The Ways to Improve Energy Efficiency and Eco-friendliness of the Specific Danube Inland Vessels. First Stage

T Garasko1, V Založ1 and S Maksymov1

1 Danube institute of National university «Odessa maritime academy», Department of Engineering Sciences, Fanagoriyskaya str. 9, Izmail, Ukraine, 68607
sergeysunyysat@gmail.com zalogh@ukr.net maksimov15477@gmail.com

Abstract. Present state of the Danube shipping is differed by insufficient provision of navigation conditions, age composition of the fleet, as well as the fleet specifics – its ability to work throughout the Danube (over 2000 km) when loaded with heavy caravans from non-self-propelled vessels. This specificity significantly differentiates the Danube navigation from navigation on other inland waterways in Europe, which provided year-round through depths, range of transitions to ten times less, and the work carried out for the most part self-propelled dry cargo and tanker vessels.

The study deals with the build a common model for managing energy efficiency and environmental performance of a self-propelled river towing and traction fleet. The differences in transportation technologies in international maritime, European inland and Danube shipping are shown. The issues of rationing of harmful emissions into the atmosphere in shipping on European inland waterways are considered. The analysis of energy efficiency indicators established in international maritime shipping, as well as the peculiarities of their use in inland navigation, was carried out. The principles of the application of energy efficiency indicators to the assessment of environmental indicators of ships in inland navigation have been determined, taking into account the specifics of navigation conditions and other factors determining the operating modes of the ship propulsion complex.

Innovative approach in the study lies in the fact that in the known studies carried out earlier, were considered the Danube fleet operating on the upper sections of the Danube. According to this, the practical solution to the problem of determining the potential to reduce harmful emissions for the existing fleet as well as the formation of the concept of energy efficiency management in the shipping industry is unresolved.

Consequently, the ways of achieving energy efficiency while reducing the amount of harmful emissions into the atmosphere were identified. A possibility of controlling characteristics of energy efficiency of existing Danube traction and self-propelled fleet without significant modernization and upgrades is presented.

1. Introduction

Research on the use for inland waterways (IWW) in Europe of the general concept of energy efficiency used in international maritime shipping, as set out in Annex VI of the MARPOL 73/78 Convention and in the relevant resolutions of the International Maritime Organization (IMO), revealed certain features in the definition of possible energy efficiency management technologies of inland navigation vessels.

The volume of cargo transportation on European IWW in the last decade has fluctuated around 550 million tons per year and it is predicted that by 2030 the share of inland navigation in the distribution of freight traffic in Europe will be about 10%, while the turnover of goods will be about 240 billion
ton-kilometers with a natural sharp increase in energy costs. Accordingly, the task of managing energy efficiency remains relevant for inland navigation in general and for the Danube in particular.

### 2. Analyses of the Literature Data and the Problem Statement

There are published results of studies of options for achieving maximum energy efficiency of inland navigation vessels while saving energy (fuel), maintaining fleet movement characteristics and simultaneously reducing harmful emissions to the atmosphere [1, 4, 5] by technical methods (using the principle of costs/benefit ratio). In short all of them presented in [7] as follows:

- **right-sizing** – modernization with the reduction of engine size for existing vessels; it means replacing a 1250kW engine to 1000kW or even to 750kW with prognoses to investment savings of at least respectively 55000EUR to 110EUR in the average investment cost scenarios and with a pessimistic fuel saving scenario, this results in a net present value of at least 136000EUR to 273000EUR in 20 years;

- **hybrid and diesel electric engines** - the total lifetime costs including investment, fuel consumption and maintenance costs is estimated for the 750kW mechanical and 250kW electric propulsion of about 102000EUR and 260000EUR with 500kW for both mechanical and electric power; a full diesel electric driveline of 1000kW requires 575000EUR additional investment costs;

- another technical solution (innovative hull project, LNG dual-fuel engine, etc.), that could be used for new vessels only.

In this list there are no references to ships with a power plant with a rated power of 1250 kW or more, which are able to work with large convoys, up to 9 units of non-self-propelled fleet and remain active in the Danube shipping. It is on this category of the Danube fleet, which has remained outside of numerous studies, that further emphasis should be placed in the formulation of research tasks. But first, we will consider other known methods for reducing harmful emissions that can be applied to this type of Danube ships in operation.

