On Energy Efficiency of Inland Waterway Self-Propelled Cargo Vessels

Aleksandar Simić
Teaching Assistant
University of Belgrade
Faculty of Mechanical Engineering

Dejan Radojčić
Professor
University of Belgrade
Faculty of Mechanical Engineering

The Energy Efficiency Design Index (EEDI) was introduced by IMO - Marine Environment Protection Committee in order to stimulate innovation and technical development of all elements that influence energy efficiency of a ship from its design phase. According to definition, it represents weight of ship's CO_2 emissions per transport work. Baseline equations for EEDI were developed for several most common types of sea-going ships. This paper presents one of the first attempts to evaluate EEDI of inland-waterway, dry-cargo, self-propelled vessels.
Within research that is explained in the paper, full-scale measurements were performed with the purpose to enrich the database according to which new mathematical model for power evaluation was developed. Large differences between the model- and full-scale measurements were also analysed. Finally, application of relatively large power margins for inland-waterway ships was suggested. EEDI baseline can be used as a benchmark of future ship designs.

Keywords: *ship resistance, delivered power, self-propelled inland ship, propulsion coefficients, power margin, energy efficiency design index (EEDI).*

1. INTRODUCTION

Although Energy Efficiency Design Index (EEDI) is primarily developed as one of the greenhouse emissions reduction measures, it can also be regarded as an indicator of energy efficiency of a ship and ship propulsion. Namely, engine emissions are more or less directly related to engine power engaged for achieving desired ship speed. In spite of the fact that ships are generally very efficient transport vehicles, there is still significant potential for further improvements of their efficiency even by applying existing technologies, as for instance more efficient engines and propulsion systems, improved hull designs, increasing their size etc. Concerning benchmarking of inland waterway (IWW) ships, the first step would imply the evaluation of a baseline of existing ships.

Within research related to the energy efficiency of IWW self-propelled cargo ships [1], due to complexity of hydrodynamic effects related to navigation, several objectives had to be elaborated, as for instance:

- Full-scale measurements of power absorption were performed in real conditions.
- Based on available model-scale experiments, a mathematical model was developed for evaluation of power required for achieving certain speed.
- A detailed analysis of external influences was done in order to explain differences between model-scale and full-scale power requirements.
- Power margins for self-propelled IWW ships were recommended.
- A method for evaluation of propulsive coefficients was indicated.
- Finally, a method for determination of energy efficiency design index (EEDI) for self-propelled IWW cargo vessels was suggested.

2. MEASUREMENTS OF POWER ABSORPTION

Full-scale measurements of power absorption were performed on various ships during navigation on natural fairway under different loading conditions and external circumstances. One of the IWW ships on which measurements were performed is shown in Figure 1.

Figure 1. "Deligrad", owned by JRB (L=95m, B=11m, T=2.7m, Δ=2490t)

Wireless equipment used for measurement of power absorption and signal acquisition consists of:

- Torque sensor - strain gauge was glued to the propeller shaft (Fig. 2),
- Transmitting unit which collects and sends signal from the strain gauge (Fig. 2),

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Correspondence to: Dr Aleksandar Simić
Faculty of Mechanical Engineering,
Kraljice Marije 16, 11120 Belgrade 35, Serbia
E-mail: asimic@mas.bg.ac.rs

- Receiving unit that receives signal (Fig. 3), and
- Computer for signal storage and analysis in real time (Fig. 3).

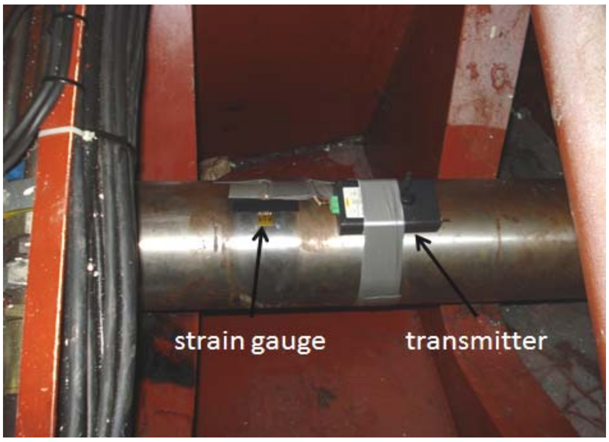

Figure 2. Rotatable parts of the equipment

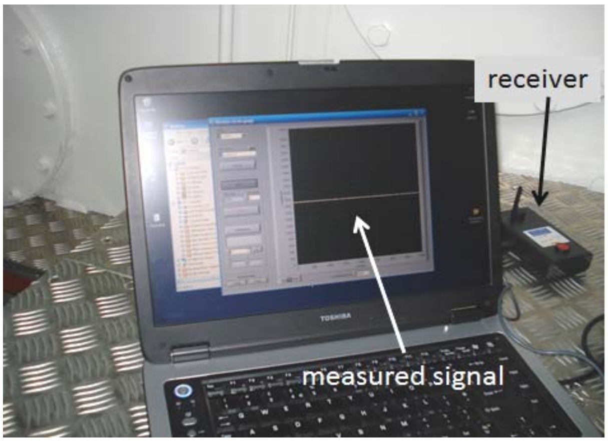

Figure 3. Analysis of measured signal in real time

Simultaneously with the measurements of shaft power, several other relevant data were also measured such as shaft speed, ship speed (ship speed through the water was estimated), waterway depth etc. Since measurements were performed on the Danube, the waterway breadth was considered to be infinite. Wind speed and its direction as well as the wave height were recorded too. Amongst other, these data were required for comprehensive analysis of the measurements.

