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Technical requirements for inland navigation ships to transport compressed natural gas

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Abstract: One of the most important aspects in inland waterway transport is to deal with the issues of construction both transport and entire transportation systems. According to the Inland Navigation Offices in Poland, in the period 2001–2014, there were 350 accidents on national inland waterways. The main reasons for them are: human factor, hydrological conditions, and technical faults. The main effects of the accidents include hull damage caused by collisions and ship grounding.
In order to prevent shipping accidents, the European Union countries worked out procedures for tightening the technical requirements for vessels, especially for the vessels carrying dangerous goods, including compressed natural gas (CNG).
In this paper, the authors analyzed the approach to ship design, and proposed the research methods that can be used in order to eliminate the risk of extreme situations in inland waterway shipping.
At the stage of determining the initial technical assumptions, transport tasks should be specified which include the supply of CNG, analysis of similar vessels data, and preparation of the list of requirements regarding the selection of parameters and main dimensions of vessels. The selection of parameters and the main dimensions are usually made on the basis of the studies results of existing vessels. The results of the analysis concerning operating parameters of inland waterways are obtained by using statistical methods. Generally, researches are concerned with defining the main dimensions of inland vessels, block coefficient, main engine power, the masses of the ship, and their displacement. The probability of the damage to the ship's hull during CNG tanks transport on the fairway can be estimated on the basis of the likelihood of an emergency.
While analyzing the factors affecting the size of the Net Present Value (NPV), methods, investment growth, and the pricing principles traditionally provided in transport services should be taken into account. The amount of the estimated costs of compensation for the analyzed transport system primarily depend on the reliability of units used to transport CNG tanks and the area of providing services.

Introduction

In inland waterway transport, one of the most important aspects connected with the construction issues of means of transport and entire transport system is to guarantee safety during transport services.

According to the data of Office of Inland Navigation Authority in the years 2001–2014, there were 350 accidents at the national inland waterways (*Diagnoza polskiego...* 2011; GUS 2014). The main reasons of these accidents are human factor, hydrological conditions, and technical defects (Fig. 1), while the main effects are hull accidents related to collision and grounding (*Diagnoza polskiego...*; Semenov 1997).

In view of the consequences of accidents in inland waterway transport (heavy casualties, the environmental pollution), the tendency has been observed in Europe towards the accurate control of inland vessels technical conditions regardless of the national shipping traditions and representing flag.

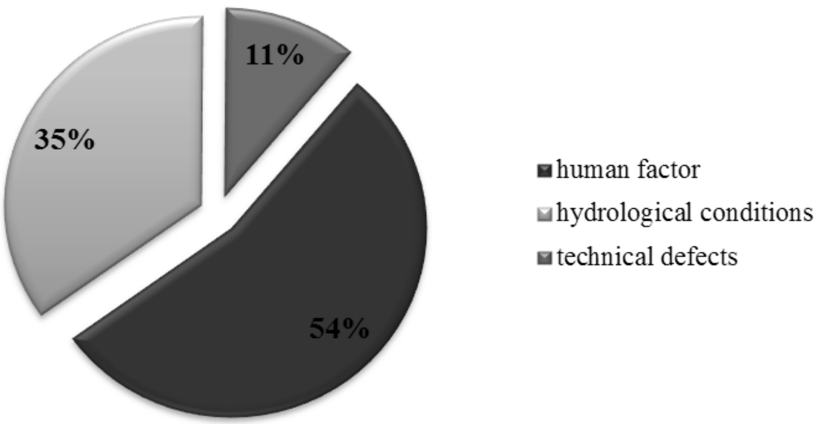


Fig. 1. The reasons of accidents in inland waterway transport

Source: own elboration based on *Diagnoza polskiego...*

In the preparation of a new vessel concept, a significant aspect is to assess the rationality of design, which takes into account:

- transport capacity, which depends on the deadweight, loading volume, and the speed of the vessel;
- functional safety, which depends on the vessel's properties (including stability, unsinkability, strength, resistance, propulsion, and maneuvering qualities); and
- operating costs and profitability of CNG supply by water.

1. Transport capacity

Due to the significant risk that may be caused by hull damage of the vessel which carries dangerous goods, including CNG tanks, specific spatial layout of the vessel is strongly required.

In order to protect the hull against damage, the following solutions are used:

- double shell plating, particularly in dangerous cargoes transportation, and
- a stowage planning system in conformity with stability and freeboard requirements.

It is worth to consider that high costs connected with the installation of double hulls by Western European shipowners not only improve the transport safety, but also affect vessels' capacity. For instance, between 2005–2012, Western European tanker fleet increased its capacity on average by 38% (*Market observation...*).