After IMO adopted the methodic of the Energy Efficiency estimation, researches for the European IWW focused to search basis of possible conventional (or directive) applying of the Energy Efficiency Indexes like IMO Index EEI, gCO2/t-km, i.e. as a specific mass of the harmful emissions rated to CO2, to the unit of transport work (in ton-kilometers, t·km) [2].

The weakness and instability of the inland water transportation market rightly determined the specificity of examining the EEI index together with the SCE (Specific Cost Efficiency) freight cost index, the specific cost-effectiveness (costs), EUR/t, as values associated with the main variable costs of the vessel, namely consumption fuel.

Fundamentally, all possible methods of monitoring energy efficiency in accordance with Annex VI of the MARPOL Convention, applied to ships in service [9], with certain assumptions fair for inland navigation vessels.

At the same time, since the mid-1990s, serious research began on the problem of reducing not only CO2, but also other harmful emissions (CO, HC, NOx, PM) in the exhaust gases of marine engines, which greatly complicated the research in search of rational energy efficiency management technologies

The main results of these researches are emission standards and norms. Fig.1 shows the situation with existing vessels and their ability to meet different stages of those [3] for Non-Road Mobile Machinery (NRMM) applied to NOx emission levels.

In the July, 2016 announced, that the European Parliament and Council have adopted a new proposition of the revision Standards of harmful emissions for the NRMM, stage V. In 2019-2020 these standards will come into force with limitations for the vessels with Ne ≥ 300 kW of carbon monoxide emission limits: CO up to 3,5 g/kWh, carbon-hydrogens HC up to 0,19 g/kWh; nitric oxide NOX up to 1,80 g/kWh and solid particles PM up to 0,015 g/kWh.
At the same time, the gas sampling procedure is regulated, the measurement procedure, the time interval during which the values of harmful emissions must be maintained below the maximum permissible level (Directive 2004/26/EC); established requirements for gas analyzers used.

For international maritime shipping, IMO has implemented an approach to rationing, planning and managing energy efficiency through the use of a comprehensive EEI index. At the same time, in inland navigation more attention is paid to quantitative restrictions of harmful emissions per unit of power of the power plant. At the same time, the problem of reducing total CO2 emissions is burdened with the additional introduction of emission standards for NOx and PM particulate matter.

The most complex in its practice realization both in the Worlds maritime shipping and in IWW is the problem of decreasing NOx on the reason of so-called «Diesel Dilemma» [8]. Estimation data of the level of decreasing NOx and corresponding changes of the Specific Fuel Consumption SFC see in the Tab. 1.

| Method                                              | NO\textsubscript{x} decreasing, % | SFC increasing, % |
|-----------------------------------------------------|----------------------------------|-------------------|
| Using water-fuel emulsion, 20% \text{H}_2\text{O}    | 15                               | 1,4               |
| Water-fuel emulsion and late injection              | 30                               | 2,9               |
| Direct water injection (50%)                        | 40                               | 3,0               |
| Gases bypass                                        | 12                               | 2,1               |
| Selective catalysts with particulate filter (SCR + DPF) | 98                               | 7 (MDO)          |
| Fuel advance angle decreasing                       | 10                               | 14 (HFO)         |

The best way to decrease NOx of those in Table 1 we can see the method of using SCR catalysts and DPF – diesel particulate filter. But the point is – fuel quality is to meet the demands of sulfur limitations not more than 10 mg/kg (Directive 2009/30/EC, valid from January, 1, 2011). One more thing – these systems are quite massive for engine rooms of inland vessels. They also need special maintenance and are too expensive – up to 15% of a new power plant.
3. Aims
The aim of this work is to present interim results of research of the ways to improve energy efficiency and to decrease harmful emissions of the specific Danube inland vessels (with power plant of \( \text{Ne} \geq 1250 \text{ kW} \)). The final purpose is working out the scientifically founded recommendations for interested shipowners: how to upgrade their existing vessels in operation and how to make it cheaper, energy efficiently and eco-friendly.

In this paper one can find some of the results of the First stage of this research. The tasks of this stage are:

- to determine list of data for the estimation of the exploitation regimes for the self-propelled dry cargo vessel with barges in a big convoy;
- to start collecting data for one type of convoy in conditions of an operational voyage;
- to work up the results of collecting data in an operational voyage;
- to work out the recommendations for the future work on right sizing and retooling power plants.