Measuring equipment was calibrated with precise calibrating-resistors according to the so called shunt-calibration method [2].

3. MATHEMATICAL MODEL FOR EVALUATION OF DELIVERED POWER

3.1 Database for development of mathematical model

Based on the measurements that were performed for this research as well as on other available sources, a relatively large database for several IWW self-propelled ships was created. It contains basic ship dimensions, waterway restrictions and measurements of power absorption. The database consists of:

- 63 model-scale measurements with more than 600 measured values and
- 39 full-scale measurements with more than 250 measured values.

All available data that were used for development of a mathematical model are shown in Figure 4.

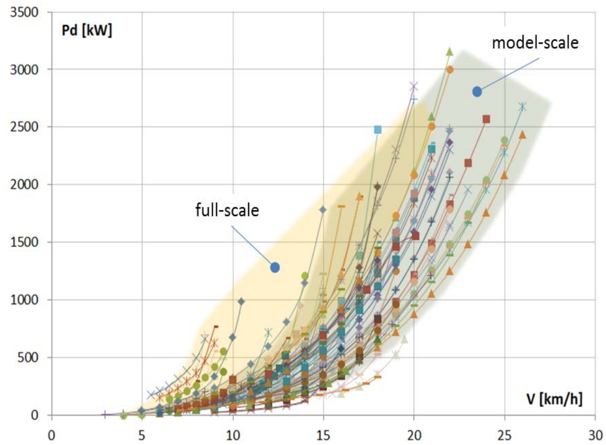

Figure 4. Database of PD=f(V) curves

Two data zones are observed Figure 4 – the left one which mainly consists of full-scale measurements, and the right one with model-scale results. Significant discrepancies between model- and full-scale tests are noticeable. The most likely explanation for discrepancies lies in external disturbances during navigation in real conditions. External disturbances obviously have significant impact on results.

3.2 Derived mathematical model

In order to evaluate power requirements with respect to:

- ship size,
- hull form and
- fairway restrictions (waterway breadth and depth),

and to avoid external influences such as:

- wind,
- waves,
- hull and propeller roughness,
- etc.,

a mathematical model for power evaluation, based on model-scale measurements, was derived [1]. For model development the mathematical method known as Artificial Neural Network - ANN [3] was used.

Before final mathematical model for evaluation of delivered power was chosen (actually, power coefficient $C_D=P_D/(\nabla \cdot \rho \cdot g \cdot V)$), more than fifty models were derived. Finally adopted model with 144 polynomial terms and root-mean-square deviation (RMSD) around 3.7% follows:

$$C_D = \frac{f\left\{c + \sum_{i=1}^{5}\left\{C_i \cdot f\left[b_i + \sum_{j=1}^{11}\left[B_{ij} \cdot f\left(a_j + \sum_{k=1}^{5}\left(A_{kj} \cdot (P_k \cdot X_k + R_k)\right)\right)\right]\right]\right\}\right\} - G}{E}$$

where: $X_k=f(L, B, T, \nabla, b, h, V)$ are input values, while $G, E, P_k, R_k, A_{kj}, B_{ij}, C_i, a_j, b_i, c$ are coefficients.

Mathematical model can be used for:

- Evaluation and analysis of required power with respect to variations of *L, B, T,* ∇*, b, h and V* (needed in the initial design phases),

- Assessment of external influences (by comparing evaluated and full-scale power measurements) and
- Evaluation of propulsive coefficients (when waterway restrictions are taken into consideration).

3.3 Reliability of derived mathematical model

A verification of reliability of derived mathematical model was done by comparing evaluated and experimental data. Relatively good agreement with negligible discrepancies is shown in Figures 5 and 6.

