POLISH MARITIME RESEARCH 2 (102) 2019 Vol. 26; pp. 85-92
10.2478/pomr-2019-0028

ENERGY EFFICIENT SMALL INLAND PASSENGER SHUTTLE FERRY WITH HYBRID PROPULSION - CONCEPT DESIGN, CALCULATIONS AND MODEL TESTS

Magdalena Kunicka, Wojciech Litwin
Gdańsk University of Technology, Poland

ABSTRACT

In recent years, there has been a significant development in "green" and energy efficient propulsion systems, which fits into the general trend of environmentally friendly "green shipping".
The pursued goal is to construct a safe passenger ship that is low in energy demand and equipped with a highly energy efficient, emission-free propulsion system.
The paper presents main problems encountered by designers of a small, hybrid-powered ferry powered lithium batteries. The conducted research allowed to create a design of an energy efficient hull shape, which decreases the demand for energy. Completed remote control model tests resulted in a proposal of an energy efficient and safe propulsion system with good manoeuvring capabilities. Measurements completed on an existing ferry permitted completing energy balance and forming an energy management policy.
The paper contains the emission calculations computed for the existing ferry that are necessary for the environmental impact analysis.
The soon to be constructed, newly designed vessel will provide a valuable contribution to hybrid-propulsion, energy management and unmanned technologies research.

Keywords: ship hybrid propulsion, energy efficiency, green shipping, energy management

Abbreviations: BMS – Battery Management System
RACK – universal terminal with connecting rail for easy connecting electrical modules, usually ventilated and with integrated energy supply

INTRODUCTION

Recent years have witnessed a significant increase of interest in eco-friendly ship propulsion systems being part of the environmentally conscious green shipping trend. This is caused by a number of factors, including economic reasons, possibilities of employing modern and sophisticated technological solutions and operational level savings [1][2][3][4]. Environmental protection regulations become increasingly restrictive with each passing year. An example of this is creating strictly defining acceptable levels of toxic substance emissions, especially regarding carbon dioxide, sulphur and nitrogen compounds, which are closely linked to fuel quality and consumption. In addition, the age and technical condition of used propulsion systems is being regulated [5][6]. At the same time, the accompanying issue of noise pollution is an increasing source of concern [7][8]. This directly results in a conclusion that in the near future, environmental concerns – mainly the awareness that certain environmental changes resulting from pollution cannot be reversed - might become of such high importance that the currently used propulsion systems will not be allowed to operate any longer. This especially applies to older units. These units may represent certain historical value force in some cases, and may be used to search for solutions which can serve as an alternative to classic and conventional ship propulsion systems. One such option is a hybrid propulsion system that produces less emissions of harmful substances [9][10][1]. The hybrid solution also presents a definite, economic advantage since operating an electrically-powered vessel is significantly less expensive than a vessel powered by a combustion engine [10][11]. While searching for sources of clean energy, scientists have also been working on fuel cells, which have successfully been implemented in shipbuilding applications [12][13][14]. Unfortunately, this solution has not become widely popular due to technical difficulties, safety concerns and its high cost.

There exists a number of modern propulsion solutions which may be employed in a small passenger ferry. In each case, all of their specific advantages and disadvantages should be thoroughly considered, respectively.

The parallel hybrid system that was designed and used for the first time in submarine propulsion is over one hundred years old [9][15][16]. The type of system consists of a combustion engine and an electric motor which may also operate as a generator. Both sources of power are connected to a transmission shaft by controllable clutches. Such solutions are characterized by their high energy efficiency and are frequently used in various applications, including on inland waterways vessels that navigate diverse bodies of water at varied speeds. Such watercraft often use battery-powered electric motors to manoeuvre in the port, while they use locks or restricted speed in populated urban areas. When going through open waters, during which navigational speeds are higher and the demand for power rapidly increases, the internal combustion engine is activated. In addition, the electric motor may work in a generator mode, which makes it possible to charge the batteries. In exceptional situations, these two types of propulsion may work together and make their combined maximum power available. However, such a solution is not without its limits and shortcomings. The main one is usually its considerable size. Such a system may be employed with relative ease in the case of a conventional propulsion system where the engine room is located at the stern and the shaft transmits power to the propeller.

