krzyz and Notec. The only ports which survived to the present day are the ports of Kostrzyn (discussed below), Ujscie, Poznan and Bydgoszcz. But in fact, the shipment only takes place on waterway links with the main rivers: Oder (Kostrzyn) and Vistula (Bydgoszcz). In the port of Ujscie the cargo has not been shipped since 1996, while in Krzyz - since 1998. On the territory of the port of Poznan a housing estate was built.

According to the AGN convention, the operation of some inland river ports existing in Poland is planned on the waterways composing the European waterway network. The list of these ports includes :

- Swinoujscie, Szczecin, Kostrzyn, Kozle, Gliwice – on the E-30 navigation route
- Gdansk and Warsaw – on the E-40 navigation route
- Kostrzyn, Gdansk and Elblag – on the E-70 navigation route.

At present, none of these ports, like none of the waterways to which they belong, meets technical conditions formulated in AGN. However, taking into account only their location, of the highest significance in the future should be the ports of :

- Kostrzyn (crossing of E-30 – E-40 navigation routes),
- Szczecin (end of E-30 navigation route),
- Bydgoszcz (links E-40 and E-70 navigation routes)
- Gdansk (end of E-40 and E-70 navigation routes)
- and perhaps Torun, Bydgoszcz, and Elblag.

Below given are the volumes of cargo shipped in selected Polish inland ports, along with the characteristics of the ports of Kostrzyn, Gdansk, Bydgoszcz, Torun, and Elblag.

Table 1. *Volumes of cargo shipped in selected inland ports (acc. to data presented by Porty Żeglugi Bydgoskiej S.A.).*

Port	Shipping capacity [thousand tonnes]	1990	1994	1998	2001
Bydgoszcz	1000	586.8	652.0	839.0	619.4
Poznan	-	7.7	30.6	-	-
Ujscie	100	22.5	0.4	-	-
Krzyz	350	15.6	5.4	-	-
Kostrzyn	550	73.8	267.7	248.5	182.8
Malbork	100	43.4	107.3	97.3	45.8
Wroclaw	1400	831.0	560.0	510.0	508.6
Gliwice	2000	937.0	-	200.6	498.1
Cigacice	-	0	38.4	59.5	453.1

The Port of Kostrzyn is situated on the right bank of the Warta River, at a distance of 1,5 km from the point where it joints the Oder River, in 617+600 km, and is the starting port for the Oder-Vistula waterway. However, due to direct vicinity to the main navigation route it is often structurally included to the complex of ports on the Oder River.

The port of Kostrzyn is the oldest port on the Oder waterway. A river port existing in this place was mentioned in historical notes as early as at the thirteenth century. The next structures which were brought into being here were: a winter port, a constructional port of the water administration, and a transportation hub located on the Warta River at a distance of 2+000 km. In the time before the Second World War 120 thousand commodities per year were shipped in Kostrzyn. Like for the majority of ports on the Oder River, the port of Kostrzyn was partially destroyed during war activities. The reconstruction lasting two years ended in 1949.

The present view of the port from the waterway side is shown in Fig. 1. In fact, this port is a reinforced Warta riverside, slightly displaced into the land from the main river bed and bordered by a high vertical berth.

Fig. 1. *Port of Kostrzyn on the Warta River (own photo, August 2006).*

Since it is an open port, the berth is adapted to operate at changing water levels in the river. The range within which the water level in the Warta River changes equals 3.5 m. Below given are the basic technical parameters of the port of Kostrzyn :

- port area : 5.94 ha
- port basin area : 0.64 ha
- total length of berths : 740 m
- length of loading berths : 240 m
- length of waiting berths : 500 m
- area of stacking yards : 11130 m^2
- area of warehouses : 1450 m^2.

Moreover, the port of Kostrzyn has berths belonging to industrial plants situated on the Warta River. One of them is shown in Fig. 2. Author's personal observations, made in August 2006, have revealed that cargo is not shipped in those places.

Fig. 2. Trans-shipment berth in Kostrzyn (own photo, August 2006).

The port of Gdansk is situated at the crossing point of main European transportation routes linking Central-Eastern Europe with Scandinavia, and Western Europe with Eastern Europe. The port has an over thousand years lasting tradition. Its strong points, beside the geopolitical location, are open water regions and the infrastructure, which allows a wide variety of commodities to be shipped.

The port of Gdansk has a typical sea trade characteristic. And it is practically unavailable for the inland watercraft. The berths are not adapted for serving this type of transport. Ship captains are not allowed to move unattended on the aquatorium and are obliged to take a harbour pilot on board, which considerably increases shipment costs covered ship owners. Moreover, the length of berths that serve passenger ships is very limited, which could be visibly testified during the first visit of the hotel ship MV Frederic Chopin to Gdansk.

At the beginning of the twenty-first century port authorities analysed an option of adapting one of the basins for inland navigation purposes. This would extend direct links with the hinterland, now making use of the road system (a bottleneck in the port transportation system) and/or the railway system. The inland port was planned to be built in the Wladyslaw IV basin, situated in direct vicinity of the exit from the internal port to the Gdanska bay. The inland port hinterland was planned to be situated on the territory of the present Duty-Free Area.

At present the basin has the following technical parameters :

- ☆ port area: 33.50 ha
- ☆ length of berths: 1070 m
- ☆ area of roofed warehouses : 38000 m^2
- ☆ area of stacking yards : 80000 m^2
- ☆ maximum length of served ships: 170 m.

The basin is equipped with trans-shipping installations of carrying capacity between 3 and 16 t. The area has good access roads, a side street and loading platforms, administrative buildings, full land development and the base for shipping fruits and vegetables.

The Port of Gdansk Authority S.A. were going to invite tenders for a competition in preparing a study of port accessibility from the side of inland waterways. Unfortunately, after changes in company's authorities, all concept of further port development have been abandoned and the above idea was not put in practice. In the context of the assumptions formulated in AGN, according to which Gdansk is the beginning for the E-40 and E-70 waterways this resignation seems to be rather rash.

The port of Bydgoszcz/Torun complex. Concepts are discussed to situate a multi-media cargo shipment terminal directing the stream of commodities from inland ships to road and railway transport and vice versa, and making use of the A1 highway and railway network in southern and eastern directions. Another concept under discussion takes into account situating in this region a well developed port with the installations serving regular passenger transport.

Elblag. Regional and city authorities make attempts to revitalise the port for the local international traffic. Moreover, despite numerous objections and protests of local and ecological circles, a concept has returned to dig a canal across the Vistula Spit at its base, which would help develop the port of Elblag as a trans-shipping place for short-range sea transport, and at the same time relieve the port of Gdansk in multi-medial land and water transport.

DEVELOPMENT PROSPECTS FOR INLAND WATER NAVIGATION IN POLAND

„State's transport policy for years 2006 – 2025" (document accepted by the Cabinet of Ministers on June 29, 2005) does not include, in practice, plans of development of inland waterways until 2025. However, the document prepared in 2006 and entitled "Strategy of Development of Polish Sea Economy for years 2007-2015" presents a quite different standpoint, and formulates clear tasks referring to inland water navigation. Present share of water transport in total transport of commodities equals about 0.9%, and for years has been kept on the same level. This, among other factors, results from the conviction of the decision makers that the inland water navigation is of marginal importance in Polish transportation system. Sample transportation solutions which are effectively implemented in other EU countries have no influence on strategic plans of state development. The scale of railway transport is also gradually reduced. The only transportation systems which are to be developed are road and air transports (of both cargo and passengers). Among all possible solutions, this one is the most expensive and least favourable from the point of view of keeping the environment in a good state. The absence of motorways and expressways, along with the bad state of the remaining existing roads is the source of certain limitations in the development of this type of transportation. Changing this situation requires huge investment expenses and long realisation time. Revitalisation of the waterways would lighten the load of the road system, and considerable reduce the emission of impurities to the atmosphere, water and ground. According to the most recent German data, the inland water transport emits to the atmosphere five times as little carbon dioxide (in g/tkm), as the road transport. Moreover, it is characterised by much lower number of accidents and victims, and in practice does not generate noise, nor water and ground pollution. Unfortunately these data (and the resultant lowest ecological costs of water transport, compared with other transportation forms) do not find their reflection in state's transportation policy.

The importance of inland water navigation and its development is not reflected either in the Water Economy Strategy, accepted by the Cabinet of Ministers on 18 September, 2005. The water transport, as one of water economy tasks, is treated exactly in the same way as in the transport policy. The above mentioned strategy discusses the use of waterways mainly in the context of protection of river valleys against flood. At the same time it is stressed that not ratifying the AGN Agreement of 1996 by Poland results in stagnation in waterway

development. Tasks planned for realisation are only limited to maintenance and modernisation of the existing waterways used for tourists purposes, taking into account the objects included to the register of monuments (the Szkarpawa River and the Oder-Vistula link, among other places, but the realisation time is not clearly defined).

POSSIBILITIES OF DEVELOPMENT OF POLISH INLAND PORTS WITHIN THE NETWORK OF EUROPEAN WATERWAYS

The above presented remarks also refer to the development of inland ports. It is only the port of Kostrzyn which stands some real chances for development in the nearest future. It is situated at the crossing point between a so-called Oder Transport Passage, which will be composed of: the arterial railway, the planned motorway A3 and the Oder Waterway, including links of the Oder River to the West-European waterway system via the Oder-Havel and Oder-Szprewa canals. Germany faces more and more problems resulting from reaching the limits of economic and ecologic sense of further development of motorways. Since 1992, intensive waterway modernisation projects have been in progress or planned on the territory of former DDR. Among other places they refer to: the Magdeburg centre (Project 17), modernisation of the Oder-Havel link (nearly completed) and the Oder-Szprewa link (planned realisation time – 2010-2015). The inland water navigation is expected to unlock „bottlenecks" in transportation passages and „heal" the transportation system – the water navigation is expected to take from the motorways 55 million tonnes of commodities per year. Therefore the nearest chance for Poland seems to be adopting the parameters of the Oder waterway, at its segment between Hohensaaten and Szczecin, to the parameters of modernised German waterways (class Vb). Unfortunately, neither of the above mentioned documents (Transport policy…, Water Economy Strategy) provide investments on such as big scale. Also the „Programme for Oder 2006", realised for some recent years, only includes adopting the Oder waterway to class III parameters.

Fig. 3. *Port of Ujscie on the Notec River, out of operation for 10 years (own photo, August 2006).*

Fig. 4. *Port of Krzyz - devastated berths (own photo, August 2006).*

In general, real chances in the near future for integration of Polish waterways and inland ports situated on them should be seen in developing passenger and tourists navigation. Recently more and more towns and cities situated on waterways begin to recognise their chances for development in intensifying water related recreation and tourism. A good example here is the project „Using inland waterways for regional development (InWater)", realised by the Gdansk University of Technology (leading partner) and 21 partners from four countries: Lithuania, Poland, Germany and Russia, within the framework of the Community Initiative INTERREG III B – Baltic Sea Region. The project aims at exchanging experience gained by particular partners, indicating directions and chances for reduction of development barriers in using inland waterways for regional development, identifying inland water connections which can be used for transport activities, promotion of best practices, and promotion of the Berlin – Kaliningrad waterway on the international forum.

The City of Gdansk (Development Programme Department) also sees its chances in activating the river network within agglomeration reach. Compared to the density of water routes the port base is extremely poor. The pride of the city – the marina on the Motlawa River (Fig. 5) is practically deprived of necessary land infrastructure. The remaining few ports are situated at a relatively large distance from the downtown, far from the hotels, gastronomy, and tourists attractions (Fig. 6). Therefore 26 places were selected on the territory of Gdansk as possible locations of small ports available for water tourists. The project of detailed technological designs is currently being worked out by „Hydroprojekt" in Wloclawek.

Fig. 5. *Gdansk marina in Szafarnia street (own photo, August 2006).*

Fig. 6. *Yacht port on Dead Vistula River (own photo, August 2006).*

The initiative of Gdansk and Elblag authorities is a good example for other towns situated on waterways, which were included to the European water network. Only developing the existing ports, and building new ones for tourists navigation purposes can again bring Polish water navigation routes into life.

Monitoring and visualization of nautical properties of inland waterways in Poland

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ABSTRACT

Monitoring of nautical properties of inland waterway covers recording, visualization and short-term prediction of their state. This paper describes the way of integration different data from many sources and simplified freshet wave propagation model on inland waterways in Poland. Computer programs developed for this task are shown as well.

Keywords : inland waterways in Poland, monitoring of nautical properties, visualization of nautical properties

INTRODUCTION

INOCOWATRANS project is dedicated to preparation of Polish inland water shipping system, as a part of international (Europe-Russia) transportation and tourism infrastructure. It contains 2 main parts. The first one is dedicated to inland fleet development, production and operation, the second one is dedicated to management of waterways infrastructure. For help in management of problems related to both of them a GIS database is developed. One of its task is delivery of current information about conditions of navigation on inland waterways in Poland, especially determined by waters state. Navigation targeted monitoring differs from usually performer one for environment or flooding protection. Basic difference covers range of water states. Low and high water caused by drought or flood exclude navigation, so only middle states are considered and existing models of flood and freshet wave are not applicable. Navigation requirements cover also short-term water state prediction for inland ships load management. This papers covers subjects as follows:

- data description
- inland navigation requirements
- water state prediction method.

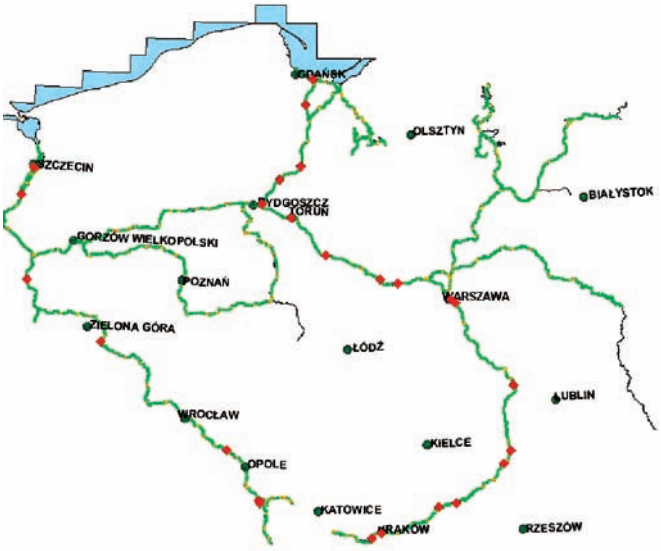
DATA

Hydrological monitoring for inland navigation requires integration and processing of data from different sources. They cover dynamically changing water state as well as relatively stable channel form (it is a simplifying assumption, channel changes are much slower than water state ones and their monitoring is a separate research problem which is not subject of this paper).

Waters state

Inland waters state in Poland is monitored by many institutions, but only Institute of Meteorology and Water Management (IMGW) provides permanent and free access to their current data, published daily in "Water State Bulletin" under Internet address: http://www.imgw.pl/wl/internet/zz/rzeki/biul_hyd_codz.html. Although set of water gauges is relatively small (only 51 gauges on Vistula River and 32 on Odra River), in connection with model of water state dynamics is good enough for navigation related tasks. Location of IMGW water gauges shows picture 1.

Picture 1. *Set of IMGW water gauges.*



Picture 2. *Set of IMGW water gauges on inland waterways.*

For data import from IMGW home page simple application is developed. It writes data to MS Access database file

wodowskaz.mdb which is connected to GeoMedia workspace. The database contains data from lat 5 days. The application is developed with Visual Basic for Application embedded in all applications of MS Office package, including MS Access. It is executed from MS Access level but it is planned to be built as dll run from GeoMedia level.

Model of object „Wodowskaz" (water gauge) contains a set of attributes where the most important for data updating are:

- ☆ SWW – middle navigable water; the average gauge indication [cm]
- ☆ GLEB – depth; current gauge indication [cm]
- ☆ DSWW – difference between SWW and GLEB [cm]
- ☆ KM – kilometrage; location of gauge on the waterway length.

Two first attributes are used for DSWW computation for water gauges and DSWW with KM is used for linear interpolation of DSWW for waterways segments between gauges.

Bathymetry

Structure of data model for INCOWATRANS project takes into consideration many rules and guides set by formal requirements of Polish and European law regulations as well as structure of exiting data used in the project. The most important rules are:

- ❖ Each water-course is divided into segments with constant properties. Additional splitting points are necessary in node location even if the segment does not change its properties. In used database (Hydrologic Map of Poland - MPHP, scale 1:50 000) length of segments varies from 20 m to 30 km.
- ❖ Data gathered in INCOWATRANS project will be used for updating and correcting of existing source databases. For providing of easy back-integration our data with source bases we do not modify definitions of attributes of existing classes. For nautical tasks not covered by source bases we define new classes (or new attributes of existing classes if they do not accomplish law regulation, even if it makes data redundant).

The layer containing bathymetry data is titled "rzeki_o" and inherited from MPHP. It was primarily not designed for bathymetry description so we extended its definition by set of attributes:

- ✶ SWW – average navigable water. This attribute describes course of channel bottom. Currently we use highly incomplete data. Their acquisition is a separate research problem due to few reasons:
  - ◆ Coherent program of inland waterways bathymetry monitoring does not exist in Poland. Some measurements are preformed in chosen locations – mainly for flooding and natural environment protection targeted analysis.
  - ◆ Channels shape is dynamically changing. In extreme cases data should be updated even every week. Measurements mentioned above are performed occasionally and we can not trust them.
    Due to reasons mentioned above for software testing we have used data from inland sailing directions, which are not current. In many cases these data are estimated on the basis of formal minimal requirements for navigation. The true value of waterway depth and width is usually higher. Permanent monitoring and acquisition of bathymetry data (with usage of satellite picture for example) is a separate research problem and is not the subject of this paper.
- ✶ KM – kilometrage; location of segment midpoint on the waterway length. According to formal rules for waterways kilometrage starts at the beginning of the highest located segment and is counted downstream. For other rivers kilometrage starts at outlet and is counted upstream.
- ✶ DSWW – the current aberration form SWW [cm] computed as follows:
  - ◆ DSWW is determined for 2 closest water gauge (one upstream and one downstream).
  - ◆ Value of DSWW is linearly interpolated between water gauges.
  - ◆ Interpolated DSWW value for segment midpoint is set for the entire segment.

$$DSWWs = DWW2 - \{(DWW2 - DWW1) * (KM2 - KMs) / (KM2 - KM1)$$

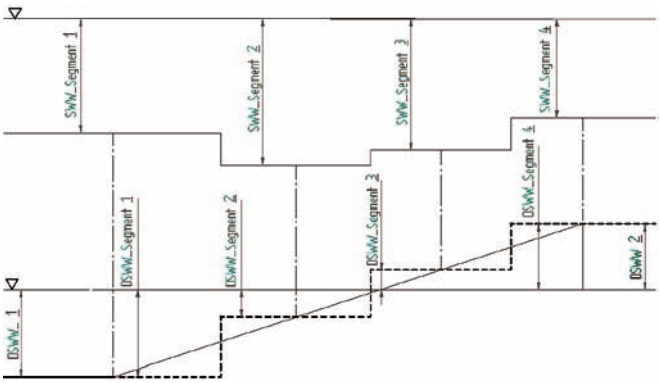
or

$$DSWWs = DWW1 + \{(DWW2 - DWW1) * (KMs - KM1) / (KM2 - KM1)\}$$

where:

DSWWs	– segment DSWW,
KMs	– kilometrage for segment midpoint,
DWW1; DWW2	– DSWW for 2 neighbor water gauges,
KM1; KM2	– kilometrage for 2 neighbor water gauges.

For segment laying out of range between first and last water gauge DSWW from the closest one is set.



Picture 3. *Graphical illustration for DSWWs computing algorithm.*

- ✶ GLEB current depth of segment [cm]; GLEB = SWW + + DSWW

NAVIGABILITY REQUIREMENTS

Requirements for navigation related water state analysis and visualization differ from the ones usually set by flooding or environment protection problems. The most significant differences are:

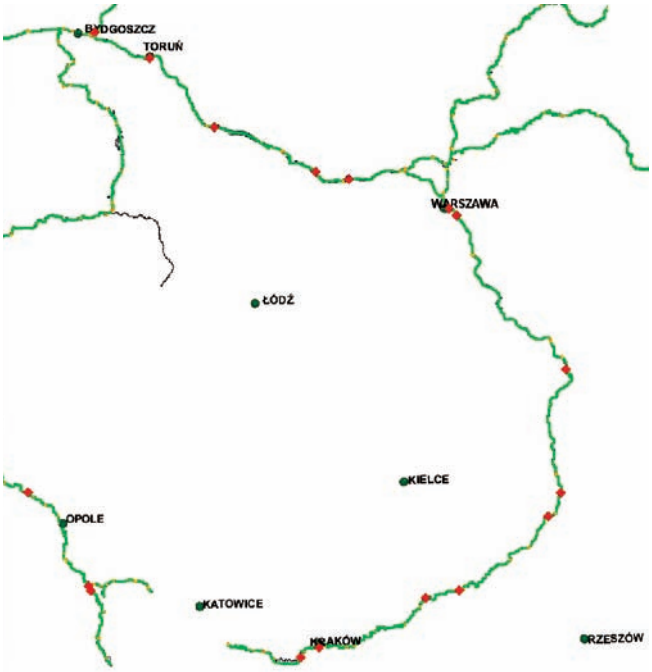
- ➢ Geographical range of analysis. The condition of waterway navigability is patency of its bottlenecks. So we are neither interested in general situation nor in the state of side streams, rather in parameters of the chosen segments.
- ➢ Very high and very low water states make waterway unnavigable so we are interested in middle states. The part

of navigability analysis is a short term prediction. Existing models of flood water propagation have limited applicability for middle states so we need new model of waters state changes propagation for middle and low states.

- The scope of analysis – we are not limited to waters state only but we have to take under consideration also:
  - Land neighborhood - navigability can be also limited through land objects. For example very important parameter is the height of bridges (pipes, cables) crossing over waterways, limiting the height of ship/cargo in conjunction with waters state.
  - Network analysis – it is also a part of transportation analysis. It can be a first stage for determining of waterways segment for next waters state analysis or in more complex case it can be an inner part of navigability analysis, driving to determining alternative trace in case of inpatent bottlenecks. Another example can be determining of mixed water/land trace with detours of bottlenecks.

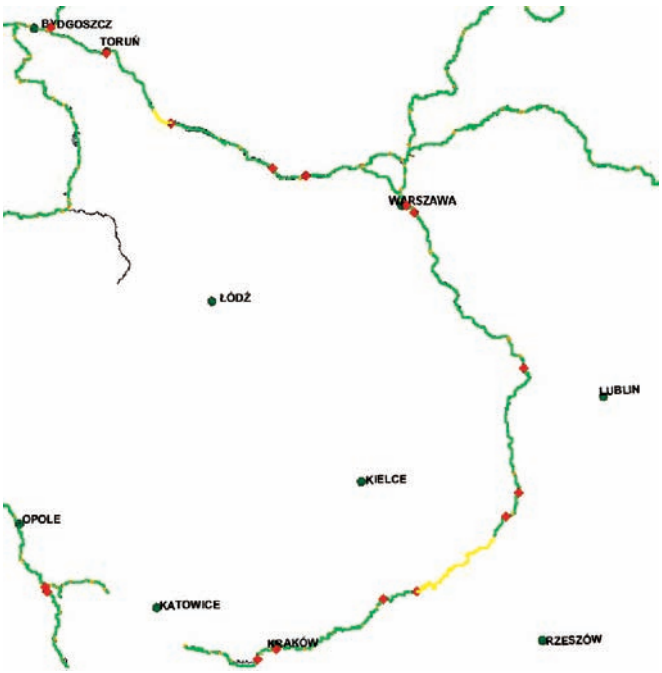
Realization of these requirements is usually possible through standard functionalities of GIS systems although few of them need extended functions available through own developed applications. In our case we have built few exemplary queries in GeoMedia 6 environment:

- Results of simple navigability analysis are shown at the pictures below. Analysis was performed for high and middle sector of Vistula River for ship with set draught (3 m) when water state changes from high (Picture 4) through middle (Picture 5) to low-middle (Picture 6). Green lines marks safely navigable segments (depth of segment > ship draught), yellow lines – navigation alert (depth is close to ship draught) and red ones – segments unnavigable (depth < draught).

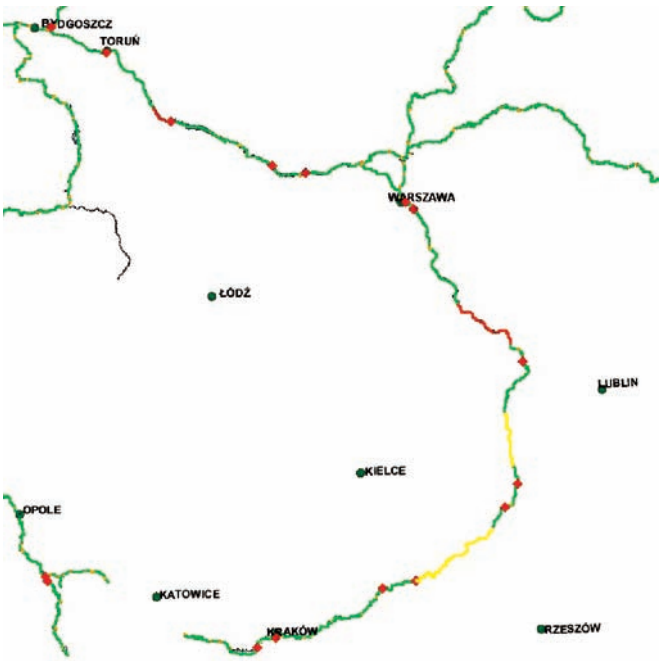


Picture 4. *Results of Vistula River navigability analysis based on current water state monitoring, for high state.*

- Network analysis – determining the shortest water way between 2 locations, without any additional conditions describing ship, cargo or waterways or their land neighborhood.



Picture 5. *Results of Vistula River navigability analysis based on current water state monitoring, for middle state.*

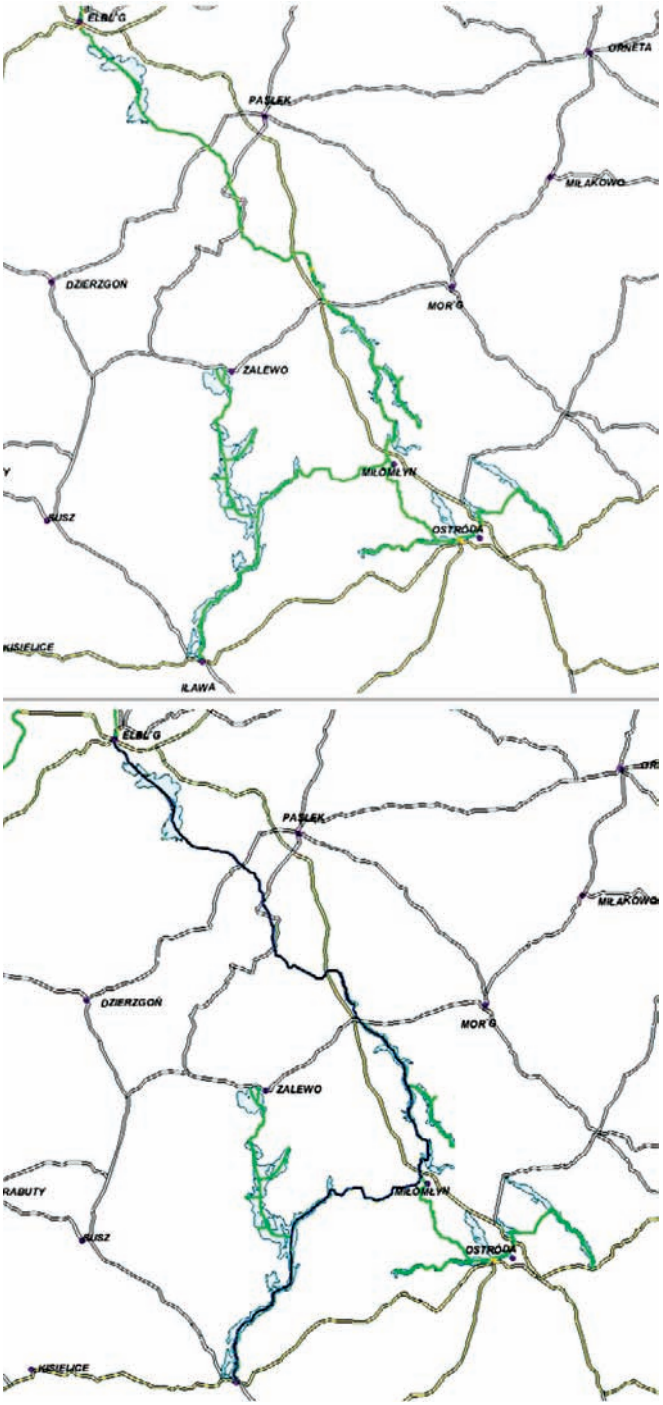


Picture 6. *Results of Vistula River navigability analysis based on current water state monitoring, for low-middle (c) state.*

- Finding existing bottlenecks on waterway. In the presented case red line shows unnavigable segments because of exceeded ship/cargo height. The reason of this limitation is height of few bridges crossing over the waterway. Developed algorithm classifies segment as unnavigable if it is crossed over by bridge segment (yellow short lines) with height over water less then ship/cargo height. The bridge height computation is based on current water state.

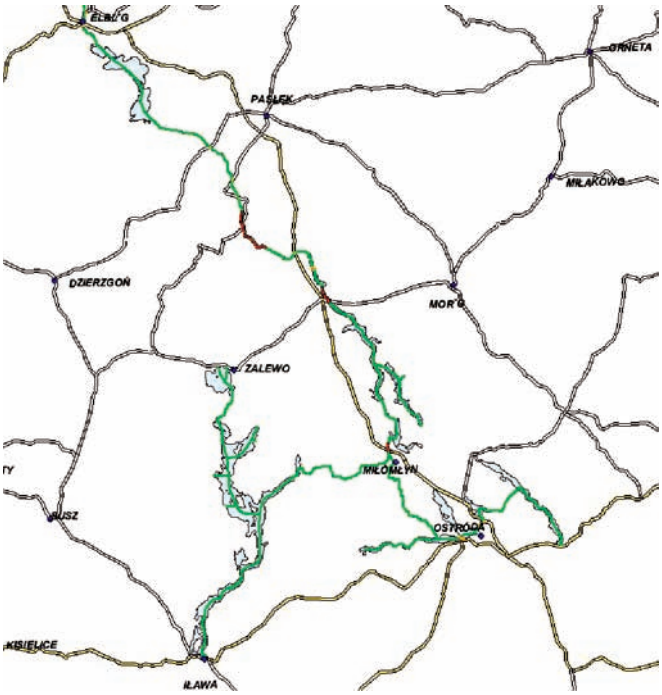
- More complex problem is determining alternative traces between 2 locations with respect to existing bottlenecks. Some additional conditions have been defined: due to reloading time and cost only one land detour is acceptable and waterway is preferred so we look for the shortest land detour. We have implemented 2 algorithms:

- finding of simple land detour of bottleneck – all segments between terminal bottlenecks are joined in single set ("congestion"), the first water/land junction before and after congestion is connected by the shortest land route. In this case algorithm has found alternative all-land way (Picture 9 – dashed blue line). The application skipped shorter route (through Dzierzgon and Susz) because of errors in land ways network connection in used database (the node near Paslek).

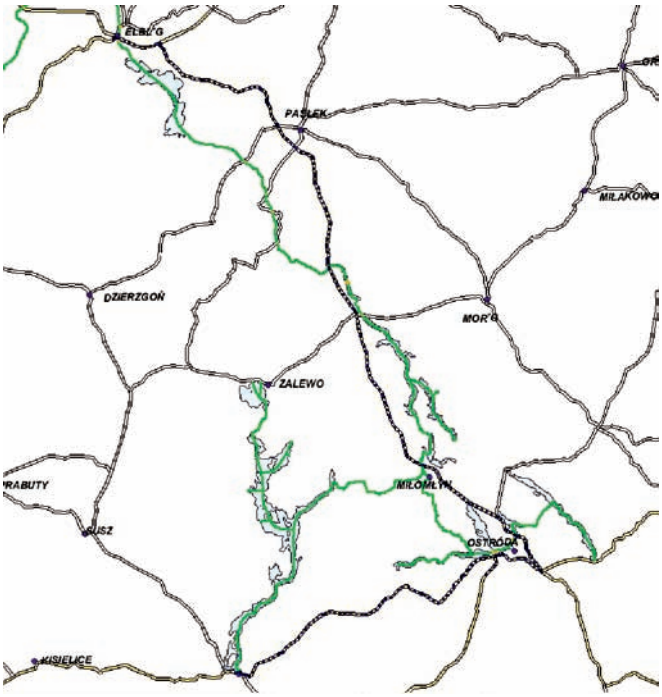


Picture 7. *Part of inland waterways in Poland (Elblag Chanel – green line) and the shortest waterway between Ilawa and Elblag (blue line).*

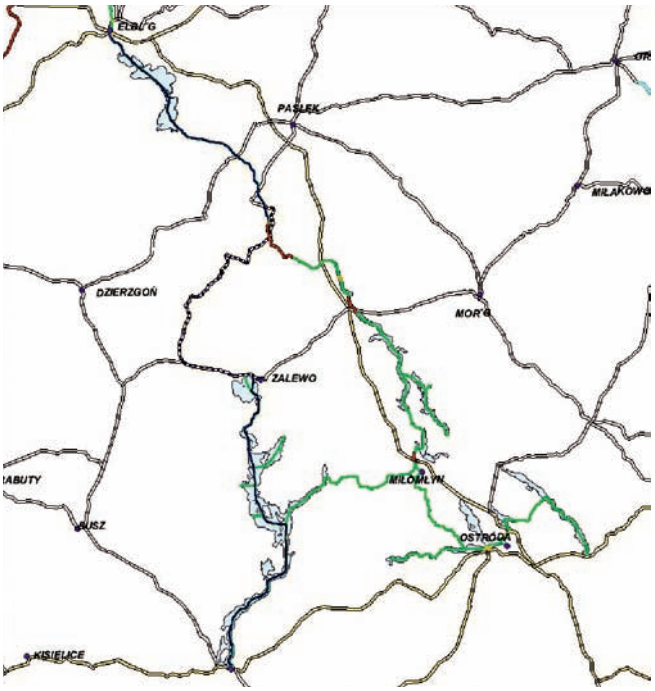
- Determining of alternative trace including alternative waterways segments. Algorithms determines many alternative waterways (if possible) up to the first unnavigable bottleneck starting from both (start and end) locations. The second stage realizes looking for shortest land connection between free ends of determined alternative waterways. Determining of land ways does not take under consideration any vehicle/cargo dimension or weight limitations. Picture 10 shows result of such analysis. Blue solid line shows water part, dashed one – land part of the route between Ilawa and Elblag by-passing bottlenecks shown on the Picture 8. Application can give solutions inconsistent with good practice or even with common sense but we should remember that its target is control of algorithm formal correctness as well as connections between water and land ways networks.



Picture 8. *Appointing nonnavigational episodes (red line).*



Picture 9. *Alternative all-land way between Ilawa and Elblag.*



Picture 10. *Alternative mixed water-land connection between Iława and Elblag*

WATERS STATE PREDICTION

One of the important problems for inland navigation and transportation planning is a short time water state prediction. His task seems to be more and more important because of reputable lower and lower waters state during last 20 years. There are many models of flooding and freshet wave propagation but their high requirements on data quality cause that they seem to have limited application to low and middle state situation, which is the most important for navigation problems. Considering lack of high quality data on channels bathymetry using computationally expensive models does not make a sense. For this reason simplified model of waters state changes propagation is developed.

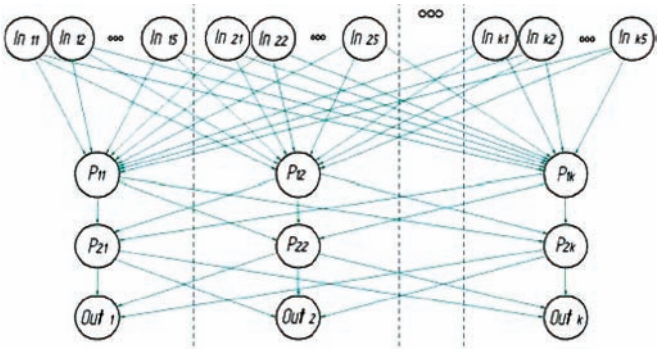
The main assumptions are:

- model should use only public accessible data
- it should be computationally inexpensive (in terms of time and resources).

The model was implemented as Neural Network developed in Matlab 6 with Neural Network Toolbox environment. The net was trained with data from published in Internet IMGW Daily Water State Bulletin for period: 01.04.2006 -01.06.2006. Testing data are from the same source and cover period 01.06.2006 – 30.06.2006. Data choice was caused by their accessibility (data gathered during project endurance were used).Two separate networks were developed, separately for Vistula (21 water gauges) and Odra (16 water gauges) rivers. Main assumptions for neural network are:

- training data are processed – we do not use water gauge indication (GLEB) but its aberration form average value (DSWW), so the model describes dynamics of waters state changes
- data covers all water gauges for main river of waterway (Vistula and Odra separately) without side streams
- only historical data from water gauges can be used (no precipitation directly considered). We have tested different range of historical data: from 2 to 10 days back, and no significant differences in results generated by nets trained on 5-10 days periods were observed. So our network is based on 5 days back data.

The network architecture: 4 layers perceptron net is used. Input layer (In) consists of cells in quantity of water gauges number multiplied by 5 (number of days back data were used), both intermediate (P1, P2) and output (Out) layers contain cell in quantity equal water gauges No (Picture 11). Input value in input cell with indexes (m, n) contains DSWW for m^{th} gauge n days back. Output cell with index m contains prediction of DSWW for m^{th} gauge for next day. Output data can be added at the beginning of input data and used for next prediction. Test shown usefulness of such procedure up to 3-days prediction.



Picture 11. *Neural Network for short term waters state prediction.*

CONCLUSIONS

Data describing current water state can be efficiently used in navigability analyses. Existing software allows for performing such analyses, but its reliability depends on existing data, which are highly incomplete. Developed model and application are ready for use, and next step should be dedicated to 2 problems:

- Data – coherent program of waterways bathymetry should be developed, including coordination of existing works realized for flooding and environment protection needs, as well as new project dedicated to navigation. Real time water gauges monitoring would be also useful. The separate problem is reliability of existing digital data (quality of used database, updating of existing data and inputting of new ones).
- Enabling of visualization data and analyses results in Internet. Currently works on publishing existing data through Intergraph Web Map are in the course. In future using Web-based Google Earth system for this task is considered as well.

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Technical aspects of environment protection with respect to a small inland passenger ship

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ABSTRACT

The article presents brief information on impurities which can be emitted to the environment by an inland passenger ship and discusses methods and devices which can help reduce or avoid these emissions.