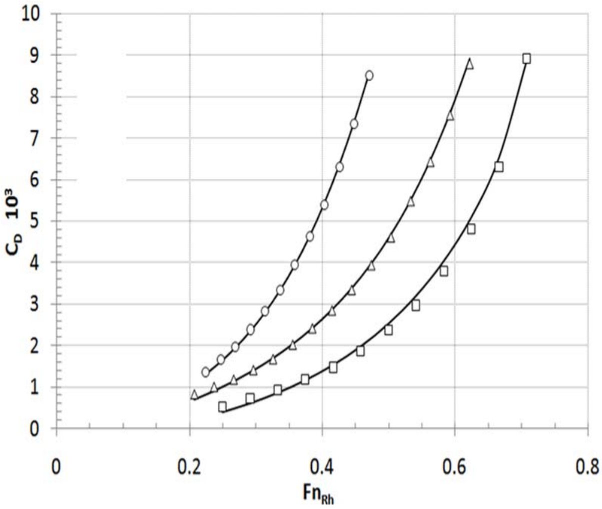

Figure 5. An example of good agreement (experimental data - dots and calculated data - lines)

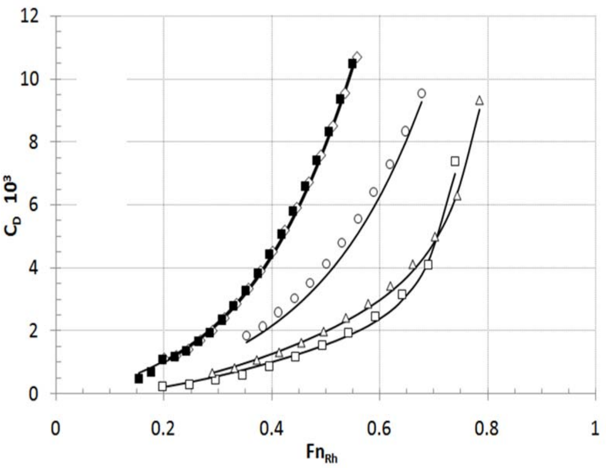

Figure 6. An example of relatively poor agreement (experimental data - dots and calculated data – lines)

Besides the so-called 2D approach, considerable effort was involved in checking the reliability and stability (evaluated values between measured points) of derived mathematical model. Sensitivity of the model on variation of independent variables was also checked. Some of the results are presented in Figures 7 to 12. During this phase of model testing (in 3D) some basic ship parameters were varied within reasonable limits, while others were kept constant. Solid lines are connecting available experimental data (large dots), while the surface (small dots) was evaluated by the mathematical model that was developed.