In a series-hybrid propulsion system, the propeller is driven by an electric motor [9]. The energy supplied to the motor usually comes from a number of sources. Among the most popular are battery packs, diesel powered generators, photovoltaic panels and fuel cells. In certain cases, while in port, the ship batteries are charged from the power grid – such a system is known as a plug-in hybrid. The fundamental advantage of a series hybrid system is the compact construction of its power transmission system which occupies very little hull space. In addition, if azimuth pod thrusters are used, which also provide steering control, then the propulsion system is located practically entirely outside the hull. The power supply system may be installed in a dispersed way inside the hull, allowing for optimum distribution of weight throughout the ship. One of the disadvantages is its low efficiency while operating in a diesel-electric mode due to the efficiency of the operating machines. Therefore, the choice of propulsion system and power supply sources is of key importance to watercraft's lasting operational capability, which should span many years. This of course also holds true for the solution described here. Various concepts of propulsion and power supply systems were considered, and the final choice was made on the basis of optimum environmental, economic and practical impact which would be obtained based on the authors' best knowledge.

Numerous problems which were encountered during the execution of the project were eventually successfully overcome. Some of them stemmed from strict regulations of ship classification societies which permit watercraft to operate. Their foremost priority is safety which quite often manifests itself as resistance to non-standard, untested in operational conditions and novel solutions which, though quite understandable and natural, may still constitute a source of frustration to designers.

The hybrid propulsion solution and the power supply system based on lithium batteries proposed by the authors continue to be viewed by the shipbuilding industry as rather novel in character. As is frequently the case, it is challenging to break through long-established habits and traditions of employing traditional solutions. They are based on fossil fuels which have proven their merit on countless occasions. Nevertheless, it seems that the system described in this paper is indeed optimum for the operating conditions mentioned below.

THE MOTŁAWA 2 FERRY – CONCEPTUAL DESIGN

The newly designed vessel is to replace the Motława Ferry currently operating in Gdańsk, which has been in service for over three decades and became quite worn out from both a technical and an aesthetic perspective (Fig. 1a). Its propulsion system and functional range are quite distant from modern standards. The new ferry conceptual design process had to take into account external limitations regarding dimensions resulting from the character of the waterbody and conducted work: hull length L=12.00 m; ship's breadth B=5.00 m; total draught T_{max}=1.30m. In addition, the capability to transport 36 passengers was required (Fig. 1b).

Fig. 1. The Motława Ferry; a) the ship in operation since 1987; b) visualization of the new ferry

SHIP POWER DEMANDS DISTRIBUTION TESTS – TOWING TANK TESTS

Experimental tests were carried out in the towing tank of the Gdańsk University of Technology's Faculty of Ocean Engineering and Ship Technology in calm water conditions. The tests were conducted using a 1:10 scale laminate model (Fig. 2). During the initial phase of testing, the model had no protruding parts (propulsive and skeg). However, in subsequent tests the model was equipped with miniature azimuth thrusters and a remote control. These tests demonstrated that the vessel would be difficult to manoeuvre. Initiating any type of manoeuvring resulted in the model entering into a practically uncontrollable rotation. This problem was solved by installing skegs (Fig. 2a), which made it possible to maintain a stable course while only slightly limiting manoeuvring capabilities. Unfortunately, the improvement in manoeuvring came with the increase of movement resistance which also meant a rise in the power demand stemming from the larger total underwater area of the hull.

The measured total resistance of the model was recalculated to the scale of the actual ferry using three-dimensional extrapolation based on the extended Froude method. The total resistance coefficient was assumed to be typically composed of:

- friction resistance coefficient depending on the Reynolds number,
- residual resistance coefficient (wave, splash and pressure) as a function of the Froude number,
- pressure resistance coefficient, that takes into account the k shape coefficient, which increases the level of friction resistance both of the ship and of the model in relation to the corresponding flat panels

The results of the initial calculations were completed using approximate parametric methods during the hull shape selection phase. The results of model tests are presented in the diagram below (Fig. 3a).