Keywords : environment protection, small inland passenger ship, passenger ship

INTRODUCTION

Inland and coastal ships often navigate on water regions which come under the regulations of both the marine and land administration. Water regions of this type in Poland include the Gdanska and Pomorska bays, and the Vistula and Szczecin Lagoons. From the point of view of environment protection, the inland ship should meet the regulations included in the Marpol convention, and those given in acts, instructions, and other legal documents concerning inland waters. These regulations, issued by various administrations, are often incompatible to each other, therefore the range of requirements to be met by the inland ship can be wider than those concerning a classical seagoing ship. A problem of current importance is also the variety of amendments to these regulations, especially those concerning environment protection.

The present article, based on Ref. [1], discusses types of impurities which can be emitted to the natural environment by a small inland passenger ship, quotes selected relevant legal regulations, and formulates certain suggestions on how to avoid or reduce these emissions. In the analysis the following assumptions were made :

- ★ Ship design, equipment and operation is to be "environment friendly" to as high extent as possible – with minimum influence exerted on the environment during the entire "life cycle", including times of building, operation (and all types of repairs), and scrapping. All that means that the ship should meet not only the regulations resulting from the current law in force (concerning natural environment protection), but at its design stage the regulations which have not come in force yet been but are known to be valid in the nearest future should also be taken into account, along with other relevant requirements, concerning seagoing ships for instance.
- ★ Ship design and equipment should meet the regulations of a selected classification society, environment protection conventions in force, and local standards resulting from the law of a country, or countries, on the territory of which the ship is going to navigate. The object of more detailed discussion will be Polish regulations which are now compatible, to a high extent, with the law in force in the remaining EU countries.

For the ship to meet the above requirements, as early as at its design stage a series of decisions is to be made on its construction and equipment. In numerous cases prevention or minimisation of impurities emitted to the environment consists in selecting a proper solution rather than a real machine, and in this process an important role is played by ship designers. For instance, the selected machines must not include parts made of noxious materials (asbestos, for instance), and must not emit to the environment considerable volumes of noxious wastes as a result of its normal use.

SHIP CHARACTERISTICS

The characteristics of a ship are given here to identify possible sources and types of impurities which can be emitted to the environment. For this purpose reports prepared within the framework of the !EUREKA-INCOWATRANS project were used. The basic data define [2] :

- ⇨ A cruising passenger-sanatorium ship (high comfort secured)
- ⇨ Sample cruising route : Berlin – Torun – Gdansk – Elblag – – Krolewiec
- ⇨ Number of passengers and crew : maximum 80 ÷ 100 people
- ⇨ Time of voyage: about 14 days, with longer stops in selected ports, attractive from the tourists' point of view
- ⇨ Two-element ship structure: a pusher tug (a driving module with crew's quarters and part of passenger cabins) and a barge (luxurious passenger cabins); total length : ~110 m, design draught 1 m
- ⇨ On the cruising route there are places such as passages under bridge spans, which require increasing draught (extra ballasting)
- ⇨ The delivery is required of: mechanical and electric energy, heat for heating purposes, drinking and sanitary water; the sources of mechanical and electric energy will be supercharged piston-type internal combustion engines fed with liquid or gas fuel
- ⇨ The waste (including noxious components) and sanitary sewage will be taken off the ship.

IDENTIFYING TYPES OF IMPURITIES EMITTED TO THE ENVIRONMENT

The impurities resulting from ship operation include :

- oil and oil mixtures from the bilge, liquid fuel, lubricating oil, and power hydraulics systems
- maintenance garbage from the ship engine room and deck (definition according to Annex V to the Marpol convention)
- products of fuel burning in piston engines (nitric oxides, sulphur dioxide, unburned hydrocarbons, solid particles, carbon dioxide)
- leakage of working agents from cooling and, possibly, fire extinguishing installations
- emission of hydrocarbon vapours from fuel tanks
- undesirable water organisms and pathogens existing in the transported ballast water and sediments covering the bottoms of the ballast tanks
- noise emitted by power plant and general purpose ship machines and devices
- utilisation of wastes (including ship scrapping).

The impurities resulting from ship function include :

- sanitary sewage and waste waters (definition according to Annex IV to the Marpol convention)
- service and kitchen garbage (definition according to Annex V to the Marpol convention).

The above listed impurities are emitted to the atmosphere and water, and increase soil pollution (sewage and waste transported to land).

LEGAL REGULATIONS

The ship can be used for navigation on Polish inland waterways if it meets the regulations of the act on inland navigation [3], complemented by relevant executory instructions [4, 5]. These regulations define requirements concerning the process of ship building and equipping, protection of water and air purity, and noise emission. They also refer to PRS codes of practice.

The act [3], the uniformed text of which was published in June, 2006, has implemented to the Polish law the purview of the 82/714/EWG directive (amended in 1994 and 2003), which formulates technical requirements for water regions constituting the inland waterway network in Western Europe, except the Rhine and Mozela Rivers. The regulations in force on these rivers, drawn up by the Central Commission for Rhine Navigation (CCNR), are more severe.

Until December 2006, the CCNR and EU regulations were harmonised, which resulted in issuing a new voluminous directive [6, 7], formulating technical requirements for inland ships and revoking the 82/714/EWG directive. New requirements will make it possible to adapt (and unify) codes of practice valid in particular EU countries to advanced standards in force in Rhine navigation. The deadline for introducing new legal, executory, and administrative regulations is December 30, 2008. Until then all relevant legal acts are to be modified [3, 4 and 5].

At present, the volumes of impurities emitted to the atmosphere in the exhaust gases generated by Diesel engines installed on inland ships are limited by the regulations formulated in the instructions [8], which implement a series of EU directives (including so-called Rhine Regulations) concerning the quality of the atmospheric air. The deadline for all regulations of these instructions to come into force is December 31, 2008 r. The final regulations say that since July 1, 2007, engines which meet requirements formulated by the Central Commission for Rhine Navigation (stage II) can be introduced to trade and mounted on inland navigation ships. The limits for gas impurities and solid particles emitted by those engines are given in Table 1. Similar limits (at stage IIIA) refer to the impurities emitted by category V1-V2 engines used as propulsion on inland ships [8].

The quality of the fuel, and most of all the content of sulphur, is defined by the directive 2005/33/WE, introduced in Poland following the resolution of the Minister of Transport and Construction, dated May 4, 2006 [9].

Since January 1, 2010, the content of sulphur in the fuel delivered for use to the ships mooring in ports of EU member countries and to inland navigation ships will not be able to exceed 0.1% m/m.

As the planned sailing route goes beyond the borders of Poland and the European Union, it is advisable to meet also the environment protection requirements formulated in the regulations of international conventions (Marpol, for instance). It is the classification societies which are obliged to implement these regulations. Five of them met their obligation by issuing supplements to their regulations in the form of notations of so-called environment classes (Table 2). The Polish Register of Shipping (PRS) issued a collection of technical requirements [10], being in fact a summary of basic IMO requirements but not composing conditions for obtaining additional class notation. An abridged collection of selected (most severe) requirements for obtaining the above mentioned notation is given in Table 3.

Additional requirements formulated in various regulations are quoted further in the article.

Table 1. *Limits of gas impurities and solid particles emitted by Diesel engines, according to Rhine Regulations [8, stage II].*

Engine power P_N [kW]	Carbon monoxide CO [g/kWh]	Hydrocarbons HC [g/kWh]	Nitric oxides NO_X [g/kWh]	Solid particles PT [g/kWh]
$18 \le P_N < 37$	5.5	1.5	8.0	0.8
$37 \le P_N < 75$	5.0	1.3	7.0	0.4
$75 \le P_N < 130$	5.0	1.0	6.0	0.3
$130 \le P_N < 560$	3.5	1.0	6.0	0.2
$P_N \ge 560$	3.5	1.0	$n \ge 3\,150$ rev/min $\Rightarrow 6.0$ $343 \le n < 3\,150$ rev/min $\Rightarrow 45 \times n^{-0.2} - 3$ $n < 343$ rev/min $\Rightarrow 11.0$	0.2

ACTIONS ORIENTED ON MINIMISING THE EMISSION OF SHIP IMPURITIES

Main propulsion

Studying the legal regulations and identifying the emitted impurities allow a conclusion to be formulated that their volume is most significantly affected by the applied solutions

Table 2. *Collection of environmental class notations for seagoing ships [11 ÷ 15].*

Classification Society	Class notation
Det Norske Veritas	CLEAN and CLEAN DESIGN
Registro Italiano Navale Group	GREEN STAR
Lloyd's Register	ENVIRONMENTAL PROTECTION
American Bureau of Shipping	ENVIRONMENTAL SAFETY
Germanischer Lloyd	ENVIRONMENTAL PASSPORT

Table 3. *Abbreviated requirements for obtaining environmental class notation, taking into account DNV, RINA, LR, ABS and GL regulations [11÷15].*

Sanitary sewage Sanitary sewage and waste waters ("grey" sewage) are to be processed, or stored and then transported to land. The sewage processing machine (if used) should meet requirements of the MEPC.2(VI) resolution.
Dealing with garbage The garbage (according to the definition given in Annex V to the Marpol convention) should be sorted, stored and transported to land.
Emission of nitric oxides Each Diesel engine of power higher than 130 kW, excluding engines intended for use in emergency cases, should meet the NO_X emission standard equal to 60% of the volume defined, according to the Formula 13 Annex VI Marpol, from the following relations : for n<130 rev/min ⇒ 17 g/kWh, for 30 rev/min ≤ n< 2 000 rev/min ⇒ $45.0 \times n^{(-0.2)}$ g/kWh, for n ≥ 2 000 rev/min ⇒ 9.8 g/kWh.
Emission of sulphur dioxide The fuel burned in engines installed on the ship: maximum content of sulphur 0.2% m/m (light fuel) or 1%m/m (heavy fuel). Alternatively: max. 2.0 g SO_X/kWh in the exhaust gases.
Fire extinguishing installation Substances used in fire extinguishing installations should have GWP<1650 and ODP=0. The use of halons is prohibited.
Cooling installation The use of such refrigerants as CFC and HCFC is not allowed. Natural refrigerants are to be used, or, alternatively, HFC revealing GWP<1890 and ODP=0.
Ship hull painting Ship hull is to be covered with paints without TBT.
Arrangement of tanks for fuel, lubricating oil, and oil wastes Tanks are to be separated from shipboard and/or bottom by cofferdams.
Required is main propulsion redundancy (obtaining class **RP** notation, according to DNV regulations is considered sufficient).

of the main propulsion and power generation systems. Of high significance is the selection of the fuel and machine in which the chemical energy of the fuel is converted into the mechanical energy (Fig. 1).

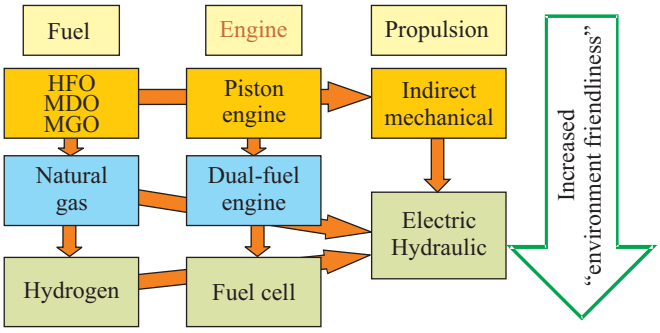

Fig. 1. *Scheme of actions oriented on selecting propulsion and power generation systems for the designed ship.*

The fuel can be diesel oil, liquid or gas hydrocarbons (CNG, LPG) or hydrogen (compressed, or in another arbitrary form delivered to a fuel cell).

At the present state of technology each piston engine can be fed with the gas fuel. Advantages resulting from the use of the natural gas (CNG) or liquefied oil-originated gases (LPG) as fuels include, first of all, low toxicity of the emitted exhaust gases, compared to those generated in the process of diesel oil burning.

From the safety point of view, the use of the natural gas in the ship's power plant is more profitable. The natural gas is lighter than the air and in case of leakage in the supply installation it moves up, which facilitates ventilation. LPG is heavier that the air and in case of leakage, some problems may occur with ventilation of the room in which the tank or gas installation is located.

A basic disadvantage of the use of the natural gas as engine fuel is its low energy density. As a result, tanks for these types of fuel (in case of CNG, the working pressure in high-pressure tanks is equal to 20 ÷ 25 MPa) take more space than those for liquid fuels or LPG. An obstacle making the wider use of the natural gas as engine fuel in Poland more difficult is its poor distribution network.

Hydrogen is a specific gas fuel, which differs most from the conventional (liquid and gas) fuels by the exhaust gas composition. Due to the absence of coal in the fuel, the carbon dioxide practically does not exists in the exhaust gas of the engine fed with hydrogen, and the main exhaust gas component accompanying the nitrogen is the steam. In fact, the only toxic components of the exhaust gas are nitric oxides.

From the point of view of environment protection, the most favourable inland ship propulsion in the nearest future seems to be a combined combustion-electric propulsion system, in which medium-speed current generators meet the requirements given in Table 1 for the level of impurities emitted in the exhaust gas. A most recent design of Volvo Penta (engine D16 with 478 kW output, Fig. 2 meets requirements of IMO, EPA2, Rhine River Step 2 and Clean Design DNV class notations. A collection of permissible emission limits of nitric oxides, according to different regulations given in Fig. 3, suggests that a sufficient requirement to be met by the piston engines with output below 560 kW, which may be used as the main drive on the designed passenger ship, is meeting the Rhine Regulations [8].

At present, there are no offers of dual-fuel or gas engines with output of an order of 200 ÷ 300 kW on Polish markets. Offers of those engines solely refer to the constructions used in road transport and stationary power systems.

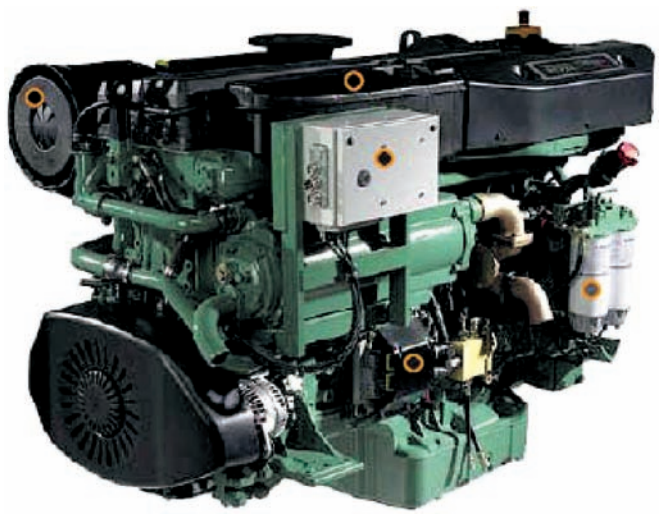

Fig. 2. General view of Volvo Penta engine, type D16 [www.volvo.com].

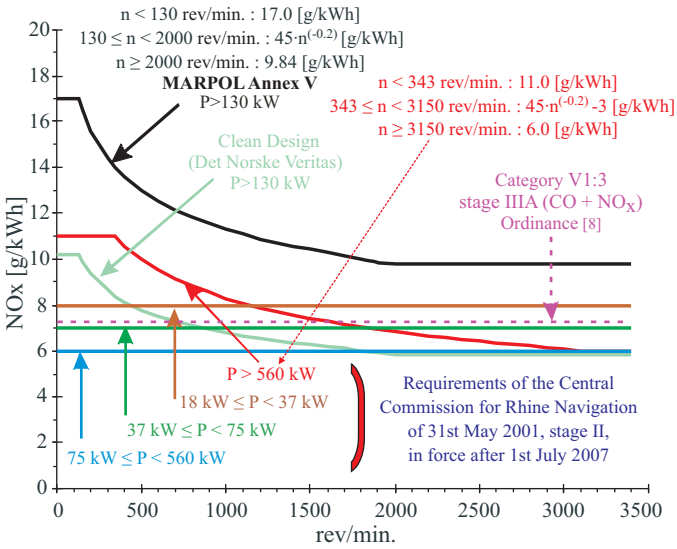

Fig. 3. Permissible levels of emission of nitric oxides, acc. to [8, 11, 16].

An alternative for the piston engine can be the use of fuel cells that directly convert the chemical energy of the fuel into the electric energy. The fuel cells are extremely environment friendly, as the by-products, such as H_2O, CO_2 or N_2 are pure, and the emission of nitric oxides, sulphur oxides, carbon oxides and hydrocarbons is very low. Moreover, they reveal low noise emission. They can be located anywhere, in practice, and occupy very little space. A disadvantage of the fuel cells is low current voltage obtained form a single cell, V< 1 V, and that they generate the direct current. At present, one of the biggest disadvantages is also their price, as the cost of a fuel cell with several hundred kW output power is over 1 million $.

A possibility to make a choice between a piston engine and a fuel cell forces the use of an electric motor as the propeller drive. A sample design of the combined combustion-electric propulsion system is shown in Fig. 4. The power plant comprises electric current generators with output power of about 200 kW each, frequency inverters, alternating-current motors, and propellers (mounted in nacelles, or as screw plus nozzle systems). The electric current generators can be replaced by fuel cells.

The propulsion system shown in Fig. 4 can be simplified using a so-called rim drive propulsor (RDP). The propulsor's propeller has a number of blades, with permanent magnets fixed to blade tips, thus constituting the rotor of the motor (Fig. 5).

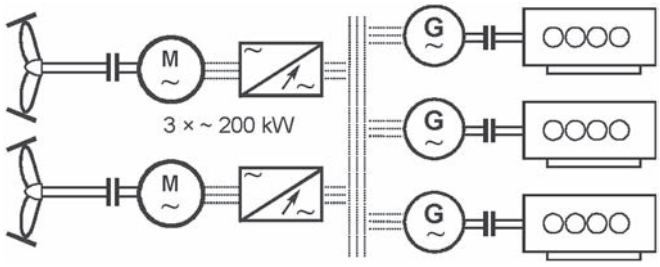

Fig. 4. Scheme of a sample propulsion system design.

The nozzle in which the propeller rotates is simultaneously the motor stator. The entire propulsor is slung under the ship hull. Art present the propulsor is undergoing research and implementation tests.

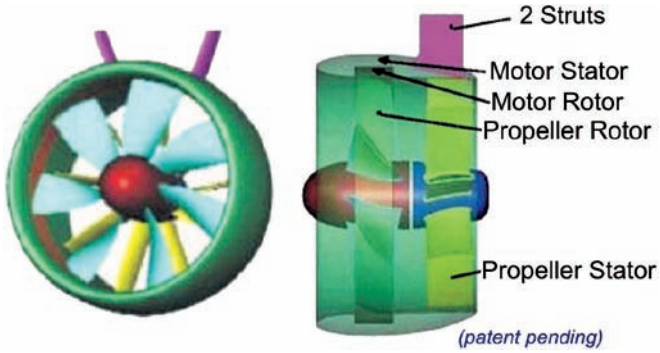

Fig. 5. View of the rim drive propulsor RDP[17].

Within the framework of the INCOWATRANS project, propulsion system solutions were analysed [18, 19], and methods for reducing volumes of impurities emitted in exhaust gases generated by piston engines were discussed, along with present and future abilities to use other fuels than the diesel oil (CNG, LNG, hydrogen, etc.).

Sanitary waste and sewage

Procedures of dealing with ship waste are given in [5]. According to the definition used in the regulation, the waste includes used oils and lubricants, and all other waste and garbage which contains oil (bilge water, used filters, oil packages, etc.), as well as the sewage from kitchens, bathrooms and laundries, fecal matter, the organic and inorganic waste collected from the hotel and gastronomy centres. All waste is to be stored on the ship and then transported to land reception points, in time intervals which prevent overfilling the used containers (tanks) or exceeding permissible levels of water in engine room bilges.

According to the regulations of the act on waste [20], the land reception point is considered a waste generator, therefore is has to have a relevant administrative decision.

Following the above recommendations, a relevant number of hull tanks, or other separate fixed tanks for storing waste are to be provided.

In order to store used oils, the engine room is to be equipped with one of more tanks of cubic capacity at least 1.5 times as big as the volume of the used oil which can be collected from oil sumps of all installed combustion engines and gears, plus the volume of the hydraulic liquid collected from hydraulic liquid tanks [6, 7].

Ship operation conditions allow the bilge water to accumulate only in the engine room bilges, with its further direct transport to land, without using a storage tank (which, however, can be used optionally). The bilge water can be

disposed of during relatively frequent stays in ports. According to various sources [21], an approximate volume of the bilge water equals 0.5 ÷ 1.5 m^3/day for ships with main engine output < 1000 kW. The recommended minimum capacity of the bilge water storage tank (for seagoing ships) equals 1.5 m^3 – according to PRS, DNV and LR regulations. The use of the gas fuel decreases oil contamination of the bilge water. In co-operation with the engine producer the use of so-called EPLs (*Environmentally preferable lubricants*) can be analysed. These lubricants are vegetable or synthetic oils revealing lower toxicity, and shorter biodegradation time than the oils obtained from crude oil processing. The same remark refers to oil lubricated shaft pipe bearings.

For storing sanitary sewage and waste waters, tanks should be provided with sufficient cubic capacity calculated taking into account the number of people on the ship, the adopted water use standards and type of sanitary installation (conventional or vacuum). The use of the vacuum installation considerably reduces the volume of the sewage to be stored. Installing a typical sewage processing machine is not required. The capacity of the tanks can be assessed based on elementary indices (table 4.) given, for instance, in PRS or RINA regulations. The collecting tank should have a capacity securing that it is not overfilled during two days, the least, taking into account the maximum number of people on the ship.

Table 4. *Elementary sanitary sewage indices.*

PRS (changes 1/2000)	RINA (Pt.F, Ch.7, Sec.1, 2.4.4
70 dcm^3/(day and person) for installations with separation into „black" and „grey" sewage, 180 ÷ 280 dcm^3/(day and person) for installations without sewage separation, 25 dcm^3/(day and person) for vacuum installations	96 dcm^3/(day and person) for conventional installations, 11 dcm^3/(day and person) for vacuum installations.

A system should be provided on the ship for collecting, preliminary processing (sorting, disintegrating, pressing) and storing of the waste, understood as the service and kitchen garbage collected from the engine room and deck areas. It is advisable to use three different waste tanks (bags, boxes, containers, etc.), the minimum, for collecting :

- ❖ the waste containing plastics
- ❖ kitchen and pantry garbage, including materials contaminated with food
- ❖ other garbage which can be subject to further sorting, in particular raw materials, such as waste paper, glass, scrap, etc., intended for further processing.

The ship can be equipped with machines for disintegrating and pressing of the waste. These actions decrease the space required for waste storage and facilitate its discharge to land. Disintegrating machines (mills) are usually installed in the kitchen and generate liquid mixture of food with water, stored in a separate tank. Pressing machines allow the volume of the waste to be reduced.

The cubic capacity of the tanks can be assessed using recommendations given in [22] and collected in table 5.

Another way is to use the below given data [21] being rough estimation of the volumes of garbage (world average) collected on passenger ships, tankers, bulk and general cargo ships, container ships, and harbour ships, assuming the minimisation of the volumes of the waste stored on ship and no discharge at sea :

- ☆ food waste – 1.4 ÷ 2.4 kg/day and person,
- ☆ service waste – 0.5 ÷ 1.5 kg/day/person,
- ☆ maintenance waste – up to 20 kg per day, depending on the age of the ship.

Dealing with other waste types, or their minimisation

Arrangement of tanks for fuel, lubricating oil, and oil wastes – it is advisable for seagoing ships to use protecting measures against oil leakage in case the ship hull is damaged, by separating the tanks from the bottom or shipboard by cofferdams. For instance, obtaining the Clean Design DNV class notation is connected with obtaining the OPP-F notation. Relevant requirements are given in [11, P.6 Ch.1 Sec.6 - Arrangement of Fuel Oil Tank]. Similar requirements are formulated by Lloyd's Register [13, P.7 Ch.11 Sec.3] and refer to obtaining an additional mark P in the ship class symbol. The most detailed requirements concerning the distribution of oil tanks are given in RINA regulations [12, P.F, Ch.7, Sec.1].

Ballast – ship operation conditions provide ballasting only when sailing under bridges with low passing clearances. As a consequence, the ballast water will be in practice taken and disposed of in the same sailing region. Therefore all procedures of dealing with the ballast water, the goal of which is to minimise passing undesired water organisms between different water regions, do not apply to the designed ship.

Hull painting – the underwater part of the ship hull should be covered with paints which do not contain TBT (table 3).

Noise – here the Code on Noise Level on Board Ships, dated 1981, which was worked out by IMO, can apply along

Table 5. *Capacities of ship waste tanks, acc. to [22].*

	Gross capacity						
	Up to 400 gt		400 ÷ 1600	1600 ÷ 4000	4000 ÷ 10000	> 10000	Ships transporting more than 50 people
	Up to 10 people	Up to 50 people					
Minimum total capacity of tanks, in m^3	0.1	0.5	0.4	1.2	2.5	5.0	1.0 m^3 per 100 people and 1 day
At least three tanks should be used. The waste contains, on average, glass, carton, etc. - in 50%, plastic – in 25%, and food waste– in 25%.							

with the regulations of the Minister of Environment of July 29, 2004, on permissible noise levels in the environment (Regulation Gazette, 2004.178.1841). An alternative is meeting requirements formulated by classification societies, which define the level of noise, vibrations and microclimate in ship compartments for so-called comfort classes. For instance , there is a notation COMF-V(…) and COMF-C(…) used by Det Norske Veritas. A compulsory obligation is to meet the following directive requirements [6] :

- noise generated by the ship in motion must not exceed 75 dB(A) at a distance of 25 m and in direction perpendicular to the shipboard
- except for loading operations, the noise generated by the ship at a standstill must not exceed 65 dB(A) at a distance of 25 m and in direction perpendicular to the shipboard

Substances damaging the ozone layers – on the ship these substances can be used as working agents in cooling systems. A limitation here is defining the maximum permissible ODP and GWP values (table 3) for the refrigerant which is to be used in the installation. Sample values of these coefficients for selected working agents are given in table 6.

Table 6. *ODP, HGWP and GWP for selected refrigerants.*

	Natural	ODP	GWP (100 years)	GWP (500 years)
HCFC-22 (R22)	no	0.0555	1 700	4 100
HFC-134a (R134a)	no	0	1 300	3 100
CFC115/HCFC22 (R502)	no	0.33	5 900	
Propane (R-290)	yes	0	3	
Ammonia (R717)	yes	0	0	0

Scrapping – at present, the regulations concerning recycling of seagoing ships are given in Res. IMO A.962(23) [23]. The instructions are arranged in 10 chapters, the most important of which are: (4) – identifying potentially harmful materials and (5) – **green passport.** The latter is the document, written out by the shipyard or the ship owner, which among other data includes the information on dangerous substances entering into the composition of the ship, its equipment and installations. The resolution also includes 5 **Appendices** with lists of harmful substances and instructions concerning the methods of making their inventory. These lists are rather voluminous and, what is more, are subject to changes resulting from activities performed on the IMO forum. Such a passport could be prepared for the designed ship – but its preparation is only possible based on the working documentation.

CONCLUSIONS

The above collected brief information on impurities emitted by the ship to the environment and the overview of machines to be installed on the ship in order to reduce or avoid these emission allow the following suggestions to be formulated :

- the regulations concerning environment protection against impurities emitted by inland ships are not as complete and clear as those in force for seagoing ships
- when designing an "environment friendly" inland ship, the regulations in force for seagoing ships can be additionally used, which is obligatory for ships navigating in coastal areas
- at present new legal regulations are implemented which refer to various impurities emitted by the ship – all this requires modifications of a series of machines and devices installed on ships, or introducing new technologies, which is executed, as a rule, with some time delay
- a general remark is the statement that for the ship to be called "environment friendly", at the design stage certain selections or decisions are to be made on propulsion and power generation systems, individual ship installations and types of the materials. This latter refers not only to the materials used for building pipeline connections and electric cables, but also to those composing machines and mechanisms delivered as a whole to the built ship. They should contain as little harmful or dangerous materials as possible.

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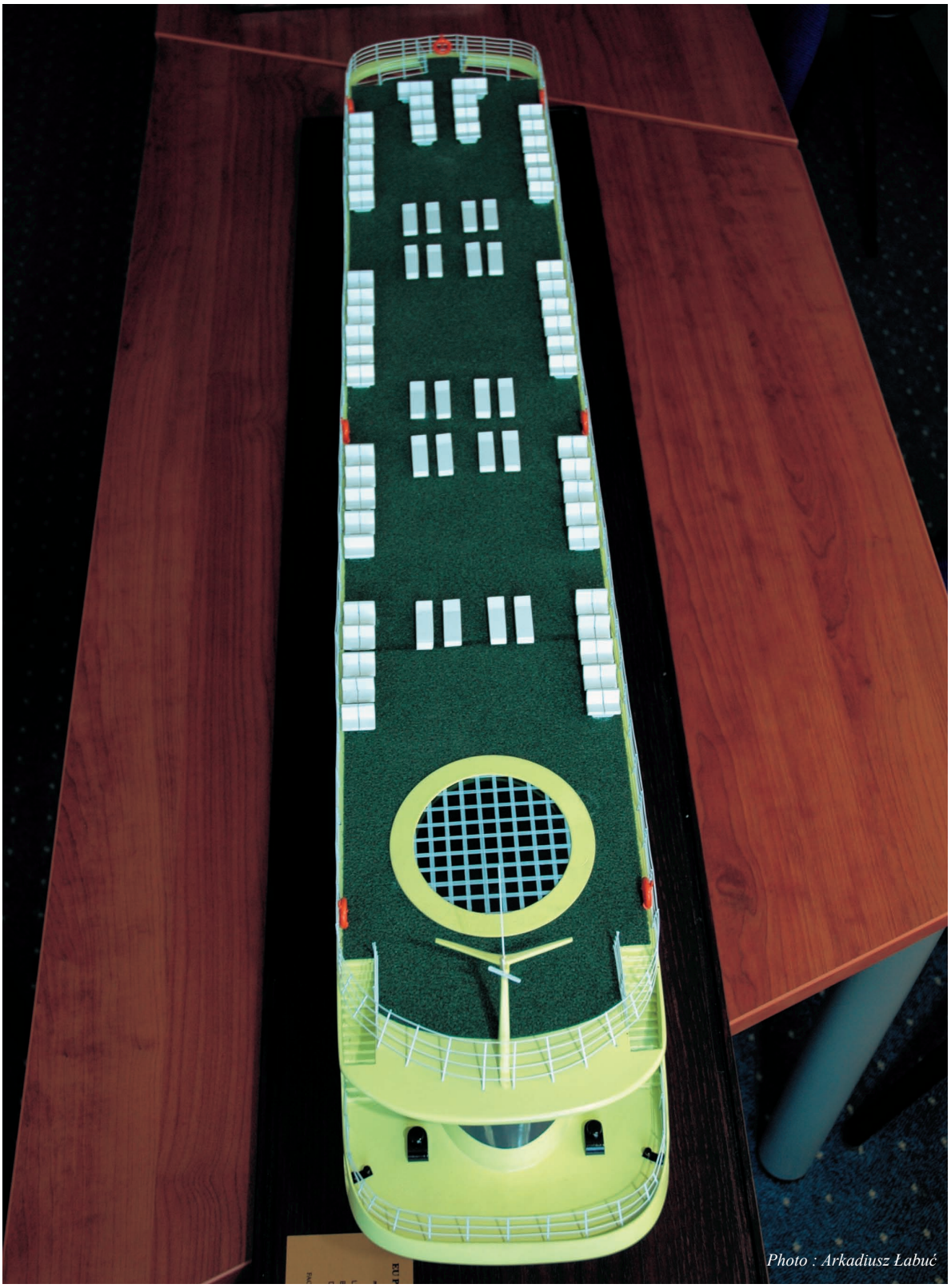

Photo : Arkadiusz Łabuć

Exhaust gas toxicity problems in ship drives

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ABSTRACT

The issues discussed in the article include exhaust gas emission, purity requirements and standards, methods of reducing the emission of harmful exhaust gas components, and alternative and future traction drive sources having the form of fuel cells. The discussion often refers to the situation of road transport, a subsystem which severely affects the environment and thus is obliged to intensify the search for solutions.

Keywords : inland navigation, diesel engine, fuel cell, emission, standards

INTRODUCTION

The transport system in each country is a basic component of the economic infrastructure. In many developed economic systems in the world the inland water transport is treated as an equivalent subsystem to other transportation forms [1]. Among other factors, its position results from the following qualities :

- ★ low power consumption
- ★ low noise emission
- ★ low environment pollution.

It is diesel engines that are used as driving units in inland navigation ships. Long-term and steady conditions of operation, along with technological achievements provide good opportunities for reducing the emission of toxic compounds in exhaust gases produced by a ship engine. But still these engines cannot be considered zero-emission devices.

EMISSION OF EXHAUST GASES

A fuel which is commonly used for feeding ship drive diesel engines is hydrocarbon fuel produced in the process of crude oil processing. The chemical energy of the fuel is converted into thermal energy in the combustion (oxidation) process executed in the engine cylinder. Then the thermal energy is converter into mechanical energy having the form of a torque transmitted to the flywheel.

The process of oxidation of carbon and hydrogen, which are fuel components, makes use of the oxygen taken from the atmospheric air, another component of which, with 79% share, is nitrogen, which also takes part in the combustion process.

Crude oil is accompanied by sulphur. Its concentration in the fuel produced from the crude oil is controlled, but the cost of processes aimed at sulphur removal is directly proportional to the removed volume.

The execution of the combustion process in the diesel engine requires excessive air volumes, defined by the air excess coefficient λ.

Products generated in the combustion process include toxic compounds, such as C_uH_v , CO, C, SO_z , NO_x . Amorphous carbon C is not toxic, but due to its ability to absorb liquid and gas components of the exhaust gas on its surface it is defined as a controlled and limited component, bearing the name of solid particles (PM or PT).

The emission of exhaust gases is directly proportional to the engine piston displacement volume (V_{ss}) and engine crankshaft rotational speed (n). Percentage composition of the exhaust gas mainly depends on the combustion system and the engine load represented by its torque (M_o).

EXHAUST GAS PURITY REQUIREMENTS AND STANDARDS

It is diesel engines which are most frequently used as inland ship drives. During the first stage of legislation activities oriented on standardising the emission of toxic compounds in exhaust gases, diesel engines composed a preferred group, with ten times as small concentration of carbon monoxide as that characteristic for spark-ignited engines. This situation changed when engine smoking, with the only reference to diesel engines, was to be reduced.

Design properties and operating characteristics were the factors deciding in favour of the domination of those engines used as high-power drives, while the development of research techniques allowed standardising so-called unit emissions, expressed in g/kWh, of four main exhaust gas components, which were CO, HC, NO_x and PM.

Table 1 collects EU Standards concerning emission limits for so-called off-road engines (closest to inland ship drives), taken from the instructions [2].

***Table 1**. Emission limits for off-road engines [2].*

PN	In force since	CO	HC	NO_x	PM
KW	-	[g/kWh]			
Stage I					
130 – 560	1999.01	5.0	1.3	9.2	0.54
75 – 130	1999.01	5.0	1.3	9.2	0.70
37 – 75	1999.04	6.5	1.3	9.2	0.85
Stage II					
130 – 560	2002.01	3.5	1.0	6.0	0.2
75 – 130	2003.01	5.0	1.0	6.0	0.3
37 – 75	2004.01	5.0	1.3	7.0	0.4
18 – 37	2001.01	5.5	1.5	8.0	0.8

Table 2 collects EU Standards concerning emission limits for inland transport engines, taken from the instructions [3].

***Table 2**. Emission limits for inland transport engines – Stage III [3].*

Category	Piston displacement volume (D) Engine power (P)	CO	NO_x + HC	PM	In force since
-	[D, cm^3] [P, kW]	[g/kWh]			[-]
V1:1	D ≤ 0.9 and P > 37	5.0	7.5	0.40	31.12.2006
V1:2	0.9 < D ≤ 1.2	5.0	7.2	0.30	
V1:3	1.2 < D ≤ 2.5	5.0	7.2	0.20	
V1:4	2.5 < D ≤ 5.0	5.0	7.2	0.20	31.12.2008
V2:1	5.0 < D ≤ 15	5.0	7.8	0.27	
V2:2	15<D≤20 and P≤3300	5.0	8.7	0.50	
V2:3	15<D≤20 and P>3300	5.0	9.8	0.50	
V2:4	20 < D ≤ 25	5.0	9.8	0.50	
V2:5	25 < D ≤ 30	5.0	11.0	0.50	

The situation in Poland is regulated by the act [4], which only standardises exhaust gas smokiness (using the light absorption method) in diesel engines at the level equal to :

- 2.5 m^{-1} for engines without superchargers
- 3.0 m^{-1} for supercharged engines.

The International Maritime Organisation (IMO) determines, in turn, only NO_x emission. Sample emission limits for engines of more than 130 kW output are given in Table 3 [5].

***Table 3.** NO_x emission limits according to IMO regulations [5].*

Engine rotational speed n [rev/min]	NO_x [g/kWh]
n < 130	17.0
130 ≤ n < 2000	$45n^{(-0.2)}$
n ≥ 2000	9.8

As a comparison, Table 4 collects emission limits defined by the Environment Protection Agency (EPA) for engines of more than 37 kW output [6] :

***Table 4.** Emission limits according to EPA regulations for engines of more than 37kW output [6].*

Category	Piston displacement volume D	CO	NO_x + THC*	PM	In force since
-	[dm^3]	[g/kWh]			[-]
Base form – off-road engine	D<0.9	5.0	7.5	0.40	2005
	D<1.2	5.0	7.2	0.30	2004
	D<2.5	5.0	7.2	0.20	2004
	D<5.0	5.0	7.2	0.20	2007**
*) THC (Total Hydro Carbons) **) Stage I (Tier 1) in force since 2004					

The experience in organization and management of water transport on the Rhine River is used for legislative activities in other areas. For better orientation in regulation tendencies, the regulation rules of the tests to be performed on Rhine ships (RheinSchUO) are quoted. These regulations introduce since 1 July, 2007, the second level of emission limits for engines used in Rhine navigation [7]. These limits have been collected in Table 5.

Since the „old“ fleet is still in use, the transitory regulations were issued as well.

***Table 5.** Emission limits in Rhine navigation, in force since 1st July 2007. [7].*

P_N [kW]	CO [g/kWh]	HC [g/kWh]	NO_x [g/kWh]	PT [g/kWh]
$19 \le P_N < 37$	5.0	1.5	8.0	0.8
$37 \le P_N < 75$	5.0	1.3	7.0	0.4
$75 \le P_N < 130$	5.0	1.0	6.0	0.3
$130 \le P_N < 560$	3.5	1.0	6.0	0.2
$P_N \ge 560$	3.5	1.0	$n \ge 3150\ min^{-1} = 6.0$ $343 \le n < 3150\ min^{-1} = 45n^{(0.2)} - 3$ $n < 343\ min^{-1} = 11.0$	0.2

The limits given in Table 5 do not apply to :

a) engines installed on ships before 1st January 2003
b) replacement engines (used engines, after overhaul, which are similar to those replaced with respect to parameters and installation conditions), to be installed before 31th December 2011, on ships, which were in operation on 1st January 2002. For engines which were installed on ships before 1st July 2007, emission limits given in Table 6 are in force.

