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INFLUENCE OF THE HULL SHAPE ON THE ENERGY DEMAND OF A SMALL INLAND VESSEL WITH HYBRID PROPULSION

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ABSTRACT

Recently, there has been a significant development of ecological propulsion systems, which is in line with the general trend of environmentally friendly "green shipping". The main aim is to build a safe, low-energy passenger ship with a highly efficient, emission-free propulsion system. This can be achieved in a variety of ways. The article presents the main problems encountered by designers and constructors already at the stage of designing the unit. The research conducted made it possible to create a design with an effective shape of the hull, with the prospect of an energy-efficient and safe propulsion system with good manoeuvrability. The scope of the research included towing tank tests, recalculation of the results in full-scale objects and a prediction of the energy demand of the propulsion system. The results obtained were compared to indicate power supply variants depending on the hull shape.

Keywords: Green shipping,Hybrid,Energy management,Propulsion,Hull shape optimisation

INTRODUCTION

Due to increasing problems with energy resources and environmental pollution, the use of new forms of energy is becoming an important direction for the development of ships, as seen in [1] and [2]. Ships generate various types of solid waste, sewage, noise and combustion products of fuels. The life cycle of any motor vessel significantly affects the level of environmental pollution. This is the main reason for making new regulations in the field of sea and ocean protection. Since exhaust gases are considered as the leading and most harmful component of pollutants, modern and more ecological solutions are needed. Hence, hybrid propulsions, which are considered sustainable, are becoming an increasingly popular option for both small and large ships in every field of marine industry. For more details, see [3]–[5]. Additionally, to improve propeller system efficiency and increase reliability, also hybrid energy storage systems are being used in transport and renewable energy systems.

As shown by Michalski [6], the energy demand of a ship results from the relation between the propelling force (effective drag) and the amount of the drag force with which the water resists the hull's motion and is directed against its motion. The propelling force and the hull resistance change with the speed, while the resistance increases with the speed and the propeller driving force decreases (with constant parameters of the propeller's motion). It follows that by reducing the hull resistance, we will reduce the total resistance of the ship, so also the energy consumption on the ship will be reduced. On the other hand, we should search for a high-performance propeller system, which will consume energy resources in an economic way.

The amount of hydrodynamic drag depends on the parameters of the hull and environmental conditions. The selection of the best solution is through choosing the most effective hull shape, so it comes down to developing a shape that has the best hydrodynamic properties. The objective function in this design task is the hull resistance value, while the highest efficiency coefficient of the propulsion system is the aim of the design task for energy management. This is a typical optimisation problem in the shipbuilding industry, involving the search for both the "most efficient" geometry and the "most efficient" method for energy consumption,

Also for this reason, economical energy management is becoming increasingly popular around the world. However, new propulsion solutions often prove to be costly, so it is desirable to reduce the operating costs as much as possible. At the same time, it is necessary for the propulsion system to work as efficiently as possible. Achieving the optimum operating parameters of the propulsion is possible through the use of various energy management strategies, accroding to [7] – [9].

The history of hybrid propulsion probably dates back to the early 19th century, when H.H. Jacobi first applied electric propulsion to a ship. Initially, this solution generated many problems. The imperfections of electrical machines and the lack of an efficient power source were among them. At the end of the 19th century, this changed with acid-based batteries and the improvement of the existing electric motors and generators (mostly for the Navy). In 1986, J. Holland launched the first fully functional and relatively safe submarine with a parallel hybrid diesel-electric propulsion. This type of propulsion is still used these days, mainly in submarines. Over the years, there was a gradual development of electric drives, used mainly on special ships such as icebreakers and passenger ships. This was caused by the possibility of a quick change of the rotational speed of the propeller shaft and the lack of vibrations of the hull, typical for large diesel engines, which had a huge impact on the comfort of sailing [10].

Another important issue influencing the growing interest in electric and hybrid propulsion was the development of light and energy-saving lithium batteries. This allowed the installation of a distributed engine room – putting a few smaller power generators in several places, instead of the conventional propulsion system with a shaft line. Electric motors that took energy from generators began to be installed in thrusters (including azimuth thrusters), so the engine could drive propellers directly, as mentioned at [11].