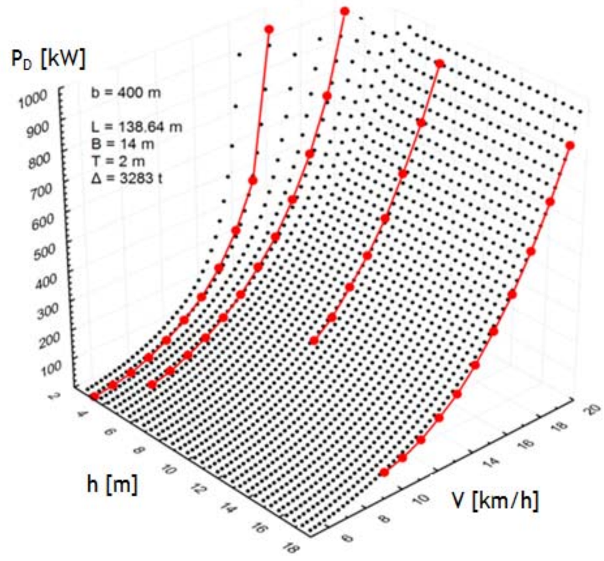

Figure 7. The influence of waterway depth on required power

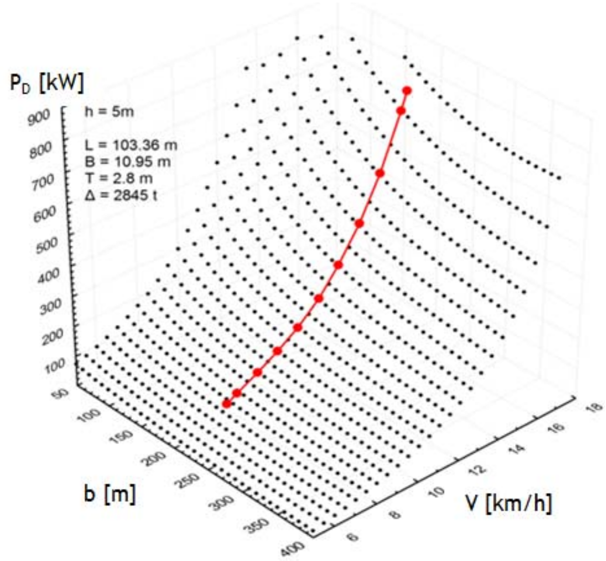

Figure 8. The influence of waterway breadth on required power

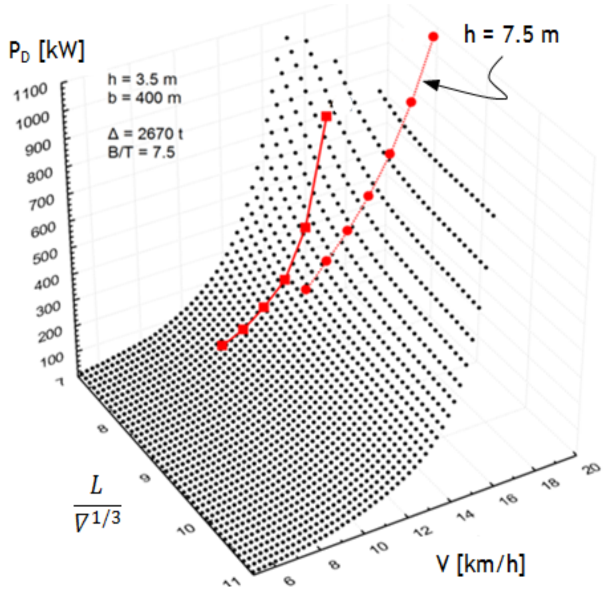

Figure 9. The influence of ship slenderness ratio on required power

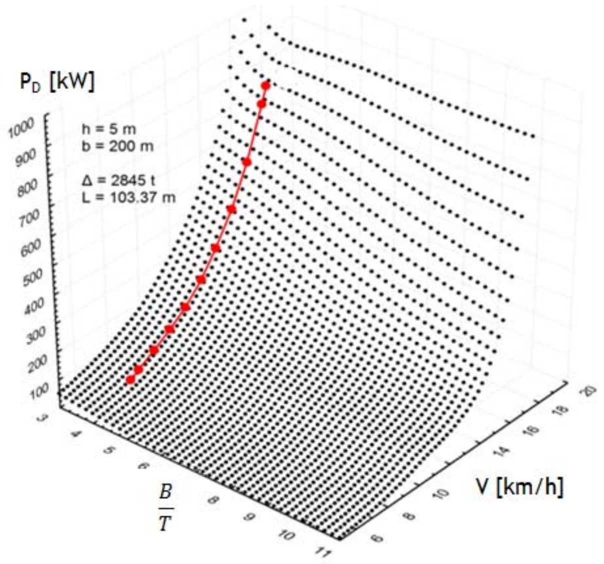

Figure 10. The influence of ship breadth-to-draught ratio on required power

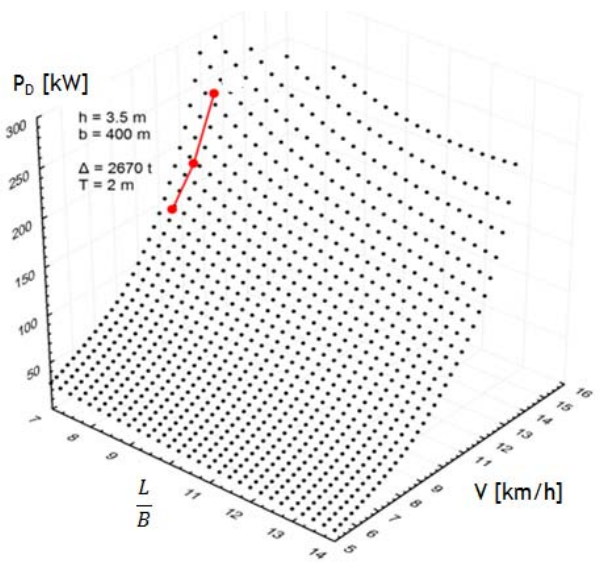

Figure 11. The influence of ship length-to-beam ratio on required power

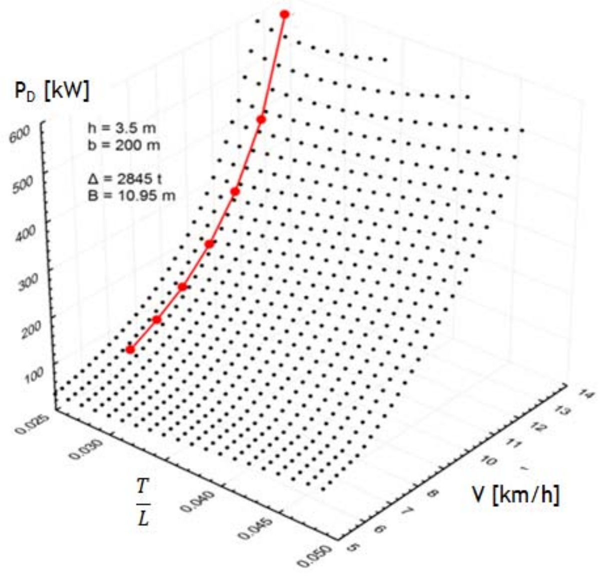

Figure 12. The influence of ship draught-to-length ratio on required power

From Figures 7 to 12 it might be concluded that in spite of small number of measurements, derived mathematical model describes physical nature of ship hydrodynamic phenomena quite well. Moreover, although the model is based on more than 600 measured values, larger data would be more than beneficial. Consequently, development of some better model requires in the first place more data points.