***Table 6.** Transitory emission limits in Rhine navigation [8].*

P_N [kW]	CO [g/kWh]	HC [g/kWh]	NO_x [g/kWh]	PT [g/kWh]
$37 \le P_N < 75$	6.5	1.3	9.2	0.85
$75 \le P_N < 130$	5.0	1.3	9.2	0.70
$P_N \ge 130$	5.0	1.3	$n \ge 2800\ min^{-1} = 9.2$ $500 \le n < 2800\ min^{-1} = 45n^{(0.2)}$	0.54

Along with RheinSchUO regulations, the European Union defines limits for inland ship engines. Since 2007, engines newly installed on ships sailing outside the Rhine River have to obey the regulations, whose limits are identical to those in force on the Rhine River.

METHODS REDUCING THE EMISSION OF HARMFUL EXHAUST GAS COMPONENTS

Methods used for reducing the emission of toxic components to the atmosphere can be divided into active (which interfere in engine settings and the combustion process) and passive (purification of exhaust gases emitted by the engine). It should be mentioned here that these methods mainly refer to diesel engines.

Active methods :

- optimising the fuel injection starting angle
- modifying the fuel ignition process
- changing the combustion system
- supercharging
- reducing the compression ratio
- exhaust gas recirculation
- introducing water to the combustion process
- using alternative fuels.

Passive methods :

- catalytic methods of CO and HC oxidation
- non-catalytic and catalytic methods of NO_x reduction
- reducing the emission of solid particles, PT, with the aid of filters.

The analysis of active methods allows a conclusion to be formulated that further interference in engine construction,

combustion process, and-or settings will not return expected effects, as it is not possible to minimise at the same time the emission of all harmful substances. Always a conflict will be observed when taking actions to reduce the contents of NO_x and HC, and solid particles [9 – 18].

Solutions which could positively affect the emission of all harmful components of the exhaust gas are already known and used (exhaust gas recirculation, supercharging, catalytic techniques). To meet exhaust gas purity standards, which are becoming more and more severe, passive methods of reduction are to be developed and-or other technical solutions are to be looked for.

The effects of the used and prognosed solutions, taking into account a so-called conflict between NO_x and PM emission reduction goals, are shown in Fig.1 [19].

The emission of harmful exhaust gas components was effectively reduced by developing high-pressure fuel injection systems and introducing the below presented systems of exhaust gas "processing".

The exhaust gas outlet system equipped with an oxidising catalyst and solid particle filter, and making use of fuel additives to facilitate the regeneration, is schematically shown in Fig.2.

The engine outlet system with a NO_x accumulating catalyst (so-called denox catalyst) is given in Fig.3.

The outlet arrangement with a system of selective catalytic reduction (SCR) is shown schematically in Fig.4.

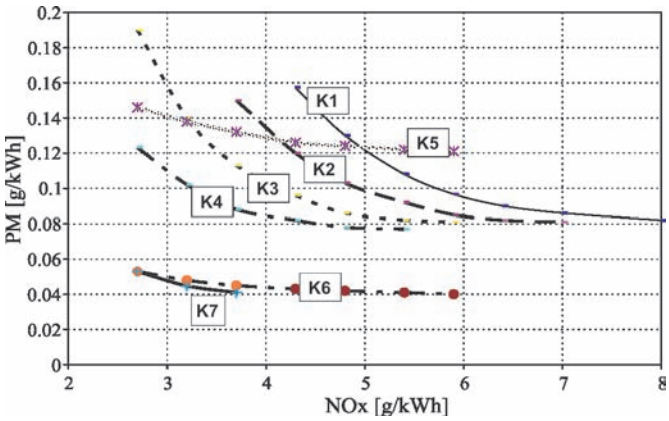

*Fig. 1. Measured and expected volumes of NO_x and PM emission for high-load diesel engine : **K1** - reference engine, **K2**, K3, K4 - engine with denox catalyst revealing efficiency equal to 15%, 30%, 45%, respectively, **K5** - EGR (exhaust gas recirculation), **K6** - EGR + exhaust gas cooling + PM filter, **K7** - denox catalyst + PM filter [19].*

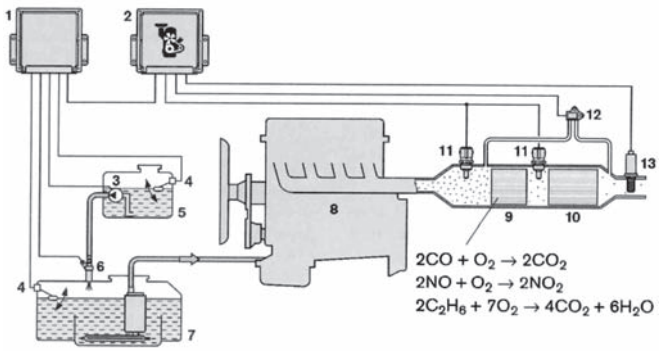

*Fig. 2. Schematic of exhaust gas outlet system equipped with oxidising catalyst and solid particle filter, and making use of fuel additives : **1.** fuel additive controller, **2.** engine controller, **3.** fuel additive pump, **4.** fuel additive level sensor, **5.** fuel additive tank, **6.** additive proportioning apparatus, **7.** fuel tank, **8.** diesel engine, **9.** oxidising catalyst DOC, **10.** solid particle filter, **11.** temperature sensor, **12.** pressure difference sensor, **13.** soot sensor [20].*

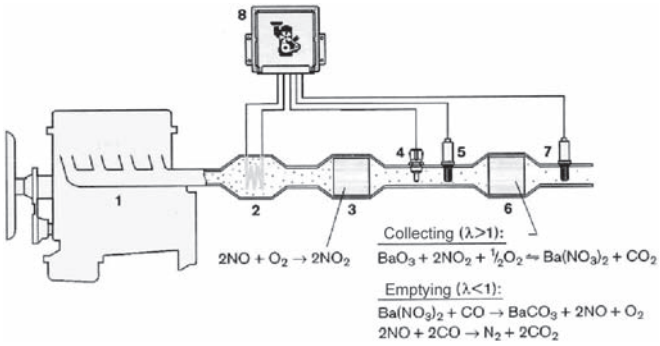

*Fig. 3. Schematic of engine outlet system with NO_x accumulating catalyst : **1.** engine, **2.** exhaust gas heating (optional), **3.** oxidising catalyst (optional), **4.** temperature sensor, **5.** wide-band lambda probe, **6.** NO_x accumulating catalyst, **7.** NO_x sensor or lambda probe, **8.** engine controller [20].*

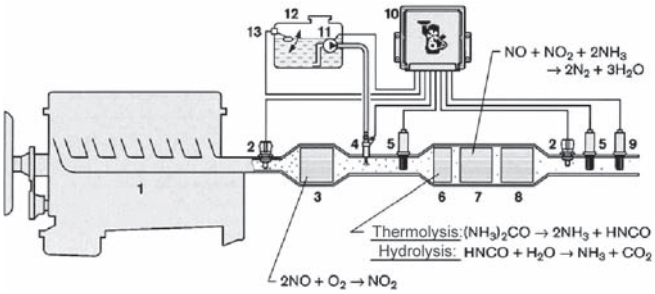

*Fig. 4. Schematic of SCR system : **1.** engine, **2.** temperature sensor, **3.** oxidising catalyst, **4.** reducer injection nozzle, **5.** NO_x sensor, **6.** hydrolytic catalyst, **7.** SCR catalyst, **8.** NH_3 blockage catalyst, **9.** NH_3 sensor, **10.** engine controller, **11.** reducer pump, **12.** reducer tank, **13.** reducer level sensor [20].*

THREATS AND PERSPECTIVES

The above presented solutions base on the principle of permanent development of methods reducing the emission of toxic compounds, with the simultaneous reduction of costs of their application, assuming that the objects of interest are classical engines in operation, fuelled by classical oil product or alternative fuel.

A multi-aspect analysis performed by the Natural Resources Defense Council (USA) on the resources of primary energy sources, effects of operation of diesel engines, and technical abilities of the epoch, provides opportunities for expecting that the situation will develop in the following directions [21] :

- decreasing number and mileage share of new vehicles driven by conventional combustion engines (Fig. 5 and 6)
- temporal increase in the number and mileage share of new hybrid combustion-electric engine driven vehicles (Fig. 7 and 8)
- increase in share of new vehicles driven by so-called fuel cells (Fig. 9), a drive making use of alternative fuel in the form of hydrogen or its products.

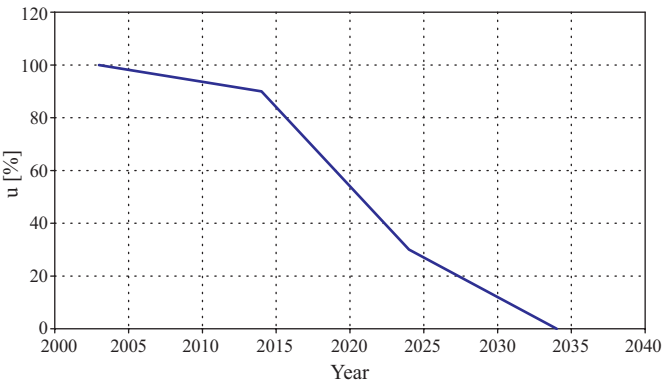

Fig. 5. Expected share of new vehicles driven by combustion engines [21].

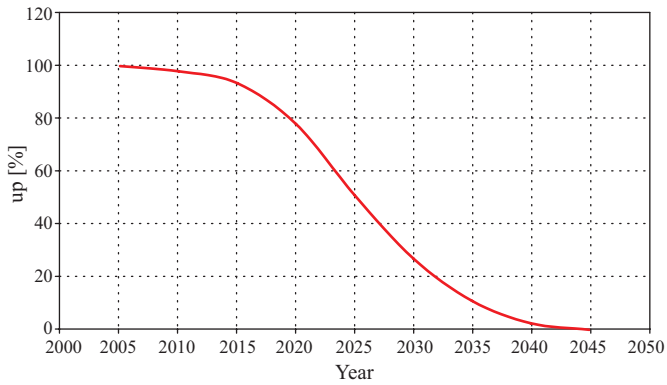

Fig. 6. *Expected mileage share of vehicles driven by conventional engines [21] .*

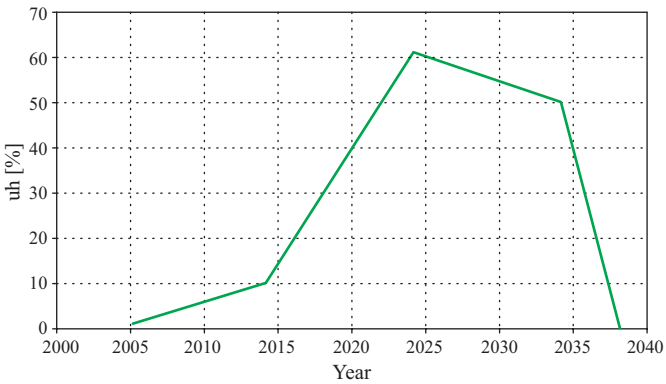

Fig. 7. *Expected share of new hybrid vehicles [21] .*

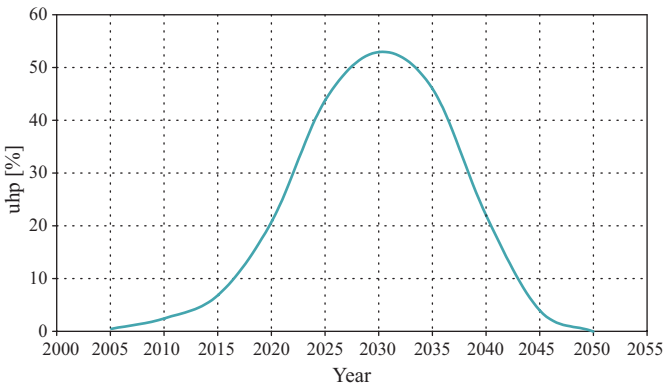

Fig. 8. *Expected share of hybrid vehicles in total mileage [21] .*

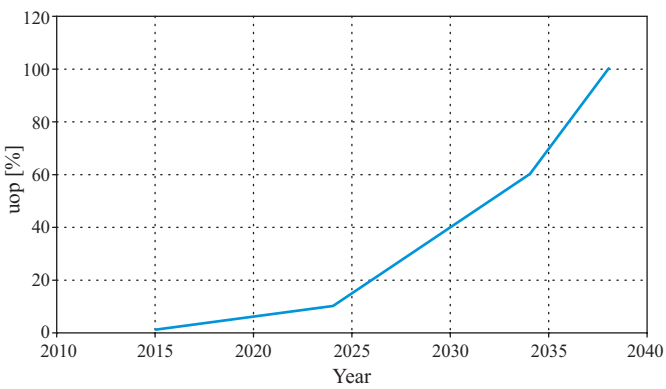

Fig. 9. *Expected share of new vehicles driven by fuel cells [21] .*

ALTERNATIVE PRIME MOVERS

Renewable energy sources include solar energy and light, water energy, biomass and wind energy. Renewable raw materials are plants which can be used for producing, in practice, all products which are now produced by the chemical industry from fossil materials [22].

A common and direct source of all renewable resources is the Sun. The potential of the solar energy and that of renewable raw materials is many times as big as the potential represented by fossil fuels.

The Sun delivers to the Earth fifteen times as much energy per year as that representing the annual consumption of nuclear energy and the energy produced from fossil fuels. Italy alone receives six times as much solar energy as the annual world energy consumption. The annual photosynthetic capacity of the flora exceeds the annual production of chemical industry by ten thousand times.

And that is why replacing the potential of fossil resources by the solar energy is quite possible.

The potential of the solar energy is characterised by three common properties which are in opposition to those specific of fossil resources.

Firstly, its capacity cannot be exhausted as long as the solar system exists, which means an approximate time period of five milliard years of Earth's future. This fact alone can prevent a world ecological crisis.

Secondly, processing these resources into the energy and secondary materials (heat, fuel, electricity) is not accompanied by the emission of impurities, or – like in case in biomass – the emission is so small that does not present a threat to our global environment.

Thirdly, the solar energy is fully or partially available everywhere, and its collection has to take a decentralised and regional course.

Making use of solar energy does not require global delivery chains. What it needs is good energy conversion technique, which can be applied locally. Since the resources of solar energy are not in a concentrated form, their use requires manufacturing large numbers of small devices, resigning from small numbers of big investment projects in favour of many much smaller projects, and resigning from buying foreign energy in favour of regional and individual self-supply.

All this means breaking residential limitations introduced in the past by the fossil resource management. At the same time, it allows us to link the areas on which this energy is collected with those on which it is consumed.

Making use of solar energy based resources means, as a further consequence, creation of regional markets and their co-existence with global technology markets – but oriented on dispersedly used energy conversion techniques.

Such a situation leads to balancing chances of all national economies, both with respect to regional collection of energy resources, and permanent regionalisation of economic circulation.

Moreover, being a source of raw materials for industrial production agriculture and forestry, which are the primary forms of economy, will take greater weight.

In the history of human civilisation, the epoch of solar energy is a sign of an expected switch from agglomeration to deglomeration. Since the economic activity must follow the location of energy sources, decentralisation of the energy sources will lead to its territorial dispersion. Due to technical reasons, the world solar economy will make concentration of resources and capital impossible.

Since the solar energy is inexhaustible, it will provide a basis for a long-lasting model of human civilisation. And since the Sun cannot be privatised, no one can threat basic rules of this civilisation.

It is therefore possible and advisable to substitute fossil fuels for solar energy.

Solar energy

Due to its changing availability, which depends on the season, part of a day, and weather conditions, the solar energy is to be converted and stored [23].

Energy conversion can be executed in :

- **field solar power plants** – in which the solar radiation is directly converted into electric energy in photo-voltaic cells
- **solar thermal power stations** – in which the solar radiation is focused, using cylindrical mirrors, on a system of pipes with water circulating inside. The generated steam drives turbines of the turbosets
- **tower-type solar power plants** – in which mirrors focus solar radiation on a power tower, thus providing opportunities for the creation of extremely high temperatures inside. These temperatures are then used for generation of heat and electric current
- **funnel-type solar power plants** – in which the air heated in a large-dimension greenhouse is then transported outside through a high funnel (of a kilometre in length). The resultant pressure difference forces the air to move and drive air turbines connected with the current generator
- **dish-type solar power plants** – in which dish-shaped mirrors are used for local production of thermal energy.

The generated electric current and heat can be used for current purposes in industrial activity and for living needs. Surplus volumes can be stored or exported using intercontinental transport grids.

The stored electric current can be used as an independent source of energy for driving vehicles. Electric current accumulators, available now on the market, are not very attractive, however, despite high efficiency revealed by the electric drive system.

An alternative solution can be the use of electric energy for the production of hydrogen, which then can be used as energy carrier. The hydrogen obtained in this way will be delivered using pipelines and tankers to industrial centres, where it can be used for producing thermal energy, for supplying classical gasoline engines of both stationary and traction types, and-or for producing electric energy in fuel cells, which offer the highest efficiency of conversion of the chemical energy collected in the fuel into the mechanical energy driving the vehicle (Fig.10).

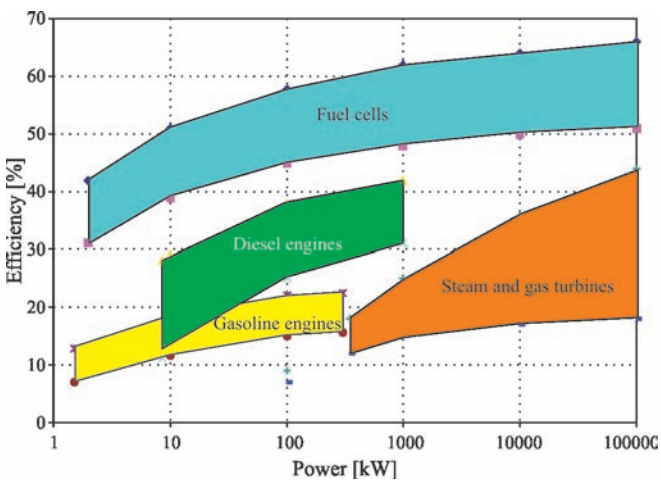

Fig. 10. Efficiency of different energy converters [24].

Use of hydrogen

Known since 1838, the controlled reaction between the hydrogen and oxygen in a fuel cell is considered a key technology of ecological energy production.

Electrochemical reactions taking place in different types of fuel cells are collected in Fig.11.

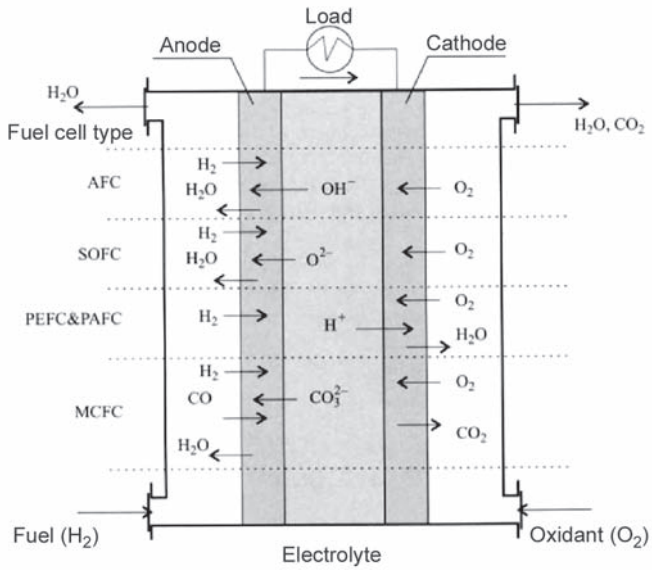

*Fig. 11. Electrochemical reactions taking place in different types of fuel cells : **AFC** (Alkaline Fuel Cell) – alkaline reactions; **SOFC** (Solid Oxide Fuel Cell) – oxide reactions, **PEFC** (Polymer Electrolyte Fuel Cell) – – polymer reactions, also labelled as **PEM** (Proton Exchange Membrane); **PAFC** (Phosphoric Acid Fuel Cell) – acid reactions; **MCFC** (Molten Carbonate Fuel Cell) – carbonate reactions [25].*

It is a hydrogen fuel cell, making use of proton membrane and bearing the name of PEMFC (Proton Exchange Membrane Fuel Cell), see Fig.12, which is considered the most promising, especially in traction applications.

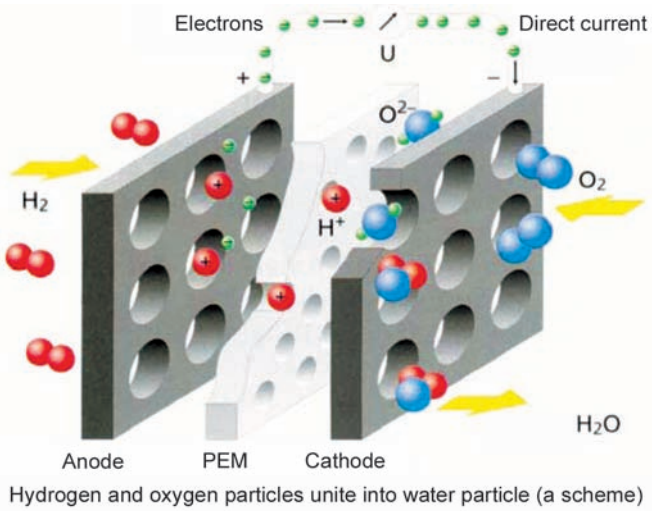

Fig. 12. Scheme of PEM fuel cell [27].

A foil covered with a layer of a catalyst, mainly platinum, is placed between electrodes in the cell. The catalyst accelerates ionisation of the hydrogen, while the membrane allows positively charged ions to pass to the side washed by the oxygen where they unite into water particles.

The reactions taking place on cell electrodes can be written in the following way :

anode : $2H_2 = 4H^+ + 4e^-$
cathode : $O_2 + 4H^+ = 2H_2O$

The electrons which stay on the "hydrogen" side produce negative charge, while on the "oxygen" side a positive charge is produced, all this leading to the creation of the potential difference of 0.6-0.9V in each cell, with the current density up to 250 mA/cm^2, which corresponds to power ranges between 0.15-0.45 W/cm^2. The temperature of operation of such a cell is equal to 80 Celsius degrees.

The power which can be obtained after combining those cells into a package is equal to 30-50 kW, at the device dimensions allowing it to be placed inside a car.

Using fuel cells in cars is connected with certain constructional limitations and problems. Prototypes which are in operation now require about 3 minutes for start, which suggests installing an additional source of energy to be used during this time. Fuel cells need hydrogen, which has to be stored as liquefied gas, (temperature -253ºC) or bounded in hydrides of metals in volumes securing reliable mileage reach. Moreover, the distribution network for this type of gas can hardly be considered satisfying. Therefore it is necessary to find an effective method of on-line hydrogen production in a car, for instance from methanol.

Applying the methanol would provide opportunities for using fuel in the liquefied form, convenient and safe in distribution. This fuel would be decomposed in a deck reactor (reformer) into hydrogen, used then as a fuel in the PEM cell, and waste CO_2 , which slightly spoils the image of a zero-emission vehicle.

Due to the highest output, it is a method decomposing the mixture of water and methanol vapours in the presence of a catalyst which seems to be the most promising for supplying traction fuel cells This method requires an additional burner for heating and evaporating the mixture, and supersaturating the vapour. The produced vapour is directed onto the Cu/ZnO catalyst and converted into a hydrogen-rich gas, which also contains undesirable CO, CO_2 , as well as small volumes of methanol and formaldehydes. Such a mixture cannot be directly passed onto the platinum catalyst in the fuel cell, which forces the use of additional installation for gas processing, including after-burning of the carbon monoxide, its absorption or filtering the products of the reforming by another membrane, of palladium-silver type for instance, which passes only hydrogen.

What makes the situation even more complicated, the reformer is to be heated to the temperature of 200 ÷ 300°C during its operation. The source of heat is a catalytic burner to burn gases which have been filtered from the hydrogen. The burner emits small volumes of CO_2 and negligibly small volumes of CO.

The above description reveals complexity of the fuel installation making use of hydrogen-oxygen cells, especially when the hydrogen is stored in the form of methanol.

The installation must include :

- ☆ methanol tank
- ☆ reformer with evaporator, burner, etc.
- ☆ installation for purification of the products of reforming
- ☆ hydrogen tank for starting the cell and supplying it in transient states
- ☆ fuel cell with own heat exchanger, tank for water generated by the cell and used for reforming
- ☆ additional batteries which drive the vehicle before the fuel cell is started and collect braking power
- ☆ control system.

The use of such numerous devices increases the cost of the entire installation, and requires proper space for it in the vehicle.

Applications of fuel cells

Advantages of fuel cells include clean and quiet operation, possible use of various types of fuel and high resistance to unfavourable atmospheric phenomena.

Fuel cells deliver energy in the form of direct current, while the in-home and industrial receivers are adapted to alternating current. As a result, the current produced in the cells is to be converted, which requires relevant converters.

In the developed countries much attention is paid to the use of fuel cells for producing heat and electric power. For some years fuel cells with power output up to 200 kW have supplied industrial installations, and have also been used as emergency generators. Fuel cells are being more and more frequently used in sewage treatment plants, composting plants, food processing plants, electric devices that do not tolerate supply breaks, and ecologically clean devices.

In the first three applications on the above list fuel cells are fed with methane, which otherwise would be undesired waste product.

At present, the cost of electric energy production from fuel cells is equal to $3000-4000 per kilowatt (data from 2002). And the price of a 200-kW device (based on SOFC technology) is equal to about $1.000.000. The producer makes this price depend on the goal of the planned application. The time of delivery is approximately equal to 2-3 months from the date of contract signature.

Large stationary fuel cells which were used in electric power plants in recent few years did not stand the test. For instance, 2 MW devices tested in Santa Clara, California, in 1995 rarely produced power exceeding 1 MW, which is only half of their design power [28].

Due to various problems, designers and producers of fuel cells focused their attention on devices with power output not exceeding 50 kW, intended for supplying one-family houses, residential buildings and small businesses, as well as to be used as traction power units [29].

Within the framework of the EU project, since 2002 city buses driven by fuel cells have been used in three European cities: Berlin, Copenhagen and Lisbon.

The MAN bus, weighting 18 Mg and 12 m long, is equipped with three sets of fuel cells produced by Nuvera, Italy. These fuel cells, the total power output of which is equal to 120 kW, drive two engines, produced by Siemens, with total power of 2 x 75 kW. The fuel in the form of liquid hydrogen is collected in tanks of total volume equal to 600-dm^{3,} located on the roof of the bus. This installation allows the bus to cover the mileage ranging up to 400 km [30].

Activities performed in the USA are oriented on prototype fuel cells revealing power output of 625 kW and 500 kW, making use of diesel oil as the fuel, and intended for driving submarines [31].

Three submarines of 212 and 214 class (out of a series of four) with the fuel cell based driving system were built in the shipyard Howaldtswerke-Deutsche Werft GmbH (Germany) [32].

The presented overview of applications of fuel cells confirms vast interest in this type of a source of drive. A wide spectrum of present applications allows us to expect extensive information to appear on its applicability as driving systems in navigation.

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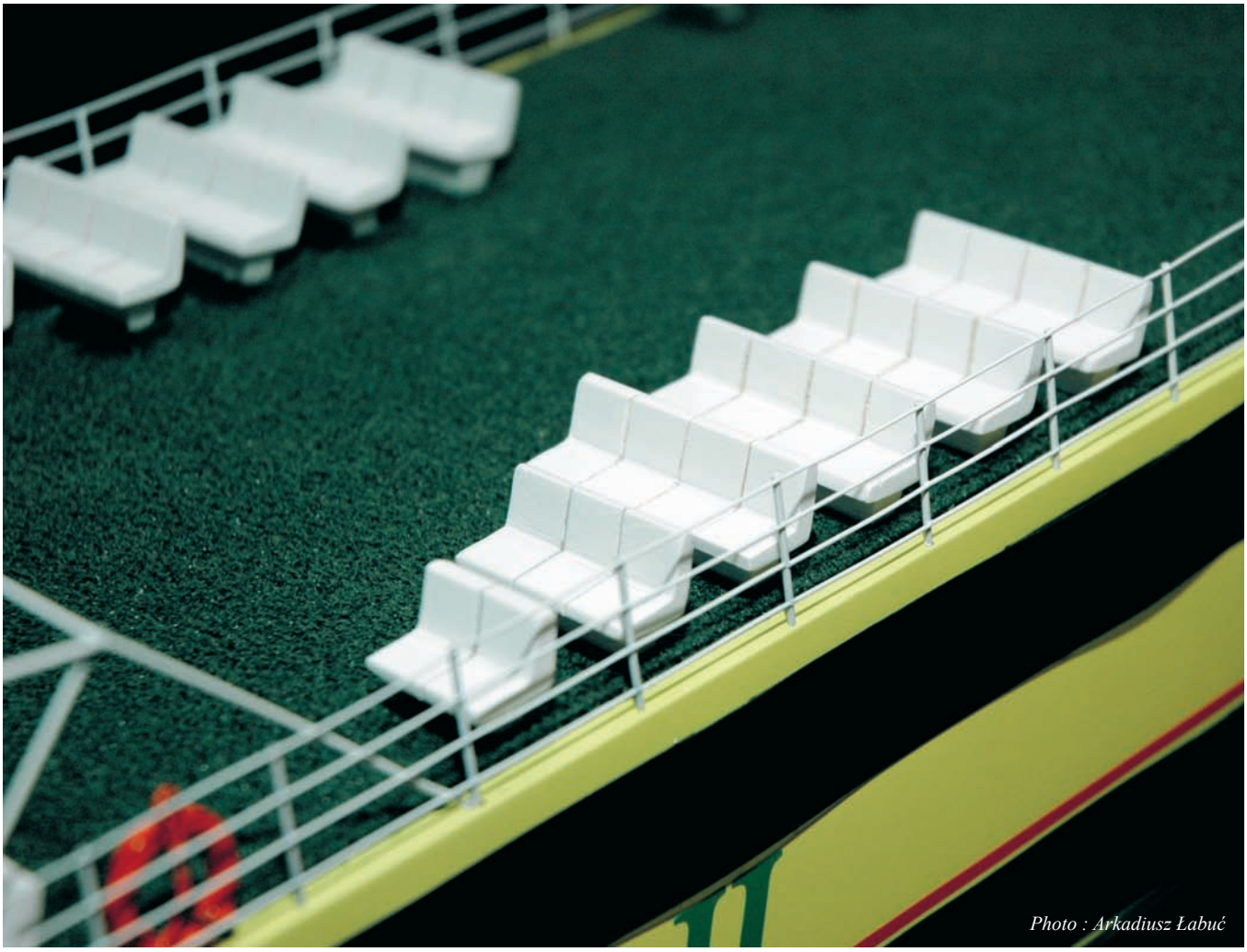

Photo : Arkadiusz Łabuć

A model of performance-oriented risk-based assessment of safety of container ships

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ABSTRACT

The paper presents some information on a performance-oriented risk-based model for assessment of safety of ships in damaged conditions. The design for safety process is integrated with the risk analysis. As safety is treated as one between the main design objectives such an approach is called the risk-based design. The assessment of safety is based on the risk level. The risk level is evaluated according to the risk-based criteria. For the risk analysis the Formal Safety Assessment methodology has been applied.

Keywords: safety of ships, design for safety, risk analysis, Formal Safety Assessment (FSA)

INTRODUCTION

The paper presents some information on modelling safety of ships in damaged conditions at the preliminary design stage by using an alternative performance-oriented risk-based method. The present regulations related to safety of damaged ships are included in SOLAS Chapter II-1 parts A, B and B-1. Those regulations are prescriptive in their character and are based on the semi-probabilistic and probabilistic approaches. Application of requirements included in those regulations to certain types of ships e.g. large passenger vessels, Ro-Ro vessels or car-carriers may lead to insufficient level of ship safety or provide unnecessary design restrictions. Instead of prescriptive regulations IMO has decided to use within the rules improving and new rules making process the safety assessment based on satisfying the objectives. One of the objectives, between the standard design objectives, is a sufficient level of safety. For this purpose IMO has recommended an application of Formal Safety Assessment methodology published as MSC Circ. 1023.

The current method of assessment of safety of ships in damaged conditions is based on the harmonized SOLAS Chapter II-1 parts A, B and B-1. The proposed alternative method is a kind of performance-oriented risk-based analysis incorporated in the design process with reduction of risk embedded as a design objective. It should be underlined that this method can easily be adopted for assessment of safety of undamaged ships as it very much depends on the problem (system) definition.

In the paper the performance-oriented risk-based method of assessing safety of ships including modelling is briefly discussed because of limited space available. Some examples of safety assessment for two container ships using the proposed method are presented in the paper. The detailed discussion regarding the method and modelling will be published by the Gdansk University of Technology later this year.

CURRENT METHOD OF ASSESSMENT OF SAFETY OF SHIPS IN DAMAGED CONDITIONS

The current method for safety assessment of ships in damaged conditions is based on the regulations included in the SOLAS chapter II-1 parts A, B and B-1. Using the current methodology the measure of safety of a ship in damaged conditions is the attained subdivision index "A". It is treated as the probability of survival of flooding any group of compartments.

The basic design criteria is the condition as follows, IMO (2005):

$$A > R \tag{1}$$

where :

A - attained subdivision index calculated according to the formula :

$$A = \sum p_i s_i \tag{2}$$

p_i - probability of flooding the group of compartments under consideration

s_i - probability of survival after flooding the group under consideration

R - required subdivision index.

The logical structure of the system for assessing the condition (1) according to the current SOLAS methodology is presented in Fig. 1.

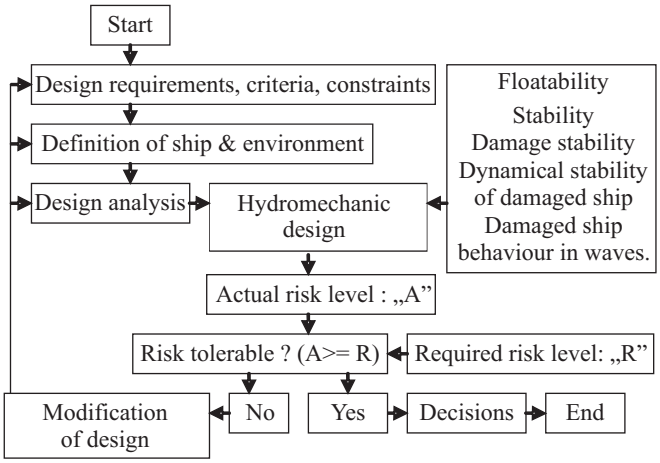


Fig. 1. *Basic logical structure of system for assessing the condition (1) according to the current SOLAS requirements.*

Both the indices A and R are calculated according to the well known formulae accepted by IMO. For the following example we may use the formula included in the Resolution MSC 19/58 regarding the subdivision and damage stability of cargo ships over 100 m. Lets consider the survivability of the 1100 TEU container ship at the early stage of design.

The main data for the calculations are as follows, Gdynia Shipyard (1999-2005) :

- ✶ length between perpendiculars L_{BP} = 145.000 m,
- ✶ subdivision length L_s = 158.655 m,
- ✶ subdivision (full) draught dL = 10.200 m,
- ✶ partial draught dP = 7.560 m,
- ✶ light ship: Mass = 6800 t,
- ✶ coordinates of centre of gravity: LCM = 58.10 m from A.P., VCM = 11.10 m above B.P.

A few graphical examples following from the survivability analysis of this ship are presented in Fig. 2.

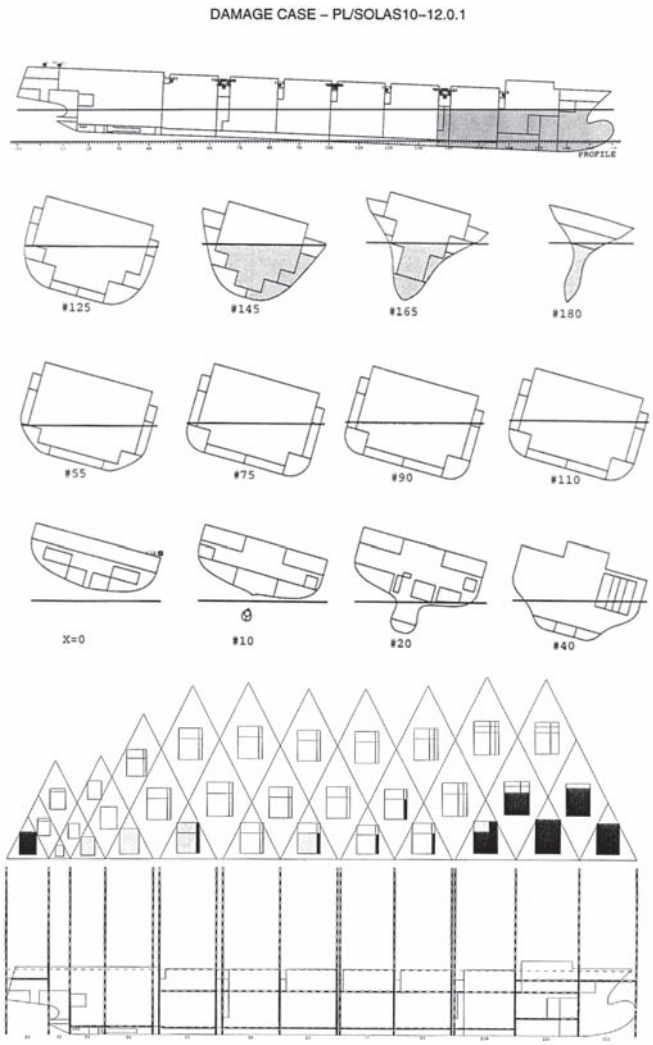


Fig. 2. *The general arrangement of internal spaces, example of final stage of flooding the data group of compartments and example of "p_i" factor calculation for the 1100 TEU container ship, Stocznia Gdynia (1999-2005).*

The calculations of the attained subdivision index A are connected with the large scale numerical calculations and they are time consuming. The final results of the probabilistic damage stability analysis for the given example are as follows :

$$A = \sum \Delta A_i = 0.52605 \quad (3)$$

$$R = 0.52510 \quad (4)$$

$$A > R \text{ as } 0.52605 > 0.52510 \quad (5)$$

From a designer point of view a question can arise if the ship is safe indeed. The briefly presented prescriptive method has been the base for creating the new techniques for solving some design problems. The nature of these techniques was prescriptive as well. It concerns the procedures for optimization of the index A and optimization of the local safety indices. Good examples concerning these are presented in the previous publications, Gerigk (2005).