It is worth emphasizing the fact that the results of approximate calculations performed using parametric methods are close to the model tests of the hull without protruding elements (Fig. 3a). The hull modernization consisting of adding the skegs and models of moving azimuth thrusters resulted in nearly doubling its drag and, as a consequence, also doubled the demand for power. The significant difference between the results obtained using parametric methods and the results of model studies for the hull equipped with skegs and thrusters is typical since approximate parametric methods do not take into account the protruding hull parts. Nevertheless, the nearly twofold rise in power demand following the mounting of skegs and azimuth thrusters seems to be overestimated. According to the study's authors, it stems mostly from larger dimensions of the model azimuth thrusters than from the accepted scale (Fig. 3a).

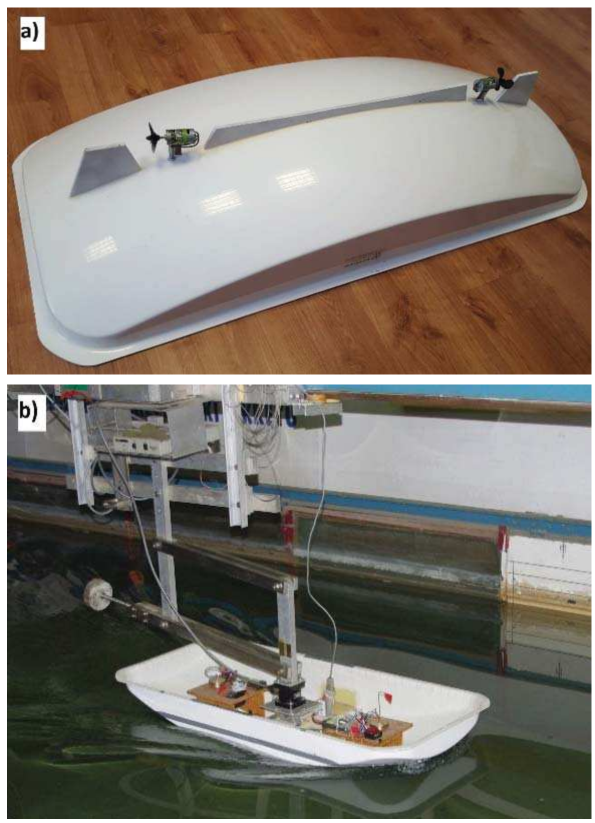

Fig. 2. The 1:10 scale ferry model; a) the final version with skegs and propulsion allowing for conducting remote control maneuvering tests using remote control; b) the model of the towing tank during tests, speed 10 km/h

Based on the towing power graph presented below, the propulsion power necessary for obtaining set speed may be approximately computed. Despite the fact that during actual operation the ferry speed does not exceed 6 km/h, due to navigational safety regulations the vessel has to be capable of operating at the speed of 12 km/h. In order to calculate the demand for electric motor power and estimate the capacity of batteries, the following moderate and obtainable energy efficiency levels were accepted:

- propeller – 55%,
- motor and controller system based on laboratory conducted measurements of similar system – 95%.

Therefore, it follows that in order for the vessel to reach a speed above higher than the one requested by the regulations, the power of both azimuth thrusters should amount to about 33 kW (Fig.4b).

The impact of air resistance or the increasing hull drag resulting from algae and crustacean deposits might be estimated at this stage. However, bearing in mind that the vessel in question is to operate on a small, well-protected body of water and its hull will be carefully shielded against biofouling by a special paint or film, the impact of these factors was not considered.