The authors paid attention to the problems linked with energy management, what is demonstrated in [12]–[14] during research on electric and hybrid propulsion and during the design of a small inland shuttle ferry with a hybrid propulsion [15]. The results and conclusions drawn from these experiences have been included in the paper.

The aim of this article is to show how to predict the energy consumption for inland shuttle ferries and to compare the influence of the hull shape on the energy demand of such objects.

In this problem, the ferry travels between the banks of the river in the city centre. It is a very unusual case of sailing as the route is very short. There are more periods of acceleration and braking than of constant motion in this trip. The analysis is based on the results of towing tank experiments carried out on two models in scale. The models differ significantly in the shape of the hull. However, the basic performance parameters and characteristics influencing the total resistance values remained the same.

The scope of the research included towing tank tests, recalculation of the results in full-scale objects and a rediction of the energy demand of the propulsion system. The obtained results were compared to indicate power supply variants depending on the hull shape.

PROBLEM OF ENERGY MANAGEMENT OF SHORT-ROUTE VESSELS

Vie [16] has shown, that electrical systems have become very popular lately so more companies are interested in using them to power vessels. First of all, electric propulsion is a fuel-saving solution, especially for units with a varying operating profile, because the generator power can be used for both types of drives (diesel-electric) through electric motors and auxiliary systems. The most important issue is the safety of shipping, as mentioned [17] [18]. Classification societies control ship designs, accept and certify specific products for use in the shipbuilding industry and supervise the technical condition of the ship during its operation. On large ships, where comprehensive solutions produced by global concerns are used, usually a high level of safety is maintained.

The situation is different for small vessels. On the one hand, designers make the driveline and power system by combining components from different contractors. This creates a lot of problems with the integration system of the propulsion and power supply. On the other hand, the problem is proper energy management, which is especially important when the propulsion system is powered by batteries, as it shown in references [19] [20]. Due to the high cost of batteries, designers try to minimise their number and weight. However, for vessels using batteries as the main source of energy, classification societies often require the installation of a generator as a backup source of power. This is to ensure safety in the case that the batteries are discharged prematurely as a result of improper management of the batteries' energy. A large number of batteries is not only a huge cost, but also creates the problem of their weight, which affects the use of the vessel. The heavier the batteries, the more submersible the ship, especially for small ones. A greater draft means worse hydromechanical properties – the greater the resistance of the ship's hull, the bigger the energy consumption.

METHODS AND CASE DETAILS

The ship discussed was developed in 2015–2016 as part of a research project on a new ferry for the National Maritime Museum in Gdańsk [15]. The goal of the project was to create a feasible proposition for a new sustainable ferry, which could replace the existing ship, named m/v Motława, in service from 1975. The main assumptions of the project were as follows:

- hull length – 12.0 m, width – 5.0 m;
- number of passengers: 36 people;
- crew: 3 people;
- construction material: steel;
- propulsion: electric, battery and photovoltaic panels;
- equal manoeuvrability forwards and backwards.

This design task was solved using an innovative design method based on multi-criteria optimisation, according to [21]. The developed hull samples were assessed against two criteria:

- stability, which related to the angle of heel due to crosswind and the location of passengers and crew to leeward;
- resistance, which concerned the wetted surface of the hull (a small wetted surface equals low frictional resistance and total resistance).

The geometry samples obtained were assessed using the Leningrad Design Office [22] and Holtrop–Mennen [23] methods (total resistance for the determined forward speed). The results of the research in references [21] [22] indicated that the optimal shape should be a compromise between a simple cuboid (highest stability) and a part of a spheroid (lowest resistance). These calculations were also confirmed by tests on a towing tank, as it shown in [24]. The developed design, described as Motława A for the purpose of this study, is shown in Fig. 1.