A PERFORMANCE-ORIENTED RISK-BASED DESIGN

The risk-based design is a formalized design methodology that integrates systematically risk analysis in the design process with the prevention/reduction of risk embedded as a design objective, along standard design objectives, SSRC (2005). This methodology applies a holistic approach that links the risk prevention/reduction measures to ship performance and cost by using relevant tools to address ship design and operation. This is a radical shift from the current treatment of safety where safety is a design constraint included within the rules and regulations. The risk-based design offers freedom to the designer to choose and identify optimal solutions to meet safety targets. For the risk-based design safety must be treated as a life cycle issue. The risk-based design in the maritime industry should follow the well-established path of quantitative risk assessment used in other industries. The term "risk based design" is also in common use in other industries. The following steps are needed to identify the optimal design solution: set objectives, identify hazards and scenarios of accident, determine the risk, identify measures and means of preventing and reducing risk; select designs that meet objectives and select safety features and measures that are cost-effective, approve design solutions or change the design aspects. This approach is briefly introduced in the logical structure of the risk-based design system presented in Fig. 3.

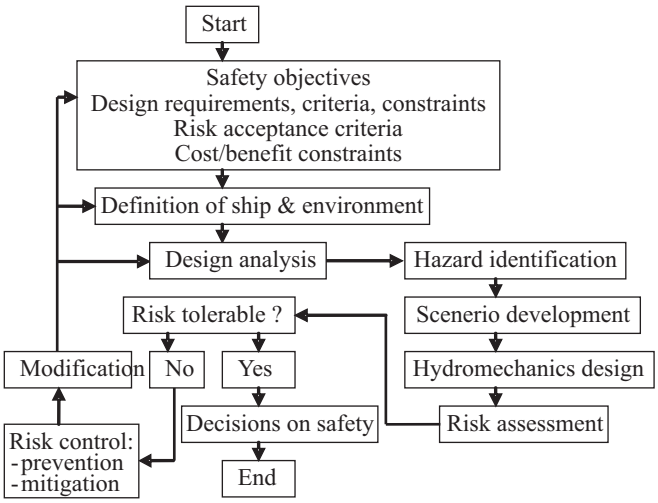


Fig. 3. *Logical structure of the risk-based design system (method).*

Because of limited space available the performance-oriented and risk-based approaches applied within the alternative method will be presented during the KONBIN Conference.

A PERFORMANCE-ORIENTED RISK-BASED METHOD FOR SAFETY ASSESSMENT OF SHIPS

The modern approach to ship safety is connected with combining the elements of system approach to safety and Formal Safety Assessment (FSA) methodology, IMO (2002). The major elements of the FSA methodology are as follows: hazard identification, risk analysis, risk control options, cost-benefit assessment, recommendations for decision making.

Combining the above mentioned with the modern ship design spiral the basis for the performance-oriented and risk-based formal method for safety assessment of ships is

considered. Integrating the systematically used risk analysis in the design process with the prevention/reduction of risk embedded as a design objective (along standard design objectives) the risk-based design method is proposed as presented in Fig. 3.

The entire structure of the method is published by Gerigk, Gerigk (2005).

Regarding the risk assessment methods, there is a research going on further incorporating the risk assessment techniques into the design procedure regarding the safety assessment of damaged ships. The following methods are used for the risk assessment, ABS (2000): hazard identification methods, frequency assessment methods, consequence assessment methods and risk evaluation methods. The current set of the hazard/risk analysis methods includes: preliminary hazard analysis (PHA), preliminary risk analysis (PRA), what-if/checklist analysis, failure modes and effects analysis (FMEA), hazard and operability analysis (HAZOP), fault tree analysis (FTA), event tree analysis (ETA), relative ranking, coarse risk analysis (CRA), pareto analysis, change analysis, common cause failure analysis (CCFA) and human error analysis (HEA).

The following risk reduction principles and strategies have been adopted for the method, Grabowski (2000) :

- reducing the probability of an accident
- reducing the probability of consequences of accident.

A method for the ships safety estimation when surviving is introduced and it is associated with solving a few problems regarding the naval architecture, ship hydromechanics and ships safety and it is novel to some extent. When preparing the method for the preliminary design purposes the global and technical approaches are used, Barker (2000). The global approach mainly regards the problems associated with the development of methodology, ship and environment definition, hazard identification and hazard assessment, scenario development, risk assessment, risk mitigation measures, hazard resolving and risk reduction and decisions made on ships safety. The technical approach concerns the logical structure of design system and computational model, design requirements, criteria and constraints, library of required analytical and numerical methods and library of application methods. There are two approaches to risk management: bottom-up approach and top-down approach. The top-down risk management methodology has been applied for the method which is suitable for design for safety at the preliminary design stage. This approach should work in the environment of performance-based standards and help designing the ships against the hazards they will encounter during their operational life.

The key issue when using the proposed method is to model the risk contribution tree. The risk associated with different hazards and scenario development in estimated according to the formula:

$$\text{Risk} = P \times C \tag{6}$$

where :

P – probability of occurrence a given hazard
C – consequences following the occurrence of data hazard and scenario development, in terms of fatalities, injuries, property losses and damage to the environment.

A logical structure of a risk contribution tree is presented in Fig. 4.

For the complex safety assessment of ships in damaged conditions the model of risk assessment has been anticipated as presented in Fig. 5.

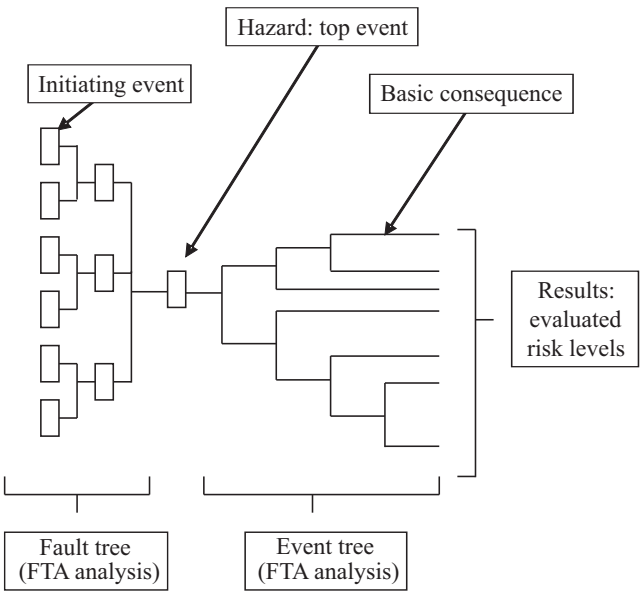


Fig. 4. *Logical structure of a risk contribution tree.*

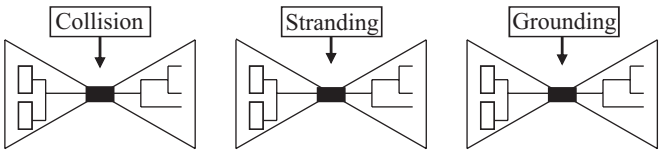


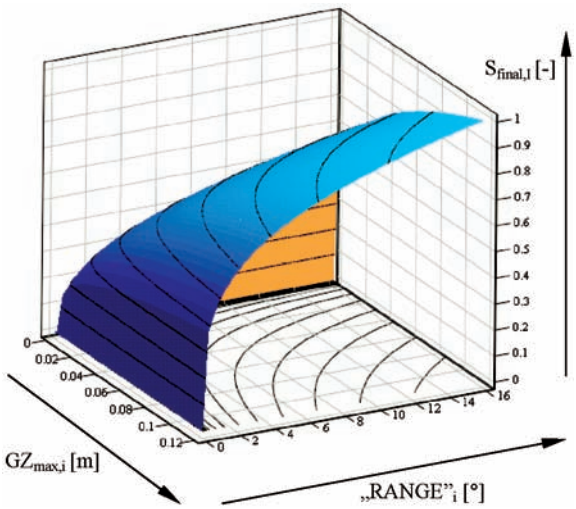
Fig. 5. *Example of model of risk assessment.*

A good example of risk and safety assessment according to the proposed method is the design analysis conducted for a container ship presented in Tab. 1.

Tab. 1. *Basic data for a container ship used for the example risk assessment.*

1.	Length between perpendiculars	L_{BP}	163.00 [m]
2.	Subdivision length	L_S	174.95 [m]
3.	Breadth	B	26.50 [m]
4.	Design draugth	d_f	9.00 [m]
5.	Tonnage	P_N	22286.00 [DWT]
6.	Service speed	V_s	20.40 [kn]
7.	Range	R	12000.00 [Nm]

In Fig. 6 the distribution of consequences "C" in terms of conditional probability of surviving the collision in the final stage of flooding "s_{final}" are given, Woznicki (2005).



The risk distribution in the form of risk levels (in terms of surviving the collision) taking into account all the possible hazards and scenarios are presented in Tab. 2.

Tab. 2. *An example of risk distribution in the case of flooding the data compartments.*

Case	Compartment	Comp. length [m]	p_i [-]	s_i [-]	$Risk_i$ [-]
1	1	6.65	0.0779	0.9991	0.0483
2	2	24.59	0.0357	0.9991	0.0357
3	3	42.59	0.0324	0.9628	0.0312
4	4	57.99	0.1107	0.9991	0.1106
5	5	82.09	0.1115	0.0000	0.0000
6	6	112.39	0.0330	0.6379	0.0211
7	7	134.79	0.0172	0.9650	0.0166
8	8	150.19	0.0357	0.0000	0.0000
9	9	166.52	0.0215	0.0000	0.0000
10	1 + 2	13.29	0.0629	0.9991	0.0628
11	2 + 3	35.89	0.0490	0.9991	0.0490
12	3 + 4	49.29	0.0682	0.9991	0.0681
13	4 + 5	66.69	0.0918	0.0000	0.0000
14	5 + 6	97.49	0.0641	0.0000	0.0000
15	6 + 7	127.29	0.0345	0.0000	0.0000
16	7 + 8	142.29	0.0336	0.0000	0.0000
17	8 + 9	158.09	0.0314	0.0000	0.0000
18	1 + 2 + 3	24.65	0.0209	0.9991	0.0209
19	2 + 3 + 4	39.99	0.0237	0.9833	0.0233
20	3 + 4 + 5	55.45	0.0023	0.9991	0.0023
21	4 + 5 + 6	94.45	0.0017	0.0000	0.0000
22	5 + 6 + 7	104.49	0.0136	0.5695	0.0077
23	6 + 7 + 8	127.79	0.0185	0.0000	0.0000
24	7 + 8 + 9	151.12	0.0047	0.1307	0.0006

CHALLENGES

Currently, there are a few problems under consideration regarding the safety of ships in damaged conditions which are associated with the existing prescriptive method included in the SOLAS Chapter II-1 parts A, B and B-1. The first problem concerns how to obtain the same required level of safety for different types of ships. The second regards updating the statistical data for the p_i factor estimation. The next problem which can probably not be solved using the prescriptive approach is the problem of calculation of the s_i factor according to the pure probabilistic concept. The new formula for s_i factor should include the components following from the fact that there are a few stages during the flooding process, IMO (2002), IMO (2004), Dudziak (2001), Santos (2001), Santos (2002), STAB (2003): creation of damage (stage 1), transient heel and intermediate flooding (stage 2), progressive flooding (stage 3), final stage (stage 4). During the above mentioned stages the internal and external impacts may appear according to the following: wind heeling moment, action of waves, ballast/cargo shift, crowding of people, launching life saving appliances, etc.

SUMMARY

The alternative performance-oriented risk-based method for assessment of safety of damaged ships is briefly presented in the paper. No details given because of limited space available. The current work regarding the method is associated with integrating the performance-oriented and risk-based analyses into the system briefly presented in Fig. 3. The method is novel to some extent and is currently published by the Gdansk University of Technology.

The method uses the performance-oriented risk-based approach. The elements of Safety Case and Formal Safety Assessment methodologies are incorporated within the method. The hazard identification, scenario development, ship hydromechanics analysis, risk estimation and risk control options are combined together. In this respect, the method is a risk-based design method as it integrates the systematic risk analysis in the design process with the reduction of risk embedded as a design objective.

NOMENCLATURE

A - attained subdivision index
R - required subdivision index
p_i - accounts for the probability that only the compartment or group of compartments under consideration may be flooded, disregarding any horizontal subdivision, as defined in regulation 7-1
s_i - accounts for the probability of survival after flooding the compartments or group of compartments under consideration, and includes the effect of any horizontal subdivision, as defined in regulation 7-2
ΔA_i - components of the attained subdivision index A concerning flooding each group of compartments for the data set of deepest, partial and light service draughts
Risk - combination of the frequency and the severity of the consequence
$Risk_i$ - components of the Risk value concerning flooding each group of compartments for the data set of deepest, partial and light service draughts
P - probability of occurrence of a given hazard
C - consequences following the occurrence of the data hazard or sequence of events (outcome of an accident)
s_{final} - probability to survive in the final equilibrium stage of flooding

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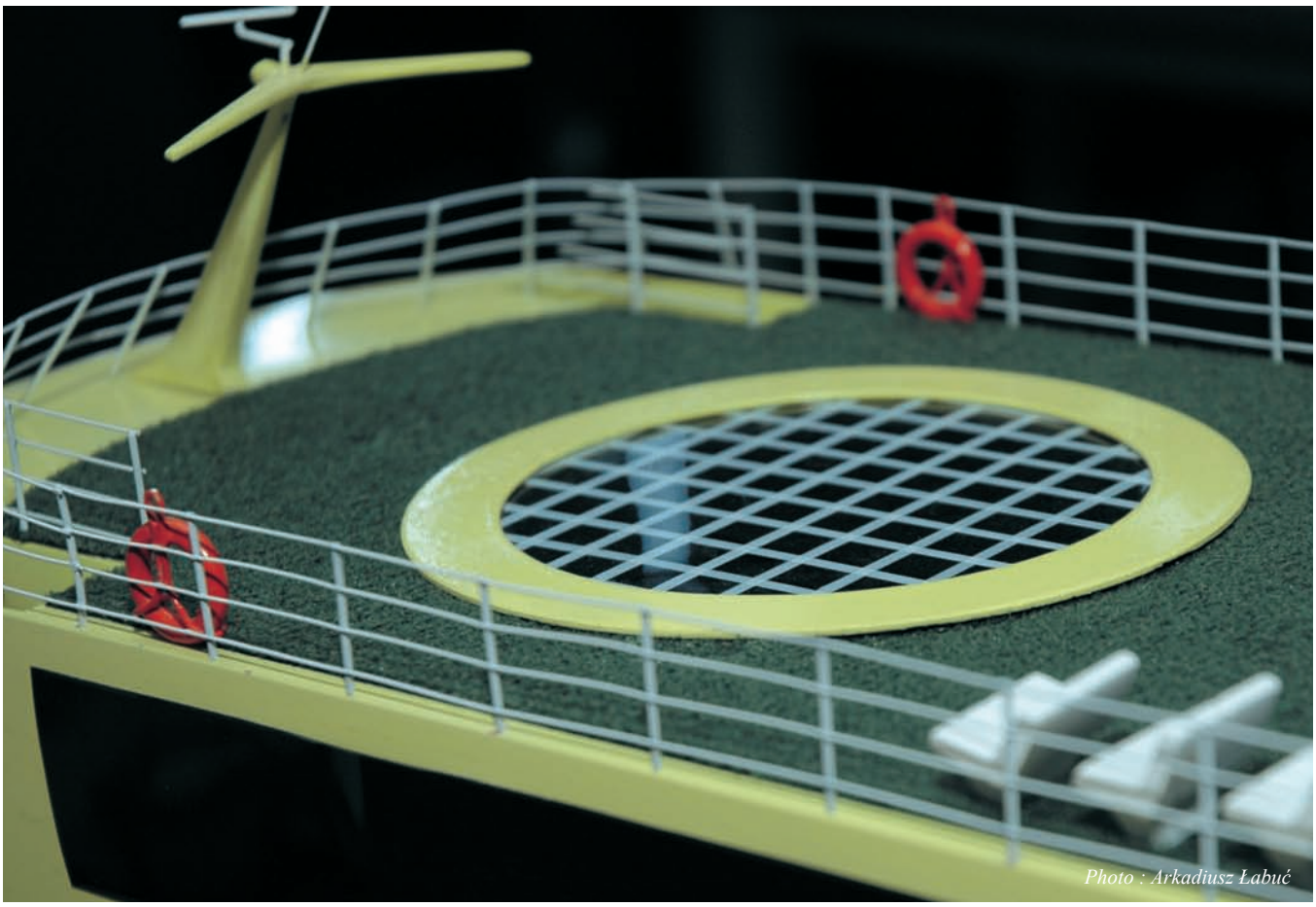
Photo : Arkadiusz Łabuć

A semi-Markov model of fuel combustion process in a diesel engine

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Gdansk University of Technology

ABSTRACT

A four-state model of the combustion process in working spaces (cylinders) of a diesel engine is presented in the form of a semi-Markov process, discrete in states and continuous in time. The values in this process are the states : s_1, s_2, s_3, s_4 corresponding to commonly accepted types of combustion in those engines, namely : s_1 – the process state which corresponds to total (complete and perfect) combustion, s_2 – the process state which corresponds to incomplete combustion, s_3 – the process state which corresponds to imperfect combustion, and s_4 – the process state which corresponds to both incomplete and imperfect combustion. It is also mentioned that proper use of diesel engines can secure a correct course of the combustion process, if it is properly attended and shaped. During this course the state s_4 does not take place. Formulas are given which make it possible to determine the probability of staying of the combustion process in the above named states, along with the interpretation of the probability $P_1 = P(s_1)$ as the probability of correct (reliable) engine operation.

Keywords :

INTRODUCTION

The combustion process in particular working spaces (cylinders) of each diesel engine significantly affects its reliability and durability. Factors which can most significantly affect the course of the combustion process include [6, 8, 10, 11] :

- ☆ physical and chemical properties of the fuel (diesel oil, heavy oil), in particular its chemical composition, cetane number, ignition temperature, and viscosity
- ☆ design properties of the engine (in particular concerning the injection systems) such as, combustion chamber type, piston material, nozzle type, and main engine dimensions
- ☆ energetic characteristics of the engine (dynamics, inertia, accumulative properties of the functional systems)
- ☆ usage, both unconditioned and conditioned by engine operation, mainly resulting from the load (especially thermal) and technical state of the engine, and represented by the following parameters : rotational speed, injection pressure, injection advance angle, volume of exhaust gases remaining from the previous working cycle, and cooling water temperature.

Both the physical and chemical properties of the fuel, and the constructional characteristics of the engine are structured in such a way that in the initial time of operation (in conditions to which this engine was adapted in the design and manufacturing phase) a correct course of combustion process can be obtained in its working spaces (cylinders).

However, the above listed factors are subject to unfavourable changes during engine operation, which frequently result in incorrect course of the combustion process. The correct course of the combustion process is only possible when in each working cycle total (i.e. complete and perfect) combustion takes place. The course of the combustion process is incorrect when instead of the total combustion, defective (i.e. incomplete and imperfect) or only incomplete or imperfect combustion takes place, and also when the combustion takes place in incorrect time with respect to both the beginning and end of its presence.

Both the incorrect and correct course of combustion in engine cylinders can be initiated at an arbitrary time instant and last certain time durations of engine work (operation). These time durations should be treated as random variables, which results from random properties of the above listed factors affecting the course of the combustion process [1, 2, 3, 7, 12].

The combustion process can be evaluated in the dynamic time ϑ (time during which the combustion takes place in the cylinders), i.e. as the process $[\{X^*(\vartheta) : \vartheta \in \Theta\}$, and in the quasi-static time t (time of engine operation during which certain task is done by the engine user) i.e. as the process $\{Y^*(t) : t \in T\}$. The evaluation of the course of the combustion process taking place in the engine cylinders (i.e. in the dynamic time) is obtained via relevant tests oriented on assessing values of the combustion parameters [8, 10, 11, 12].

From the obtained values of those parameters the course of the combustion process can also be evaluated for a quasi-static state, such as, for instance, engine operation between two preventive services, or the operation before the first engine failure, etc. However, evaluating the combustion process during long-lasting engine operation requires additional probabilistic measures, which can only be determined after working out a relevant model of combustion process in working spaces (cylinders) of the diesel engine.

COMBUSTION PROCESS CHARACTERISTICS IN PROBABILISTIC APPROACH

As already mentioned, the process of fuel combustion in particular working spaces (cylinders) of each diesel engine can be analysed either in the dynamic state $\vartheta \in \Theta$ (short time during which this process is executed in one operation cycle of the examined engine) or in the quasi-static time $t \in T$ (longer time, for long-lasting operation (work) of the examined engine).

That means that the combustion process in the cylinders of each engine can be considered a two-dimensional process :

$$\{W^*(\vartheta, t) : \vartheta \in \Theta, t \in T] = [\{X^*(\vartheta) : \vartheta \in \Theta\} \quad \{Y^*(t) : t \in T\}] \; ; \; \Theta, T \subset R_+ \tag{1}$$

the components of which are mutually dependent processes $\{X^*(\vartheta) : \vartheta \in \Theta\}$ and $\{Y^*(t) : t \in T\}$, whose parameters : $\vartheta \in \Theta$ and $t \in T$, respectively, are not random variables. The random variables are the values of those processes attributed to parameters ϑ, composing the set Θ and to parameters t, composing the set T . The elements of those two sets belong to a set of real non-negative numbers R_+.

The combustion process in the dynamic time (ϑ) exerts direct influence on engine durability and reliability, among other parameters. The course of this process is evaluated using various systems which diagnose, in the first place, the quality of transformation of the chemical energy collected in the fuel into the thermal energy. Various indices (parameters) of engine operation are analysed, in particular those which significantly affect not only the energetic qualities of the engine, but also its reliability and durability. These parameters include : average ($\Delta p/\Delta\alpha$) and instantaneous ($dp/d\alpha$) rate of pressure built-up (p) in cylinders as a function of crankshaft rotation angle (α), the highest combustion pressures (p_{max}) and the highest combustion temperature (T_{max}) in the cylinders, heat emission coefficient (w_c), heat consumption coefficient (w_w), heat evolution coefficient (w_{wc}), heat evolution rate (w), the coefficient being the quotient of the maximum heat evolution rate (w_{max}) to the ignition delay time (τ_{zz}), pressure gain factor (φ), preliminary decompression ratio (ρ), the exhaust gas composition at the smoke limit, as well as the contents of such chemical compounds as : carbon monoxide (CO), carbon dioxide (CO_2) hydrocarbons (C_nH_m), nitric oxides (NO_x), solid particles, sulphur compounds (SiO_2, SiO_3, H_2SO_3, H_2SO_4), aldehydes, etc. in the exhaust gases. The course of the process $\{X^*(\vartheta) : \vartheta \in \Theta\}$ depends on the conditions of engine operation, for instance on its mechanical and thermal load, crankshaft rotational speed, quality of adjustment of the engine injection system and timing gear, and technical state of the engine. All this suggests that the course of the combustion process during engine operation needs proper attendance and prognosing. What is necessary is analysing the execution of the fuel combustion in the engine cylinders during the entire time of engine operation (working time), in other words, analysing the process $\{Y^*(t) : t \in T\}$.

In this process such adjacent states can be named, from which a four-element set of state classes, simply named the states, can be created, namely :

$$S = \{s_1, s_2, s_3, s_4\} \tag{2}$$

with the following (commonly accepted) interpretation of these states :

s_1 – the process state which corresponds to complete and perfect combustion
s_2 – the process state which corresponds to incomplete combustion
s_3 – the process state which corresponds to imperfect combustion
s_4 – the process state which corresponds to both incomplete and imperfect combustion.

These states take place (appear) randomly during engine operation (work), at an arbitrary operating time. Therefore the events consisting in the appearance of these states can be considered random events. If so, the probability should be evaluated for these states to appear during the operation of the diesel engine of concern. Determining those probabilities will make it possible to perform quantitative assessment of the course of the combustion process in the cylinders of this type of engines.

The course of the combustion process taking place in engine cylinders in time $t \in T$ can be quantitatively assessed based on the mathematical model $\{Y(t) : t \in T\}$ of the real combustion process $\{Y^*(t) : t \in T\}$, the values of which are the states $s_i \in S$ (i = 1, 2, 3, 4). The analysis of chances for the appearance of those states indicates that the above model $Y(t) : t \in T\}$ can be worked out in the form of a semi-Markov process, continuous in time and having a limited (four-element) set of states.

MODEL OF COMBUSTION PROCESS IN ENGINE CYLINDERS

It results from the theory of semi-Markov processes that working out a model of an arbitrary real process in the form of a semi-Markov process is possible if its initial distribution and functional matrix can be defined [5, 8].

Taking into account the specifics of the combustion process in the working spaces (cylinders) of the diesel engines we can assume that the combustion process $\{Y(t) : t \in T\}$ with the state set $S = \{s_1, s_2, s_3, s_4\}$ has the following initial distribution [2, 4] :

$$P_i = P\{Y(0) = s_i\} = \begin{matrix} 1 \text{ for } i = 1 \\ 0 \text{ for } i = 2, 3, 4 \end{matrix} \tag{3}$$

and functional matrix :

$$Q(t) = \begin{bmatrix} 0 & Q_{12}(t) & Q_{13}(t) & 0 \\ Q_{21}(t) & 0 & 0 & Q_{24}(t) \\ Q_{31}(t) & 0 & 0 & Q_{34}(t) \\ Q_{41}(t) & 0 & 0 & 0 \end{bmatrix} \tag{4}$$

where :

$$Q_{ij}(t) = P\{Y(\tau_{n+1}) = s_j, \tau_{n+1} - \tau_n < t \,|\, Y(\tau_n) = s_i\}$$

$$s_i, s_j \in S \; ; \; i, j = 1, 2, 3, 4 \; ; \; i \neq j$$

The above initial distribution (3) bases on the fact that after manufacturing the combustion engine should be fully efficient [2], and its combustion process $\{Y^*(t) : t \in T\}$ (taking place in particular cylinders) should take such a course that the state s_1 can be recognised as the value of the process $\{Y(t) : t \in T\}$ being the model of the already mentioned process $\{Y^*(t) : t \in T\}$. The appearance of the remaining states $s_i \in S$ (i = 2, 3, 4) results from worsening engine abilities, in particular incorrect action of injection apparatuses during engine operation.

The change state graph for the process $\{Y(t) : t \in T\}$ as resulting from the functional matrix (4) is given in Fig. 1. This graph, and, as a consequence, the functional matrix (4), result from the rational use of the engine. This use takes place when after detecting the state s_2, or s_3, by the engine user, relevant technical action is taken to regain full engine abilities, i.e. to return to the state s_1. In case the diagnosing system detects the state s_3, the engine user should remove causes of its appearance and bring again the engine to the state s_1, with total (complete and perfect) combustion in the cylinders. In practice, this action is not always possible, as a consequence of which the state s_4 frequently appears. Then the only sensible action of the engine user is that leading to the technical service which will return the process to the state s_1.

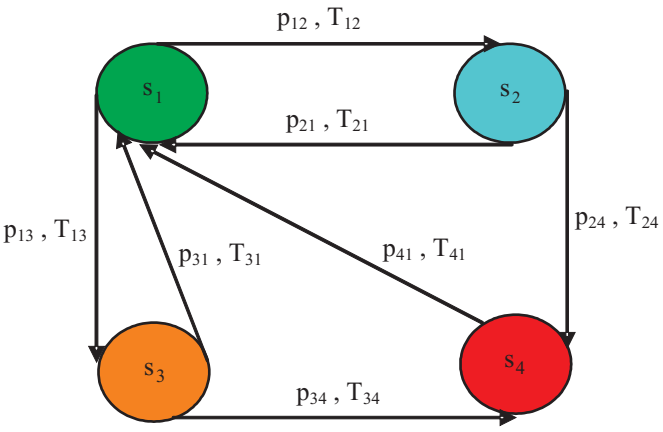

Fig. 1. *State change graph for process {Y(t) : t ∈ T} :*
s_1 *– state corresponding to complete and perfect combustion;* ***s_2*** *– state corresponding to incomplete combustion;* ***s_3*** *– state corresponding to imperfect combustion;* ***s_4*** *– state corresponding to incomplete and imperfect combustion;* ***p_{ij}*** *– probability of process change from state s_i to state s_j;* ***T_{ij}*** *– time duration of state s_i provided that the next state is s_j; (i, j = 1, 2, 3, 4; i ≠ j).*

An important characteristic of the process {Y(t) : t ∈ T}, applicable for evaluating the course of the combustion process Y*(t) : t ∈ T} in diesel engine cylinders, is a set of conditional probabilities of passing to particular states during the time not longer than t, namely :

$$P_{ij}(t) = P\{Y(t) = s_j | Y(0) = s_i\} \quad (i, j = 1, 2, 3, 4 ; i \neq j) \tag{5}$$

bearing the name of probabilities of passing from the state $s_i \in S$ at time t = 0, to the state $s_j \in S$ at time $t \neq 0$.

The probabilities $P_{ij}(t)$, formula (5), can be calculated using the Kronecker symbol δ_{ij} and making use of the equation system [4] :

$$P_{ij}(t) = \delta_{ij}[1 - G_i(t)] + \sum_{k=1}^{4} \int_0^t P_{kj}(t-\zeta) dQ_{ik}(\zeta) \tag{6}$$

which is operationally solved using the Laplace-Stieltjes transformation. In formula (6) : $G_i(t)$ is the distribution function of a random variable T_j representing the time duration of the state s_i (i = 1, 2, 3, 4) of the process {Y(t) : t ∈ T}, independently of the state to which the process is going to pass. When analysing in longer time intervals t (theoretically $t \to \infty$), these probabilities tend to constant values, and after this time form the limiting distribution [2, 8, 12] :

$$P_1 = \lim_{t\to\infty} P\{Y(t) = s_1\},\ P_2 = \lim_{t\to\infty} P\{Y(t) = s_3\}$$
$$P_3 = \lim_{t\to\infty} P\{Y(t) = s_3\},\ P_4 = \lim_{t\to\infty} P\{Y(t) = s_4\} \tag{7}$$

Detailed solutions, see : formula 6, applicable in operating practice can be obtained provided that the distributions $Q_{ij}(t)$ and $G_i(t)$ are known. These quantities can be determined from the following relations [2, 8, 12] :

$$Q_{ij}(t) = p_{ij}F_{ij}(t) \ ;\ G_i(t) = \sum_{j=1}^{4} Q_{ij}(t) \tag{8}$$

where :

p_{ij} – probability of passing of the Markov chain placed in the process {Y(t) : t ∈ T}

$F_{ij}(t)$ – distribution function of a random variable T_{ij}, representing the time duration of the state s_i provided that the next state is s_j in the process {Y(t) : t ∈ T}, (i, j = 1, 2, 3, 4; i ≠ j).

Formula (8) reveals that the subsequent characteristics of the process {Y(t) : t ∈ T}are quantities $Q_{ij}(t)$ and $G_i(t)$ representing random variables T_{ij} and T_i, respectively.

Of highest applicability for evaluating correctness of the combustion process course in the diesel engine cylinders over a relatively long time is the limiting distribution. The theory of semi-Markov processes says that this distribution, with the interpretation given by the formula :

$$P_j = \lim_{t\to\infty} P\{y(t) = s_j\} \ ;\ s_j \in S, j = \overline{1.4} \tag{9}$$

can be determined from the following relation [2, 8, 12] :

$$P_j = \frac{\pi_j E(T_j)}{\sum_{k=1}^{4} \pi_k E(T_k)} \ ;\ j = 1, 2, 3, 4 \tag{10}$$

where the limiting distribution π_j, j = 1, 2, 3, 4 of the placed Markov ch n {Y(π_n : n = 0, 1, 2, ...} fulfils the equation system [4, 9, 12] :

$$[\pi_1, \pi_2, \pi_3, \pi_4] \quad = [\pi_1, \pi_2, \pi_3, \pi_4] \tag{11}$$
$$\pi_1 + \pi_2 + \pi_3 + \pi_4 = 1$$

From equations (10) and (11) the following form of the limiting distribution for the process {Y(t) : t ∈ T}can be obtained :

$$P_1 = \frac{E(T_1)}{M} \ ;\ P_2 = \frac{p_{12}E(T_2)}{M}$$
$$P_3 = \frac{p_{13}E(T_3)}{M} \ ;\ P_4 = \frac{p_{12}p_{24}E(T_4)}{M} \tag{12}$$

taking into account that :

$$M = E(T_1) + p_{12}E(T_2) + p_{13}E(T_3) + p_{12}p_{24}E(T_4)$$

where :

P_1, P_2, P_3, P_4 – probabilities that the process {Y(t) : t ∈ T} is in one of the states : s_1, s_2, s_3, s_4, respectively

$E(T_1)$, $E(T_2)$, $E(T_3)$, $E(T_4)$ – expected values of time durations of the states : s_1, s_2, s_3, s_4, respectively

p_{ij} – probabilities of process passing from the state s_i to the state s_j : i, j = 1, 2, 3, 4; i ≠ j.

The probability P_1 can be considered an indicator of correct fuel combustion in engine cylinders and, consequently, correct engine operation (work), while the probabilities P_j (j = 2, 3, 4) can be considered indicators of incorrect fuel combustion in the cylinders and incorrect engine operation.

Rational action of the engine user should be oriented on avoiding the state s_4 (then $P_4 = 0$) and should lead to the situation in which time durations of the states s_2 and s_3 of the fuel combustion processes were as short as possible. This requires proper control of the combustion process during engine operation, for instance by making use of concepts presented in [2, 8, 10, 11]. Then a combustion process model {Z(t) : t ∈ T} can be obtained, the state change graph of which is shown in Fig. 2.

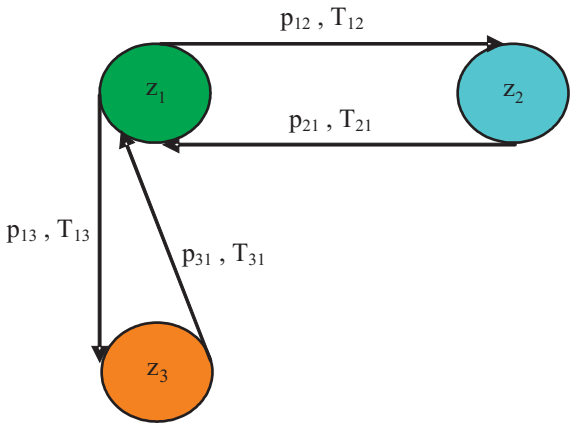

Fig. 2. *State change graph for process {Z(t) : t ∈ T} : z_1 – state corresponding to complete and perfect combustion; z_2 – state corresponding to incomplete combustion; z_3 – state corresponding to imperfect combustion; p_{ij} – probability of process change from state z_i to state z_j, T_{ij} – time duration of state z_i provided that the next state is z_j; (i, j = 1, 2, 3 ; i ≠ j).*

Like for the process {Y(t) : t ∈ T} we can assume that the values of the combustion process {ZY(t) : t ∈ T} are the elements of the state set Z = {z_1, z_2, z_3} having the following interpretation :

z_1 – the state corresponding to complete and perfect combustion
z_2 – the state corresponding to incomplete combustion
z_3 – the state corresponding to imperfect combustion.

These states have the same interpretation as the states s_1, s_2, s_3 in the process {Y(t) : t ∈ T}. The above mentioned process {ZY(t) : t ∈ T} has the following initial distribution [2] :

$$Q(t) = \text{[redacted]} \tag{13}$$

and functional matrix :

$$P_i = P\{Z(0) = s_i\} = \begin{matrix} 1 \text{ for } i = 1 \\ 0 \text{ for } i = 2,\ 3 \end{matrix} \tag{14}$$

where :

$$Q_{ij}(t) = P\{Z(\tau_{n+1}) = s_j, \tau_{n+1} - \tau_n < t | Z(\tau_n) = s_i\}$$

$$s_i, s_j \in S\ ;\ i, j = 1,\ 2,\ 3\ ;\ i \neq j$$

Like for the process {Y(t) : t ∈ T}, when discussing the model of the real combustion process in the form of the process {Z(t) : t ∈ T}, we can define its limiting distribution as :

$$P_1 = \frac{E(T_1)}{N}\ ;\ P_2 = \frac{p_{12}E(T_2)}{N}\ ;\ P_3 = \frac{p_{13}E(T_3)}{N} \tag{15}$$

taking into account that :

$$N = E(T_1) + p_{12}E(T_2) + p_{13}E(T_3)$$

where :

P_1, P_2, P_3, P_4 – probabilities that the process {Z(t) : t ∈ T} is in one of the states : z_1, z_2, z_3, respectively

$E(T_1)$, $E(T_2)$, $E(T_3)$ – expected values of time durations of the states : s_1, s_2, s_3, respectively

p_{ij} – probabilities of process passing from the state z_i to the state z_j : i, j = 1, 2, 3; i ≠ j.

The probability P_1 can be considered an indicator of correct fuel combustion in engine cylinders, while probabilities P_j (j = 2, 3) are to be considered indicators of incorrect fuel combustion in the cylinders and, consequently, incorrect engine operation (work). Rational action of the engine user should lead to the situation in which time durations of the states z_2 and z_3 of the fuel combustion process were as short as possible.

FINAL REMARKS AND CONCLUSIONS

- The presented probabilistic models of the combustion process in diesel engine cylinders can be used for evaluating adaptation of certain types of engines for complete and perfect fuel combustion during a relatively long time of their operation (work), and for assessing correctness of use of these engines in certain operating conditions [3, 5, 6, 11]. It can be assumed in general that lower probabilities P_1 indicate more incorrect use of the engines, and opposite, when the remaining probabilities are low, the engine is better used.
- The probabilities defined by relations (12) and (15) can be considered indices of diesel engine reliability. Determining values for these probabilities requires relevant operating examination to assess the number of state changes for the presented models of fuel combustion processes in engine cylinders. The entire procedure consists in determining numbers n_{ij}, for a sufficiently long time interval [0, t] and obtaining the realisation t_{ij}^m , m = 1, 2, ..., n_{ij} of random variables T_{ij}. All this will make it possible to calculate the distribution functions $F_{ij}(t)$, probabilities p_{ij} and expected values $E(T_j)$, and, finally, probabilities of staying of the combustion processes in particular states $s_i \in S$ (i = 1, 2, 3, 4) or $z_i \in Z$ (i = 1, 2, 3).

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An electric ring thruster as auxiliary manoeuvring propulsion system for watercraft – construction analysis

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Krzysztof Falkowski, Ph.D.

ABSTRACT

The reported project aimed at examining properties and purposefulness of use of modern electromagnetic bearings for a screw propeller in a prototype version of a synchronous ring motor with rare earths magnets. Bearings of this type generate electromagnetic forces which keep the rotor in a state of levitation. The rotating machine with magnetic bearings can work in any environment which reveals diamagnetic properties (air, vacuum, ***water****, liquid gases, etc.). However, a basic quality of the magnetic bearings is elimination of cooling installation and lubrication, which is necessary for proper operation of rotating machines with rolling and slide bearings, undergoing wear with time. Therefore the lifetime of the machine supported on magnetic bearings is incomparable with others. Also torque losses on this bearing are the smallest, compared to all known types of bearings. Ring thrusters can be used as the main drive for relatively small sea-going and inland vessels, and as manoeuvring drive for ships of arbitrary size, especially for AES (All Electric Ship) type vessels. This type of propeller is extremely useful for any types of abyssal vessels, autonomous and remotely controlled, and on submarines. It can also be used as effective generator of electric current for charging batteries in towing trains, barges for instance. The project consisted of three research tasks:* ***1.*** *Designing, manufacturing and examination of a magnetic bearing on-line controlled by a digital controller,* ***2.*** *Manufacturing a model of a ring thruster and examination of characteristics of a propeller mounted in the ring,* ***3.*** *Examining the ferrofluid seal.*

A concept of the new thruster is a consequence of investigations carried out in Poland upon propellers and magnetic bearings in years 2001-2005.

