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Analysis of the power balance of a solar catamaran

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Abstract. Significant changes are expected in the percentage distribution of vehicles in the world over the next decade. It is planned to gradually replace conventional internal combustion vehicles with electric drive ones, thereby reducing environment impacts and the production of gases contributing to the greenhouse effect. It is necessary to foster similar trends regarding watercraft, replacing the internal combustion engines with electric motors. An experiment used a solar-powered catamaran equipped with a standard electric motor Minn Kota Endura 34, a 450 W monocrystalline solar cell and a 40 Ah lithium iron 12 V battery. A pyranometer was used to measure solar energy. The experiment used a data logger GL 220 that measured the energy flow to the battery and the electric motor. The experiment was conducted in Jelgava on 5 July 2022, with the maximum altitude of the sun reaching 56.7°. The experiment identified that at an average solar intensity of 500 W m^{-2} on a sunny day, the solar catamaran could be moved by means of solar energy without discharging the batteries at all power settings.

Key words: charging, motor power, solar intensity, solar catamaran, solar panel power.

INTRODUCTION

The world's population and the technologies that contribute to pollution tend to increase year by year. One of the most significant sources of pollution is motor vehicles that are equipped with internal combustion engines. With the development of alternative technologies, there are attempts to use solar energy and biofuels in motor vehicles, e.g. in cars (Birzietis et al., 2017; Gailis & Pirs, 2017). However, at the current stage of technological progress, solar cells are capable to provide only a part of the energy required to propel vehicles (Patel, 2019). The use of solar cells in vehicles is usually constrained by the cell area and a complex solar cell control system ensuring that energy from all the solar cells is used in the most optimal way. The entire surface area of a car usually makes up to 5−6 m^2, which can provide a power output of up to 1,500 W with current technology. Since an average of 4.3 kW of power is required to propel a 1,500 kg passenger car at a speed of 50 km h^{-1}, the power output of solar cells can provide only 30% of the power required in the best conditions for solar energy generation. Therefore, a conventional electric car powered by solar cells needs additional energy to be propelled. Solar energy can be used in lightweight land vehicles such as solar tricycles as the main power source (Berjoza et al., 2021).

Solar energy is easier to use in watercraft because high power output is not required to propel the watercraft at low speeds. Equipping watercraft with solar cells is also easier because the solar cells could be used, for example, as a roof. When moving, watercraft are at a greater distance from each other than cars are, which makes it possible to place the solar cells outside the hull of the watercraft.

Using solar energy in watercraft is an interesting solution not only for light-duty watercraft but also for various recreational vessels, ferries and tourist watercraft. Watercraft could use solar panels not only as the main power source but also as a component of the hybrid energy system. Diab et al. have found that a hybrid solar- diesel energy system can reduce up to 10,000 tonnes of greenhouse gas emissions over the life cycle of the watercraft. The payback period calculated for the watercraft examined was about 3 years, while the fuel cost saved during the life cycle could reach USD 300,000. The research examined the full life cycle of the watercraft, incl. the production, operation and disposal of the watercraft. The watercraft researched was 41.98 m long, it was equipped with two 638 kW motors, and it was possible to place solar panels on the deck, the area of which reached 400 m^2 (Diab et al., 2016). The use of solar cells in watercraft made both ecological and economic effects.

Solar cells could be conveniently used as an additional source of energy in hybrid energy systems in tourist watercraft anchored to the shore for some time and waiting for tourists. During this period, the batteries are charging, and the energy could be used later, i.e. during the trip. Low-power solar cells are sometimes used in recreational watercraft to power auxiliary equipment (refrigerator, lighting). The efficiency of using solar cells increase if fossil fuel prices increase.