It is also worth noticing that at low speeds the drag of the submerged hull part is very low, which indicates that the demand for power is minimal (Fig. 4b). For the speed of 6 km/h the power drawn by the propulsion system amounts to just 2.5 kW. Nevertheless, one should bear in mind that the presented results were obtained in conditions of steady-state and uniform motion. As such they do not take into account the considerable forces of inertia exerted by the twenty ton vessel. Especially during sudden emergency manoeuvres, such as collision avoidance, the helmsman may use the entire available power of propulsion.

Specific operating conditions and watercraft properties, such as low drag, short distance between the river banks, and considerable inertia of the twenty ton ship lead to a conclusion that the strategy of ferry operation should be considered through the perspective of minimizing energy consumption.

CONCEPT OF PROPULSION AND POWER SUPPLY SYSTEM

The body of water on which the Motława Ferry operates is located in the historic old city centre which is very crowded, especially during the tourist season. The character of its covered route is not typical for shuttle ferries and requires considerable manoeuvring skills from the helmsman. Even though the covered distance is quite short and amounts to only 100 meters or so, navigating it requires operating along a curved trajectory. In addition, the helmsman is forced to correct the course quite frequently in order to avoid collisions.

The proposed solution – a parallel hybrid propulsion system based on two azimuth thrusters (Fig. 4) – allows for obtaining the desired sound manoeuvring capability. In order to obtain high reliability of propulsion, each of the two azimuth thrusters powered by permanent magnet electric motors is equipped with its own battery pack. Due to safety requirements and the expected unsinkability, the ship is divided into watertight compartments. The bow thruster is powered by batteries installed in the bow compartment and the stern thruster draws power from the stern compartment battery pack (Fig. 4). The design reviewing classification society made a suggestion of employing a solution which would allow for switching the power supply between the bow and the stern. However, the design authors decided not to follow the suggestion, based on their conclusion that it would unnecessarily complicate the control system and make it harder for the crew to use, especially in emergency situations. The two main power supplying electrical installations do not overlap. Therefore, a breakdown in one of them will not result in malfunction of the second one and will allow the vessel to maintain its operational capability. The heart of the entire power supplying system is the main switchboard located in the central part of the ship, which is easily accessible from the crew room (Fig.4).

Due to safety concerns, the lithium batteries are placed inside sealed containers with mechanical ventilation of varying outputs as a function of the battery cell temperature.

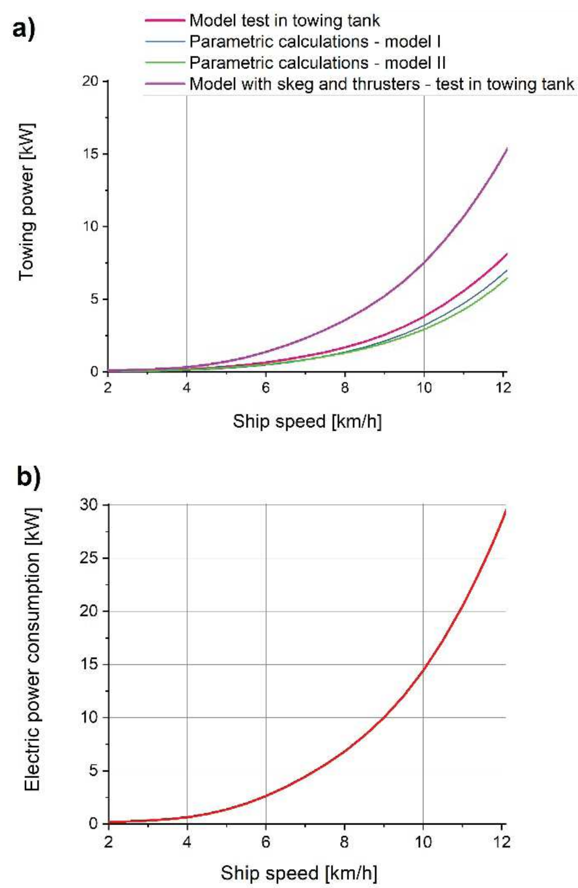

Fig. 3. The results of calculations and model tests; a) comparison of calculation results and measurements performance in the towing tank, b) electrical power consumption of ship's propulsion system as a function of speed