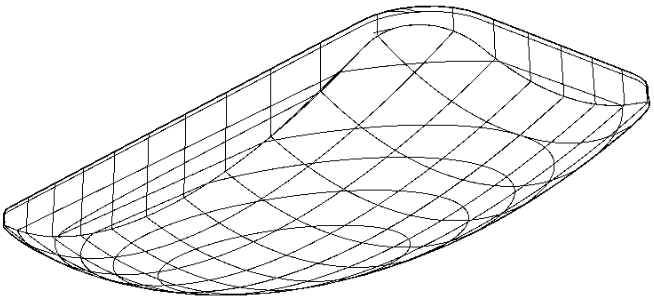

Fig. 1. Hull of Motlawa A

However, it should be noted that the methods used are appropriate for assessing uniform forward motion, which is a case of the long-distance cruise of a sea or inland waterway vessel at a constant speed. Estimation of the propulsion power necessary to obtain the design speed is based on the determination of the amount of resistance in a research laboratory by towing a scale model. These tests are the basis for calculating the propulsion power and make it possible to estimate the energy consumption during the cruise when the main energy consumption is while the ship is moving at a constant speed in open water. Different energy consumption is not taken into account, for example due to acceleration or other manoeuvres, because in this case they are small in comparison to the total demand.

However, for a shuttle ferry using a gliding motion, such standard methods of calculating the demand for propulsion power, based mainly on the empirical models of uniform motion shown in [25] [26], are probably useless from a practical point of view. They can only be considered as design support tools, indicating qualitative, not quantitative, solutions. In the case under examination, the ferry covers a distance of approximately 100 m and makes a lot of manoeuvres (accelerates or brakes) for a significant part of the cruise.

Guided by this conclusion, in this paper, apart from the considerations on the method of determining the ship's energy demand, we also wanted to check whether in the case of such a specific ship it is justified to optimise the shape of its hull in terms of resistance.

For this purpose, a twin of the designed ferry was developed, which represented a simplified version of the hull while maintaining the basic dimensions of the hull L, B and the wetted surface Sw. The difference in length on the waterline Lwl was 2%, which in the case of the Froude number Fn gives the difference in values of 1 / 1000. It was assumed that the values of depth D and draft T may change but cannot be greater than the value of the base hull. This assumption allowed for a hydrodynamic equality between the resistance of the original model and the simplified sample. The developed shape sample was described as Motława B. The hull redesign process was entirely carried out using algorithm generating software (Grasshopper for Rhinoceros) instead of standard CAD modelling systems. A visual comparison of the hulls is shown in Fig. 2.

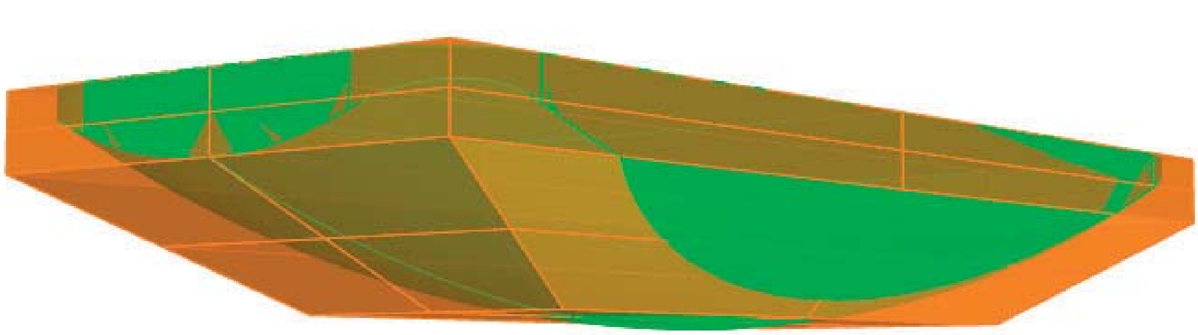

Fig. 2. Green hull – Motława A, gold hull – Motława B

The diagram of the propulsion system for the tested vessel, named for the purposes of the article Motława A, is shown in Fig. 3.