Vehicles differ from stationary equipment in that their orientation towards the sun changes independently during manoeuvres. Solar panels on vehicles could also be placed at different tilt angles. To maximally collect energy from the sun, Shih-Hung Koa and Ru-Min Chao propose to use a modified MPPT algorithm, which has a shorter response time and higher accuracy. The performance of this algorithm was tested on a small-sized watercraft model (Ko & Chao, 2012; Tang et al., 2017). The algorithm needs to be adjusted also in case of using different solar panels with different areas and power output. Such a combination of panels makes it possible to better use the entire surface area of the vehicle. Lan et al. have examined the effect of the tilt angle of solar panels placed on the watercraft to maximize the collection of solar energy. The research studies also examined the optimization of energy collection if part of the solar panels is shaded (Lan et al., 2015).

Due to the need to reduce emissions from sea transport, ferries are equipped with hydrogen fuel cells, the energy generated is used to charge the batteries and power two 300 kW electric motors. The next upgrade for such zero−emission ferries involves equipping them with solar cells, which would increase the efficiency of exploitation of the ferries (Letafat et al., 2020).

Mingyang Huang et al. propose using hybrid power generated from solar and wind energy and from hydrogen cells in watercraft. Such a hybrid system can pay off even in 2−3 years and make a significant contribution to the reduction of harmful emissions from the watercraft: CO_2, SO_x and NO_x (Huang et al., 2021). Carlo Beatrice et al. succeeded in reducing fuel consumption by the watercraft's hybrid system (diesel engine and electirc motor- generator with battery pack) by 6%, NO_x emissions by 11% and CO emissions by 4% (Beatrice et al., 2022). Despite the reduction in harmful emissions from the hybrid system equipped with an internal combustion engine, it was not possible to achieve emission-free operation of the watercraft, unlike is the case with solar-powered watercraft.

Syrnek K et al. researched small-sized autonomous solar watercraft. The research used three different monocrystalline solar panels with a power output of 50–70 W. At a solar intensity of 850 W m^{-2}, the research achieved a maximum power output of 41.7 W (Sornek et al., 2022).

The solar panel system of a watercraft usually also uses a battery system. If the system contains several power–consuming devices, as well as several batteries, it is necessary to develop a special system for dynamic balancing of the batteries, which increases the service life of the batteries and ensures accurate energy management for all the power–consuming devices (Zeng et al., 2021).

Chybyung Park et al. analysed the life cycle of a solar-powered boat by simulating it with MATLAB/Simulink. The simulation was performed for 29 countries that had a maritime boundary. The simulation was done for a 39.9 m long vessel, which was supposed to use 245 solar panels with a power output of 345 W each, resulting in a total power output of 84.5 kW. The research analysed the impact of generating a kW of electricity on the environment in each of the countries analysed and the average solar radiation and temperature in each of the countries. The possibility of using different batteries was also simulated, comparing 7 different ones. According to the simulation results, about two times less electricity could be collected from solar panels in the northern countries than in the southern countries during the year. This was mainly due to the horizontal placement of the solar panels; therefore, the efficiency of horizontally placed solar panels would be higher in southern countries (Park et al., 2022).

The present research aims to experimentally examine the possibilities of using solar energy in a small-sized watercraft. To achive the aim, the research conducted an experiment on a prototype of the small-sized watercraft.

MATERIALS AND METHODS

The experiment was conducted to identify the operational parameters of the solar-powered catamaran. A research methodology was developed for the experiment, which was adapted to the specific research object and water traffic conditions in a certain section of the river and the canal in Jelgava city.

Research object and measurement equipment

The experiment used the prototype of the solar-powered catamaran. A standard plastic pedal-drive catamaran Pelican Monaco was used as a basis for the construction of the catamaran. A special frame was made for the solar cell to be mounted on (Fig. 1). The solar cell also served as a roof that protected the riders from the sun. The solar cell and a controller were attached to the frame. An original frame was constructed for mounting the electric motor Minn Kota Endura 34 in it. The motor has 5 power settings for forward movement and 3 power settings for reverse movement. The 3rd, 4th and 5th electric motor standard power settings were used for the experiments. The catamaran was steered by turning the motor by means of an original control lever-rudder.