Suggested boundaries of applicability of the model are:

$$7.0 \le L / B \le 14.0$$
$$3.5 \le B / T \le 11.0$$
$$7.0 \le L / \nabla^{1/3} \le 11.0$$
$$3.0 \text{ m} \le h \le 20.0 \text{ m}$$
$$50 \text{ m} \le b \le 400 \text{ m}$$

Upper boundary of ship velocity depends on waterway restrictions and covers usual navigational speeds. Use of mathematical model outside suggested boundaries is not recommended.

4. ANALYSIS OF RESULTS OBTAINED BY FULL-SCALE MEASUREMENTS

For the sea-going vessels it is usual practice to take into account real or service conditions, which is actually disparity between the model- and full scale power requirements. This is usually accounted through application of *service allowance* or *power prediction factor* and is a multiplier to total resistance or effective power. Accordingly, in this research the above-mentioned differences for IWW ships are denoted as *external influence*s, see Figure 13.

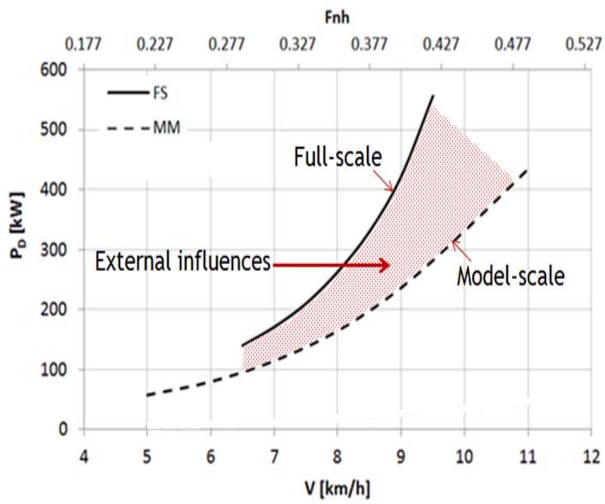

Figure 13. Typical full-scale vs. model-scale power measurements

External influences (relative to model conditions for which mathematical model was derived) consist of:

- Disturbances during full-scale measurements
- Hull condition and navigational circumstances.

In order to explain external influences, the following should be also analysed (Figure 14):

- Effective power (P_E),
- Hydrodynamic efficiency (η_D).

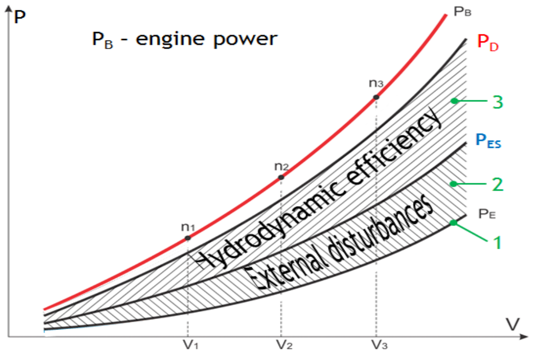

Figure 14. Typical correlation between effective power and delivered power

4.1 External disturbances on a fairway

While navigating in real conditions, the ship is usually exposed to various external disturbances that, along with hull conditions, can significantly affect power demands. The most important external disturbances are:

- waterway restrictions (depth and breadth),
- wind,
- waves,
- river current,
- gravity resistance,
- water temperature
- etc.

The ship hull conditions and navigational circumstances can also affect results of measurements, i.e.:

- hull roughness,
- propeller condition,
- rudder deflection,
- ship drift angle,
- additional displacement,
- trim,
- etc.

Therefore, during the trials it is not only shaft power and ship speed that should be measured, but also environmental conditions and other relevant ship data.

External disturbances for IWW ships may be estimated by applying, and adapting if necessary, empirical methods developed for maritime vessels (see Table 1 and Reference [4]). Summarizing, external influences for IWW ships might be up to 40% compared to model-scale results.

Table 1. Resistance increase due to moderate external influences

Source	Method	Estimated resistance increase
Waterway depth	*Lackenby*	direct calculation
Waterway breadth	*Landweber*	direct calculation
Rudder deflection (±10°)	*ISO 15016*	< 5%
Drift angle (±10°)	*ISO 15016*	< 5%
Hull roughness (~40μm/year)	*Townsin*	< 5% (5 years)
Propeller roughness	*Atlar*	< 10% (3 years)
Wind (up to 30 km/h)	*Blendermann*	< 5%
Waves (less then 1m)	*Kreitner*	< 10%
Additional displacement	*AC*	direct calculation
Trim	-	direct calculation
Water temperature	*ISO 15016*	< 2-3%
Gravity resistance	-	< 1%

4.2 Effective power

Effective power, according to definition, is

$$P_E = R_T \cdot V$$

The most accurate way to determine resistance of a ship is still based on model tests. Nevertheless, only small percentage of newly built ships are model tested and new designs are usually based on previous experience. Methods used for evaluation of resistance are also based on previous model experiments of more or less similar vessels. Resistance evaluation methods used for IWW ships are often slightly corrected methods developed for the sea-going ships, see for instance [5].