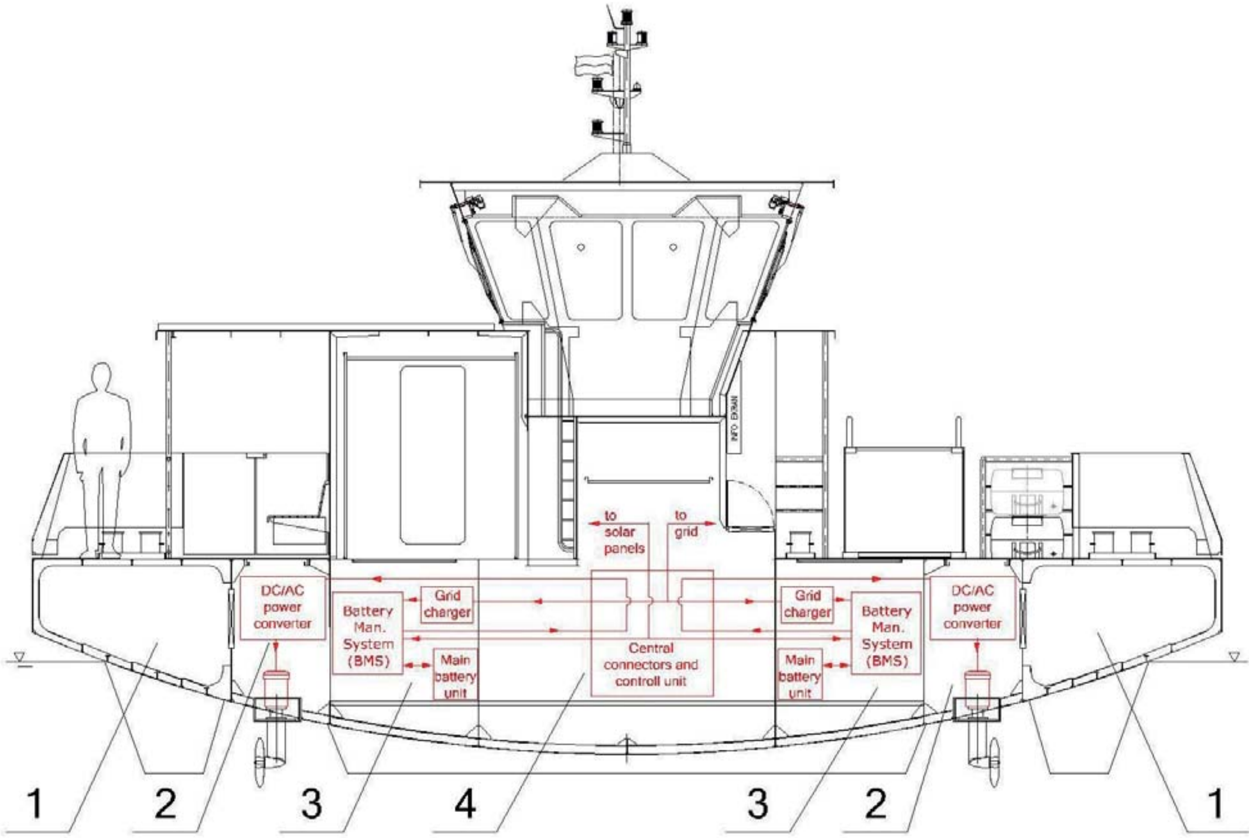

Fig. 3. Propulsion and power supply system schematic of the Motława A ferry; 1 – collision bulkhead; 2 – propulsion compartment, 3 – battery compartment, 4 – crew room with main switchboard [27]

TESTS

TOWING TANK TEST FOR BOTH MODELS

Tests have been carried out at the hydrodynamic laboratory of the Institute of Naval Architecture and Ocean Engineering of GUT. The dimensions of the towing tank are 40 m in length, 4 m in breadth, and 3 m in depth. The tests were performed in accordance with the ITTC procedure [28], and the measurement uncertainty of the recorded data was calculated in accordance with [29]. The model was fastened to the carriage in a way which preserved two degrees of freedom (heaving and pitching).

Two models in 1:10 scale were used in the experimental research. The model number 511 represented the Motława A ship and the model number 010 represented a simplified version of the Motława B hull. The basic parameters of the models and full-size vessels are given in Table 1. Both models are shown in Fig. 4 and Fig. 5.

Tab. 1. Main parameters of the models and the full-scale ship

Parameter	Full-scale ship Motława A	Model 511	Full-scale ship Motława B	Model 010
L – ship length [m]	12	1.2	12	1.2
B – ship breadth [m]	5	0.5	5	0.5
L_{WL} – ship waterline length [m]	10.47	1.047	10.23	1.023
T – ship draught [m]	0.93	0.093	0.74	0.074
V – displacement volume [m^3]	23.12	0.0231	23.12	0.0231
Aw – wetted area [m^2]	50.53	0.5053	50.53	0.5053

Fig. 4. Model no 511 – Motława A

Fig. 5. Model no 010 – Motława B

The measured total resistance of the models was recalculated to the real ship scale using three-dimensional extrapolation based on the extended Froude method. The total resistance coefficient was composed of:

- friction resistance coefficient depending on the Reynolds number *Rn*;
- residual resistance coefficient;
- pressure resistance coefficient taking into account the k shape coefficient, which increases the level of friction resistance of both the ship and the model in relation to corresponding flat plates, according to [23] [30].