The main technical characteristics of the experimental prototype and its equipment are presented in Table 1.

Figure 1. Catamaran prototype used in the experiment.

Table 1. Main technical characteristics of the experimental catamaran and its equipment

No.	Parameter	Value
	Solar panel Longi LR4-72HIH-445M	
1.	Weight	22 kg
2.	Maximum power output	445 W
3.	Voltage at maximum power	41.3 V
4.	Current at maximal power	10.78 A
5.	No-load voltage	49.1 V
	MPPT charging controller PWM VS3024AU	
6.	Nominal system voltage	12 / 24 V
7.	Maximum solar panel voltage	50 V
8.	Nominal charging voltage	14.6 V
9.	Lowest connection voltage	12.6 V
10.	Lowest cut-off voltage	11.1 V
	Dimensions and technical characteristics of the catamaran	
11.	Weight of the catamaran and its equipment	65 kg
12.	Length of the catamaran	2.29 m
13.	Width of the catamaran	1.59 m
14.	Maximum carrying capacity of the catamaran	300 kg
15.	Height of the catamaran with the solar panel and frame	1.39 mm
16.	Weight of the prototype with the equipment	112.65 kg

A data logger Graphtec midi Logger GL220 was used to record the electrical data obtained during the experiment. The data were saved 10 times per second. The logger had a built in 4.3 inch screen, the supply voltage was 8.5–24 V. A separate 12 V 7.2 Ah battery was used to power the logger during the experiment. The data logger had 10 channels, while 5 of them were used to record battery voltage and current, motor voltage and current and pyranometer voltage data.

A pyranometer Apogee SP–500 was used to measure the intensity of solar radiation. The pyranometer was placed next to the solar cell, in the front part of it, in the same plane as the solar panel. A Garmin Edge 830 GPS logger was employed to record the catamaran’s route, path and speed. A circuit diagram for the experimental equipment is presented in Fig. 2.

Methodology of the experiment

The experiment was conducted in summer, on 5 July, during a sunny day on the Driksa canal in Jelgava city from 10.00 to 18.00. The coordinates of the canal were as follows: 56.65° latitude and 23.73° longitude. During the experiment, the height of the sun ranged from 39.3° (10.00) to 31.1° (18.00) with a maximum height of 56.1° at 13.30. The experiment was carried out on a 1,620 m long section of the canal and represented round trips (Fig. 3).

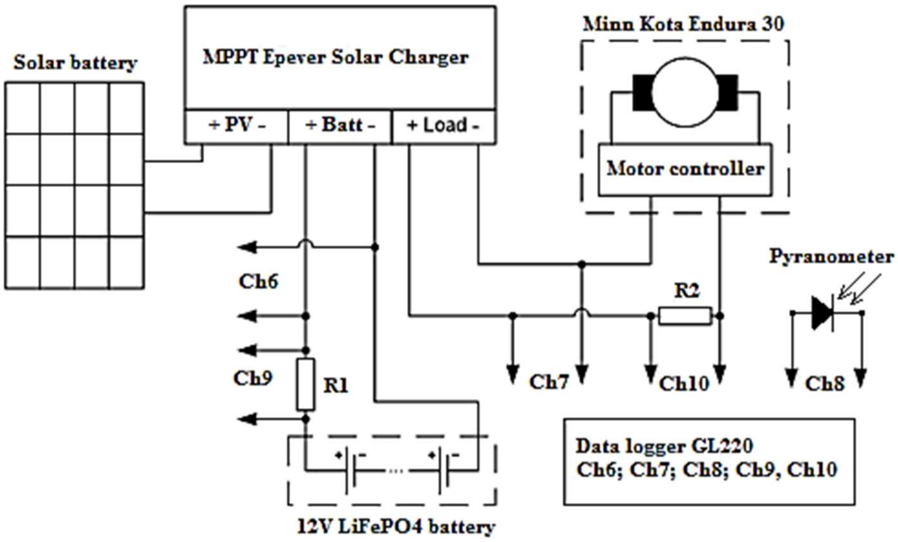

Figure 2. Circuit diagram for the experimental equipment:
Ch 6 − battery voltage; Ch7 − motor voltage; Ch8 − pyranometer voltage; Ch9 − battery current; Ch10 − motor current.