The cargo hold capacity of inland vessel adapted to CNG tanks transport can be evaluated by the following equation:

$$W = C_B \times L \times \left(B - 2\,B_k\right)\left(H - H_k\right) \tag{1}$$

where:

C_B – block coefficient inland hull of the ship,
W – collection of batch input in each supply chain,
L – the length of the hull of an inland vessel,
B, H, – width, height of the hull of an inland vessel, respectively.

The safety level of an inland vessel is affected by the height of a double bottom (H_k) and the distance between outer and internal broadsides (B_k). Enlarging of the above-mentioned parameters affect the limitation of cargo space, transport capability, as well as CNG cost-effectiveness and the increasing safety level of a vessel.

2. Functional safety

The possibility of inland vessel's hull damage during CNG tanks transport on the fairway and economic loss as a result of this accident may be evaluated by the probability of extreme situation occurrence:

$$P\left[A \geq B_k\left(H_k\right)\right] > 0 \tag{2}$$

The probability of extreme situation occurrence $P[A \geq B_k(H_k)]$ may be calculated in two different ways [6]:

$$\text{I.}\quad P[A \geq B_k(H_k)] = \int_{A=B_k(H_k)}^{A=B(H)} P(A)\,dA \tag{3}$$

$$\text{II.}\quad P[A \geq B_k(H_k)] = \int_{0}^{A=B(H)} P(A)\,dA - \int_{0}^{A=B_k(H_k)} P(A)\,dA = 1 - P(A) \tag{4}$$

where:
P(A) –a probability of avoiding extreme situation, which means $A < B_k(H_k)$.

The probability of the vessels' hull damage which arose as a result of the collision that took place between 1960–2010 is shown in Table 1.

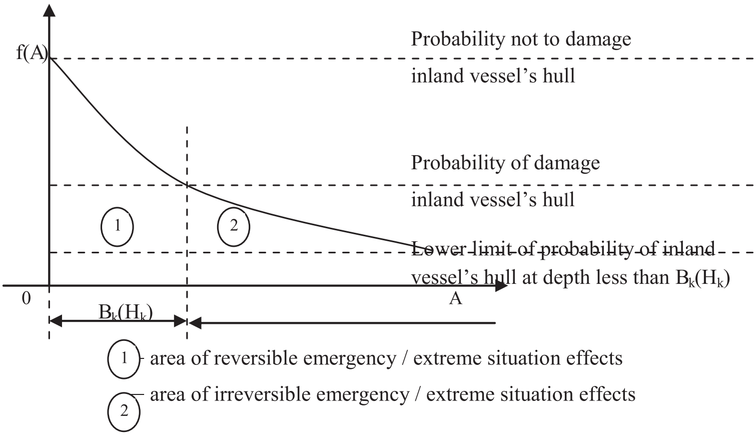
Table 1. Probability of CNG vessels' hull damage

	The probability of hull's damage depths										
***L*, м**	**0 – 0.5**	**0.5 – 1**	**1 – 1.5**	**1.5 – 2**	**2 – 3**	**3 – 4**	**4 – 6**	**6 – 8**	**8 – 10**	**10 – 15**	**Sum**
Up to 50	0.30	0.22	0.10	0.20	0.08	0.07	0.03	–	–	–	1.0
50–70	0.28	0.20	0.06	0.20	0.12	0.06	0.04	0.04	–	–	1.0
70–90	0.23	0.16	0.12	0.10	0.14	0.10	0.09	0.02	0.02	0.02	1.0
90–110	0.20	0.16	0.10	0.08	0.06	0.12	0.10	0.10	0.06	0.02	1.0
110–130	0.19	0.13	0.09	0.08	0.06	0.04	0.17	0.12	0.07	0.05	1.0
130–150	0.17	0.12	0.08	0.07	0.06	0.13	0.21	0.09	0.05	0.02	1.0
150–170	0.15	0.11	0.07	0.06	0.12	0.10	0.16	0.12	0.06	0.05	1.0
170	0.12	0.10	0.06	0.05	0.05	0.12	0.15	0.15	0.10	0.10	1.0

Source: own elaboration based on Lausen (2000) and *The Annual Report*.

Effective reduction of adverse effects during the exploitation of an inland ship is only possible with a system approach for the operation. Due to the large number of emergency situations, an increasingly important role is played by compensation funds.

The depth of inland vessel's hull damage is illustrated by distribution *f(A)*, as shown in Fig. 2.



where:
H_k – a height of inland vessel's double bottom,
B_k – the distance between inland vessel's outer and internal broadsides,
A – dimensionless acceleration of hull of an inland vessel.