In order to calculate the energy demand of the propulsion system, it was necessary to take into account the energy efficiency of this system. It was decided to use AC motors with permanent magnets. The motor is controlled by a frequency converter powered by a lithium battery pack. During previous tests, the energy efficiency of a similar propulsion system was measured and it was found that the energy efficiency of such a propulsion unit exceeds 90%. For more detail, see [31] [32]. The efficiency $\eta mot = 0.9$ was chosen for further calculations. It is known, however, that the main source of energy losses in the system is the thruster (or the propeller). When the vessel is moving at a constant speed, the efficiency of a properly selected propeller can reach 55%. A slightly lower value, obtained on a similar vessel, was chosen for the calculations: $\eta prop = 0.5$. Therefore, on the basis of classical model tests, it was possible to determine the demand for propulsion power when the ship was moving at a constant speed (Fig. 6).

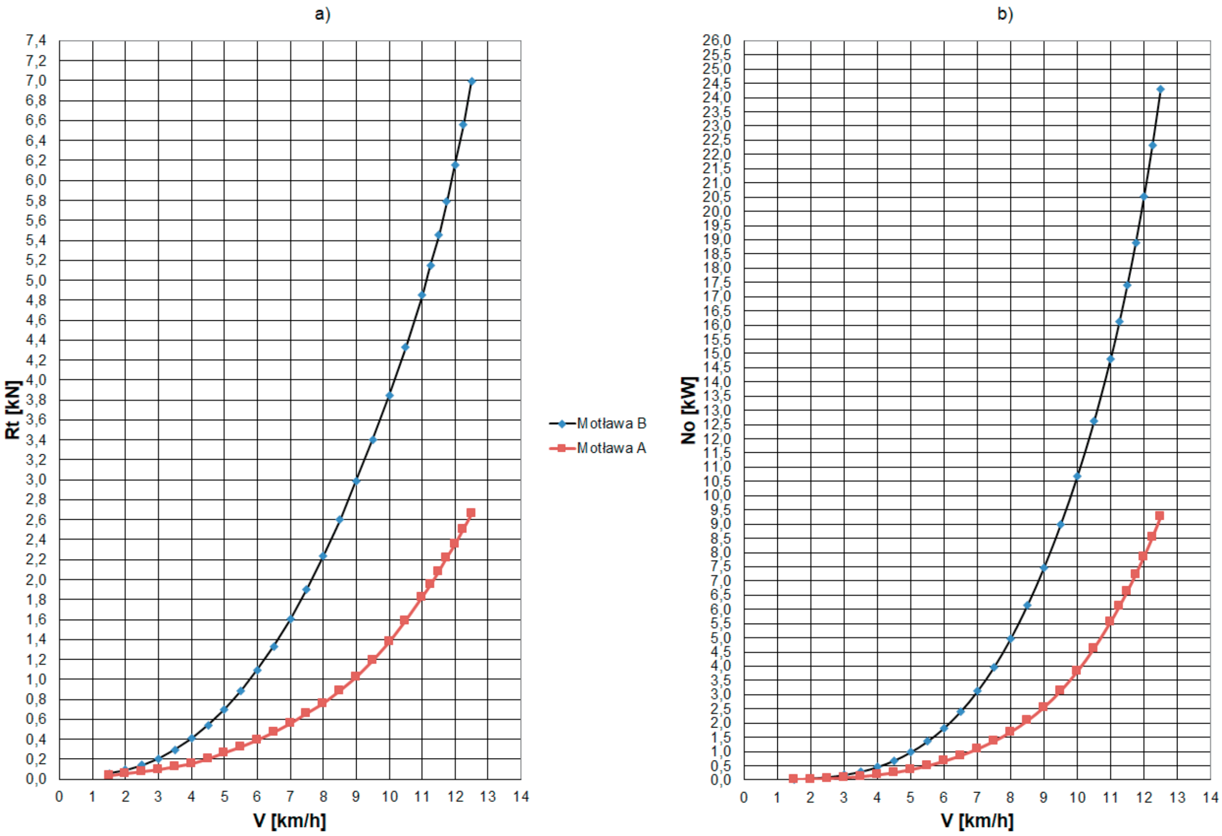

Fig. 6. Comparison of the results of model tests of the Motława A and B ferry as a function of speed: a) resistance as a function of speed; b) towing power as a function of speed