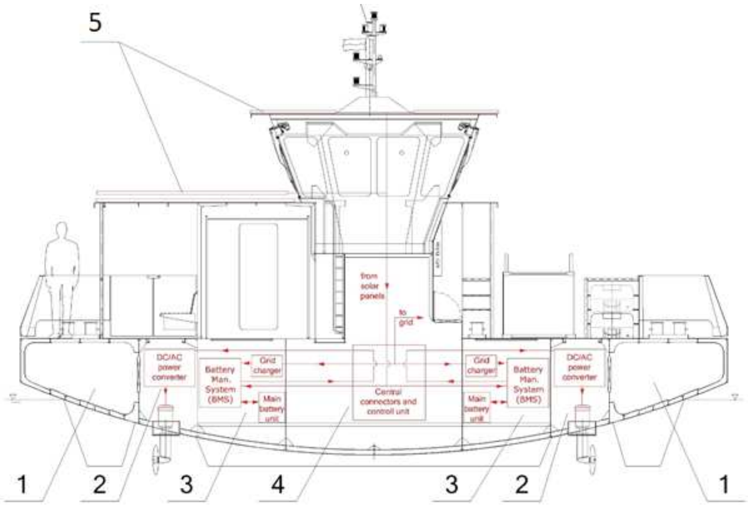

Fig. 4. Propulsion and power supply system schematic of the Motława II Ferry; 1 – collision bulkhead; 2 – propulsion compartment, 3 –battery compartment, 4 – crew room with main switchboard, 5 – solar panels

Lithium batteries grouped into water resistant modules of 86V rated voltage and 5kWh capacity were proposed for the power supply. Each of such modules consists of 78 LiFePO4 cells connected in a series-parallel circuit (configuration 26S3P). The modules are provided with a battery management system (BMS) which protects them from excessive discharging, overcharging and overheating. In addition, the system is equipped with a balancer responsible for charging evenly the series-connected cells.

The battery compartment will house typical RACK type cabinets inside which a given number of battery modules may be installed. Communication with the BMS will be conducted through a CAM rail. The control system allows for easy identification of a damaged or depleted battery module and allows for unproblematic replacement without a total shutdown of the entire power supply system, which is quite important from an operational perspective.

The selected battery capacity must provide a full day of continuous operation during the summer season. During navigation, the thrusters are powered from the batteries and photovoltaic panels. At night the ferry will be connected to the power grid and, due to the expected high durability of the batteries, will not be charged more than once in 24 hours. Similar watercraft are quite frequently equipped with an emergency source of electricity, either a diesel generator or an emergency battery, allowing the vessel to operate for at least 30 minutes. However, the classification society agreed, that the ferry is not necessary to be equipped with such an emergency power source. This decision was justified by the character of the navigated body of water - in particular its small size, as well as the fact that two independent propulsion and power supply systems are employed.

ENERGY BALANCE AND ENERGY MANAGEMENT

The power demand curve presented earlier is sufficient to show the energy balance of a typical ship. Consumption of electrical energy is of key importance on longer routes with the vessel travelling at a constant speed. The amount of energy required for manoeuvring, which takes only a fraction of the entire travel time, is estimated as a certain percentage of the total demand. However, in the case of the planned ferry, a different approach was necessary due to the ship's distinctive operating characteristics.

During the preliminary design phase the capacity of batteries had to be assessed, especially in the aspect of their mass. This data was required by the hull designers to determine the ship's draught and then the levels of resistance generated by the ferry hull. The parameters assumed during that stage are presented in Table 1.