Key words : Electric motor, steering, magnetism, ferrofluid seals

INTRODUCTION

Variety of tasks performed by inland vessels, in particular extremely difficult navigation conditions in narrow canals and sluiceways require excellent manoeuvring abilities from this type of watercraft. These abilities can be obtained by the use of additional and untypical propulsion systems securing steering quality at extremely low speeds and limiting depth of the water basin. The ring propeller fulfils these requirements the best, due to small power related dimensions and electric supply. Ring thrusters (understood as screw propellers, blades of which are mounted in a ring nozzle, with simultaneous absence of a hub and propeller shaft) can be used as the main drive for relatively small sea-going and inland vessels, and as manoeuvring drive for ships of arbitrary size, especially for AES (All Electric Ship) type vessels. It can also be used during barge towage as an effective generator of electric current charging a set of batteries, for the barge to have an independent source of energy during manoeuvres.

The presented thruster can work in a version without seals, thanks to the use of an electromagnetic bearing and corrosion resistant materials, but this version needs further testing. Contact-free support of the ferromagnetic rotor is obtained using electromagnetic bearings. These bearings generate electromagnetic forces which keep the rotor in a state of levitation. The rotating machine with magnetic bearings can work in any environment which reveals diamagnetic properties (air, vacuum, water, liquid gases, etc.). However, a basic quality of the magnetic bearings is the elimination of installations for cooling and lubrication, necessary for proper operation of rotating machines with rolling and slide bearings. This quality considerably improves the reliability of the entire device.

The proposed thruster makes it possible to eliminate the propeller shaft, which is the source of losses decreasing the efficiency of the entire propulsion system.

Other profits resulting from the use of the ring thruster supported on magnetic bearings are the following :

- its construction allows easy assembly on vessels in operation – increasing manoeuvring abilities at lower expenses than those borne in case of standard modernisations,
- developing a new type of propulsion system revealing high efficiency, dynamics and life time,
- considerable reduction in space required for installing the system on the modernised vessel.

The presented ring thruster has no propeller shaft, thanks to which it has most compact construction than other known propulsion systems. During manoeuvres it can be easily advanced from the hull, and the electric supply from the batteries via an inverter additionally facilitates the operation and the process of rotational speed control. Within the framework of the project, a prototype of the thruster supported on mechanical bearings was manufactured, but the version with an electromagnetic bearing and ferrofluid seal is also being worked out. The ferrofluid seal reveals the smallest drag during rotor operation, and properly reacts to lateral whip. Here the drag is of high significance as the diameter of the sealed area is large. The problem of sealing was recognised while studying the construction of the thruster in a dry version (in opposition to

the wet version, in which the water penetrates the motor inside) where the construction of the device is more complicated but its efficiency is becoming much higher.

The most remarkable solution in the presented concept of a new propulsion system is the use of modern electromagnetic bearings for the screw propeller in the prototype version of the synchronous ring motor with rare earths magnets. So far, a ring thruster with traditional bearings did not undergo sufficiently detailed examination in the past, the same even more refers to the version with a magnetic bearing used as contact-free support for ferromagnetic rotors. The lifetime of devices with magnetic bearings is significantly longer than that of other designs. In the version with magnetic bearings there are no parts which are subject to wear in a traditional meaning of this word, as the rotor works without physical contact with other components. In conclusion, the efficiency of a new-generation ring thruster is twice as high as that of the power units examined in the last century fifties. Then this concept was left aside due to about 18% efficiency, as compared to about 60% efficiency revealed by traditional free-propeller drives. At present, the development of technology and driving systems has provided opportunities for obtaining efficiency of about 40% (variant with the electromagnetic bearing), which along with unique advantages of the use of the ring propeller makes it very attractive for driving tow trains.

PRINCIPLE OF RING THRUSTER OPERATION

A concept of the new thruster is a consequence of investigations carried out in Poland upon propellers and magnetic bearings.

A new type propeller is a genuine contribution to the area of knowledge on water drives and their bearing systems making use of modern and very promising technologies. A few problems need clarifying here. The protecting and accelerating nozzles of ship propellers are in wide use in present shipbuilding. They are used everywhere where high thrust is required at relatively small forward speed. Until recently they have been mainly used on harbour and ocean tugs, trawlers and fishing base ships, drilling platforms, floating cranes, dredgers, and other specialised watercraft, including submarines. Now they are also in common use in driving modules on oceanotechnical objects, where they are most often used as components of dynamic positioning. Their special forms are thrusters and active rudders. An additional advantage of the new solution is possible operation of the screw in the uniform velocity field, both for thrusters and driving modules. Propeller's operation in a uniform field eliminates unfavourable pressure pulses induced in the space around the propeller (with resultant unfavourable vibrations of the entire structure). For the thrusters, eliminating the torque transmission path in which the torque is transmitted from the engine via the gear to the propeller shaft, and transmitting it via a tip ring results in full geometric and dynamic symmetry. This situation is very favourable for the operation and reliability of those devices. An additional, very important factor which considerably improves the reliability of this propulsion system is the innovatory use of magnetic bearings, an action which in the examined case is fully realisable and necessary, and develops this field of knowledge. A very important advantage of the new propulsion system is also extremely high power density, i.e. power related to the mass of the drive, which is much higher than recorded for other types of drives.

Below, a general concept of operation of the ring thruster equipped with electromagnetic bearings is presented.

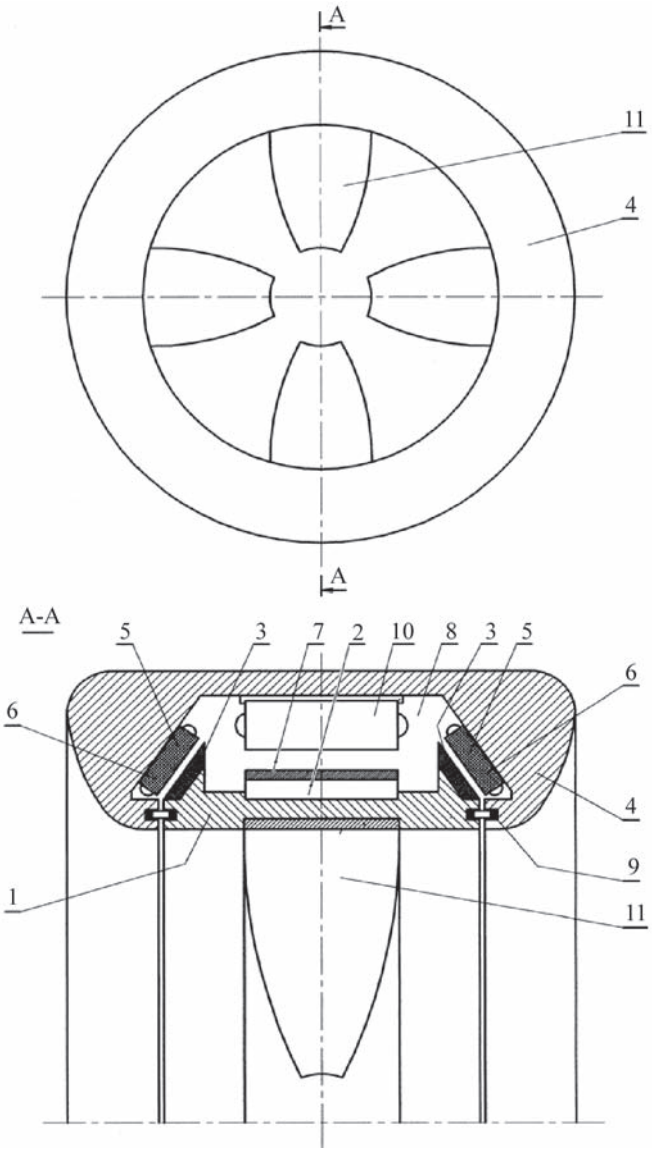

Fig. 1. *General concept of the thruster with a ring propeller, version with magnetic rotor bearing:* ***1.*** *Leading ring,* ***2.*** *Rotor,* ***3***. *Bearing raceway,* ***4.*** *Ring housing,* ***5.*** *Electromagnetic bearing forces,* ***6.*** *Electromagnets,* ***7.*** *Magnets,* ***8.*** *Internal space,* ***9.*** *Seal,* ***10.*** *Stator,* ***11.*** *Propeller,* ***12.*** *Passive wheel,* ***13.*** *Ferrofluid seal or labyrinth seal.*

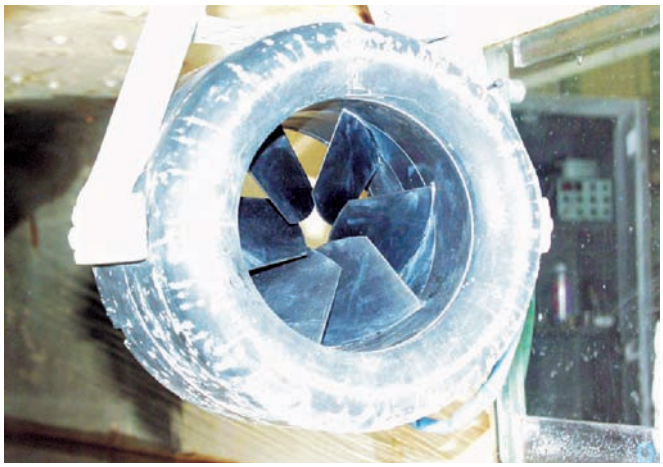

Fig. 2. *Ring thruster during tests in cavitation tunnel, version with ball bearing.*

The bearing centre consists of two magnetic cores, in which eight electromagnet coils are mounted (four differential actuators). Each coil is fed via a power amplifier. Between the

magnetic cores the stator of a motor which drives the propeller is mounted. The magnetic bearing is on-line controlled by a digital controller. Due to the presence of strong coupling between the bearing planes, a complex global control system is used.

The position of the propeller in the gap is determined using contact-free sensors of vortex-current or induction type. Other types of sensors cannot be used because of the possible action of sea-water.

CONICAL MAGNETIC BEARINGS

Like for conventional bearings, in the group of magnetic bearings radial, axial and conical bearings can be distinguished. The presented classification is connected with the direction in which the load is carried by the bearing (direction of electromagnetic force generated in the magnetic bearing). Since different types of bearings generate electromagnetic forces in different planes, their construction also differs. The radial bearing is designed to generate electromagnetic forces which counteract radial movements of the rotor. The rotor bearing system most often comprises two radial bearings which limit four freedom degrees of the rotor. Each bearing has two electromechanical actuators and two sensors measuring rotor movements in the air gap. This bearing system is to be complemented by an axial bearing which limits axial movements of the rotor. Bearings of this type are equipped with one electromechanical actuator and at least one sensor measuring rotor position in the bearing's air gap. Thus the bearing system of a rigid rotor is composed of two radial bearings and one axial bearing (five differential actuators and at least five sensors). If we use conical bearings for constructing the bearing centre, we can reduce the number of actuators to four and use only four sensors measuring rotor's position in the air gap. An additional advantage resulting from the use of this type of bearing systems is the ability to support short, large-dimension rotors (having the shape of a ring or disc). Rotors of this type do not have space for placing two radial bearings and one axial bearing. The article presents the construction of a propeller designed for driving submarine vehicles. Lack of space for placing three bearings was the reason why conical bearings were used. At the same time the number of actuators (electromagnets, power amplifiers) and sensors measuring rotor's position in the air gap was also reduced.

The designed bearing centre can be used for supporting large-dimension rotors. In particular, the proposed solution can be used in fan drives on hovercraft, while in helicopters this type of drive can replace the rear airscrew. Devices of this type find very frequent applications in marine technology (thrusters, propulsion systems on underwater vehicles and robots)

An additional advantage of the proposed solution is the use of the magnetic bearing, which considerably improves operating characteristics of the device, which in practice does no need attendance. In classical bearing systems the bearings undergo rapid wear. During manoeuvres, the vehicle is subject to strong gyroscope moment, just being the source of wear of classical bearings. Additionally, signals recorded by the sensors can be used for monitoring the technical state of the vehicle.

Along with numerous advantages, the presented solution reveals some limitations concerning the range of axial loads carried by the bearing. If we want to obtain a large axial force we should tend to reach the maximum possible inclination angle γ. However, when the inclination of the surface is large, it generates strong coupling between the actuators. The 38° inclination angle, used by the authors, secures obtaining required axial component of the electromagnetic force, but is a source of strong coupling between the actuators.

The simplest remedy is to change the inclination angle of the conical surfaces of the actuators and raceways. However, such a change will result in significant reduction of electromagnetic force axial component, which is the basic component carrying the main load.

In the majority of publications on conical bearing designs, the used inclination angles range between 15° ÷ 20°. Selecting an optimum angle to secure required axial force components and, at the same time, limit the coupling between the actuators is the object of authors' further research activities.

FERROFLUID SEALS

A characteristic feature of the conditions in which ferrofluid liquids are used in propulsion systems is high linear speed of the rotor with simultaneous relatively small pressure difference (about. 0.05 Mpa). As the measured data illustrate, the examination was performed for relatively high pressures to check limiting characteristics of the examined liquid. This part of the report is to be meant as a feasibility study, the aim of which was to check whether this type of seal can be used in the examined power unit. The answer to this question is positive and the next step of research will be more detailed examination of boundary values. These investigations are carried out in 2006.

Ferromagnetic, or ferrofluid seals belong to the group of absolutely tight seals, in which the magnetic liquid is kept by the magnetic field concentrated in a small gap between the elements composing, together with the liquid, the sealing system. In practical applications, the height δ of the gap filled with the magnetic liquid equals: $\delta = (0.1 \div 0.3)$ mm. The magnetic field is generated using high-power permanent magnets or electric coils fed by electric current with proper intensity. For the seal to be effective, the magnetic induction B in the gap filled with the liquid is to be equal to: $B = (0.6 \div 0.8)$ T.

In case of seals applied to rotating elements (shafts) the most frequent solution makes use a stationary magnetic system consisting of permanent magnets and pole shoes placed in a housing and generating magnetic field in circumferential gaps, filled with the magnetic liquid, which were created between the rotating shaft and the stationary magnetic system. Due to functional similarity, this seal is sometimes called „fluid O-ring seal". The magnetic liquid is a suspensoid of magnetic particles, having about 10 nm in diameter, in the carrying liquid.

Fe_3O_4 – the magnetite is most frequently used as material for magnetic particles. Other more rarely used materials include nickel, cobalt or their compounds revealing magnetic properties.

The carrying liquid can be an arbitrary liquid used in technology. However, in practical applications liquids revealing good chemical stability and high durability are selected. Of high importance are rheological characteristics of the carrying liquid, as they are the factors deciding on the drag of the seal in motion. Liquids are avoided which reveal toxic properties, as well as those which chemically of physically react with seal components.

The most frequently used carrying liquids include: water, mineral oils and other products of oil refinery, synthetic hydrocarbon or hydrogen fluoride compounds, and organic and inorganic ester compounds.

As compared to other types of seals, the ferromagnetic seals reveal a number of remarkable advantages, such as :

- ★ excellent tightness within the pressure range between 10^{-8} mbar and 3.0 MPa (leakage < 10^{-8} mbar · litre/s)
- ★ low power losses

- ★ possible operation at extremely high shaft rotational speeds (up to 30000 rev/min)
- ★ high durability and reliability of operation.

When designing seals with magnetic liquid, some limitations are to be taken into account, as resulting from properties of materials used for their manufacturing, and from the principle of operation of these seals :

- ✦ these seals work efficiently up to the pressure of 5.0 MPa
- ✦ most magnetic liquids lose sealing abilities in temperatures exceeding 130°C
- ✦ for operating conditions with high peripheral speed and higher temperature, a seal cooling system is to be provided
- ✦ the magnetic system of the seal takes relatively much space.

The above characteristics, advantages and disadvantages of the magnetic liquid seals mainly refer to their applications in the gas environment. The subject of the present report is checking whether this method can be used in the water environment. Possibilities of use of magnetic liquids for sealing machines working in the liquid environment have not been satisfactorily recognised yet. Some descriptions of technical solutions can be found for selected cases, such as for instance, seals of ship propeller shafts, or seals of roll passes in track roller cooling systems used in metal mills. However, a lot of important data are unknown, including the range of operating parameters, constructional solutions applied in those seals. Moreover, credible information on the effectiveness and durability of these seals is also missing.

In some research centres experimental works were conducted, which found their description in the technical literature on the subject. Results of these works confirm that the use of magnetic liquid seals for sealing machines in operation in the liquid environment is quite possible.

It is believed at the present stage of research and constructional activities that the basic problem in practical application of magnetic liquid seals for operation in the liquid environment is penetration of the sealed liquid to the magnetic liquid on the interface between the sealing and sealed phases. Due to relative motion of these phases, taking place in the majority of known applications of magnetic liquid seals, this liquid is subject to emulsification which leads to gradual degradation of the seal.

It is noteworthy that along with the dynamics of motion on the phase interface, of fundamental importance for the process of emulsification are physical and chemical characteristics of the magnetic liquid, in particular its carrying part. Some liquids belonging to the group of organic esters are known to reveal strong hydrophobic properties, as a result of which their emulsification in the water environment can be considerably reduced.

The experience gained so far on magnetic liquid seals working in the gas environment, and the information on application of these seals in the liquid environment make it advisable to start the research to assess parameters of useful and effective work, and develop design solutions of these seals.

RING THRUSTER

A ring thruster is a new type of propeller for which there is no experimental data to be used for verifying design calculations.

A characteristic feature of the ring thruster is the absence of a shaft. Propeller blades are fixed to a ring rotating inside the housing, which has the shape of a propelling nozzle. For this reason the ring thruster is closest, with respect to both to the construction and principle of operation, to the Kort nozzle propeller.

The absence of a shaft and no gap between the blades and the nozzle make it impossible to fully rely on results obtained from Kort nozzle propeller examination. What is more, the already existing computer codes developed for designing Kort nozzle propellers cannot be directly used for designing ring thruster either. That is why for this purpose a new code determining hydrodynamic characteristics based on the theory of the vortex lifting surface will be used.

When using this method, some differences between calculated and experimentally recorded results are expected to be observed. To a considerable extent, the level of the torque taken by the thruster will be affected by the drag of the rotating ring to which the blades are mounted. The results of investigations of a propeller equipped with a rotating ring suggest that the expected torque increment may reach as much as a few per cents, at corresponding levels of axial force (thrust).

At the present stage on ring propeller investigations of, there is no data available on how to shape ring propeller blades. Possible comparison calculations, done with the aid of the existing computer code, will allow, the most, the shape of the blades to be determined for preliminary tests in the cavitation tunnel and on a self-propelled model. And only the results obtained in these tests will provide opportunities for verifying preliminary design calculations. It should be stressed, however, that developing design procedures for this type of propellers will require additional optimising calculations, with further experimental verification. And this should be the subject of separate investigations.

CONCLUSIONS

Preliminary investigations of three basic elements composing the ring thruster, i.e. ferrofluid seals, electromagnetic bearing, and ring propeller indicate that manufacturing this ring thruster is advisable. However, prior to the manufacturing of the operating prototype, optimisation studies are to be done. The preliminary examination has been already performed, thanks to which directions of further modifications of particular centres are known.

The machine durability problem focuses on the loss of tightness. This is the most possible failure which may happen during long-lasting use of the ring thruster. During the last test, as a result of high dynamics of motion on the interface between the sealing phase (magnetic liquid) and the sealed phase (usable water under pressure), the layer was destroyed after 64 hours, which well corresponds to the results of investigations of he magnetic liquid alone recorded during earlier tests. However, this time is rather inconclusive, and further tests are in progress in 2006. It is noteworthy that the reported tests were performed in the conditions of direct action of the entire volume of the liquid on the examined seal, while in known descriptions of technical solutions and in research works hybrid sealing systems are often used, such as for instance a double system consisting of a preliminary front-type seal and a final magnetic liquid seal, to secure absolute tightness. The task of the preliminary seal in this case is to limit the volume of the liquid which comes into contact with the magnetic liquid in the final seal. The results of investigations are so promising that they justify continuation of research activities oriented on examining magnetic liquid seals designed to work in the liquid environment.

Independently of design solutions (including the motor, bearings, lubrication, seals) worked out for the presented

propulsion system, more comprehensive model investigations should be carried out to determine relevant empirical corrections which would allow these types of drives to be designed in a way similar to that followed when designing Kort nozzle propellers.

High efficiency and dynamics of electric drive systems used on watercraft resulted in their increased proportion in total number of propulsion applications. Thanks to the development of mechatronics, electrotechnics and hydrodynamics, the time has come when earlier solutions in this area can be put in practice. Among water propulsion systems, especially attractive properties are represented by ring-type propellers, but only with electromagnetic bearings. A characteristic feature of the motor, being an extension of a classical synchronous motor with permanent magnets, is that the ring with propeller blades is a part of the rotor. Dimensions of the nozzle in which the winding is mounted do not exceed dimensions resulting from the optimum geometry of the Kort nozzle propeller for the assumed power. As recently as a few years ago the development in the field of magnetic materials, ferrofluid liquids, non-linear control techniques and hydrodynamics reached a level providing opportunities for effective introduction of ring-type propulsion systems on a large scale. A drive which is expected to be especially promising in the nearest future is the ring thruster, used as a manoeuvring drive, and the main drive on smaller watercraft. The experience gained in designing ring thrusters with magnetic bearings has provides opportunities for manufacturing an efficiently working prototype and offering it on the market of water propulsion systems.

Ring propulsion systems with classical bearings are slowly becoming more and more popular, but still their efficiency is lower than 20% due to relatively high drag. A quantitative break-through in the field of efficiency improvement can be only secured by the use of magnetic bearings.

An additional advantage of the ring thruster is its ability to switch to turbine operation, in which it can be used as electric power generator. In numerous situation this property makes it possible to recover energy.

NOMENCLATURE

B – magnetic induction
δ – seal gap height
γ – conical inclination angle

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Photo : Arkadiusz Łabuć

Ring thruster – a preliminary optimisation study

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ABSTRACT

The ring thruster is a new type of propeller, for which there is no experimental data to verify analytical design calculations.

A significant feature of the ring thruster is the absence of a shaft. Propeller blades are mounted to the ring rotating inside the housing, which has the shape of a nozzle. For this reason the ring thruster is closest, with respect to both the construction and principle of operation, to the Kort nozzle propeller.

The absence of a shaft and no gap between the blades and the nozzle make it impossible to fully relay on results obtained from Kort nozzle propeller examination. What is more, the already existing computer codes developed for designing Kort nozzle propellers cannot be directly used for designing ring thrusters either. That is why for this purpose a new code determining hydrodynamic characteristics based on the theory of the vortex lifting surface will be used.

When using the above method, some differences between calculated and experimentally recorded results are expected to be observed. To a significant extent, the level of the torque taken by the thruster will be affected by drag of the rotating ring to which the blades are fixed. Examining a propeller equipped with a rotating ring has revealed that the expected torque increment may reach as much as a few per cent, at the comparable level of axial force (thrust).

At the present stage of ring propeller investigations there is no data available on how to shape the ring propeller blades. Possible comparison calculations, done using the existing computer code, will allow, the most, the shape of the blades to be determined for preliminary tests in the cavitation tunnel and on a self--propelled model. And only the results obtained in these tests will provide opportunities for verification of preliminary design calculations. It should be stressed, however, that developing design procedures for this type of propellers will require additional optimisation calculations, with further experimental verification. And this should be the subject of separate investigations.

Keywords : thruster, marine engine, hydrodynamics

GOAL AND SCOPE OF EXAMINATION

The goal of the reported activities was to perform preliminary hydrodynamic tests of the prototype ring thruster delivered by the employer. The main dimensions of the examined thruster were the following :

- ⇨ Outer ring diameter Dzd = 0.208 m
- ⇨ Inner diameter of ring motor Dw = 0.130 m
- ⇨ Width of housing (nozzle) B = 0.1365 m
- ⇨ Number of blades z = 6.

The scope of the examination includes measurement of the axial force induced by the ring thruster at different propeller revolutions and different velocities of the water approaching the thruster.

A tensometric dynamometer JK-21-2-500N-2003 IMP PAN allows total thrust force of the Tpx unit to be measured. This force comprises the thrust generated by the propeller and the nozzle, and the drag generated by the elements connecting the thruster with the dynamometer (connectors and a cable).

The torque is determined from the power calculated based on measurements of parameters of the electric current supplying the rotor, and therefore it can be burdened with some error.

RESEARCH RIG

The research rig, which is the cavitation tunnel K11-MH IMP PAN, was prepared for examining the new generation ring thruster (a general view of the rig is shown in Photo 1).

A prototype strain-gauge dynamometer JK-21-500N-2003 IMP PAN, mounted with relevant accessories and fixing system, is shown in Photo 3.

The system for measuring, storing and processing of changing forces Tpx and Rox makes use of a microprocessor measuring amplifier AWO 100, linked with the computer via RS 232C interface.

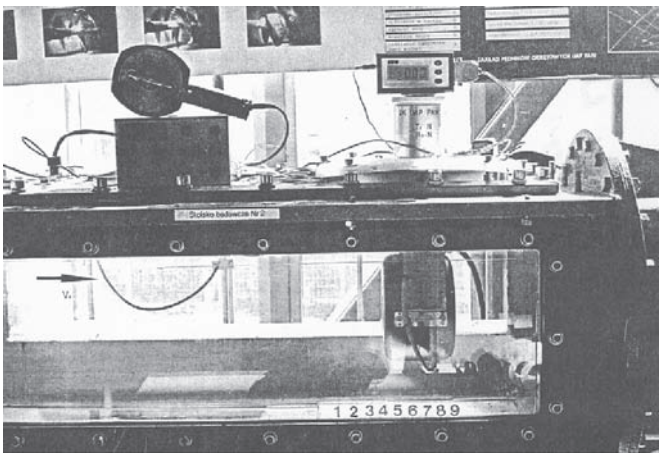

Photo 1. *Research rig for ring thruster examination.*

The average velocity in the measuring section of the cavitation tunnel was determined from the pressure difference measured in the tunnel confusor using a liquid-column gauge.

The propulsion system of the ring thruster consists of the nozzle-shaped housing and the internal ring with six blades fixed to it, (Photo 2).

Revolutions of the propulsion motor were controlled using a programmable inverter.

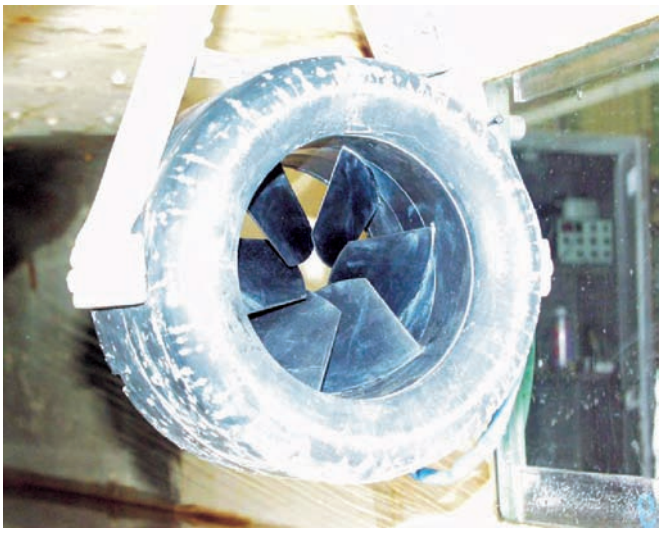

Photo 2. *Ring thruster installed in the cavitation tunnel.*

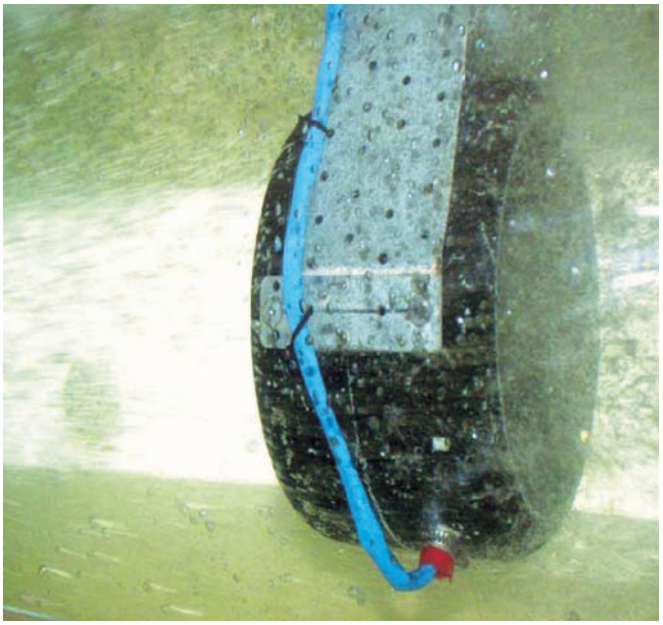

Photo 3. *Ring thruster in operation.*

EXAMINATION PROCEDURES

The substitute ring thruster (Dw= 0.13 m) delivered by the employer was mounted in a strain-gauge dynamometer JK-21-2-500N-2003 IMP PAN, especially manufactured for this purpose, and then installed on the properly instrumented research rig No. 2 (Cavitation Tunnel, type K11-MH) in the Szewalski Institute of Fluid-Flow Machinery PAN, Gdansk.

Ring thruster examination included the following tests :

- ✶ drag generated by a dummy ring thruster at different water velocities
- ✶ mechanical drag generated by the ring thruster in the air for different propeller revolutions
- ✶ ring thruster examination for different water velocities and different rotational speeds of the propeller.

During the examination the following quantities were recorded :

- ✦ propeller revolutions n [rev/min]
- ✦ speed of water in tunnel measuring section V [m/s]
- ✦ total thrust and drag generated by ring thrusters Tpx [N]
- ✦ drag generated by dummy ring thruster, console, and cable Ro [N]
- ✦ total torque taken by thrusters Q [Nm]
- ✦ internal ring thruster drag torque in air Qo[Nm]
- ✦ other recorded quantities included electric current intensity and voltage generated by the inverter supply system in the ring thruster motor.

The examination was performed for steady water velocities and changing ring propeller revolutions.

The examination was divided into test series, and the results of measurements were stored in the computer, in files named for instance „1200-01.dat" which means the first test series at revolutions 1200 rev/ min.

Instantaneous torque values were stored in computer's memory and then averaged, while the thrust generated by the thruster were averaged in the microprocessor based measuring instrument, by introducing a filter. The averaged results were then presented on a digital display.

Photo 4. *Research rig during ring thruster examination.*

RESULTS OF EXAMINATION

The tables below collect selected results of measurements, recorded on the research rig in the cavitation tunnel with the ring thruster. These results are grouped in properly numbered series.

Quantities mentioned in the tables :

Water velocity at the entrance to the measuring section is given in mm water column Δ h. Real velocity is determined from the relation :

- ❖ $V = 0.1412 \sqrt{\Delta h}$ [m/s]
- ❖ total thrust (measured) Tpx generated by the entire set is given in [kG]
- ❖ torque is given in [kGm]
- ❖ revolutions are given in [rev/min].

The results of measurements, obtained after doing relevant recalculations to dimensionless coefficients of thrust, K_T, and torque, K_Q, are given in Figs 1 and 2.

Table 1. *Results of ring thruster examination.*

File	n [rev/min]	Tpx [kG]	Δh [mm]	Q [kGm]	No. of series
1200-01.dat.	1200	11.4	15		1
1000-01.dat.	1000	7.75	10		1
1200-01.dat.	1200	11.32	11.32		1
800-01. dat.	800	4.96	6		1
700-01.dat.	700	3.76	5		1
1250-01.dat.	1250	12.35	16		1
1100-02.dat.	1100	8.0	35		2
1000-02.dat.	1000	6.32	30		2
800-02.dat.	800	3.35	30		2
700-02.dat.	700	2.26	30		2
1200-02.dat.	1200	9.2	40		2
1000-02.dat.	1000	5.91	40		2
1200-02.dat.	1200	9.2	40		2
1300-03.dat	1300	7.8	76		3
1200-03.dat.	1200	6.57	90		3
1000-03.dat.	1000	3.37	86		3
800-03.dat.	800	0.9	82		3
700-03.dat.	700	-0.14	80		3
1300-04.dat.	1300	3.22	200		4
1200-04.dat.	1200	-1.62	196		4
1000-04.dat.	1000	-1.3	190		4
1400-05.dat.	1400	15.2	20		5
1300-05.dat.	1300	13.1	18		5
1200-05.dat.	1200	11.1	16		5
1000-05.dat.	1000	7.76	10		5
800-05.dat.	800	4.88	6		5
800-06.dat.	600	-0.8	85	0.24	6
1000-06.dat.	1000	3.26	87	0.5	6
1200-06.dat.	1200	6.33	93	0.6	6
1300-06.dat.	1300	8.1	96	0.75	6
1400-06.dat.	1400	10.12	100	1.0	
1400-07.dat.	1400	5.16	205	0.9	7
1300-07.dat.	1300	3.19	204	0.65	7
1200-07.dat.	1200	1.47	202	0.5	7
1000-07.dat.	1000	1.44	198	0.3	7
800-07.dat.	800	-3.71	195		7
1500-07.dat.	1500	6.91	215		7
1450-08.dat.	1450	16.74	24		8
1400-08.dat.	1400	15.32	20	1.0	8
1300-08.dat.	1300	13.13	18	0.7	8
1200-08.dat.	1200	11.2	16	0.6	8
1000-08.dat.	1000	7.74	10	0.4	8
800-08.dat.	800	4.96	6		8
1477-08.dat.	1477	16.9	24	0.9	8

Table 2. *Torque generated by ring thruster working in air Q_0.*

Series	n [rev/min]	Q_0 [kGm]
MOM 1400	1400	0.15
MOM 1200	1200	0.125
MOM 800	800	0.085

Fig. 1 shows the results of measurements of thrust (axial force) induced by the entire ring thruster, in the arrangement: dimensionless thrust coefficient K_T vs. advance coefficient J.

Fig. 2 presents the results of measurements of the torque taken by the ring thruster, in the similar arrangement: dimensionless torque coefficient K_Q vs. advance coefficient J. The dimensionless coefficients are defined as :

$$K_T = T/(\rho n^2 D^4)$$

$$K_Q = Q/(\rho n^2 D^5)$$

$$J = V/(nD)$$

Fig. 1 and 2 show two curves, of which the broken curve refers to the thruster working in water. The continuous curve was obtained by deducting torque Q_0 , representing internal drag, from the total torque Q .

The scope of measurements included thruster operation above J = 0.2 (measuring points are shown in the figures). For J lower than 0.2, including J = 0, the curves were extrapolated using the analogy to other Kort nozzle examinations. Using the same analogy the thrust induced by the entire thruster was hypothetically divided into part induced by propeller blades and that induced on the nozzle (ring). The proposed division is shown in Fig. 3.

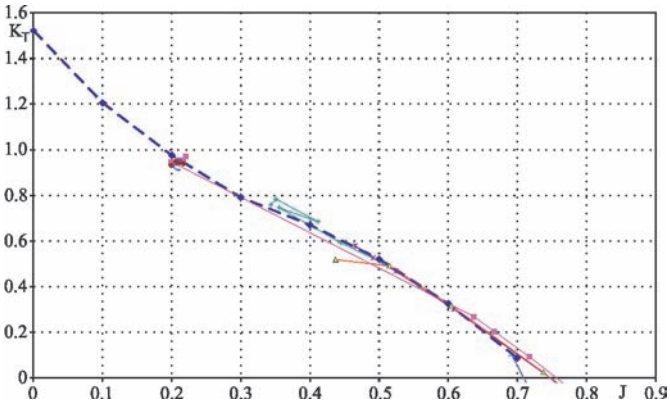

Fig. 1. *Results of calculations of thrust coefficient K_T induced by the entire thruster.*

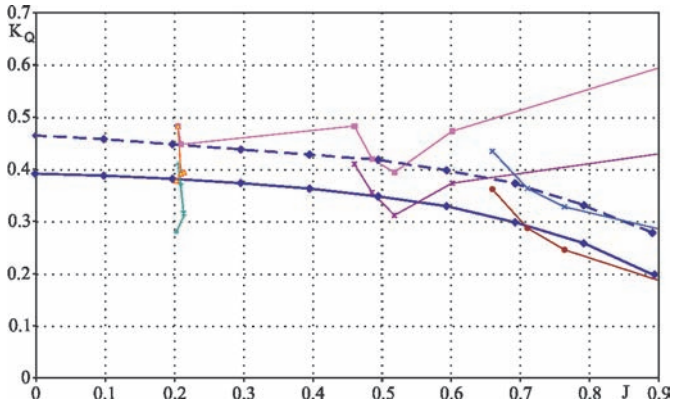

Fig. 2. *Results of calculations of torque coefficient K_Q.*

The presented results should be treated as concerning preliminary investigations of this type of propellers in Poland. Very interesting results were obtained for total thrust and torque induced by the entire thruster. Diagrams in Fig. 1 and 2 deliver a lot of new information on the performance of these types of propellers, but at the same time new problems can be addressed which need solving.

What needs clarifying first is why the measured torque, induced on the blades and the ring, differs so dramatically (more than twice) from the calculated value of the torque induced by the blades alone. It would mean that the torque induced

on the ring is very high and considerably affects thruster's performance. If so, its reduction is a priority for improving thruster's performance.

It would also mean that the substitute seal and bearings of the examined thruster do not fulfil requirements concerning the minimisation of drag forces generated by the ring moving in the gap.

In this type of investigations, good preparation and execution of measurement of a torque attributed to viscous losses on the ring, irrelevant of the torque induced by the blades, is the high priority.

The analysis of thrust examination results (table 1) reveals that the ring surrounding the propeller has favourably affected the total thrust. Figure 3 shows a diagram with hypothetical division of the total thrust K_{Tz} into part K_{Ts} induced by the blades and part K_{Tp} induced by the ring.

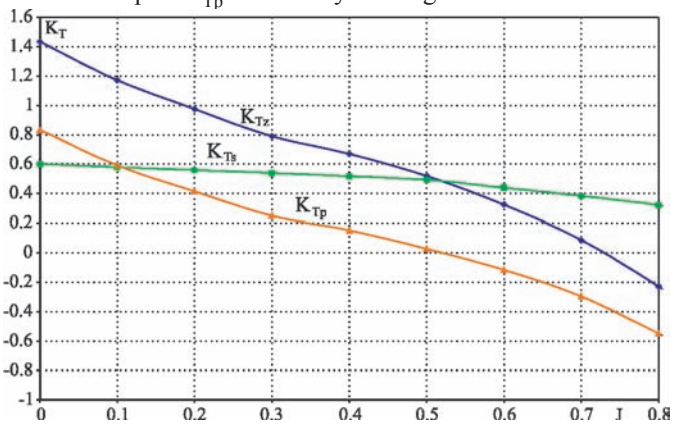

Fig. 3. *Approximate division of total thrust K_{Tz} into part K_T induced by thruster blades and part K_{Tp} induced by the surrounding ring (nozzle).*

The curve K_{Ts} was created using as a basis the point calculated for the blades alone and assuming the analogy to the Kort nozzle propeller examination. The shape of the curves is realistic, but it should be confirmed (or verified) by relevant examination of a propeller driven in a way classical for the Kort nozzle propeller system.