MANAGEMENT OF ENERGY CONSUMPTION DUE TO THE WAY OF MOVING FOR BOTH HULL VARIANTS

The typical equipment of a towing tank is usually not designed to take measurements when the model is accelerated to the specified speed. Therefore, three different acceleration characteristics of the model were programmed in the test laboratory to determine the energy requirements during the acceleration of the shuttle. This made it possible to register the drag force during acceleration of the model to a given speed. When the speed of the model was determined, the towing force was calculated. However, during acceleration and braking, the ship's propeller works in unfavourable conditions and its efficiency is difficult to estimate. Therefore, in these motion phases, due to the greater load, a lower propeller efficiency was chosen and set to 35%. The efficiency values were determined on the basis of typical propeller efficiency curves from the hydromechanical characteristics, as mentioned in [33] [34]. For each phase the motor efficiency was the same value 90% ($\eta mot = 0.9$).

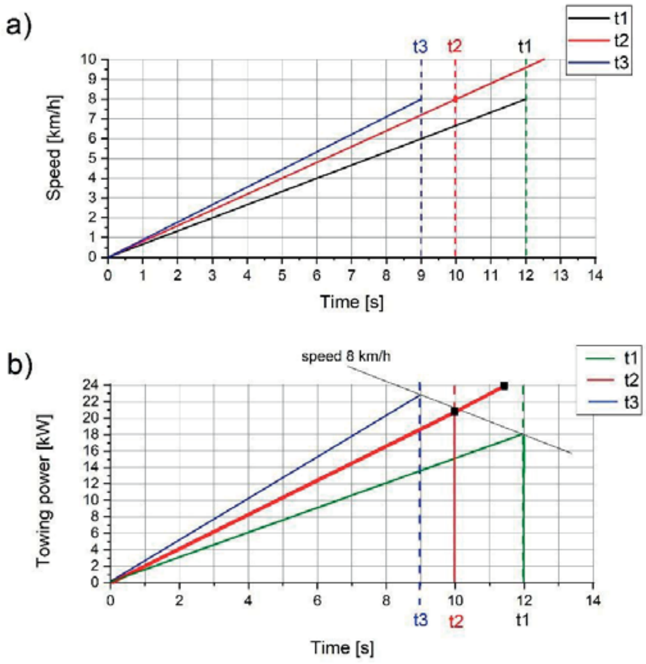

Fig. 7. Measurement results in the model test laboratory during the acceleration of the Motława A model, showing acceleration variants from t1 to t3; a) the speed distribution of the ship; b) the towing power of the ship

Due to the limitations of the towing tank, which was not adapted to tests at variable speed and was designed to tow the model with a constant speed, only three different characteristics of acceleration to the speed of 8 km / h were determined. The process was indicated as *t1*, *t2* and *t3* (Fig. 7). The acceleration process was carried out with three different acceleration values so the duration to the speed of 8 km/h was *t1* = 12 s, *t2* = 10 s and *t3* = 9 s.

Various strategies of the vessel's movement were proposed and developed for the model, showing that it is possible to cover the same route at the same time with different energy consumption [19]. For comparison of the energy consumption one of the developed strategies ACB (Acceleration, Constant, Braking) for the maximum speed of 8 km / h was chosen. The energy consumption for the acceleration and braking phases for Motława B was estimated and calculated by the resistance difference between Motława A and Motława B for the constant speed phase. Verification of the results of that phase will be verified in subsequent stages of empirical research.