Fig. 2. Probability distribution f(A) of damage depth in the hull of an inland vessel (A) adapted to CNG tanks transport

Source: own elaboration based on Semenov (2004).

Even light damage of an inland vessel's broadside at the level of waterline may cause heavy losses, such as tweendecks flooding or loss of stability, which can lead to environmental pollution.

Losses caused by hull damage, resulting in environmental pollution, may be evaluated by Y_1 quantity, then the risk of these losses per year of the operation of an inland vessel may be determined by the following equation:

$$R = P_0\left[1 - P(A)\right]\left[P_d\, Y_d + (1 - P_d)\, Y_1\, k_a\right] \tag{5}$$

where:
P_0 –a probability of inland vessel's hull damage within a year,
Y_d –an economic loss caused by sinking of inland vessel,
P_d –a probability of inland vessel's sinking according to the condition $A > B_k(H_k)$,
k_a –a coefficient of economic losses as a result of damage of two or more cargo compartments.

The increase of vessel's safety level within k year range of the operation of an inland vessel equals:

$$PR_k = PR - R = PR_0\left[1 - \frac{C_B \times L \times (B - 2B_k)(H - H_k)}{C_B \times L \times B \times H}\right] - \\ - P_0[1 - P(A)][P_d Y_d + (1 - P_d)Y_1 k_a], \tag{6}$$

Determining of the overall effect of increasing an inland vessel's safety:

$$PR_S = \sum_{k \in K} PR_k. \tag{7}$$

3. Operating costs and profitability

The annual income obtained from operating an inland vessel adapted to CNG tanks transport can be determined by the following equation:

1. PR_0 – assuming that $B_k = H_k = 0,$
2. PR – assuming that $B_k \neq 0$ and $H_k \neq 0,$ then:

$$PR = PR_0\left[1 - \frac{C_B \times L \times (B - 2B_k)(H - H_k)}{C_B \times L \times B \times H}\right] \tag{8}$$

Due to numerous extreme situations, the role of compensatory funds, which are used by ship owners to secure vessels, is more significant nowadays. It is assumed that during an operation process of an inland vessel, the necessity of indemnity may occur at least once. Therefore, it is purposive to invest in safety systems which allow to rationalize the size of fund according to the expenses minimization criterion for the compensation of possible accidents' effects during CNG tanks transport. The criterion may be determined by the following equation (Semenov, 2004):

$$\Delta S(C) = \sum_{i=1}^{m} \Delta P_i Y_i \to \min \tag{9}$$

where:

Y_i –a loss as a result of *i*-type accident,

ΔP_i –a change of probability of *i*-type accident,

m –a number of possible accident types accompanied by the environmental pollution.

4. Conceptual design process

The process begins with the analysis of demand for gas, the selection of internal gas distribution directions, and assessment of the advisability of such supplies. This information is necessary for defining transport tasks.