CONCLUSIONS

- To sum up, from the point of view of hydromechanics, independently of definite design solutions (including the motor, bearings, lubrication, seals) worked out for the presented propulsion system, more comprehensive model investigations should be carried out to determine relevant empirical corrections which would allow these propellers to be designed in a way similar to that followed when designing Kort nozzle propellers.
- High efficiency and dynamics of electric drive systems used on watercraft resulted in their increased proportion in total number of drive applications. Thanks to the development of mechatronics, electrotechnics and hydrodynamics, the time has come when earlier solutions in this area can be put in practice. Among water propulsion systems, especially attractive properties are represented by ring-type propellers, but only equipped with electromagnetic bearings. A characteristic feature of the motor, being an extension of a classical synchronous motor with permanent magnets, is that the ring with propeller blades is a part of the rotor. Dimensions of the nozzle in which the winding is mounted do not exceed dimensions resulting from the optimum geometry of the Kort nozzle propeller for the assumed power. As recently as a few years ago the development in the field of magnetic materials, ferrofluid liquids, non-linear control techniques and hydrodynamics reached a level providing opportunities for effective introduction of ring-type propulsion systems on a large scale. A drive which is expected to be especially promising in the nearest future is the ring thruster, used as a manoeuvring drive, and the main drive on smaller watercraft. The experience gained in designing ring thrusters with magnetic bearings has provides opportunities for manufacturing an efficiently working prototype and offering it on the market of water propulsion systems.
- Ring propulsion systems with classical bearings are slowly becoming more and more popular, but still their efficiency is lower than 20% due to relatively high drag. A quantitative break-through in the field of efficiency improvement can be only secured by the use of magnetic bearings.
- An additional advantage of the ring thruster is its ability to switch to turbine operation, in which it can be used as electric power generator. In numerous situations this property makes it possible to recover energy.

NOMENCLATURE

B - width of housing (nozzle) [m]
Dzd - outer ring diameter [m]
Dw - inner diameter of ring motor [m]
J - advance coefficient
K_Q - torque coefficient
K_T - thrust coefficient
K_{Tp} - thrust from ring
K_{Ts} - thrust from blades
K_{Tz} - total thrust
n - propeller rotational speed [rev/min]
Q - total torque taken by thrusters [Nm]
Q_o - internal ring thruster drag torque in air [Nm]
Rox - drag generated by dummy thruster, console, cable [N]
T - thrust
Tpx - total thrust and drag generated by ring thrusters [N]
z - number of propeller blades
p - pressure
V - speed of water in tunnel measuring space [m/s]

Δh - difference of the height

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Ring thruster – a preliminary optimisation study of ferrofluid seal and propeller

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Leszek Matuszewski, Ph.D.

ABSTRACT

The article reports the course of preliminary examination of a ferrofluid seal applied in liquid environment. A newly built research rig is described, and results of pressure tests performed for different shaft rotations are discussed. Other studies carried out in the past only referred to the gas environment, while the present examination aims at finding an answer to the question whether magnetic liquids can be successfully used in underwater applications. The obtained answer is positive, but further, more comprehensive investigations of the problem are necessary.

Keywords : ferrofluid seals, underwater propulsion

FERROFLUID SEAL – GOAL AND SCOPE OF EXAMINATION

The goal of the examination was preliminary assessment whether a chamber filled with water in motion can be effectively sealed with the aid of a magnetic liquid seal.

It was assumed that the examination would be carried out for the pressure of the working agent (usable water) equal at least to 1.0 MPa, and for different rotational speeds of the seal, increased from the minimum value of 125 rev/min to the value at which the seal loses its tightness.

Eight hours of continuous work of the seal without loss of tightness was assumed as a preliminary criterion of correct seal operation.

RESEARCH RIG

The Seal Technology Laboratory in the Department of Machine Design and Operation, AGH, Krakow, has three research rigs used for testing magnetic liquid seals. On these rigs, properties of the seals when in operation in gas environment are examined. In one of those rigs, labelled as MAST-1, constructional changes were introduced to allow it to be used for examining magnetic liquid seals in operation in liquid (usable water) environment. The essence of the introduced changes consisted in mounting an elastic membrane at the end of a hollow shaft to separate the gas, supplied from outside to the shaft hollow, from the area of a chamber created by the examined magnetic liquid seal, cover, screen and membrane, and filled with the working (sealed) liquid.

Fig. 1 shows half-cut/half-view of the measuring head after introducing constructional changes to it. This head consists of a stationary housing 1 with a shaft 3, hollow in part and resting on bearings. A mounting 5 is fixed on rolling bearings 6 in the housing 1. The examined magnetic liquid seal consists of two pole shoes 9, 10, permanent magnets 11, multi-edge sleeve (8 sealing edges) mounted on the shaft 3 and magnetic

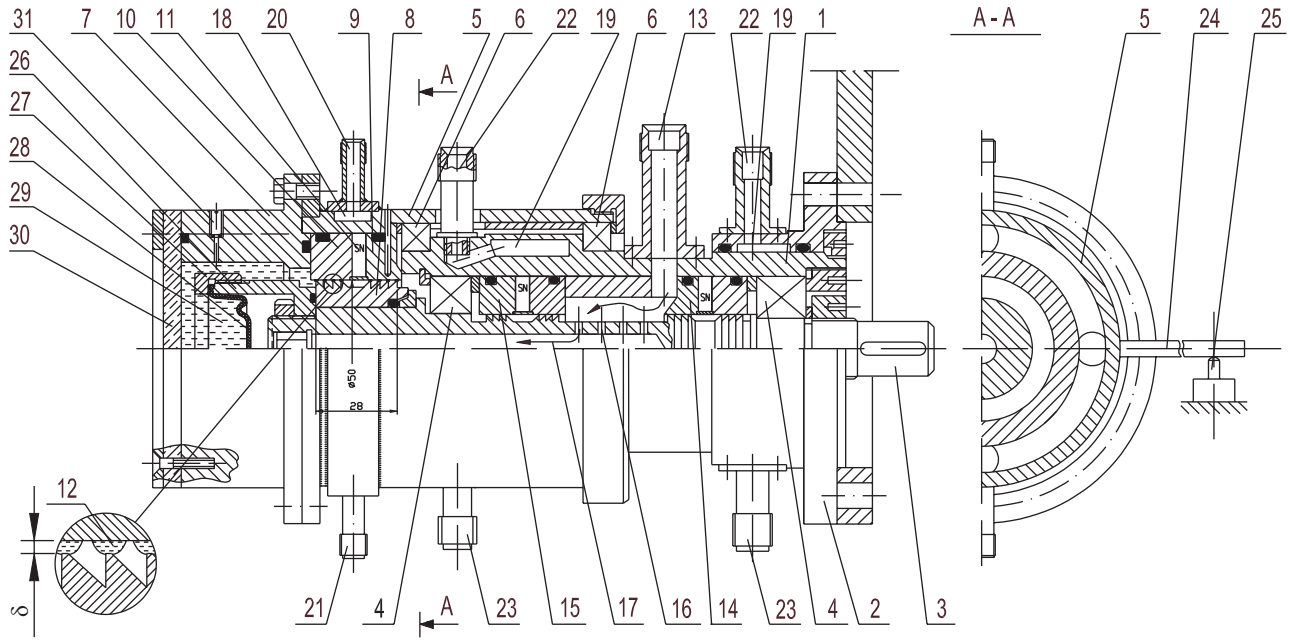

Fig. 1. *Measuring head adapted to examine magnetic liquid seals in liquid environment. Numbers in figure indicate :* ***1*** *– housing;* ***2*** *– flange;* ***3*** *– shaft;* ***4, 6*** *– rolling bearings;* ***5*** *– mounting;* ***7*** *– cover;* ***8*** *– removable multi-edge sleeve;* ***9, 10*** *– pole shoes;* ***11*** *– permanent magnet;* ***12*** *– magnetic liquid;* ***13*** *– supply terminal;* ***14, 15*** *– auxiliary ferromagnetic seal;* ***16*** *– lateral opening;* ***17*** *– longitudinal opening;* ***18, 19*** *– cooling chambers;* ***20, 22*** *– inlet terminals;* ***21, 23*** *– outlet terminals;* ***24*** *– lever;* ***25*** *– force sensor;* ***26*** *– distance sleeve;* ***27*** *– clamping ring;* ***28*** *– elastomer membrane;* ***29*** *– chamber with working (sealed) liquid;* ***30*** *– screen;* ***31*** *– opening for working liquid dosage.*

liquid 12 filling the radial gaps δ between sleeve projections and pole shoes. At the end of the shaft 3 a distance sleeve 26 is mounted, to which an elastomer membrane 28 is fixed using a clamping ring 27. The membrane 28 separates the working (sealed) liquid, which fills the chamber created by the examined magnetic liquid seal, cover 7, distance sleeve 26, screen 30 and membrane 28, from the gas supplied from outside to the hollow in the shaft 3 via terminal 13.

During the measurement of the „burst pressure" in the magnetic liquid seal the gas is supplied under pressure to the shaft hollow and exerts pressure on the sealed liquid via the elastic membrane. When the seal is tight, there is a balance between the pressures created by the liquid and the gas. These pressures can be measured using relevant measuring instruments (precise pressure sensors, or conventional manometers). When the examined seal is broken, the pressure of the sealed liquid in the chamber drops and this drop is recorded by the pressure sensor. The pressure level at which the loss of tightness is observed bears the name of „burst pressure" of the magnetic liquid seal.

Fig. 2 shows the system that supplies the measuring head with the compressed gas (air) and measures the pressure in the examination chamber. The system consists of the compressed air tank 32, air supply conduit 33, cut-off valve 34, and pressure control manometer 35.

For research purposes reported here a simplified measuring system was used which made it possible to observe the phenomenon of tightness loss in the sealing system.

The construction of the measuring head and the methodology of research conduction are the subject of patent application.

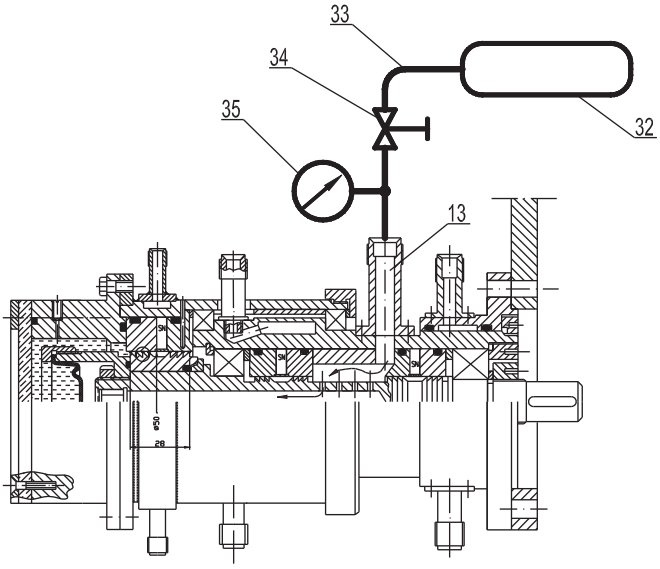

Fig. 2. *Measuring head supply with compressed gas (air) and pressure measurement in the examination chamber. Numbers in figure indicate :* ***13*** *– supply terminal,* ***32*** *– compressed air tank,* ***33*** *– air supply conduit,* ***34*** *– cut-off valve,* ***35*** *– pressure control manometer.*

MAGNETIC MATERIALS USED IN EXAMINATION AND EXAMINATION PARAMETERS

The examination was carried out using one type of magnetic liquid, bearing the symbol of C2-40M and delivered by SKTB Polyus, Russia. Table 1 below gives the characteristics of this liquid.

The magnetic field in the sealing system was generated using permanent magnets in the form of discs of the dimensions φ16x5 mm, sintered from samarium–cobalt mixture. Table 2 below gives the characteristics of the permanent magnets used in the examination.

Table 1. *Parameters of magnetic liquid used in the examination.*

Basic liquid	Silicon liquid
Magnetic particles	Magnetite Fe_3O_4
Volume concentration of magnetic particles %	11
Density ρ[g/ml]	1.414
Saturation magnetisation M_s [kA/m]	39.1
Plastic viscosity at temperature 20°C, η_{pl}[Pa/s]	0.520
Dynamic viscosity of basic liquid at temperature 20°C, η [Pa/s]	0.043

Table 2. *Parameters of permanent magnets used in the examination.*

Magnetic material	Sm-Co
Residual magnetic induction B_r [T]	0.77
Coercive force H_c [kA/m]	540
Maximum magnetic field energy density $(BH)_{max}$ [kJ/m^3]	55

GEOMETRY OF EXAMINED SEALS AND EXAMINATION PARAMETERS

The examined seal consists of permanent magnets, two pole shoes stationarily mounted in the head housing, and replaceable, multi-edge sleeve mounted on the rotating shaft. On the outer surfaces of the sleeve a number of sealing projections are machined. These projections have trapezoidal shape in the cross-section and are situated symmetrically with respect to the medial of the cylindrical surface of the sleeve.

In the examination one sleeve was used with the number of sealing projections: Z = 8, and radial gap : δ = 0.1 mm. The nominal diameter of the sealed opening was : d = 50 mm. The tests were performed for the following rotational speeds : n = 125, 250, 500, 750, 1000, 1500, 2000, 3000 rev/min. Moreover, one test was performed for continuous, gradual increase of rotational speed until the sealing system lost its tightness. All tests were performed at the set compressed air pressure equal to: p = 0.15 MPa.

EXAMINATION PROCEDURE

A number of permanent magnets 11 were mounted in the measuring head housing between the pole shoes 10 (Fig. 1). The magnets, having the shape of discs, were distributed uniformly along the circumference. Then the sleeve with sealing projections 8 was drawn over the shaft, and, during this operation, the gaps were gradually filled with the examined magnetic liquid, in a volume V_0 = 100μl per each sealing projection. The magnetic liquid was dosed using a precise laboratory feeder of MINILAB 100 type.

When the assembly was completed, excessive volume of the magnetic liquid was removed from the seal and the membrane 28 was mounted to separate the space filled with the liquid from the area in which the pressure is generated by the compressed gas action. After checking the tightness of the pressure generation system, the research chamber was mounted

on the measuring head and fixed with bolts to the head housing. Finally it was filled with the usable water.

The air form the tank 32 (Fig. 2) was supplied to the gas space via conduit 33, terminal 13 and openings 16, gradually increasing the pressure to the required level of 0.15 MPa. When the required pressure was reached and the tightness of the system was checked, the cut-off valve 34 was closed. This way a small volume was obtained in which the pressure was built up by the compressed air. Thanks to it the time when the magnetic liquid seal loses its tightness can be precisely determined from observation of the air pressure drop recorded on the manometer 35. The propulsion motor was started and when the required revolutions were obtained, the 8-hour examination cycle, identical for all tests, began. Due to preliminary nature of the research and the necessity of observation of the system in operation, the compressed air pressure in the examined system was not recorded.

RESULTS OF EXAMINATION

In total, eight eight-hour test cycles were executed for different steady-state rotational speeds. Moreover, one test cycle was executed during which the rotational speed was continuously and gradually increased up to the propulsion system limit, n = 12000 rev/min. Results of these tests are shown in Table 3.

Table 3. *Results of examination of a magnetic liquid seal working in liquid environment. Sealed agent : usable water. Sealing sleeve: 8 projections, gap height 0.1 mm. Magnetic liquid: C2-40M based on silicon liquid.*

No. of test	1	2	3	4	5	6	7	8	9
Shaft revolutions [rev/min]	125	250	500	750	1000	1500	2000	3000	0 to 6800
Time duration [h]	8	8	8	8	8	8	8	8	About 0.3
Starting pressure [MPa]	0.150	0.150	0.150	0.150	0.150	0.150	0.150	0.150	0.150
Final pressure [MPa]	0.152	0.153	0.153	0.156	0.158	0.167	0.172	0.181	About 0.09: loss of tightness

Test 9 was carried out for gradually increasing rotational speed.

The frequency converter (inverter) that controls the revolutions of the propulsion system was set for gradual increase of rotational speed until maximum revolutions n = 12000 rev/min were reached in 30 minutes. During the test, after about 18 minutes from the start, at the rotational speed approximately equal to n = 6800 rev/min gradual, but clearly visible pressure decrease was recorded in the compressed air space and traces of leakage through the magnetic liquid seal were observed.

For the shaft diameter d = 50 mm, the rotational speed n = 12000 rev/min corresponds to the linear velocity equal to 31.4 m/s. After recalculating this velocity to the rotational speed of a propeller with the seal diameter equal to d = 250 mm we obtain 2400 rev/min i.e. the optimum speed for a 10 propeller. The scaling principle is not precisely valid here, but with high probability one can expect that laboratory tests of the seal with 250 mm diameter will confirm this result. Further tests are planned with changed sealing agent, for longer time durations and higher linear velocities.

EXAMINED MAGNETIC MATERIALS AND PARAMETERS OF TEST 9

The test was carried out using one type of magnetic liquid bearing the symbol of C2-40M and delivered by SKTB Polyus, Russia. Table 5 below gives the characteristics of this liquid:

Table 5. *Parameters of magnetic liquid used in test 9.*

Basic liquid	Silicon liquid
Magnetic particles	Magnetite Fe_3O_4
Volumetric concentration of magnetic particles %	11
Density ρ[g/ml]	1.414
Saturation magnetisation M_s [kA/m]	39.1
Plastic viscosity at temperature 20°C, η_{pl}[Pa/s]	0.520
Dynamic viscosity of basic liquid at temperature. 20°C, η [Pa/s]	0.043

The magnetic field in the sealing system was generated using permanent magnets having the shape of a discs, of the dimension φ 16x5 mm, which were sintered from samarium–cobalt mixture. Table 6 below gives the characteristics of the permanent magnets used in test 9.

Table 6. *Parameters of permanent magnets used in test 9.*

Magnetic material	Sm-Co
Residual magnetic induction B_r [T]	0.77
Coercive force H_c [kA/m]	540
Maximum magnetic field energy density $(BH)_{max}$ [kJ/m^3]	55

Fig. 3 below shows the friction torque as a function of temperature of the warming liquid. A noticeable tendency here is drag decrease during seal's operation. The examination was carried out for the pressure *p* between the air and the nitrogen equal to 1 Mpa.

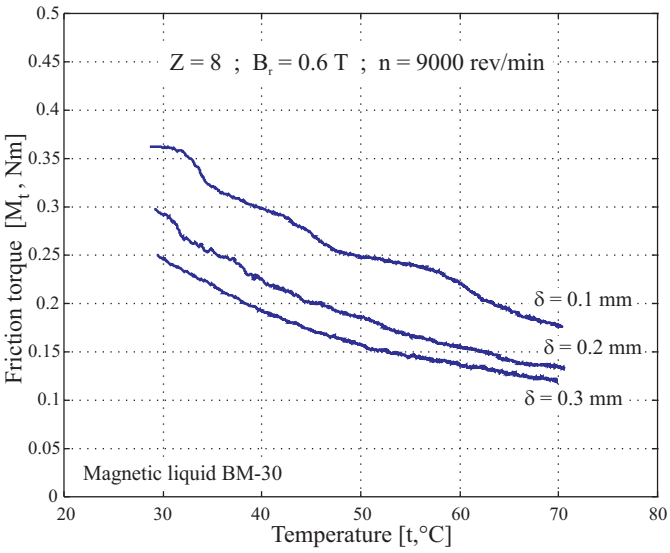

Fig. 3. *Friction torque M_t vs. temperature t recorded during examination of the magnetic liquid seal BM-30.* ***Z*** *= 8 ,* B_r *= 0.6 T ,* ***δ*** *= 0.1 ; 0.2 ; 0.3 mm,* ***n*** *= 9000 rev/min.*

Fig. 4 shows the burst pressure for the parameters taken from Fig. 3.

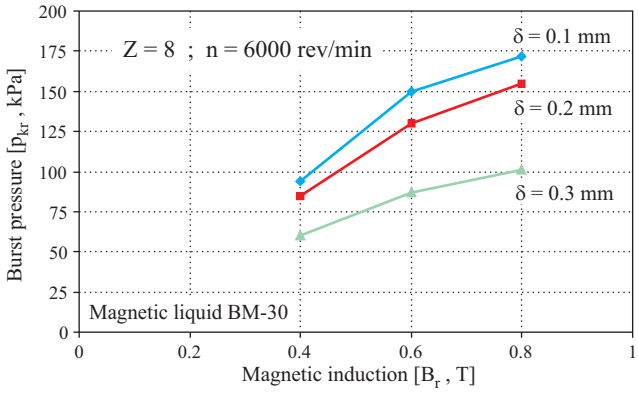

Fig. 4. *Burst pressure p_{kr} vs. magnetic induction B_r in the magnetic liquid seal BM-30.* ***Z*** *= 8,* ***δ*** *= 0.1 ; 0.2 ; 0.3 mm,* ***n*** *= 6000 rev/min.*

CONCLUSIONS

- In the reported examination, all test cycles were executed without changing magnetic liquid in the seal. Therefore it can be assumed as first approximation that that the durability of the seal in operating conditions in the usable water environment was equal to 64 hours, the least.
- The loss of seal's tightness observed in the last test resulted most likely from both high dynamics of motion at the interface between the sealing phase (magnetic liquid) and the sealed phase (usable water under pressure), and possible fatigue of the magnetic liquid, accumulating during previous tests.
- It is noteworthy that the examination was carried out in the conditions of direct action of the entire volume of the liquid on the examined seal. However, in known descriptions of technical solutions and research works hybrid sealing systems are often used, for instance a double system consisting of a preliminary front-type seal and a final magnetic liquid seal, which secures absolute tightness. The task of the preliminary seal in this case is to limit the volume of the liquid that comes into contact with the magnetic liquid in the final seal.
- The reported tests allow a conclusion to be formulated that the research rig has a correct construction and provides opportunities for obtaining assumed research goals. Further constructional modifications of the research rig are suggested to allow more complex sealing systems to be examined.
- The obtained preliminary results of seal examination are so promising that they justify continuation of research activities oriented on examining magnetic liquid seals designed to operate in the liquid environment.
- High efficiency and dynamics of electric drive systems used on watercraft resulted in their increased proportion in total number of propulsion applications. As recently as a few years ago the development in the field of magnetic materials, ferrofluid liquids, non-linear control techniques and hydrodynamics reached a level providing opportunities for effective introduction of ring-type propulsion systems on a large scale.

NOMENCLATURE

Z - number of sealing projections
d - diameter
n - rotational speeds
p - pressure
V_o - volume
δ - radial gaps

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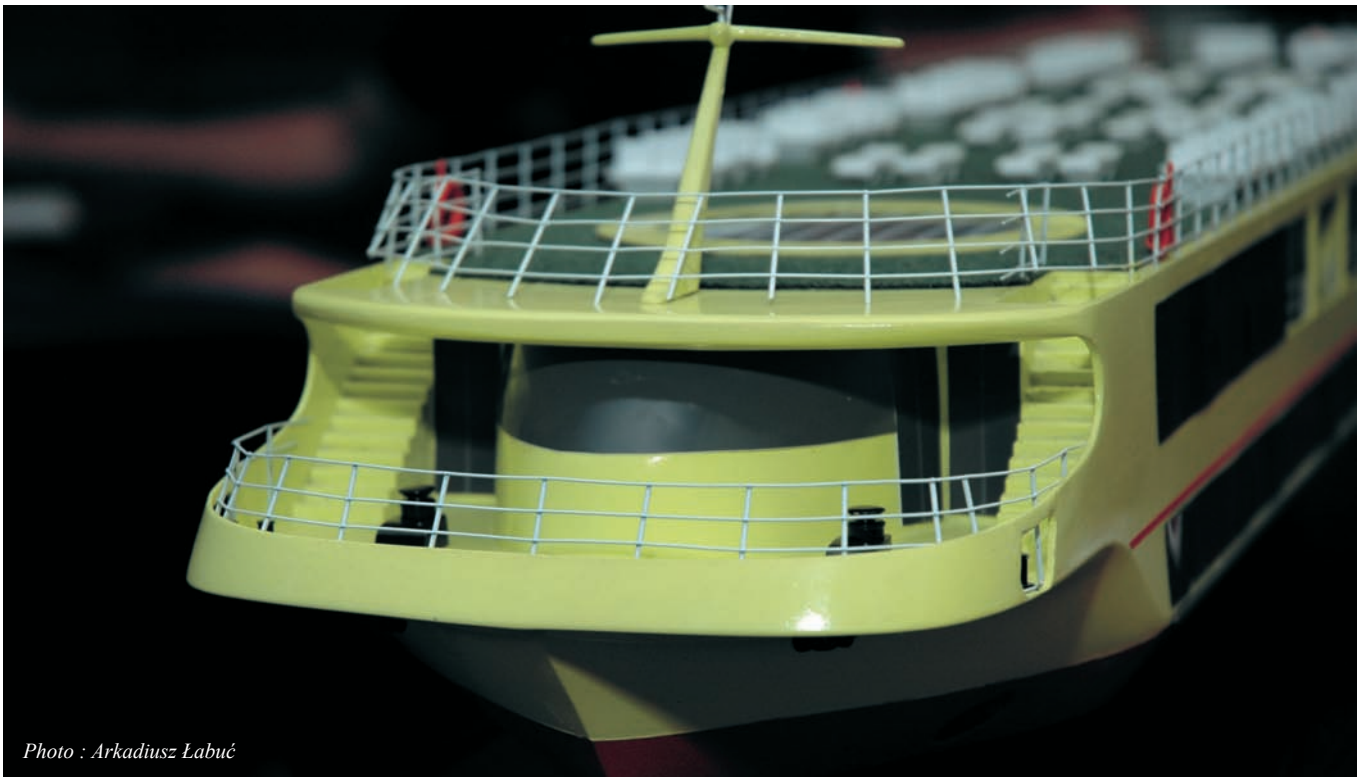

Photo : Arkadiusz Łabuć

Frame technology of pusher tug construction for a two-element inland passenger ship

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Gdansk University of Technology

ABSTRACT

The article presents a frame technology for a pusher tug, the construction of which was developed within the framework of the INCOWATRANS project. The technological division was made using a so-called mass criterion. The weight of the biggest sections does not exceed 12 tonnes, which allows the steel hull to be built using even as small a crane as the truck crane of approximate carrying capacity of 20 tonnes. Subsequent building stages are illustratively shown in the figures.

Keywords : frame technology, tug construction, inland passenger ship

INTRODUCTION

The subject of the article is the proposed technology for building the pusher tug hull of mixed panel and conventional structure. In particular it refers to Phase 10, [1], presented in Table 1.

Table 1. *Part of Table 4-1 from Ref. [1].*

Panel part – „raw”				
Phase number	**Phase name**	**Unitary division**	**General scope of work**	**Events**
10	Preparing documen-tation	Concept of constructional and technological division of the ship into panel and conventional parts	Catalogue of construction centres (panel joints with conventional construction)	Preparing documen-tation and selecting centres
			CAD Project	

The basic data for the article was a set of design drawings for a pusher tug and hotel barge, prepared by DESART on October 18, 2005. They show one of design variants and that is why the present proposal should be treated as one of possible technological divisions – a preliminary stage.

The CAD project, executed with the aid of UNX3 code package, includes the visualisation of the technological process of building of the ship's hull panel part.

CONCEPT OF TECHNOLOGICAL DIVISION OF THE PUSHER TUG

According to the assumptions concerning the frame hull building technology, [1], the following sequence of actions was adopted within the framework of phase division of ship building technology, and the ship construction was divided into two parts :

- conventional – referring to the bow and stern of the ship
- panel part – consisting of a grate, made of tube profiles and filled with panels, and a single-sheet (conventional) construction in the board and bilge regions.

Principles and qualification of the design and technology documentation were prepared based on the already existing, well-known division defined in the standard, adapting it to the purposes of prototype watercraft building. What is innovative here is proposed changes in principles of numbering *Classes, Groups* and *Subgroups,* [1, item 4.1]

The design of the pusher tug was modelled in UNX3.

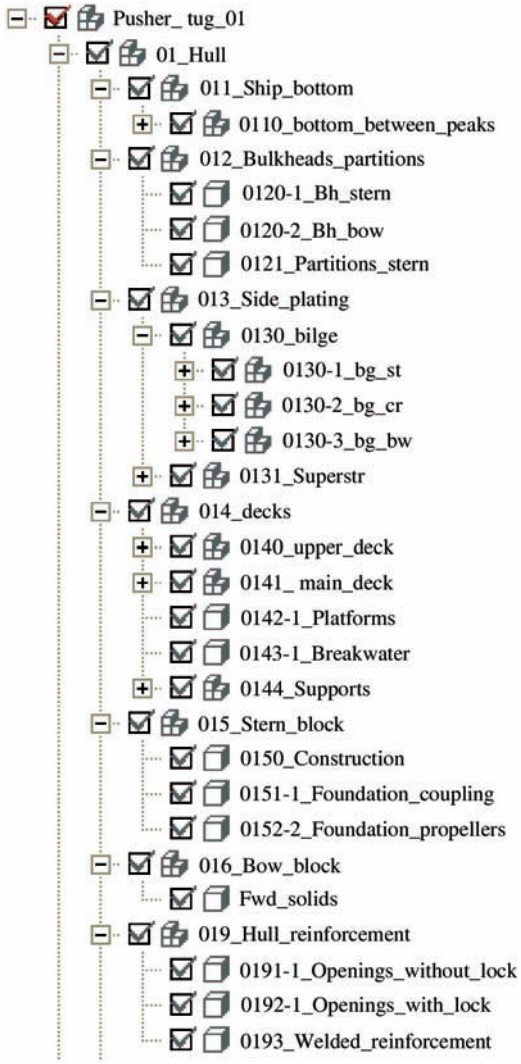


Fig. 1. *Structure of pusher tug construction, extended to three levels.*

Section and block division of pusher tug construction

The pusher tug construction was divided into block-sections, which then were divided into flat sections, consisting of a truss (grate) made of rectangular cross-section beams. The space inside the grate was filled with panels, Fig. 3. The main criterion of the division was the weight (mass) criterion. The total weight of each block-section element does not exceed 12 tonnes. All sections can be transported and manoeuvred by a crane of maximum carrying capacity of about 20 tonnes.

A collection of approximate masses of particular sections is given in Table 2.

Due to a variety of drawings illustrating subsequent building stages, a limited number of figures were selected for a simplified presentation illustrating the course of building.

Table 2. *Specification of pusher tug block-sections.*

Item	Name of block-section	Symbol	Mass from design [t]	M(sk) [t]	Identifier from NX **Tech_01**
1	**Stern – classical construction**	RU_01		7	RU_01
2	**Stern superstructure**	RU_02		5	RU_02
		Total :	**21.278**	**12**	
3	**Bottom**	DN_01	5.878	7	DN_01
			2.265	3	DN_01_P_01
4		DN_02	4.515	6	DN_02
			2.013	3	DN_01_P_03
5		DN_03	6.607	7	DN_03
		Total :	**21.278**	**26**	**BOTTOM**
6	**Main deck**	PG_01	10.753	12	PG_01
			1.381	2	PG_02_Pi_Sc
			2.796	4	PG_01_P_01
7		PG_02	5.084	6	PG_02
			1.258	2	PG_02_Pi_Sc
8		PG_03	8.555	10	PG_03_RAMA
			1.888	3	PG_03_Pi_Sc
			2.484	3	PG_03_P_03
		Total :	**34.199**	**42**	**Main deck**
9	**Upper deck**	PY_01	2.796	4	PY_01_P_01
			0.959	2	PY_01_Pi_Sc
			10.709	12	PY_01_RAMA
10		PY_02	5.084	6	PY_02_RAMA
			0.750	1	PY_02_Pi_Sc
11		PY_03	0.678	1	PY_03_Pi_Sc
			7.634	9	PY_03_RAMA
			2.484	3	PY_03_P_03
		Total :	**31.094**	**38**	**Upper deck**
12	**Bilge + board over bilge+ board between main and upper deck**	OB_01_LB	2.788	4	OB_01
		OB_01_PB	2.788	4	
		Total :	**5.576**	**8.0**	**Bilge st**
13	**Bilge + board over bilge+ board between main and upper deck**	OB_02_LB	2.074	3	OB_02
		OB_02_PB	2.074	3	
		Total :	**4.148**	**6.0**	**Bilge Ct**
14	**Bilge + board over bilge+ board between main and upper deck**	OB_03_LB	2.582	4	OB_03
		OB_03_PB	2.582	4	
		Total :	**5.164**	**8.0**	**Bilge bw**
15	**Bow**	DZ_01		6	DZ_01
16	**Bow superstructure**	DZ_02		5	DZ_02
		Total :		**11**	
TOTAL				**151**	

J – single-sheet structure, **R** – grate, **P** – sandwich panels; **M**(sk) – (corrected mass).
Figure does not take into account total mass including all small details.
Correction was assessed as equalling from 10% to 40% of the mass of the construction object of concern.

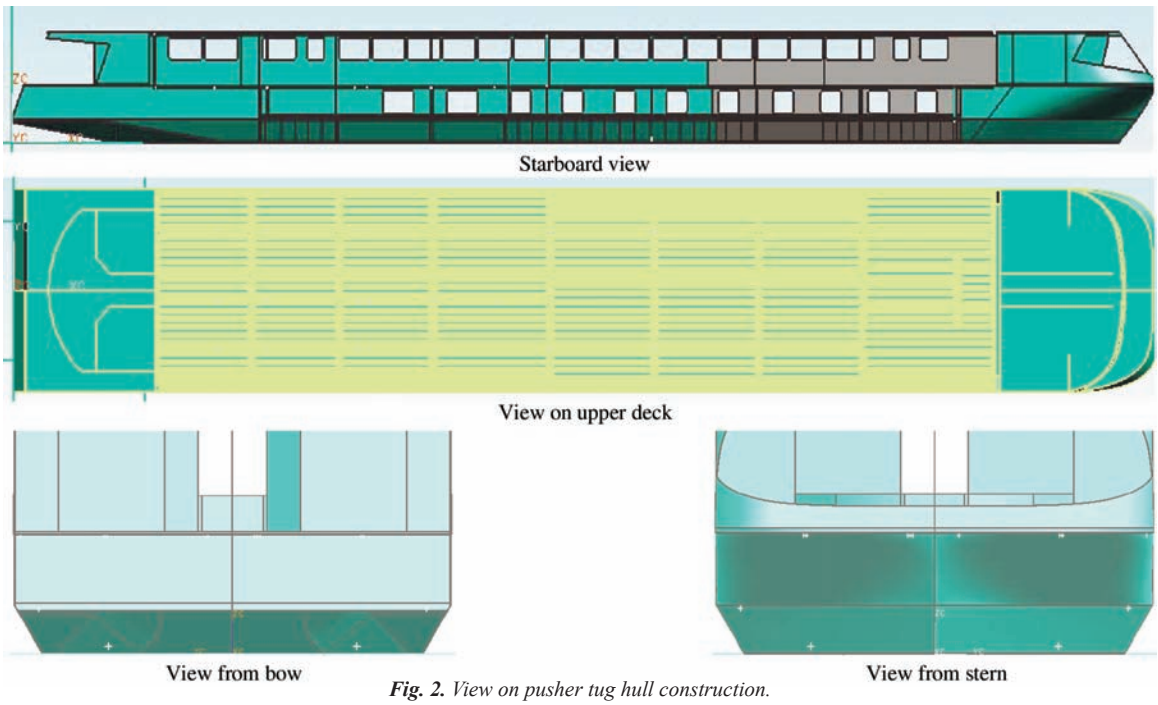


Fig. 2. *View on pusher tug hull construction.*

Certain simplifications were adopted which the reference to the description of building conditions. In particular they refer to :

- the place of building which is convenient for launching, such as a dry dock or a crane with carrying capacity above 200 t (MAJA, for instance)
- blocking made of poppets, for instance, to give an access from the bottom side for welding and checking tightness of joints
- knowledge on welding processes concerning thickness of steel sheets and construction elements, and types of welds and positions in which they are made
- the prepared catalogue of standards of manufacturing for panel and mixed panel-conventional constructions
- issues referring to power plant and cabin equipment were omitted
- the installations (pipelines) were assumed to be led mainly in the region of bilge tanks.