4.3 Hydrodynamic efficiency

For explanation of differences between the full-scale power requirements and corresponding model-scale power, propulsive coefficients are needed. Propulsive coefficients are depicted in Figure 15 (shown is typical power transmission from engine to propeller).

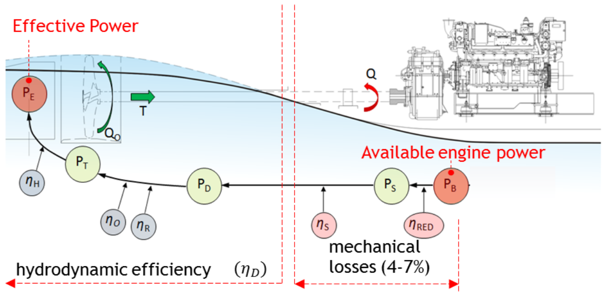

Figure 15. Power transmission and propulsive coefficients of IWW ship

Hydrodynamic efficiency is a ratio of power used to propel the ship and delivered power:

$$\frac{P_E}{P_D} = \frac{\text{used power}}{\text{delivered power}} = \eta_D = \eta_O \cdot \eta_R \cdot \eta_H = \eta_O \cdot \eta_R \cdot \frac{1-t}{1-w}$$

For the purposes of this analysis the effective power was estimated by Holtrop & Mannen method [6]. Delivered power data for two ad hoc chosen ships was retrieved from the database mentioned before. Since circumstances during the measurements were unknown, it was assumed that resistance increase due to external influences varies from 0 up to 40%. Accordingly, results obtained are shown in Figure 16.

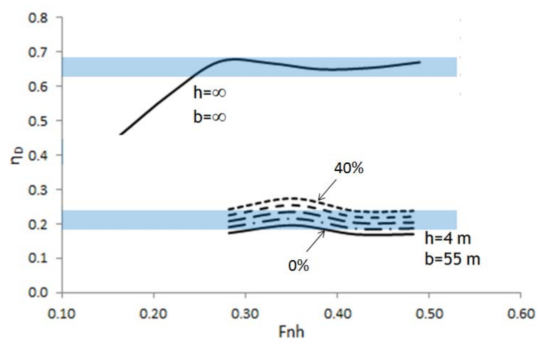

Figure 16. Hydrodynamic efficiency for two ad hoc chosen IWW ships

Results presented in Figure 16 clearly illustrate the significant impact of fairway restrictions on the hydrodynamic efficiency, i.e. hydrodynamic efficiency dramatically drops due to restrictions of the waterway.

More detailed, hence accurate too, evaluation of hydrodynamic efficiency requires evaluation of propulsive coefficients (w, t, η_H and η_R). As they are almost always unknown, Figure 17 indicates how w, η_H and η_R could be obtained through the full-scale measurements. It should be noticed, however, that full-scale thrust measurements are much more complex than torque measurements. For evaluation of thrust deduction (t), ship resistance is needed and it can be evaluated by empirical methods mentioned earlier.

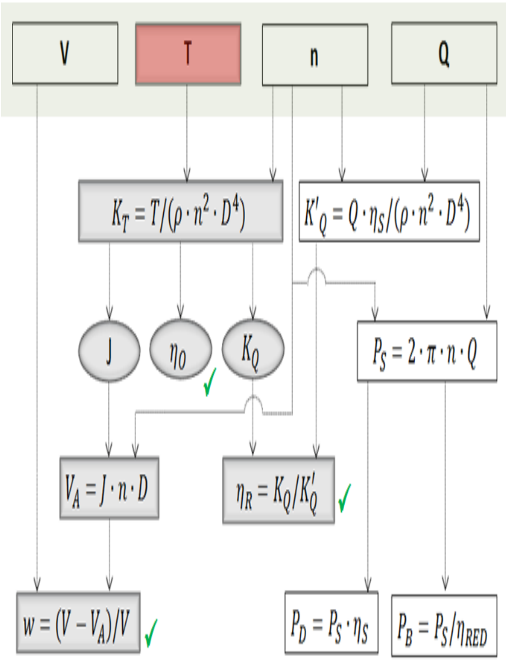

Figure 17. Recommended procedure for determination of propulsive coefficients

5. ENERGY EFFICIENCY DESIGN INDEX

Energy Efficiency Design Index (EEDI) was introduced by IMO - Marine Environment Protection Committee (MEPC) in 2008 as one of greenhouse reduction measures regarding maritime shipping [7].