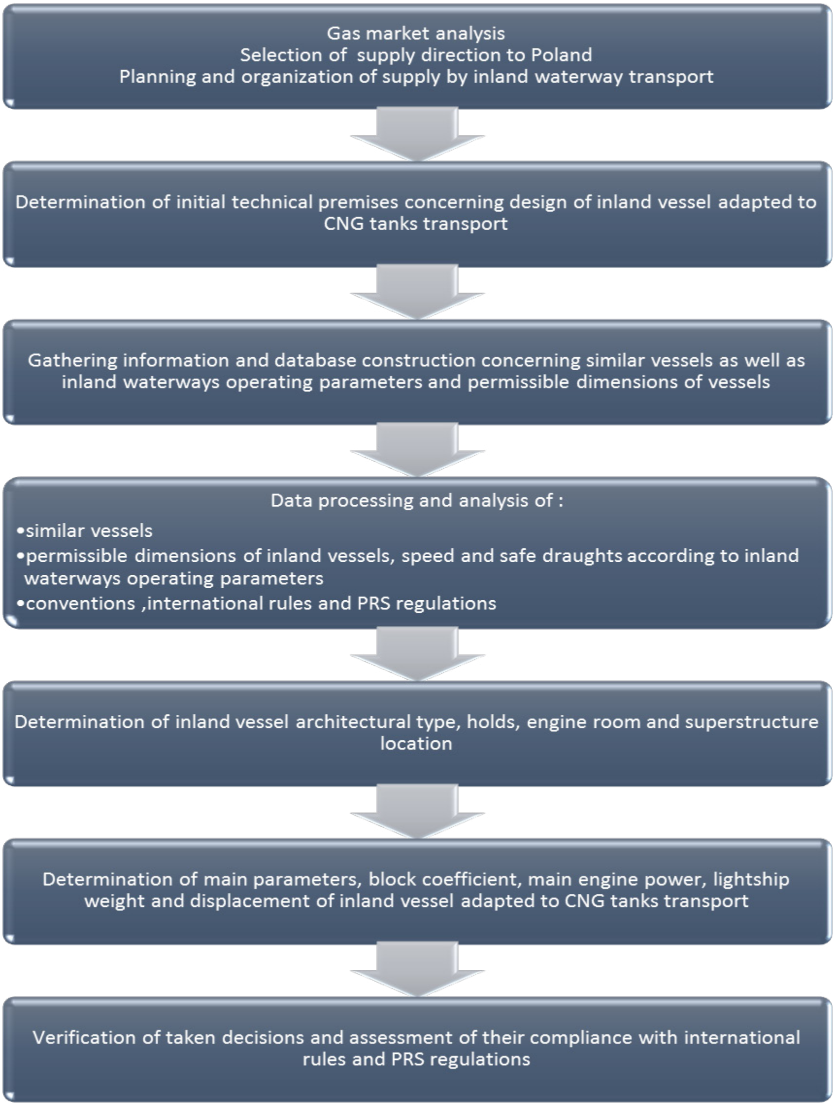


Fig. 3. Flowchart of a conceptual designing process of an inland vessel adapted to CNG tanks transport

Source: own elaboration.

Fig. 4. Initial design premises of an inland vessel adapted to CNG transport tanks

Source: own elaboration.

At a stage of determining the initial technical assumptions, transport tasks should be specified. They consist in deliveries of containers with CNG tanks, considering the navigation restrictions on supply routes. Additionally, data analysis should also be made, including the analysis of similar vessels' data, as well as a list of requirements concerning the selection of parameters and vessel's main dimensions should be drawn up at this stage.

The selection of parameters and main dimensions is usually performed on the basis of studies results of existing similar vessels and analysis results of inland waterways operating parameters obtained by using statistical methods. Most often, studies concern the determination of inland vessel's main dimensions, block coefficient, main engine power, lightship weight, and her displacement. In addition to this, a vessel architectural type, holds, an engine room, and a superstructure location are defined.

For the purposes of design, numerous data bases are made and used.

The creation of many data bases is caused by the need to take into account both the size of cargo batches consolidated according to the orders of CNG consumers and the parameters of Odra River waterway linear and spot elements.

The following parameters were taken into consideration:

- inland waterways and approach fairways to selected inland ports,
- technical and operational descriptions of river hydro-technical constructions,
- vessels' draughts enabling a safe entrance to the selected ports, and
- permissible speed of vessels on specific sections on Odra River.

The flowchart of a conceptual designing process of an inland vessel adapted to CNG tanks transport and initial design premises of an inland vessel adapted to CNG transport tanks are presented in Fig. 3 and 4.

Conclusions

1. Functional safety in the assessment of vessel design rationality may be evaluated on the basis of extreme situation occurrence probability.
2. The size of compensation funds, whose existing is substantiated by numerous extreme situations, must be taken into consideration while analysing the operating costs and profitability during the assessment of vessel design rationality.
3. The creation of a conceptual design of an inland vessel adapted to transport CNG, should contain the analysis of the possibilities of waterway gas transport market, as well as the analysis of similar vessels' parameters and operating requirements of inland waterways for the appointed sailing area.

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WYMAGANIA TECHNICZNE STATKÓW ŚRÓDLĄDOWYCH DO PRZEWOZU GAZU NATURALNEGO W POSTACI SPRĘŻONEJ

Słowa kluczowe: statki śródlądowe, projektowanie statku, CNG

Streszczenie: W żegludze śródlądowej, jednym z najważniejszych aspektów w jakich rozpatruje się zagadnienia budowy zarówno środków transportu jak i całych systemów transportowych jest zapewnienie bezpieczeństwa podczas wykonywania usług.
Ze względu na szczególne zagrożenie jakie może spowodować uszkodzenie kadłuba jednostki przewożącej ładunki niebezpieczne, do jakich zaliczane są zbiorniki z CNG, wymagane jest określone rozplanowanie przestrzenne statku.
Ważnym aspektem podczas przygotowywania koncepcji nowej jednostki jest ocena racjonalności projektu, na która składa się ocena zdolności przewozowej statku, jego bezpieczeństwo funkcjonalne oraz koszty eksploatacji i rentowność.
Na etapie ustalenia wstępnych założeń technicznych powinny zostać sprecyzowane zadania przewozowe, jak również powinny być wykonane analizy danych, w tym danych o statkach podobnych oraz sporządzone listy wymagań dotyczących wyboru parametrów i wymiarów głównych statków oraz parametry eksploatacyjne założonego rejonu pływania.

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