Tab. 1. Initially assumed preliminary battery capacities and weights

	Power demand and capacity of main batteries	Number/ Amount	Mass	Unit
1	Daily operating time during peak summer season	12		h
2	Number of full cycles both ways in one hour	10		
3	Effective travel time both ways	4		minute
4	Average estimated power demand	12		kW
6	Hourly electric energy consumption	8		kWh
7	Daily electric energy consumption	96		kWh
8	Total battery capacity with 10% reserve	105,6		kWh
	Estimated specifications of the main battery pack			
1	Battery module 86.5V 5kWh	1	45	kg

	Power demand and capacity of main batteries	Number/ Amount	Mass	Unit
2	Number of modules	22	990	kg
3	Mass reserve (cables, protection etc.)		150	
	TOTAL:		**1185**	**kg**

The conducted model tests demonstrated that the resistance generated by such small watercraft travelling at low speeds is minor. However, the fact that about a third of the approximately 2 minute long river crossing time is spent accelerating or slowing down does create a problem. Speed distributions recorded using GPS during consecutive river crossings are very similar to each other but by no means identical. This of course stems from the fact that the vessel is controlled by a helmsman who, by manoeuvring, adjusts the speed and course to the conditions on the busy waterway. The recorded and then generalized navigational strategy employed by the helmsman was used for verifying the preliminary energy balance. The diagrams below present the speed profile of a 2 minute long river crossing and the approximate power demand based on the conducted model tests. (Fig. 5).

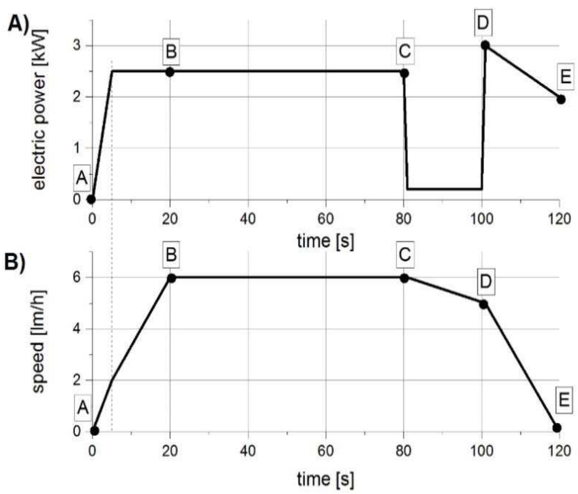

Fig. 5. Approximate power demand (A) and speed profile (B) during the 2 minute long Motława II crossing

The capital letters mark successive phases of navigation resulting from concrete steps taken by the helmsman. Following unmooring (A), the helmsman increases the engine speed and the ferry starts to gently accelerate. After approximately twenty seconds (B), the vessel reaches the speed of 6 km/h and covers most of the route at that constant pace. During that time the helmsman usually does not alter the engine speed. At a certain distance from the river bank, following approximately 180 seconds of travel, the helmsman reduces the engine speed and the ferry gradually loses velocity. In direct proximity of the berth (D), the helmsman activates the reverse gear of the propeller and the ferry starts to decisively slow down (with decrease power usage). The ferry stops and is moored at the berth (E). Successive river crossings demonstrated that time differences in performing the consecutive manoeuvres do not differ significantly. The approximate power distribution diagram (Fig. 5A) allows for initial verification of the energy balance presented in Table 1.

As the diagram indicates (fig. 3), the initially accepted average propulsion power is five times higher than the one stemming from the resistance curve and the specific character of navigation. It is worth adding that the consumption of power from the batteries may be even lower because, on sunny days, about one additional kilowatt of energy may be expected (minimum power of solar panels was set as 1 kWp). Performed calculations indicate that a single two-way ferry crossing requires approximately 0.14 kWh of electrical energy. Assuming 12 hours of daily operation in a season and ten crossings per hour, the energy demand amounts to approximately 17 kWh i.e. over six times less than initially assumed (Table 1).

If the battery capacity was limited to about 17 kWh, then, in the event of a necessary shipyard visit, the ferry travelling at a speed of 10 km/h would have the range of only 10 km. Therefore, in the opinion of the authors, the battery capacity may not be drastically reduced because of operating safety and battery life concerns, among other reasons.