According to definition

$$EEDI = \frac{Environmental\ costs}{Benefit\ for\ society}\ .$$

The numerator becomes an expression for CO_2 emissions by incorporating carbon factor (CF), specific fuel consumption (SFC) and engine rating, while the denominator becomes an expression for transport work by using vessel specific capacity measure and design speed. Consequently:

$$EEDI = \frac{P_B \cdot SFC \cdot CF}{K \cdot V_{ref}} \quad \left[\frac{g\ CO_2}{t \cdot km}\right]$$

Analysing EEDI for significant number of marine vessels of the same type, several baseline EEDI curves were introduced for different types of sea going ships. See for instance baseline EEDI for maritime oil tankers, Figure 18.

It should be noted that EEDI was developed for a preliminary assessment of ship performance at the design stage (note that Energy Efficiency Operational Indicator - EEOI also exists). Therefore, EEDI baselines are considered as benchmarks of energy efficiency at design stage for new ships. Determination of baselines, therefore, is very important. It should be noted that lower values of EEDI indicate higher efficiency of a ship.

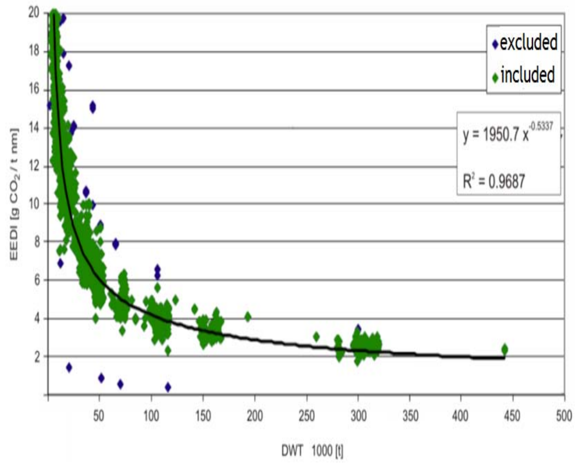

Figure 18. Baseline EEDI for marine Oil Tankers [8]

Within this research an attempt was made to evaluate values of EEDI for IWW ships. According to recommendations given in [7] for the sea going ships, however, reference speed is speed of the vessel corresponding to 75% of installed engine power. Since the main engines of IWW ships are usually more powerful than necessary for achieving designed speed (due to safety and other reasons), mentioned recommendation cannot be applied for IWW ships. Moreover, service speed of the IWW ships is changing over time due to waterway restrictions and other obstacles on the fairway (bridges, bends, shallow sectors, other ships, etc.), as shown in Figure 19 for instance.

Taking into account above-mentioned, within this research it was decided to develop few baseline curves instead of just one, i.e. one curve for each speed, with engine loadings corresponding to particular speed. Also, to enable comparison of similar vessels on the same basis, external disturbances were not taken into consideration. Accordingly, data for shallow and/or restricted water should be recalculated to deep water data etc.

Mathematical model developed here was used for evaluation of power. 200 g/kWh was adopted for the specific fuel consumption (SFC), while CF is a non-dimensional conversion factor between fuel consumption measured in t and CO_2 emissions (measured also in t and based on carbon content). For IWW ships main propulsion engines are diesel engines, so according to [7] suggested value for CF should be 3.2 t CO_2/t-fuel. Applying the procedure described above, for five ad hoc chosen IWW ships EEDI baselines are depicted in Figure 20.

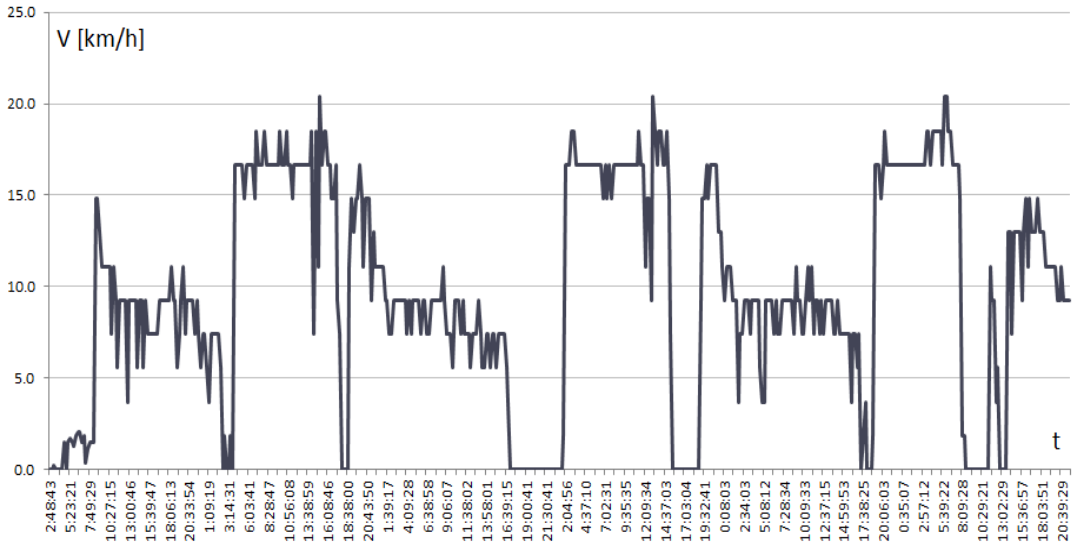

Figure 19. Ship speed variations during 5 days, between Duisburg, Germany and Rotterdam, Holland [9]