The measurements allowed us to determine the characteristics of the instantaneous power demand and speed as a function of time (Fig. 8). The analysis used measurements of the power needed to accelerate the vessel when the speed of 8 km / h was reached in 10 seconds (t2). It was assumed that in each of the analysed cases the cruise lasts an average of 65.5 seconds, and the route is 100 m long. It was also assumed that the cruise was safe and that the ferry does not have to avoid obstacles or make sudden manoeuvres to avoid a collision.

In the case of the ACB strategy to cover the route, the results from classical measurements (Fig. 6) and the acceleration phase (Fig. 7) were used. For the braking phase, it was assumed that the energy consumption was equal to half of the energy needed to accelerate the ship. This is due to the fact that the resistance of the ship naturally slows down the movement of the ship. It is hard to estimate the efficiency of a propeller operating in water when using the propeller to stop the ship. The same method, time and braking distance were adopted for each characteristic.

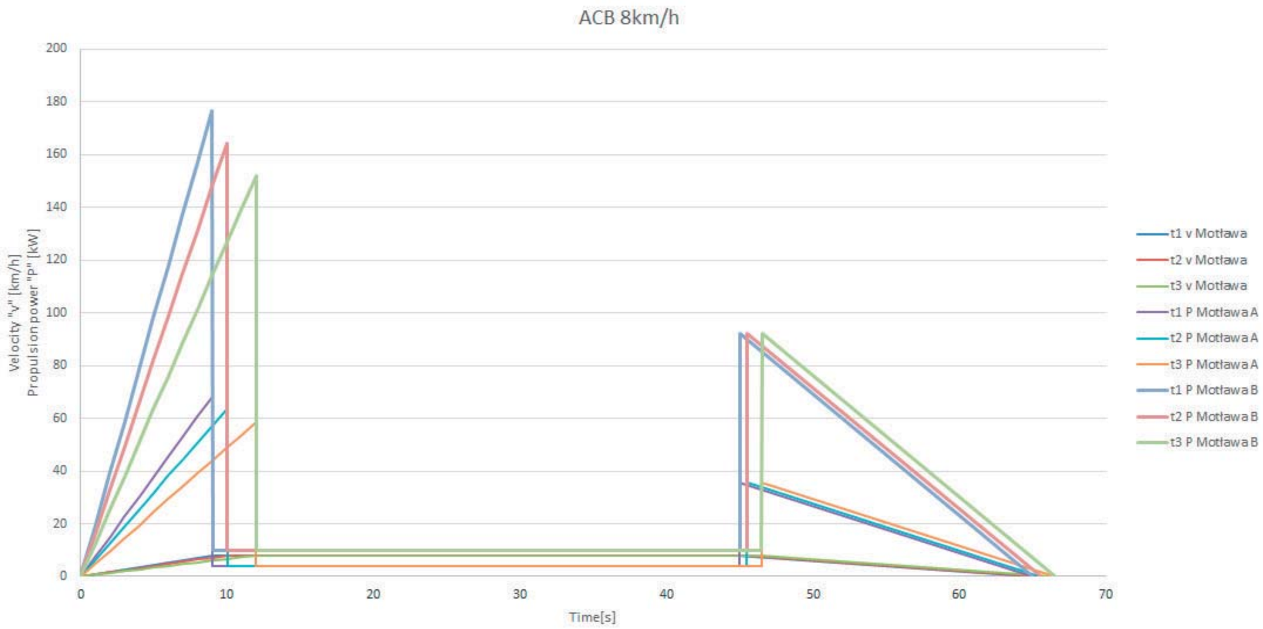

Fig. 8. The differences in energy consumption for the same movement strategy, depending on the shape of the hull

RESULTS AND DISCUSSION

The greatest demand for ferry operation occurs in the summer season, due to the number of tourists visiting the city. The ferry is scheduled to make 10 return trips per hour. Currently, it is planned that in the summer period, when the intensity of tourist traffic is the highest, the energy stored by the vessel must be sufficient for a 12-hour cruise, during which up to 120 round trips will be made.

The results obtained make it possible to calculate the energy demand depending on the shape of the hull with the same parameters. The time needed to complete the one-way course was also included in the calculations. The results of energy consumption, depending on a given acceleration characteristic, prepared in the previously presented graph (Fig. 8) for one hour of the cruise, during which 10 round trips were made, are presented in Table 2.