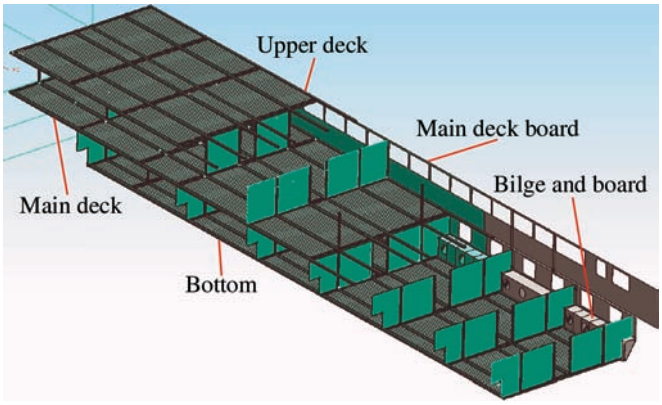


Fig. 3. *View on pusher tug panel part.*

Grate prefabrication and filling with panels for the bottom region

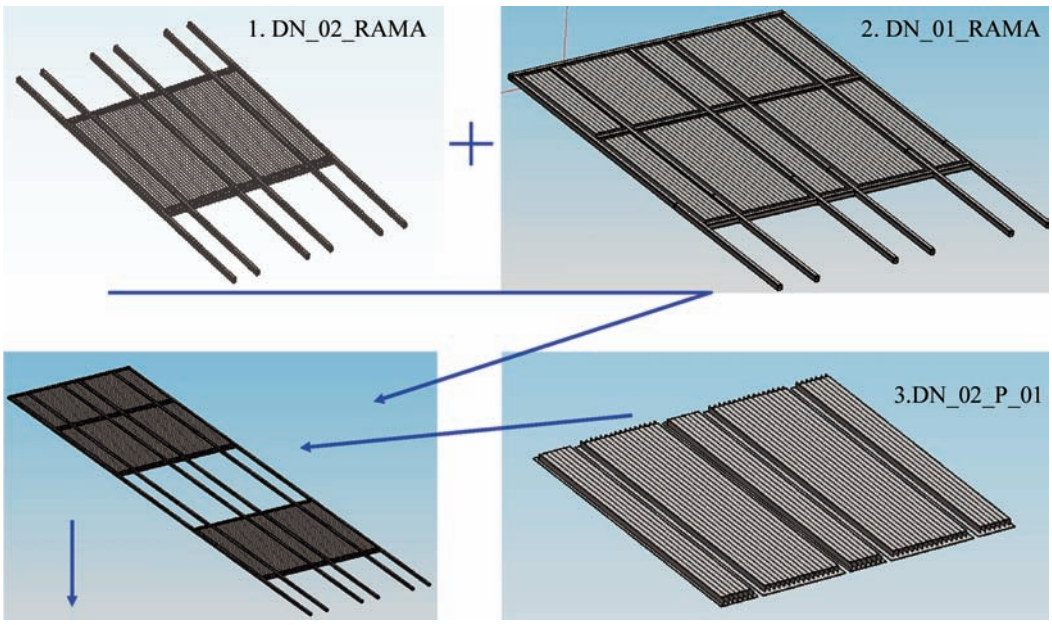


Fig. 4. *Bottom region prefabrication.*

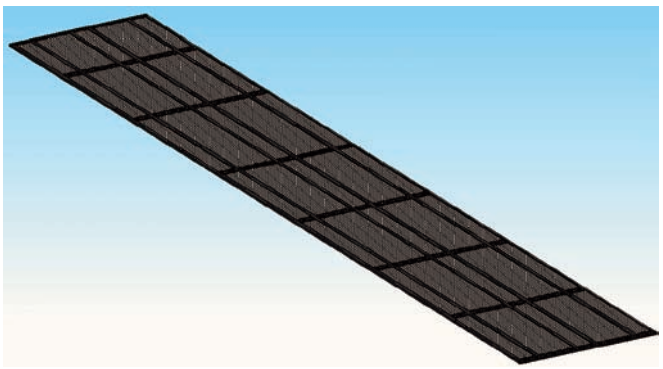
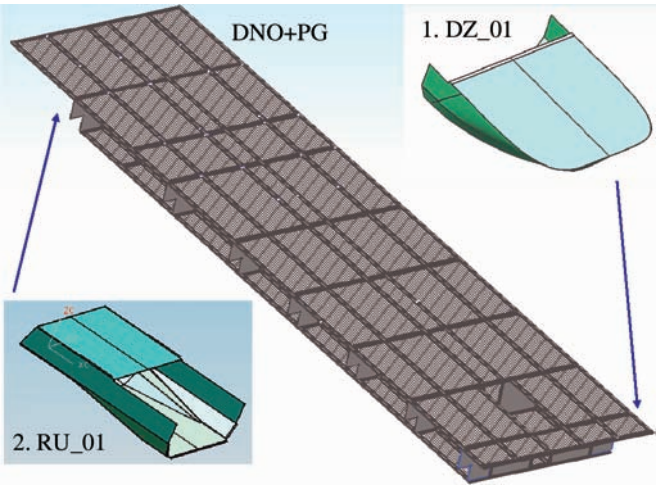


Fig. 5. *Bottom after prefabrication.*

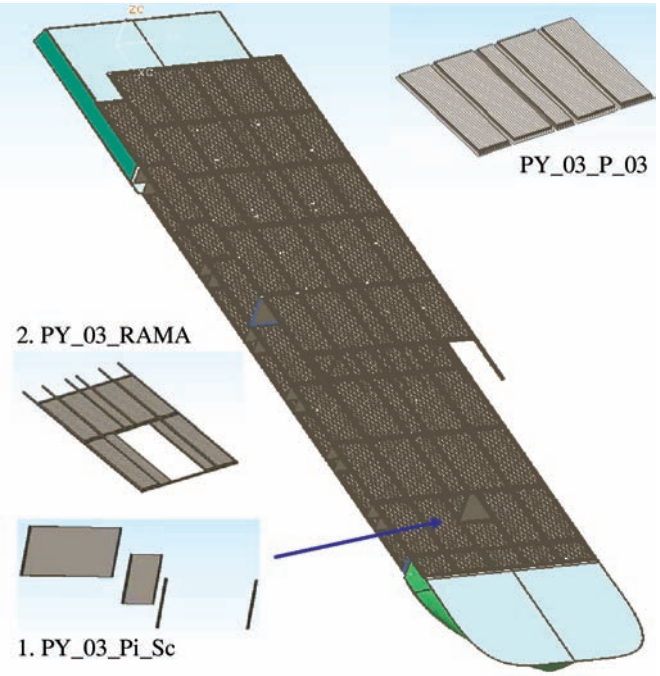
The bottom comprises items 3, 4 and 5 from Table 2.

Building the main deck together



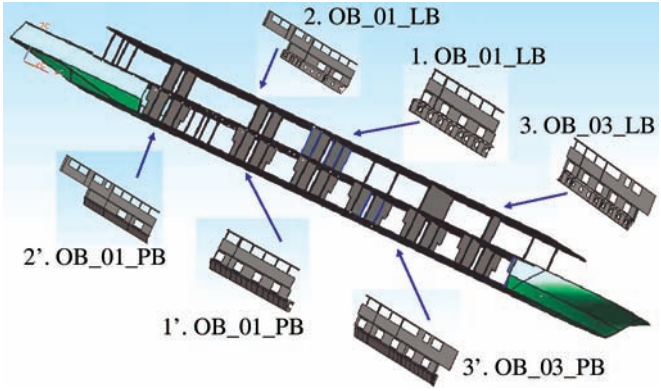
with bow and stern parts

Fig. 6. *Sequence of assembling bow and stern parts with the bottom and main deck construction.*



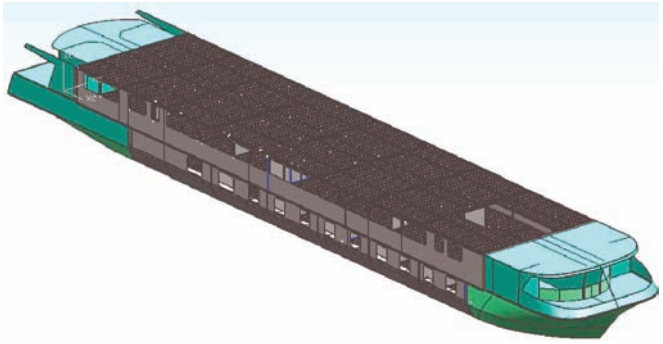
Building the upper deck

Fig. 7. *Sequence of assembling pillars and walls on the main and upper decks.*



Assembling board and bilge sections

Fig. 8. *Assembling conventional sections with the frame construction.*



Steel construction of the pusher tug hull

Fig. 9. *View on pusher tug hull after assembly and welding.*

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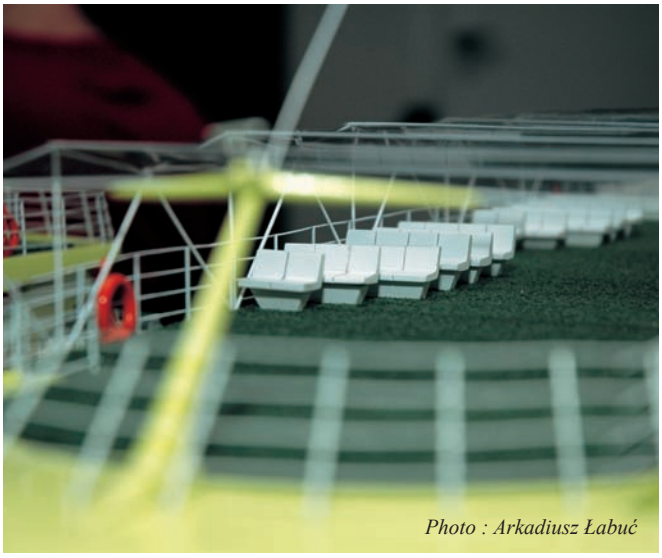

Photo : Arkadiusz Łabuć

SUPLEMENT

Mourning

9 August 2006 was the time of a deep sorrow
for the circle of Polish shipbuilders as

Professor Jerzy Doerffer

passed away this day.

Graduate of Shipbuilding Faculty of University
of Glasgow and Gdansk University of Technology.
Professor of Gdansk University of Technology
where he worked since 1948.

The organizer and the first Head of the Department
of Ship Technology and its auxiliary unit.

The Dean of Shipbuilding Faculty
in the years 1953-54 and 1958-64.
The Rector of Gdansk University of Technology
in the years 1964-67.

The Chairman of the Forum of Shipbuilding
and Ship Repair Industry.

The creator of the scientific school in the domain
of shipbuilding technology.
He was a worldwide recognized authority
on this domain.

The co-author of novel design solutions
and manufacturing techniques in ship technology.

Doctor *Honoris Causa* of Gdansk University of Technology,
Leningrad Shipbuilding Institute, University of Glasgow,
University of Rostock, Polish Naval University and
Technical University of Szczecin.

He was also honoured with William Froude Medal
by the Royal Institution of Naval Architects, London.

Prof. Doerffer was not only an outstanding engineer-
-inventor but also a moral authority of wonderful personality.
Due to his attitude and work he won respect from the side
of the whole circle of Polish shipbuilders.

He was a figure-symbol of whom the circle
of Polish shipbuilders boasts.

Humanist and teacher. He promoted a whole generation
of Polish engineers in shipbuilding technology.

A member of prestigious scientific
institutions in Poland and in the world.

***It is two-parts paper published after Professor Doerffer death
to emphasize the involvement of the author in the Incovatrans programme.***

Devices improving the manoeuvrability characteristics of ships

Part I
Laboratory tests on models in cavitation tunnel and towing tank

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Gdansk University of Technology

ABSTRACT

An account of research activities on the devices improving the manoeuvring abilities carried out at the Gdansk University of Technology is reviewed. These devices could be placed on the bulbous bow (opening bulbous bow) and at the stern end (wake pressure equalising device, stern shield, opening rudder). Researches with segments of models of these devices in a cavitation tunnel and on self propelled models of ships in a towing tank were performed as well as on open lakes.

Keywords : opening balbous bow, opening rudder, stern shield, steering braking device, braking the ship

INTRODUCTION

Collisions, ramming and grounding amount to about seventy percent of all the ship's casualties. Officially they were mainly attributed to human factor, but the lack of appropriate manoeuvring characteristics is not allowing the master to correct his navigational mistakes.

Therefore it was advocated to start an extensive programme on manoeuvring standards. From the safety point of view the most important are :

- ★ head reach while braking the ship without any side transfer
- ★ turning diameter.

Considerable number of accidents could have been avoided, if the manoeuvring characteristics could be improved. Inertia braking the ship and reversing the propeller are the only means of lowering the speed and stopping the ship. A stern rudder is the only device for changing the course of the ship and a side thruster additionally at harbour speeds on some ships. No special devices are used on commercial transport ships to improve the manoeuvring abilities despite increasing congestion on shipping lanes and traffic routeing. Inertia braking is a very lengthy procedure, the ship looses her speed due to the resistance of water and wind and thus the head reach is exceedingly large. Reversing the propeller is also a lengthy procedure, on some large diesel engine takes at least 30 seconds and sometimes even up to one minute. On a steam turbine ships this operation takes over one minute. Reversing the propeller results in considerable loss of power astern as compared with running forward (diesel engine about 15% and steam turbine about 60%). This is assisted by a steering moment, which makes the ship to deviate from the original course in an uncontrollable manner causing a side transfer up to 3 x ship lengths. Propeller working astern causes high vibrations, which are most unpleasant for the crew and in case of resonance may cause fatigue damage to ship's structure and her outfit.

On large steam driven tankers the head reach from service speed to full stop amounted to over 15 x the length of the ship and the side transfer to over 3 x the length of the ship. Turning diameter was well above 4 x length of the ship. It was quite obvious that it is absolutely necessary with routeing the ship lanes that the ship would comply with the minimum standards worked out by this Subcommittee on Ship Design and Equipment and adopted by appropriate IMO bodies.

RESEARCH PROGRAMME

Very wide research programme concerning the improvement of steering characteristics was undertaken at the Gdansk University of Technology. The required improvement could not be achieved by modifications in existing devices and new devices had to be developed, being capable of generating large forces indispensable to destroy high kinetic energy of large ship proceeding at service speed in order to stop the ship. These devices should be also capable of creating large transverse forces to decrease the diameter of circulation. The following devices have been invented which were located in the fore end and after end of the ship :

- ☆ fore end - opening bulbous bow
- ☆ stern end - stern shield; steering and braking device; wake pressure equalising device.

First of all they were tested in a cavitation tunnel until promising results were achieved and only then fitted on several different self-propelled models, which were tested in a 250 m long and 12 m wide towing tank. When good results were obtained the models were brought to open water in order to prove the improvement in manoeuvring characteristics. A model of a „Panamax" 65000 TDW in the scale 1:24 was used most extensively (Tab. 1). It was hand controlled by a skipper sitting in the model, whereas some models operated on the open lake were radio remote controlled. These tests allowed to state that simple and quite inexpensive devices could be installed aboard new and existing vessels in order to radically improve the manoeuvring characteristics.

Tab. 1. *Principal dimensions of a „Panamax" ship and model.*

Item			Ship	Model
Length overall	L_{OA}	[m]	218.6	9.200
Length between perpendiculars	L_{PP}	[m]	205.0	8.541
Length on water line	L_{WL}	[m]	214.6	8.940
Displacement	-	[m³]	-	4.200
Breadth	B	[m]	30.48	1.270
Draft : Forward	T_F	[m]	11.56	0.482
Aft	T_A	[m]	11.54	0.482
Block coefficient			0.807	0.807
Scale			**1:24**	

OPENING BULBOUS BOW

Bulbous bow on large ships lowers the resistance by 10 to 15%. Through opening the bulbous bow this effect would be dispensed with due to radical change in flow pattern round the bow. Additional increase in resistance is obtained due to the increase in head area of underwater section of the hull. Several methods of cutting the bow were tried, but finally transverse cutting to a certain depth on both sides of the bow and two longitudinal cuttings along both sides of plain of symmetry (Fig .1). This method of cutting gave a fixed centre part of the bulb [1] and two large side flaps [2], which could be hinged sidewards to an angle of 110°. The flaps at higher speeds when opened asymmetrically could be used as bow rudders. A side thruster [3] could be fitted in the centre part, which could be used at slow speeds when the bulbous bow is opened. The side flaps of the bulbous bow, when opened to an appropriate angle will increase the effectiveness of the side thruster. In fact at higher speeds a parallel side transfer of the ship could be achieved without changing the course. This happens by opening one bow flap and the stern rudder. Thus powerful side forces are created without any turning moment, giving a side transfer of the whole ship without any protrusion of the stern, what is occurring by rapid turning in order to avoid head collision.

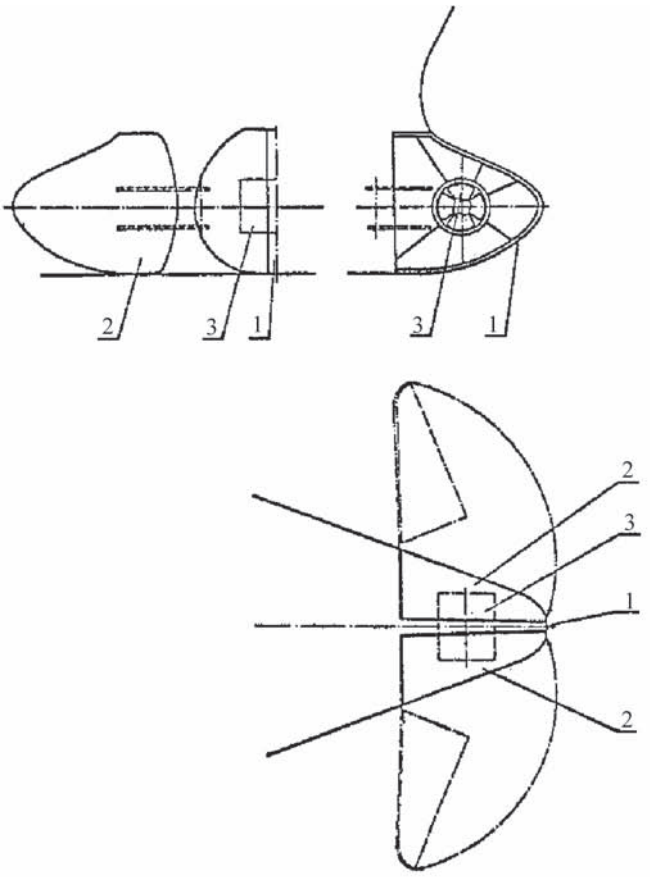

Fig. 1. *Bow cutting of a model for experiments.*

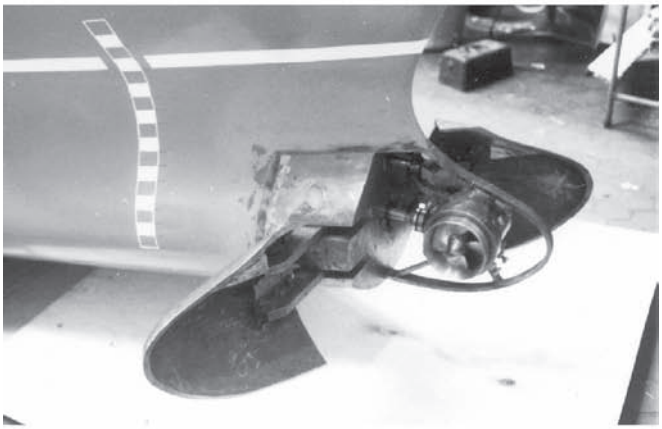

Photo of opened bow.

A very wide series of tests of opening bulbous bow were carried out in a cavitation tunnel. The aim of these tests was to establish the differences in resistance between a closed and opened bulb at different modes of cutting and angles of opening with respect to speed of flow and with regard to positioning the opened flaps in relation to the hull of the ship. These tests were to clarify the impact of following factors :

- area of flaps
- angle of opening of flaps
- width of centre part of bulbous bow
- shape of centre part
- internal stiffeners of the flaps
- proximity of opened flaps from the hull.

The results of these tests gave background to design and to test the opening bulbous bow on large scale self-propelled models of ships given in Tab. 2.

Tab. 2. *Models of ships tested with opening bulbous bows.*

Type of ship	Displacement [m³]	L_{PP} [m]	B [m]	T [m]	Scale
Ro-Ro ship	38150	210.0	30.5	9.50	1:5
OBO ship	123700	236.0	38.7	15.00	1:24
Fishing vessel	322.6	49.5	-	2.20	1:12

The experiments conducted with these models confirmed great effectiveness in lowering service speed without any assistance from the main engine drive. The energy required to open the flaps is extremely low, as the flow of water is forcing the flaps to open and the hydraulic installation is needed for control of their synergetic movement. The flaps could be opened and closed at service speed symmetrically, when braking effect is required, and asymmetrically, when additional turning effect is necessary. At low speeds this device is ineffective for braking the ship and the flaps should be closed, because the wake of the ship running faster than the ship in process of braking, might drive the ship forward meeting opened flaps. Opened bulbous bow at harbour speeds increases the resistance of the ship and thus lowers the dead slow sustained speed, what is of significant importance for safety of harbour manoeuvres. Opened flaps and side thruster fitted in the bulb help the steering at very slow speeds.

STERN END DEVICES

The idea of utilising the force generated by redirecting the propeller wake momentum for braking and steering purposes of ships is not new. The first patents in this field were granted in the final years of XIX century. But these patents were never implemented on any large scale with the exception of jet propulsion applied to small and fast boats. This principle is widely used for braking aeroplanes.

First experiments were carried out with a model of a braking shield in a cavitation tunnel with a test section 0.3 m x 0.3 m. These experiments were to prove that the idea of redirecting the propeller wake momentum by means of a shield was a workable proposition for ships. It has shown many advantages such as :

- braking forces at service speeds, which were induced by the propeller, were approximately twice as big as the propeller thrust forward

- there was no need to reverse the direction of rotation of the propeller and thus no usual losses in power were to be considered. Additional advantage was the elimination of the reversing gear and on turbine ships there was no need to install the reversing turbine
- full course control could be exercised with ordinary rudder during the braking process
- very limited vibrations.

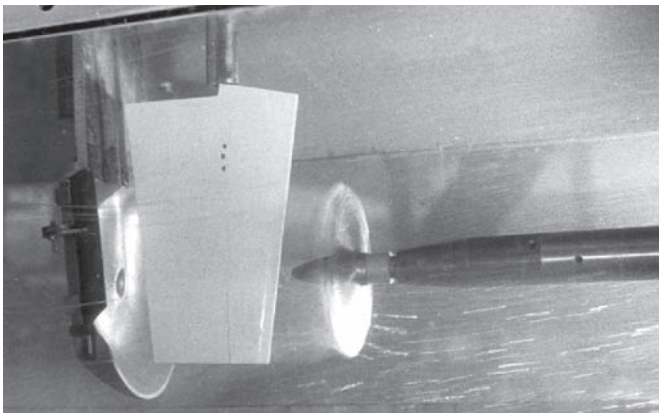

Photo of braking shield ZUH1 in cavitation tunnel.

The results were very encouraging and two devices were invented and a wide programme of research was carried out. These devices were :

- stern shields - two types (ZUH1 and ZUH2)
- steering and braking device – "Doerffer's Rudder" (SUH).

These devices are simple and easy to fit on any type of new or existing ship.

STERN SHIELDS

Two types of stern shields were invented :

- square profile shield (ZUH1) with bottom edge [1] rounded to fit the cross section of stern overhang, in which it is housed (Fig. 2).

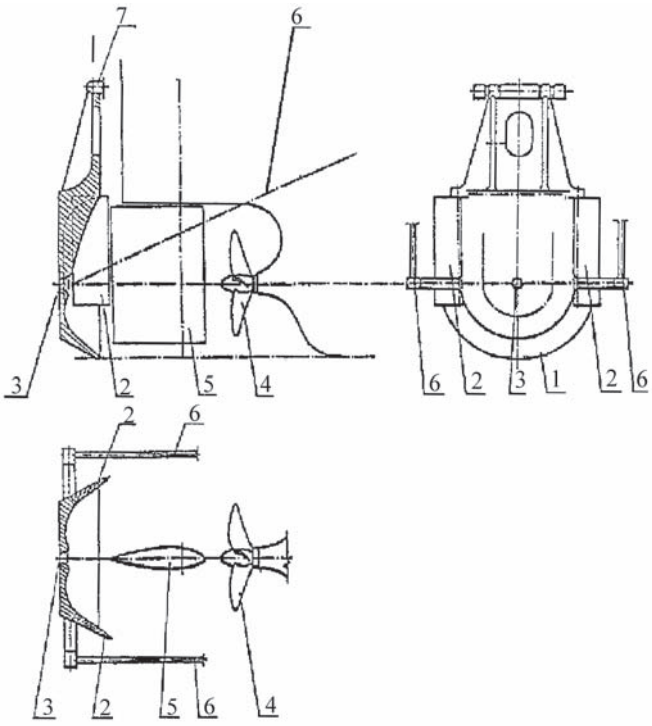

Fig. 2. *Rectangular stern shield ZUH1.*

Two vertical straight side edges are provided with hinged vertical flaps [2] enabling the angle of outflow of propeller wake to be regulated from 0° to 90° for controlling the braking forces and by asymmetrical opening the flaps for creating a side force for auxiliary steering. Top edge is straight with an overhang forward. Shields are placed behind the propeller [4] and the rudder [5]. Thus no major modifications of ship's hull are required. The shield has a three point suspension consisting of two bottom stays of fixed length [6] fastened hinge wise to each vertical edge of the shield and to the ship's hull. Top attachment of the shield consists of one hinged bearing fastened to a sliding crosshead [7].
This mode of attachment allows lowering and lifting the shield by means of hydraulic lifting device within 10 seconds. In stowed position the shield is completely above the water matching the external lines of the ship and thus does not create any resistance.

- circular profile shield (ZUH2) of 190 mm diameter (1.6 x propeller diameter) of simplified design and without flaps (Fig. 3).

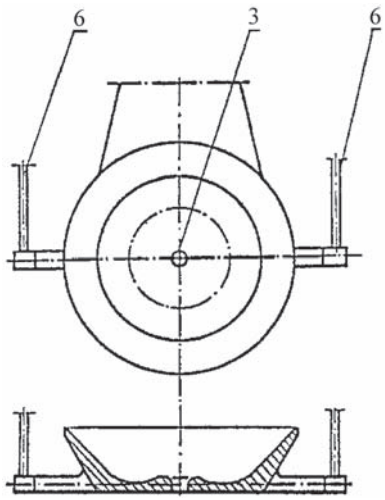

Fig. 3. *Circular stern shield ZUH2.*

Both these devices were tested on the "Panamax" model at a steady propeller speed 750 min^{-1}. The results of these tests show great effectiveness of these devices (Fig. 4 & 5) as compared with inertia braking and propeller reversed at – 375 min^{-1}.

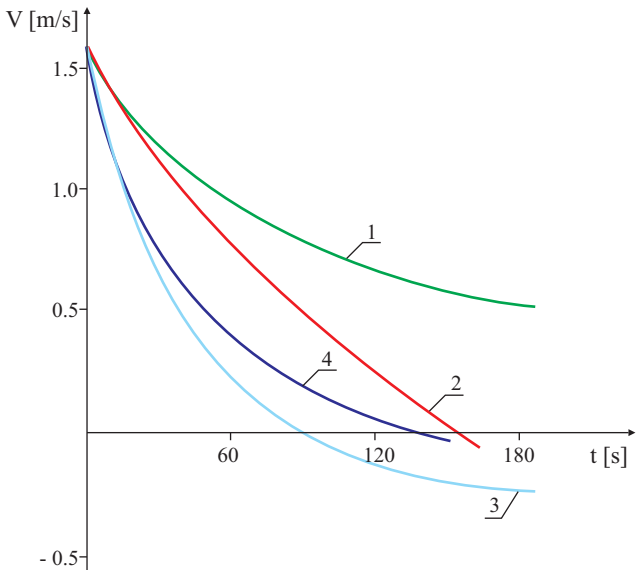

Fig. 4. *Speed versus braking time.* ***1*** *– inertia braking;* ***2*** *– reversing the propeller 375 min^{-1};* ***3*** *– ZUH1;* ***4*** *– ZUH2.*

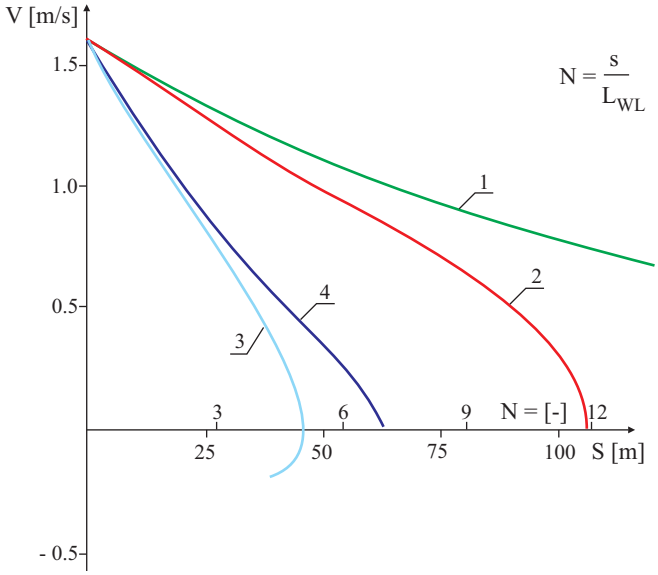

Fig. 5. *Speed versus distance travelled.* ***1*** *– inertia braking;* ***2*** *- reversing the propeller 375 min^{-1};* ***3*** *– ZUH1;* ***4*** *– ZUH2.*

The device ZUH1 shows better effectiveness than ZUH2. The head reach in comparison with the reversed propeller braking (106 m = 11.86 x L_{WL}) is considerably shortened with the stern shield ZUH1 (46.0 m = 5.15 x L_{WL}) and ZUH2 (63.0 m = 7.0 x L_{WL}). When the model comes to a full stop with the shield lowered and the engine continuing to work forward at a steady speed of 375 min^{-1}, the model begins to move aft with increasing speed down to – 0.3 m/s. There is no need to stop and to reverse the engine. The engine is working all the time forward. Full course control is maintained during the whole process of braking and backing by means of ship's conventional rudder.

In order to get independent results of these two braking devices (ZUH1 + opening bulbous bow) tests have been ordered by the Gdansk University of Technology to the Ship Design and Research Centre (CTO) and they were carried out in the towing tank with a self propelled model of a 55000 TDW bulk carrier in scale 1:45.71 (length of the model L_{WL} = 4.618 m; speed of the model = 1.216 m/s equivalent to 16 knots of the ship). The results are shown in Tab. 3.

The above obtained results refer to the model only. Inertia braking distance was shortened by 44.4% with the use of bulb device (test No. 2). Crash stop of a full size ship according to trial report amounted to 1.980 m with a 80° change in course of ship. For the model it was accepted as 41 m (test No. 3). The effect of devices upon the braking distance are shown as results of tests Nos. 4, 5 & 6. The design of the ZUH1 should be improved because large part of the propeller stream was escaping above the shield.

The shield gives an improved manoeuvrability at slow speeds, where balance rudder is not efficient enough or in case of the loss of normal steering equipment for auxiliary steering, as was the case with S/T "Amoco Cadiz".

STEERING AND BRAKING DEVICE - - "DOERFFER'S RUDDER"

Stern shield gave impact to further studies and a new steering & braking device called "Doerffer's Rudder" was invented and developed (Fig. 6). It works at braking on the same basic principle as the stern shield. This rudder consists of a fixed forward part [1] and a swinging after part divided in the plane of symmetry into two blades [2 & 3], which can be swung open independently to on angle of –40° to +110° forming a shield behind the propeller. A vertical flap [4 & 5] is fitted on the trailing edge of each blade. These flaps could

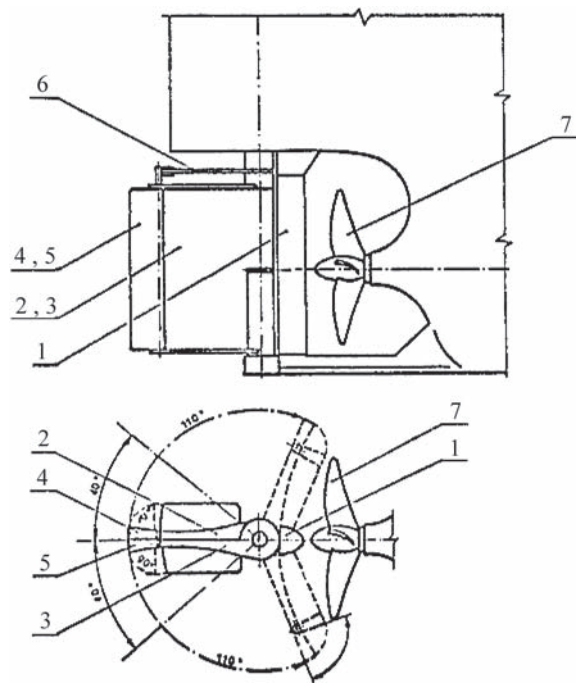

Fig. 6. *Steering and braking device "Doerffer's Rudder" (SUH).*

Tab. 3. *Test results of braking the model of 55000 TDW.*

Test No.	Description of test	Braking distance S [m]	Braking time T_h [s]	Distance decrease [%]	Summary force in stays [kG]	Propeller revolution [s^{-1}]
1	Inertia stopping	115.5	291	-	-	0
2	Inertia braking with bow device	64.2	176	44.4 [1]	-	0
3	Crash stop	41.0	82	-	-	17 forw. 12 revers.
4	Braking with ZUH1	31.6	72	23 [2]	3.8	17
5	Braking with ZUH1 + bow device	28.5	68	30.5 [2]	3.78	17
6	Crash stop + bow device	29.7	67	27.6 [2]	-	17 forw. 12 revers.

Note:
[1] - referred to braking distance in test No. 1
[2] - referred to braking distance in test No. 3

be swung open through an angle from 0° to 90°. As each blade has to be operated independently there are two rudder stocks fitted– an internal and an external one. Each rudder stock is activated by a separate steering engine through a total angle of 150°. The flaps could be activated by a fixed length stays [6] proportionally to the angle of blade opening or independently by hydraulic power hinges.

This type of rudder was fitted on the model of a "Panamax" ship and very thoroughly tested with regards to stopping and steering abilities. A very wide programme has been carried out in order to find optimum angles of opening the blades and flaps and the related braking and turning forces. The following parameters were recorded and the results are presented in Tab. 4 :

- time taken to stop the model [t] seconds
- distance travelled [s] meters
- speed astern [–V] m/sec after 240 seconds with propeller working forward.

Attention is to be drawn to the method of conducting the braking tests. On a stationary model the propeller is reversed to the required speed and only then it is accelerated to the equivalent service speed with the towing carriage. After this speed is reached, the towing carriage is disengaged and the braking process is commenced with "Doerffer's Rudder" the rudder is opened to required angle and the propeller is started forward. The model is accelerated to required speed and only then the towing carriage is disengaged. Thus in these tests no stopping and reversing the engine is simulated and thus the results are better than they would have been on a real ship. With "Doerffer's Rudder" this manoeuvre is very much shorter and once the opening procedure is started the braking process starts right away.

Tab. 4. *Measured test parameters.*

Opening of blades [°]	Opening of flaps [°]	Time taken to stop [s]	Distance travelled		Speed astern after 240 sec.
			S [m]	N = s/L_{WL}	
30	0	-	-	-	-
	30	-	-	-	-
	60	-	-	-	-
60	90	-	-	-	-
	0	-	-	-	-
	30	146	68	7.6	0.20
	60	97	58	6.3	0.35
90	90	115	67	7.5	0.40
	0	92	55	6.1	0.55
	30	63	43	4.8	0.60
	60	77	42	4.7	0.64
	90	90	52	5.8	0.58
100	60	90	47	5.2	0.50
103 110	30	76	42	4.7	0.65
	0	68	44	4.9	0.72
	30	90	50	5.6	0.58
	60	100	51	5.7	0.50

The best results are obtained with blades opened to 90° and flaps opened to 30° and 90°. Increasing the angles beyond these figures is not necessary, because it might complicate full size design. The possibility of obtaining astern speed with propeller running forward is a very positive feature of this device. All the speeds from top speed forward to top speed aft could be obtained by means of opening the blades (Fig. 7). Zero or near zero speeds could be obtained by opening the blades and flaps to angles shown in Table 5. Although the propeller is working at top revolutions the model remains stationary.

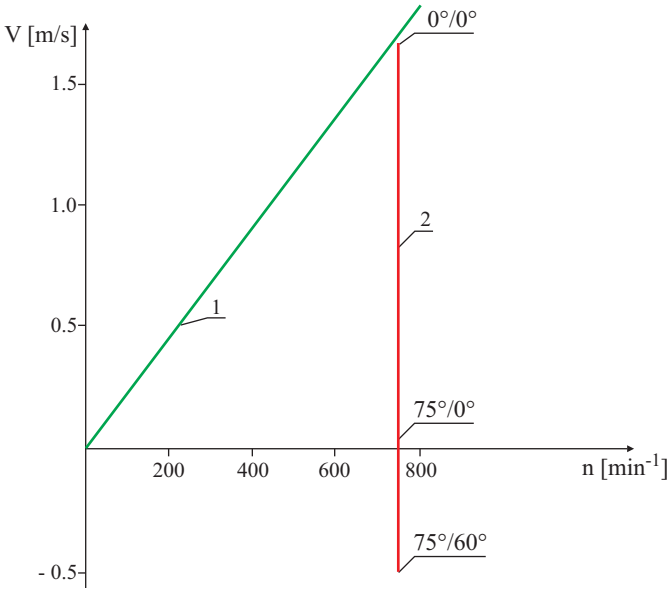

Fig. 7. *Speed of ship versus revolutions forward;* ***1*** *– speed with rudder blocked;* ***2*** *– speed with rudder opening at steady 750 min^{-1} forward.*

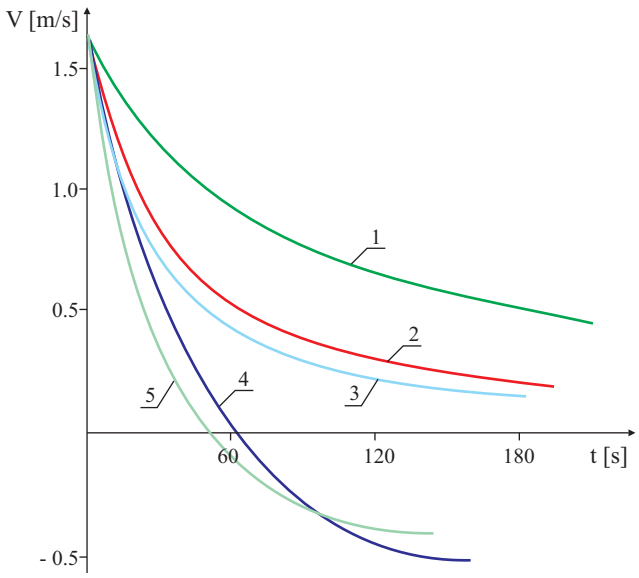

Fig. 8. *Speed versus braking time.* ***1*** *– inertia braking;* ***2*** *– DUH with 50° opening;* ***3*** *– DUH with 110° opening;* ***4*** *– SUH with 90°/30°;* ***5*** *- DUH 70° + SUH 90°/70°.*

Tab. 5. *Angles of blades and flaps opening for zero speeds.*

Angle of blade opening [°]	Angle of flap opening [°]	Speed of model at 750 min^{-1} [m/s]
75	0	0.00
45	60	- 0.04
45	90	+ 0.07

In the towing tank of 12.0 meters width this model (9.2 meters long) has shown excellent manoeuvring abilities carrying out comfortably pullout test and a 180° turn at a speed of 0.6 m/sec. The result of braking the model with "Doerffer's Rudder" only opened to an angle 90°/30° brought the model to a full stop the head reach s = 4.8 x L_{WL} is shown on Fig. 8 & 9 by curve [4]. When at the beginning of braking operation

the bulbous bow is opened simultaneously to 70°, the result is shown by curve [5]. The head reach is reduced to s = 3.2 x L_{WL}. This result compared with inertia braking [1] and with braking by means of reversing the propeller about 12 x L_{WL} is astonishingly good. This means shortening the stopping distance by 60% and when DUH1 is added, by 77.15% with full course control and no side transfer.

The model was showing exceptional manoeuvring abilities. The model managed to manoeuvre out of the avanport of the model tank by its own means (Fig. 10) and to enter the model tank. From position [1] it moved to position [2 & 3] and then swung moving slowly forward to position [4], from which it sailed into open area of model tank.