4. Studying the Ways to Improve Energy Efficiency and to Decrease Harmful Emissions of the Specific Danube Inland Vessels (with power plant of \( \text{Ne} \geq 1250 \text{ kW} \)), The First Stage
For the first step is determination of the way to estimate energy efficiency, quantity of components of harmful emissions and correlation between relevant characteristics. For this purpose, the next approach was proposed. The total emission can be determined as a sum of different components

\[
EM = \sum_{i=1}^{k} EM_i, \tag{1}
\]

where \( k \) – total quantity of harmful components.

In general, the mass fraction of the emission into the atmosphere of each component depends on a number of factors: fuel chemical composition, power plant composition, characteristics of the main engine operating cycle, fuel consumption, etc.

To estimate energy efficiency of the inland vessel, consider the approach proposed by the IMO. Energy efficiency index:

\[
\text{EEI} = \frac{\text{Total Emission}}{\text{Transport Work}} = \frac{EM}{\text{Capacity} \cdot \upsilon}, \tag{2}
\]

where \( \text{Capacity} \) – Deadweight (for cargo vessels) or Gross Tonnage (for the passenger ships), tons; \( \upsilon \) – velocity of the vessel, knots.

According to the IMO

\[
EM = P \cdot SFC \cdot C_F, \tag{3}
\]

where \( P \) – effective power of the main engine (ME), kWt; \( SFC \) – specific fuel consumption, g/(kWh); \( C_F \) – conversion factor between the emissions and \( \text{CO}_2 \).

Obviously,

\[
P \cdot SFC = B_h, \tag{4}
\]

it means, that just the hourly fuel consumption is the factor both of total emissions and emission of each harmful component too.

For the inland conditions, in general, the hourly fuel consumption \( B_h \) is the function of the ME rotation speed \( n \), flow rate \( \upsilon_f \); head wind speed \( \upsilon_w \); depth and breadth of the fairway \( H \) and \( B \) correspondently; its tortuosity (for riverbed); local restrictions, i.e.

\[
B_h = f (n; \upsilon_f; \upsilon_w; H; B; \rho). \tag{5}
\]

So, on this base the forms for further operational tests were worked out. The first trial was held on the m/v “Mekhanik Sinilov” (owner – the Ukrainian Danube Shipping Company). In short, the results
The results of the first trial of the first stage are presented.

The main dimensions and characteristics of the m/v "Mekhanik Sinilov"

- Vessel’s type – elf-propelled, dry cargo, pusher
- Length overall – 95,16 m
- Breadth – 11,03 m
- Height – 3,20 m
- Depth moulded – 2,73 m
- Deadweight – 1900 t
- Power plant 2100 h.p. (2×772 kW)
- Velocity without convoy – 19 km/h
- Crew – 7 persons.

An operational voyage, during which measurements and tests were carried out, were held in March, 2018. The conditions of the voyage were as complex as possible for the operation of the main engines, the total cargo tonnage of the vessel with pushed 5 barges amounted to 9970 tons (Fig. 2). Additionally: high levels of water in the Danube river; the spring flood; somewhere the flow speed reached 5 km/h.

**Figure 2.** The caravan scheme during the trial. *Credit: conclusion of the scientific and technical expertise, by Danube Institute of the National University "Odessa Maritime Academy"*

At the beginning of the tests to control the fuel consumption two flowmeters were installed into the fuel system of the left main engine: one at the entrance to the left ME, and the other at the exit from it.
The difference in reading was calculated fuel consumption for the left ME. Exhaust gas analysis (for the results see Fig. 3) and engine indexing (example on the Fig. 4) were also carried out.

![Figure 3](image_url)

**Figure 3.** The results of exhaust gases analyses for trials of the m/v “Mekhanik Sinilov”. Credit: modified from conclusion of the scientific and technical expertise, by Danube Institute of the National University "Odessa Maritime Academy"
6. Conclusions

The introduction and subsequent tightening of the norms of harmful emissions of the Inland European Shipping poses the additional task of developing a methodology for an economic and environmental assessment of the efficiency of production of transport products (ton-km) in combination with the methods of increasing the energy efficiency of shipping.

Taking into account the real actions on the overall integration of European Inland Waterways as transport corridors into a single network, research should be intensified on the development of special technologies to reduce harmful emission standards for vessels in service, taking into account their residual life cycle resource, which will ensure that they continue to work on rivers special control.

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