The values presented in Table 2 show quite significant differences in energy demand. The calculations for the averaged result of the three characteristics show that the theoretical minimum energy consumption during 12 hours of intensive voyage for Motława A is 12 × 4.5 kWh, so about 55 kWh. For a hull with a different shape coefficient – Motława B, it is 12 × 11.7 kWh, so about 140 kWh. The difference between the results obtained indicates that, depending on the hull shape, other power supply variants should be selected.

Tab. 2. Comparison of energy consumption with the same movement strategy for different hull shapes of the tested vessel

For *t1*	Acceleration	Constant	Braking	Total
Time [s]	12	34.5	20	66.5
Road [m]	13.2	75.9	11	100.1
Energy demand [kWh] – Motława A	0.0979	0.0360	0.0988	0.2326
Energy demand [kWh] – Motława B	0.2535	0.0932	0.2558	0.6024
Energy demand [kWh] - 10 Return trips in 1h - Motława A				**4.6525**
Energy demand [kWh] - 10 Return trips in 1h - Motława B				**12.0486**

For *t2*	Acceleration	Constant	Braking	Total
Time [s]	11	35.5	20	66.5
Road [m]	11	78.1	11	100.1
Energy demand [kWh] - Motława A	0.0882	0.0370	0.0988	0.2240
Energy demand [kWh]] - Motława B	0.2284	0.0959	0.2558	0.5800
Energy demand [kWh] - 10 Return trips in 1h - Motława A				**4.4794**
Energy demand [kWh] - 10 Return trips in 1h - Motława B				**11.6002**

For *t3*	Acceleration	Constant	Braking	Total
Time [s]	9	36	20	65
Road [m]	9.9	79.2	11	100.1
Energy demand [kWh] - Motława A	0.0853	0.0375	0.0988	0.2216
Energy demand [kWh] - Motława B	0.2209	0.0972	0.2558	0.5739
Energy demand [kWh] - 10 Return trips in 1h - Motława A				**4.4325**
Energy demand [kWh] - 10 Return trips in 1h - Motława B				**11.4788**

CONCLUSIONS

The research shows that the shape of the hull with the same parameters is very important for the design of the propulsion system. The generated resistances for the tested vessel differ approximately 2.5 times. So if the choice is to install standard 2.5 kWh lithium battery modules on board, it is necessary to install more than twice as many as on a vessel with an optimal hull shape. Such a solution will not only significantly increase the weight of the vessel, taking up space on a small ferry, but also mean the ferry is able to carry fewer passengers per trip.

The initial strategy of the vessel's movement was to accelerate to a speed of 6 km / h and complete the route in about 120 seconds. The load of the propulsion during acceleration to a higher value turned out to be an aspect worth considering. Initially the value of 8 km / h seems to be the optimal value, because with higher acceleration the energy consumption increases faster and faster, which can be read directly from the resistance curve. However, it is possible to use higher speeds if a different movement scenario is used. Developing the most optimal strategy is not easy. Therefore, the use of a propulsion with a higher power makes the motor, speed controller and gears work with high efficiency. On the other hand, high power brings with it significant friction forces, which are especially important in the case of bearings and gears. The high initial speed in the first phase of the cruise also leads to an increased risk of collision and the possibility of a sudden stop of the vessel with high energy consumption. It is worth noticing that for short routes, as in the discussed example, the first phase of the cruise is of particular importance, because the distance travelled by the vessel is relatively small, with relatively high energy consumption. In the case of long sea routes, this phase is not considered when estimating the energy demand because the energy consumption in acceleration is low compared to the rest. As the distance increases, the second phase becomes more important as the energy consumption depends on the speed. In these cases, the braking stage was always the same. It was assumed that the drive was started in order to brake the ship at a speed of 4 km/h. The assumed braking time of about 20 seconds allows the vessel to stop slowly, which is convenient for passengers and does not put additional strain on the propulsion system. For a shuttle ferry, a significant part of the ship's total energy consumption during a single journey results from the first phase of the cruise when the ship is accelerating. Choosing a non-optimal shape of the hull additionally increases the drag and causes a significant increase in the energy demand of the vessel. Therefore, already at the design stage it is possible to try to significantly reduce the cost of the designed power supply devices and leave more free space that can be used for another purpose.

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