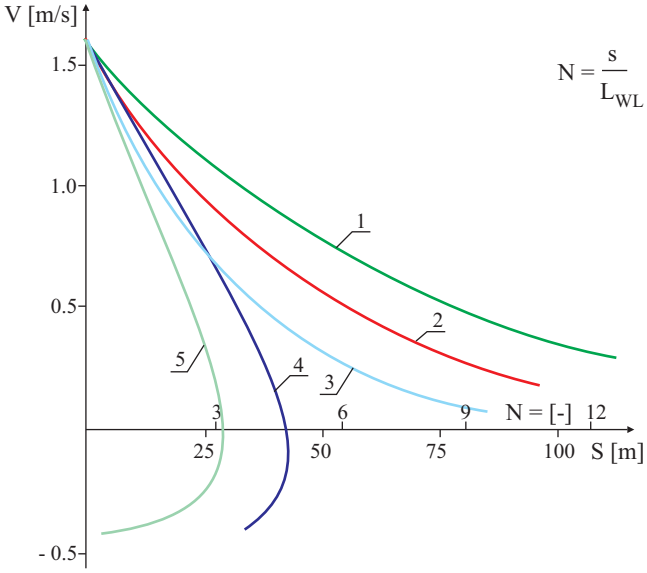

Fig. 9. Speed versus distance travelled.

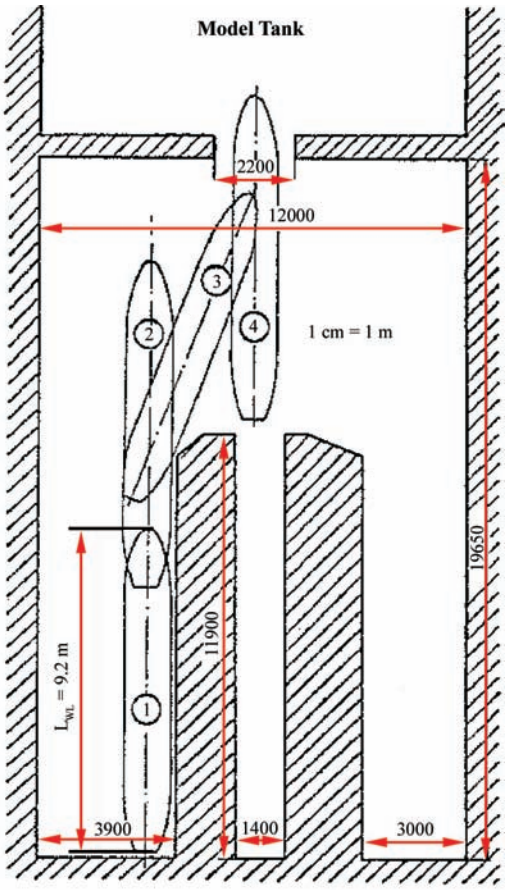

Fig. 10. Panamax model manoeuvring in avanport of model tank.

WAKE PRESSURE EQUALISING DEVICE

It is a well known fact, that the wake behind the ship in the area of propeller disc has different pressures and speeds, originating the vibrations and lowering the efficiency of the propeller. In order to prevent this a device has been invented (Fig. 11), which consists of two water intakes at the bilges [1] joining into one duct [2], supplying water to a pump of 98 mm diameter [3] accelerating this water and delivering it through the slots in upper part of the stern frame [4] into the area of decreased water pressure and speed. The pump has been designed for n = 1.125 min^{-1}, the speed of outflow stream was is 1.14 m/s and output of 8.6 l/s.

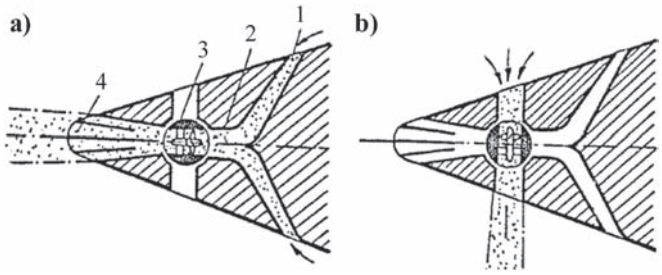

***Fig.11.** Wake pressure equalising device (RUS).*
***a)** - position of equalising and emergency propulsion;*
***b)** – position of stern side thruster.*

The model has been tested with various speeds of the pump n = 450; 900; 1,350 and 1,800 min^{-1}. The measurements of outflow speeds were taken over an arc of ± 40° at V = 0 as well as for V = 1.63 m/s (Fig. 12).

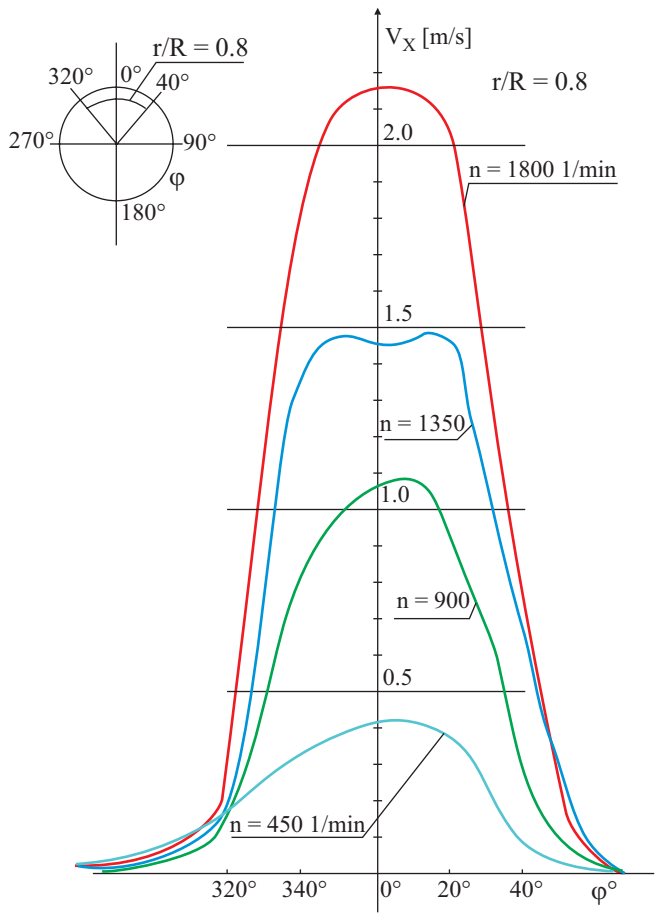

***Fig. 12.** Outflow speeds Vx at a model zero over an arc ± 40° at different pump revolutions.*

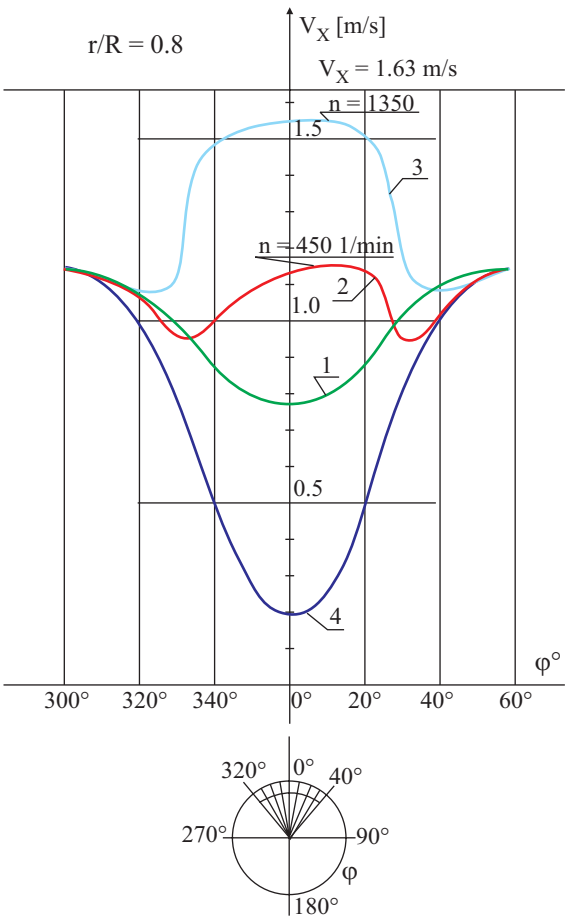

Fig. 13. *Outflow speed Vx at model speed 1.63 m/s over an arc ± 40°.* ***1*** *– pump stopped;* ***2*** *– pump at 900 min^{-1};* ***3*** *– pump at 1350 min^{-1};* ***4*** *– extremely bad design of stern end.*

The speed of water outflow V was measured over an arc ±40° at model speed 1.63 m/s (Fig. 13). Curve [1] shows the speed of water behind the well designed stern frame, curve [2] when the pump is working at 900 min^{-1} and [3] at 1.350 min^{-1}. Curve [4] shows the speed V at the extremely bad design of stern end.

As the pump is housed in a cylindrical casing it can be turned by 90° and used as a stern side thruster. This device could be used as an emergency drive in case of the failure of main propulsive machinery. In this case the pump should be driven by independent diesel generator. In order to take full advantage of this mode of emergency drive, it is necessary to have a free revolving fixed blade propeller or a variable pitch propeller, where the blades could be placed in a fore & aft direction.

CONCLUDING REMARKS

As the results of the tests with "Doerffer's Rudder", carried out in the cavitation tunnel and with models in the towing tank, have shown great merits of this device, it was decided to implement this device on a full size ship and to prove its applicability in real working conditions of a ship. Results of these trials are presented in part II of the paper titled "Doerffer's Rudder" – experience learnt from tests carried out on real ships".

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"Doerffer's Rudder" on mt. "Kolen".

Devices improving the manoeuvrability characteristics of ships

Part II
”Doerffer’s Rudder” – experience learnt from tests carried out on real ships

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ABSTRACT

An account of research activities on the devices improving the manoeuvring abilities carried out at the Gdansk University of Technology were presented in Part I of the paper. Experience from implementation of open rudders on real ships is presented in Part II. Open rudders were fitted on two full size ships: a 1000 BHP harbour tug and a 2500 BHP long line fishing vessel. Designs were made for four types of ships: motor sailing passenger ship “Gwarek” (2 x 1.032 BHP and 1800 m² sail area); arctic expedition sailing ship m/y “Polarex” (length 40,4 m, 1200 BHP); rescue vessel R-27 (two engines à 600 BHP with single propeller); harbour tug m/t “Atlas” (2500 BHP). None of these designs was implemented due to financial difficulties of the owners. Further model experiments with a self propelled model of a cargo liner m/s “Hollandia” exceeding 20 knots were carried out on the lake as well as with a model of a twin screw vessel.

Keywords : the results of tests with „Doerffer’s Rudder”, opening balbous bow, opening rudder, stern shield, steering braking device, braking the ship

INTRODUCTION

The results of tests with “Doerffer’s Rudder” carried out in cavitation tunnel and with models in towing tank have shown great merits of this device. A decision was taken to implement this device on a full size ship and to prove its applicability in real working conditions of a ship. First of all it was necessary to find a ship of very poor manoeuvring characteristics which could be used for the experiments and later on could be returned to service to see the merits of this device in every day life. That ship should have be easily accesible to the designers in order to make some improvements in the design or to carry out any repairs. Our first choice was a 24 years old harbour tug “Achilles” of very low manoeuvring characteristics, which was meant to be scrapped in few years time. In case the new rudder was a failure she could be scrapped with no great loss. The second vessel chosen for installation of “Doerffer’s Rudder” was a deep sea fishing trawler m/t “Kolen”.

HARBOUR TUG “ACHILLES”

The only change that was introduced in the rudder of “Achilles” was the limitation of angles of opening of blades from +110°/-40° to +75°/-25°. For conventional steering the rudder blades could be blocked and activated with one power unit and for braking they should be opened symmetrically to an angle of 75°. When the rudder blades were opened to an angle of 48° the resultant thrust i.e. the difference between the propeller forward thrust and the force induced by the propeller wake on the opened rudder was equal to zero. Decreasing this angle below 48° gives a gently increasing resultant force forward, while increasing this angle above 48° gives the resultant force acting aft and the ship begins to move aft. This gives a possibility to start the main engine with the rudder opened to an angle of 48° and to obtain half or full revolutions ahead, while the ship is moored at the dock side.

The steering column contains two hand levers for setting the desired angle of opening of each blade and there are two pointers indicating the actual position of each blade. Two steering systems are provided :

- ⇨ a follow-up system, automatically setting the blade to the desired angle as indicated by the position of the lever
- ⇨ a press button system, activating respective power unit of a steering engine in required direction as long as the button is being pressed.

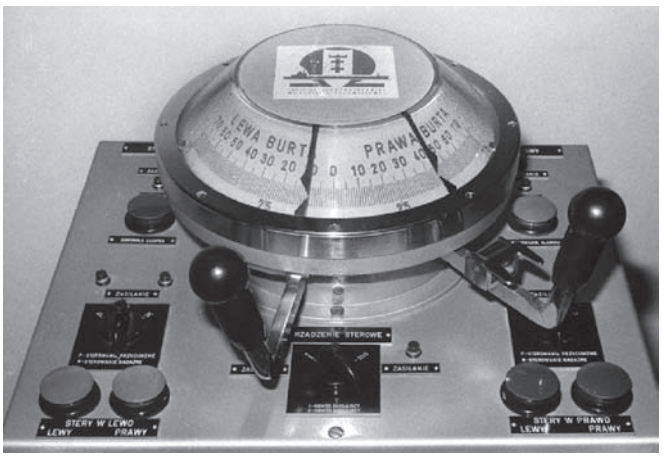

Fig.1. *Photo of “Achilles” steering column.*

Normally the first system is being used and the second system is considered as an emergency procedure. An additional emergency hand steering system is provided.

The results of tests have shown the following results :

- ✦ The speed of the ship has been slightly increased – service speed increased from 10.23 knots to 10.46 knots (curve [1] to curve [2] – Fig. 2). There exists a possibility of continuous regulation of speed from maximum forward to maximum

astern with constant revolutions forward of the main engine through varying the angle of opening the blades (curve [3]), what is done by the skipper from the bridge. At the angle of 48° of opening the blades the resultant force is zero and the ship remains stationary despite the main engine working at full revolutions forward

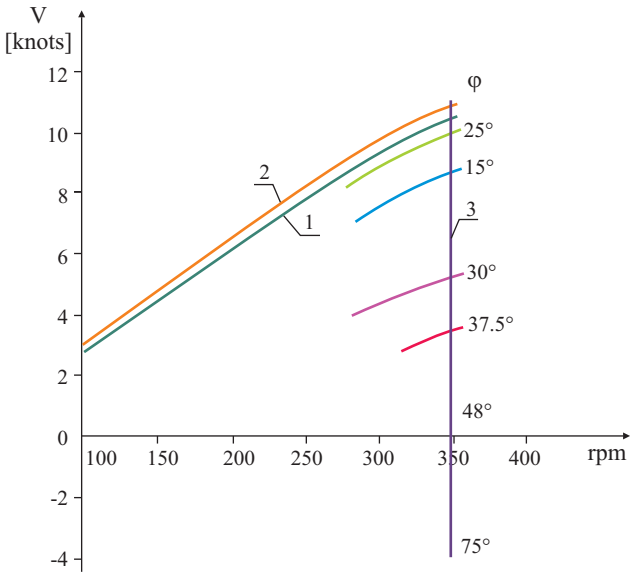

Fig. 2. Speed versus revolutions of "Achilles" main engine.

- turning ability with blocked blades and activated by one steering power unit to 25° P & S at full, half and slow speeds has shown slightly larger diameters of circulation, this being due to higher initial speed of the ship. When a smaller diameter of circulation was required than the blades should be freed and larger angles applied. The ship is capable of rotating in place around her bow when one blade is opened to 75° and the other one to 25° in the same direction, making one full turn within 80 seconds
- stopping test has been carried out with blocked rudder blades by reversing the propeller and with rudder blades opening to an angle 75°/75°. The stopping distance was 145 m as against 198 m what means shortening of stopping distance by 36.5 %
- bollard pull forward (Fig. 3) has increased by 15% with the new rudder [2] and astern pull with reversed engine by 20% [5]. With opened angle 75°/75° and the engine running forward the astern pull [5] amounted to 4 tons (about 80% of pull with balanced rudder and reversed revolutions of main engine)

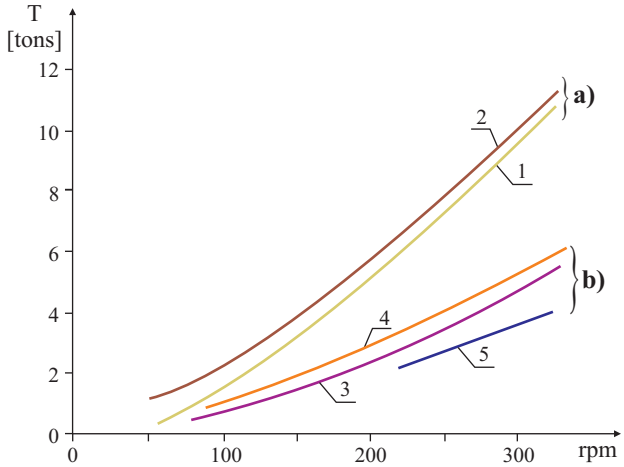

Fig. 3. Bollard pull forward and astern of "Achilles".

- transverse thrust at zero speed could be easily obtained by appropriate opening the rudder blades. By asymmetric opening the rudder blades to angle 45°/-20°at 350 rpm a very powerful transverse thrust was created up to 7.0 tons through the propeller stream emerging to one side only. Thus the rudder can act as a powerful stern side thruster
- the reliability of all the manoeuvres is enhanced with the engine running all the time without stopping and reversing/restarting the main engine
- no vibrations during stopping ad astern running
- cheaper maintenance of main engine due to running under steady parameters.

Opening rudder has shown many advantages in full size application. It has shown that it could be easily applied on existing ships and radically change manoeuvring characteristics. The only disadvantage was the increase of daily fuel consumption. This was due to running the engine all the time even when waiting at the dock side. The tug was working successfully for several years, but finally had to be scrapped due to corrosion of the hull.

The above results are spectacular and this is because of the very high ratio of installed main engine power to displacement of this harbour tug which is equal to 4.0. Dry cargo ships have generally this ratio not exceeding 0.3 and some large tankers have even below 0.1. As the effects of this rudder are connected with this ratio, the application of "Doerffer's Rudder" on such vessels will give very good results but not as spectacular. Apart from considerable improvement in manoeuvring characteristics of large dry cargo ships and tankers there should be considerable fuel savings, reliability of main engine installation should be improved, maintenance costs should be lowered and break down limited.

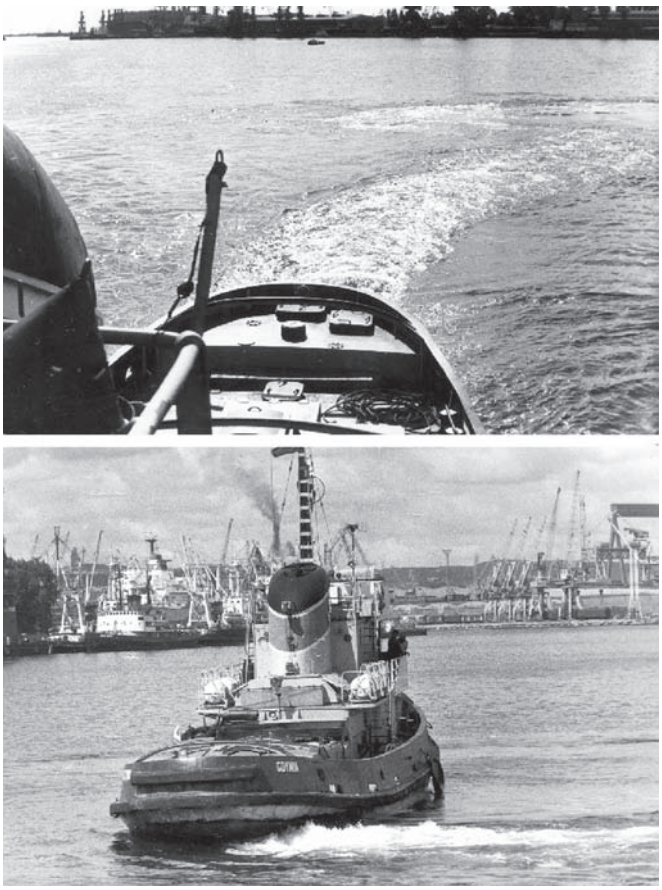

Fig. 4. Photo of Tug "Achilles" showing her manoeuvring ability and producing transverse force.

FISHING TRAWLER M/T "KOLEN" AND OTHER PROJECTS

The second vessel chosen for installation of "Doerffer's Rudder" was a deep sea fishing trawler m/t "Kolen" which had to be adapted for long line fishing. For this method of fishing smaller vessels were being used, generally not exceeding 50 m length with very good manoeuvrability. But m/t "Kolen" was 75.5 m long and the main engine was 2500 BHP (Fig. 5).

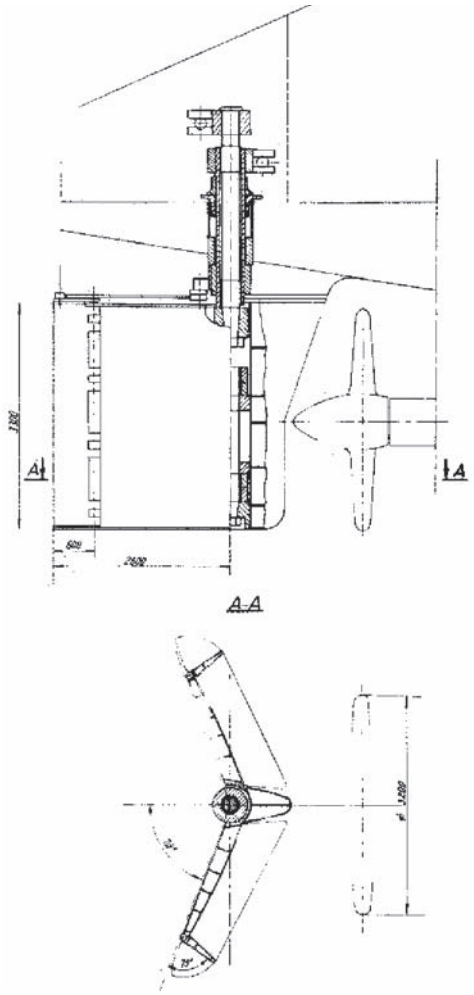

Fig.5. Stern frame and opening rudder of m/t "Koleń".

The stern frame had no heel supporting the rudder at its bottom end. So a special rudder front support had to be designed and built into the ship structure with a possibility of dismantling this bottom part in order to make the propeller and tail shaft dismantling possible for repairs. The ship with after being equipped opening rudder, demonstrated excellent manoeuvring characteristics and it was working successfully on the Atlantic.

There were also ship owners of special purpose ships who ordered the designs of opening rudder for their ships – the ships were :

- ★ motor sailing passenger ship s/y "Gwarek" (212 passengers, 1800 m² sail area, length 99 m, main engines 2 x 1032 BHP) (Fig. 6). The ship has been fully fitted with opening rudder, but before final completion the owner declared bankruptcy and after some years a Swedish owner bought that uncompleted vessel, lengthened her and completed as a luxury sailing ship. He demanded to have a well known simple balance rudder because of the high underwriting costs in case having a rudder of unknown type.

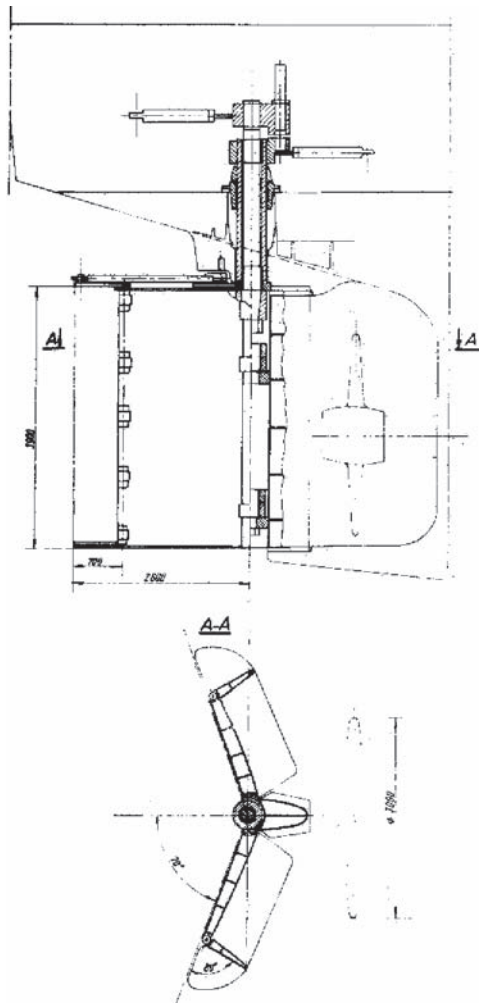

Fig.6. Stern frame and opening rudder s/y "Gwarek".

- ★ arctic expedition sailing ship m/y "Polarex" (length 40,4 m, 1200 BHP). Design has been completed, but again the owner declared bankruptcy after the launching of the ship. The hull has bought by Maritime Academy in Gdynia, the ship has been lengthened and completed as a training vessel. It should be mentioned that before the design was made extensive ice braking trails were made with the tug "Achilles", which have shown exceptional ice breaking abilities. These were due to very high transverse side thrust obtained with opened rudder which could be easily obtained by opening the rudder several times to P and then to S. Powerful transverse force one after the other acted in the similar way as the carpenter trying to free the wedge not by pulling it out but by several knocks from the side. The emerging wake cleared the water from ice floes.
- ★ Polish Salvage Company had four rescue vessels R-27. These ships had two 600 BHP diesel engines working through reduction gearing on one propeller. The gearing was of very complicated design and was easily breaking down. This was unacceptable for a rescue vessel. Thus we were asked to design an opening rudder which would allow simplifying the reduction gearing and improving the manoeuvring characteristics of the ship. The design was completed, but the owners got a possibility of replacing the old reduction gearing by a new one and they have decided to purchase the gearing. And thus our design was not implemented.

SHIPS WITH SPEED ABOVE 20 KNOTS

Despite all the difficulties we had in full size implementation of opening rudder we continued our research on application of this rudder on ships with speeds above 20 knots. First question asked by any owner was the problem of increase in resistance of the ship due to new type of the rudder and possible increase in power requirement to maintain the speed before new rudder was fitted. The second question concerned the benefit from increased manoeuvrability. In order to answer these two questions we had to carry out several trials with radio controlled self propelled large scale models in model tank as well as on a lake at Joniny (Wdzydze Lake). These trials gave encouraging results, but it's difficult to state whether model tests will be fully confirmed by a full size implementation. They can be treated as an indication that we are on the right way but the actual values obtained with a ship may differ from the values obtained on a ship model. After long discussions, the open water trajectory experiments were carried out on the lake at Joniny with a model of a containership m/s "Hollandia" of dimensions given in Tab. 6.

Trajectories of circulation were worked out for initial speed of 1.93 m/s, and different angles of opening 70°/-40°; 70°/-25° and 45°/-25°. For initial speeds 1.50 m/s and 0.00 m/s only one opening of blades was experimented with (Fig. 7).

Tab. 6. *Containership m/s "Hollandia".*

Item			Ship	Model
Length between perpendiculars	L_{PP}	[m]	193.10	6.4367
Length on waterline	L_{WL}	[m]	196.78	6.5593
Breadth	B	[m]	30.80	1.0267
Draft: Forward	T_F	[m]	9.20	0.3067
Aft	T_A	[m]	9.20	0.3067
Displacement		[m³]	32211	1.193
Wetted Surface		[m²]	6566	7.2957
Block coefficient CB			0.589	
Model Scale			**1:30**	

Trajectories of braking the ship model were worked out for three initial speeds of the model: 1.50 m/s, 1.00 m/s and 0.00 m/s and for three different angles of rudder symmetrical opening: 50°/50°; 65°/65° and 80°/80°. From Fig. 8 it can be seen that the model running with initial speed 1.50 m/s with rudder blades opened to 80°/80° after 30 seconds looses its forward speed, begins to move astern and looses control of the course.

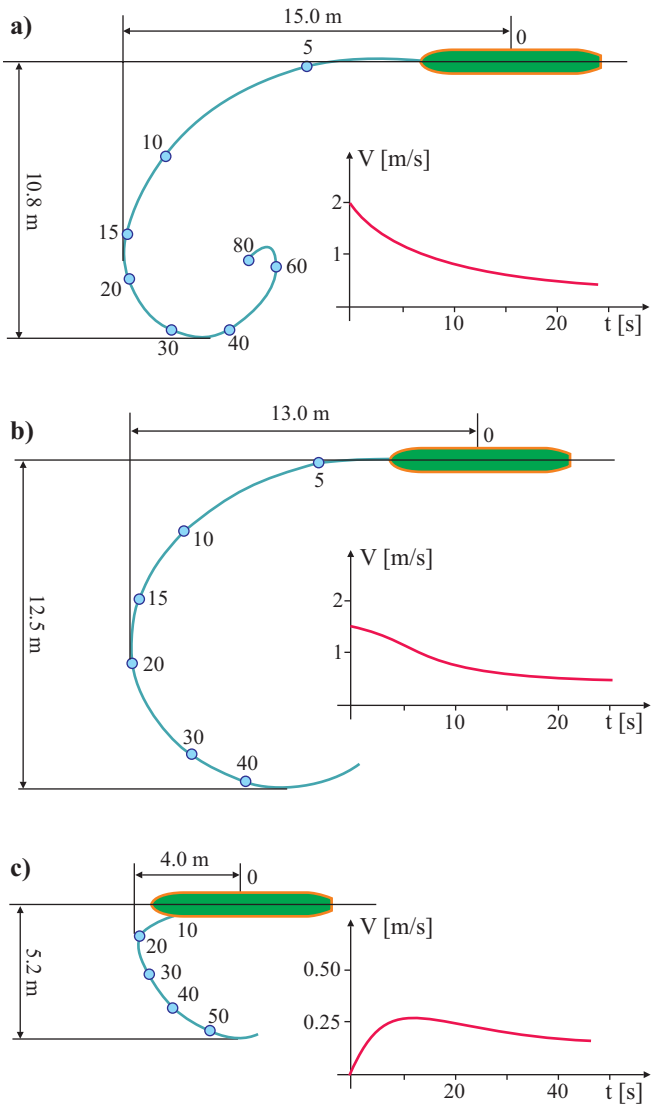

Fig. 7. *Trajectories of circulation for initial model speed:* ***a)*** *1.93 m/s,* ***b)*** *1.50 m/s and* ***c)*** *0.00 m/s and one angle of opening the blades: 70°/-40°.*

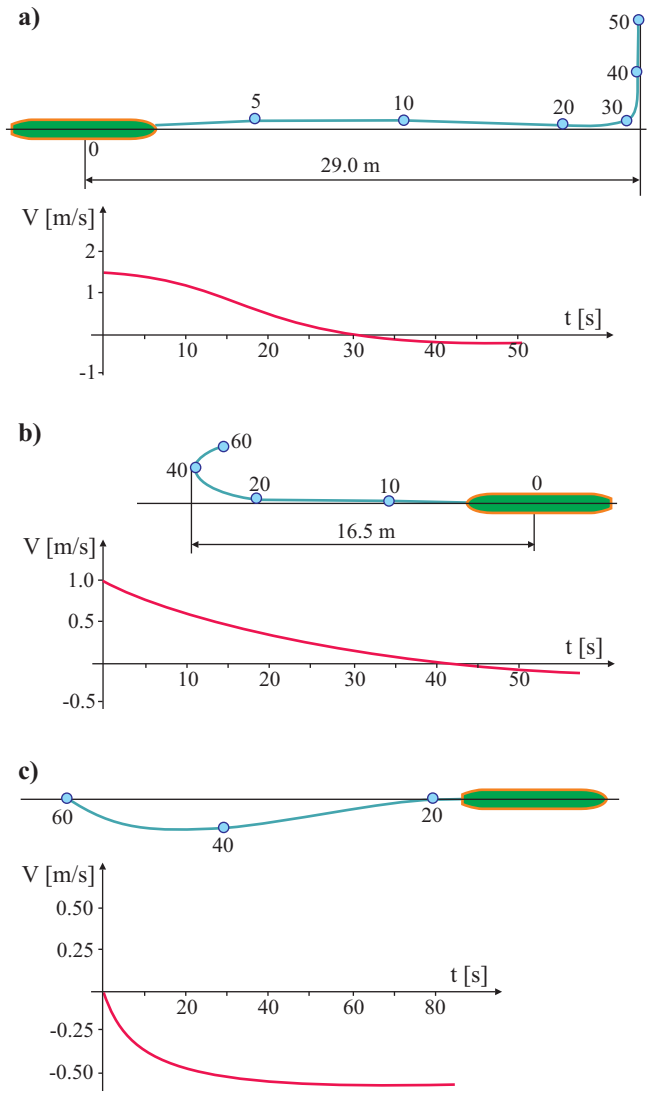

Fig. 8. *Trajectories of braking the ship model with initial speeds of model:* ***a)*** *1.50 m/s,* ***b)*** *1.00 m/s and* ***c)*** *0.00 m/s and for one angle of rudder symmetrical opening 80°/80°.*

TWIN SCREW SHIPS

For the purpose of testing a twin screw ship, existing model was used and was fitted with two balance rudders and alternately with two "Doerffer's Rudders". It was a model of a ship of length L_{WL} = 148.85 m in scale 1:20. The resistance tests have shown that the model fitted with two "Doerffer's Rudders" had at the speed of 16 knots an increase in resistance by 6.5% as compared with ordinary balance rudders which lowered the service speed by 0.5 knot. But these rudders improved the manoeuvrability especially at low and harbour speeds. Opening of rudder blades and flaps and both propellers working forward created an astern pull amounting to about 40% of forward thrust at service speed. This fact allowed to reach the astern speed amounting to about 35% the astern speed with reversed propellers i. e. about 5 knots with both propellers working forward. This astern thrust allows the shortening of braking distance with a full course control by 35%. When the blades and flaps are opened to appropriate angles the ship circulates with a zero diameter of circulation.

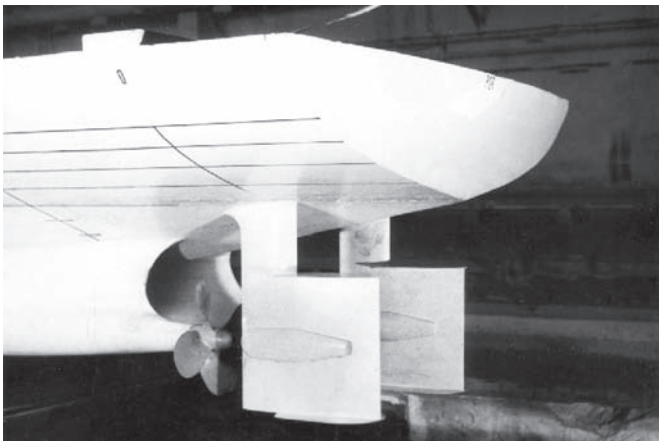

Fig. 9. *Photo of tween screw stern model*

These tests have clearly shown that the owner has to make a choice between the service speed and manoeuvrability, based on what is more economical for him. Poor manoeuvrability may mean hiring the tugs at each harbour entrance, losses in time waiting for tugs or weather to improve. Slower steaming by 0.5 knot may be of no great importance.

CONCLUDING REMARKS

The results of the model tests with "Doerffer's Rudder" carried out in the cavitation tunnel and in the towing tank have demonstrated significant and multiple positive effects of the device on manoeuvrability characteristics of ships.

Full size ship trials performed on real vessels – a harbour tug and a fishing trawler – confirmed the model test results in real working conditions.

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Abilities of contemporary tugboats, photo: Cezary Spigarski

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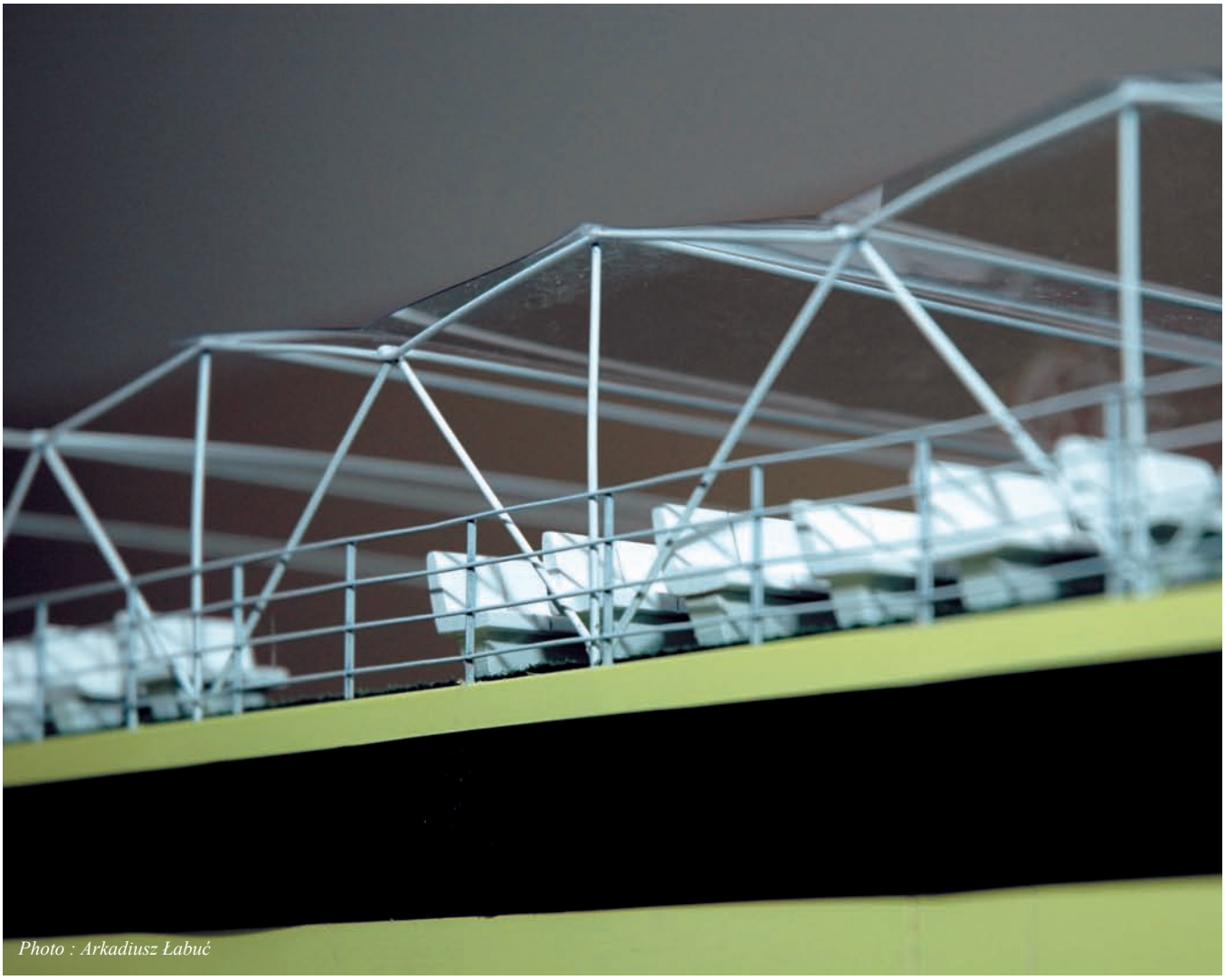

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