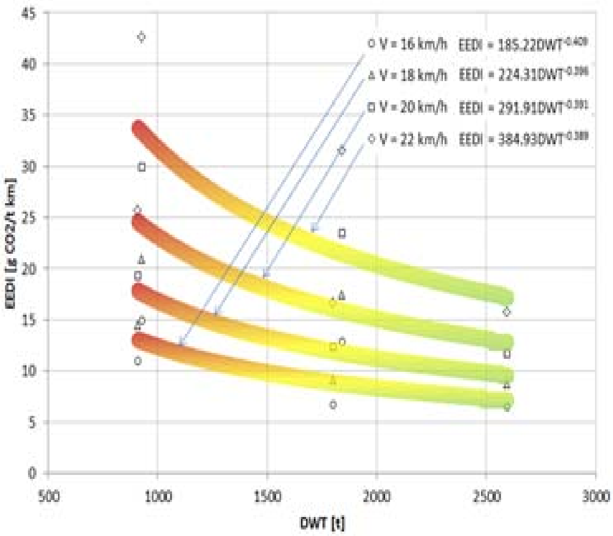

Figure 20. Proposed EEDI baselines for IWW ships (for ship speeds 16, 18, 20 and 22 km/h)

From Figure 20 it can be clearly noticed that energy efficiency of a ship increase with

- Ship capacity and
- Speed reduction,

which is in the line with expectations.

Evaluation of EEDI baselines according to the procedure explained is obviously a very rough estimation. If proposed procedure would be accepted, much more IWW ships of the same type should have to be considered.

6. CONCLUSION

Presented is an attempt to calculate Energy Efficiency Design Index for inland waterway, self-propelled, dry cargo ships, and to establish EEDI baselines for new ship designs. Unlike the usual approach for seagoing ships according to which one EEDI baseline should be derived for all ships of the same type, within pioneering procedure developed here it is recommended that one EEDI baseline should be derived for each speed. Thus different ships of the same type, which are sailing at different speeds, are actually freed from external disturbances and are adjusted to the same fairway conditions, hence appropriate benchmarking is enabled.

Important contribution of this research is also development of a mathematical model for power evaluation of self-propelled IWW ships.

Initially confusing and unexplainable discrepancies between the model- and full-scale power demands are explained. This led to introduction of relatively large power margins for IWW self-propelled ships (compared to the sea-going ships).

Taking into account that the knowledge about propulsive coefficients for IWW vessels is inadequate, a procedure for more accurate determination of propulsive coefficients, based on the results of full-scale measurements, is also recommended.

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NOMENCLATURE

B	ship breadth
b	waterway breadth
Fnh	Froude number based on depth of water
g	gravitational acceleration
h	waterway depth
L	ship length
n	propeller rotational speed
P_B	engine power at maximum continuous rating (MCR)
P_D	delivered power
P_E	effective power
R_T	ship resistance
T	ship draught
t	thrust deduction
V	ship speed through the water
w	wake fraction

Greek symbols

∇	ship displacement
η_D	hydrodynamic efficiency
η_H	hull efficiency
η_O	propeller open water efficiency
η_R	relative rotative efficiency
η_{RED}	gearbox efficiency
η_S	shaft efficiency

О ЕНЕРГЕТСКОЈ ЕФИКАСНОСТ РЕЧНИХ САМОХОДНИХ ТЕРЕТНИХ БРОДОВА

Александар Симић, Дејан Радојчић

Да би се у фази пројектовања брода анализирао утицај форме и примењених техничких решења на енергетску ефикасност, поткомитет IMO-а задужен за заштиту животне средине (MEPC) предложио је у увођење тзв. индекса енергетске ефикасности при пројектовању (EEDI). Предложени показатељ представља однос масе угљен-диоксида емитованог у атмосферу, и количине терета која је при томе превезена по километру. За неке типове морских бродова већ су развијене једначине које одређују референтне вредности за EEDI. У овом раду је представљен један од првих покушаја процене вредности овог индекса за речне самоходне теретне бродове.

У току истраживања су спроведена испитивања речних самохотки на пловном путу у реалним околностима. Проширена је база података и на основу ње је развијен нови математички модел за процену потребне снаге мотора у зависности од основних димензија брода и ограничења пловног пута. Анализиране су и значајне разлике између резултата моделских испитивања и испитивања бродова у природној величини, а на основу чега је процењена вредност тзв. додатка за службу. У раду је предложен приближан поступак за одређивање коефицијената пропулзије на основу испитивања апсорпције снаге брода. Коначно, наговештен је начин на који се могу одредити референтне вредности индекса EEDI које би могле да се користе при пројектовању бродова овог типа.