Another challenging issue is the human factor. The authors are familiar with a case when an inexperienced helmsman in just four hours managed to deplete all the energy meant for a full day of operation. In view of that fact, a special training for the crew is planned. In addition, data on the power consumption of each crossing will be displayed on an information screen. The display will also indicate the crossing which consumed the least energy. This will allow for analysing and drawing conclusions as to the optimum strategy of operation.

In the opinion of the authors, the batteries should have the capacity of approximately 35 kWh. The one hundred percent energy reserve relative to the performed energy balance, should allow for ensuring a high level of energy safety even during the most intense, daily, summer season operations. It is worth adding that it is technically possible to increase the battery capacity by connecting additional modules of 5 kW capacity in RACK type cabinets installed in the battery compartments and that the maximum capacity may amount to 110 kWh (Fig. 5).

Utilizing electrical propulsion on the new vessel is of significant impact to the natural environment. As it has already been mentioned, the currently operating Motława Ferry is powered by a diesel engine of technological level dating back to the 1980s. The engine does not meet any current standards regarding emission levels. The graph below (fig. 6) illustrates its impact on the natural environment resulting from a year-long operation which on average consumes three tons of fuel.

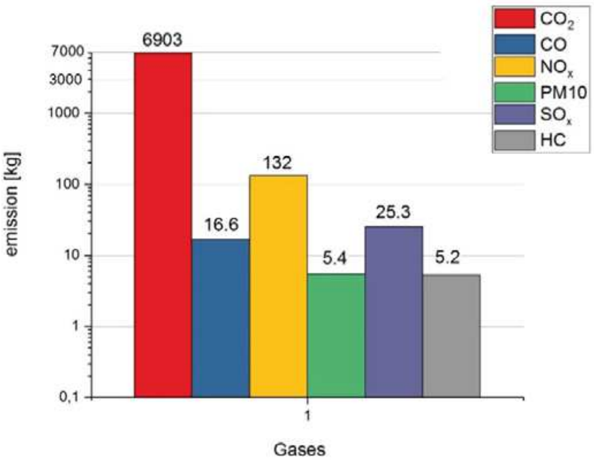

Fig. 6. Average annual engine exhaust gas emissions of the Motława Ferry. (Authors calculations)

Employing clean and quiet electrical propulsion is in line with the global trend of environmentally friendly transport i.e. green shipping. It is worth adding, that the new, increasingly strict regulations will likely lead to a complete elimination of conventionally powered watercraft from city centers, as is already the case with certain other types of vehicles.

SUMMARY AND CONCLUSIONS

Lithium batteries of considerable capacity placed in a single location constitute a significant hazard to the safety of passengers, crew and surrounding environment. In order to increase the safety level, the individual cells are enclosed in hermetic casings. The whole batteries are placed in watertight compartments. The BMS system described earlier guards, among others, against increase in cell temperature and in the event of its rise disconnects the pack from the circuit. Therefore, in the opinion of the authors, it can be stated with confidence that the system ensures a reasonably high level of safety.

Studies to be performed on the new ship will allow for assessing whether the energy balance was performed correctly. Nevertheless, the power supply system is designed in a way which allows for increasing the battery capacity if the need arises. The ferry will also be a valuable object of research which will no doubt provide very interesting data covering, among others, energy management - especially in the aspect of operating strategy's impact on energy consumption. Another future point of interest is complete automation of navigation leading to creation of an unmanned surface vessel.

Excessive weight and underestimated energy consumption of propulsion systems are among the most frequently encountered faults in watercraft design. One should bear in mind that in fact, one mistake stems from the other. The increased mass means greater resistance and therefore also a rise in energy demand.

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CONTACT WITH THE AUTHORS

Magdalena Kunicka
e-mail: magkunic@pg.edu.pl

Gdańsk University of Technology
Narutowicza 11/12, 80-233 Gdańsk
Poland

Wojciech Litwin
e-mail: wlitwin@pg.edu.pl

Gdańsk University of Technology
Narutowicza 11/12, 80-233 Gdańsk
Poland