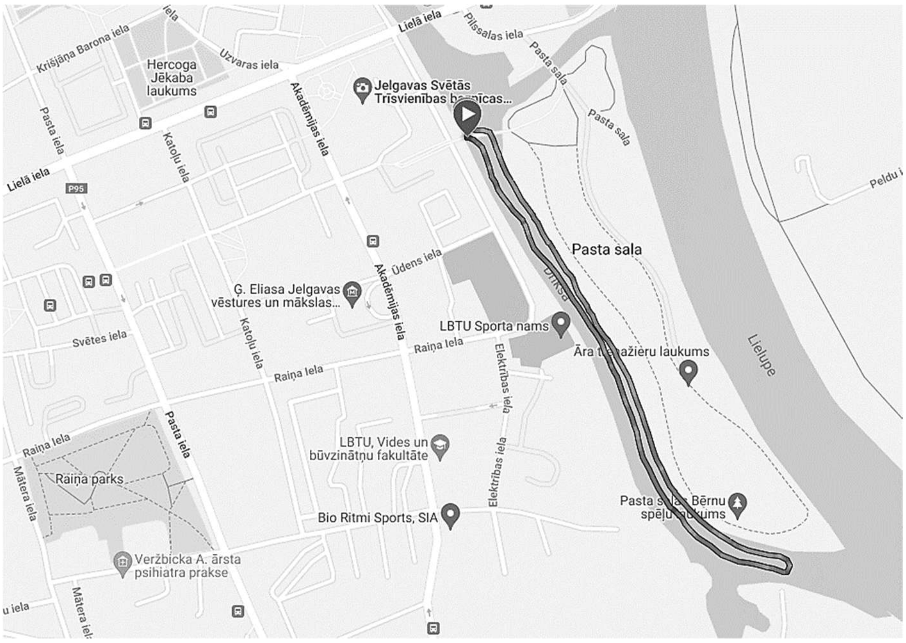

Figure 3. Experimental section of the Driksa canal.

The round trips were made to take into account the speed of the water current (less than 0.1 m s^{-1}) and the effect of wind speed (less than 0.2 m s^{-1}). The experiment was performed by two operators. One operator steered the catamaran, while the other turned on and off the measuring devices. The experimental trips were made in compliance with all water traffic rules for the Driksa canal. The experimental trips were made at power settings 3, 4 and 5 and repeated five times. The experimental trips were also made at power settings 1 and 2; however, since these power settings were not used for normal movement of the catamaran but only for manoeuvring, the experiment was not carried out in full at these power settings. The movement of the catamaran started when the data storage devices were turned on, while the data recording was stopped 5–10 seconds after the catamaran stopped.

RESULTS AND DISCUSSION

During the experiment at power setting 5, the catamaran completed the route in 1,653 seconds at an average speed of 3.67 km h^{-1} (Fig. 4). During a replication of the experiment, the average height of the sun above the horizon was in the range of 52.70−54.48°. In the graphs, negative values of battery power output show battery charging from the solar cell, while positive values show power consumption for running the motor. At the early stage of the experiment, i.e. up to the 625^{th} second, power consumption from the battery tended to be low, ranging from 10 to 66 W. At the next stage of the experiment, the catamaran stopped, as evidenced by a decrease in the motor's power output from 325 W to 0 W. At this moment, there was an excess of solar energy, and all of it was used to charge the battery, decreasing from 320 W to 116 W. The battery was charged at the maximum charging current set, reaching a maximum wattage of 280 W, which decreased to 140 W in 5 seconds during the replication.

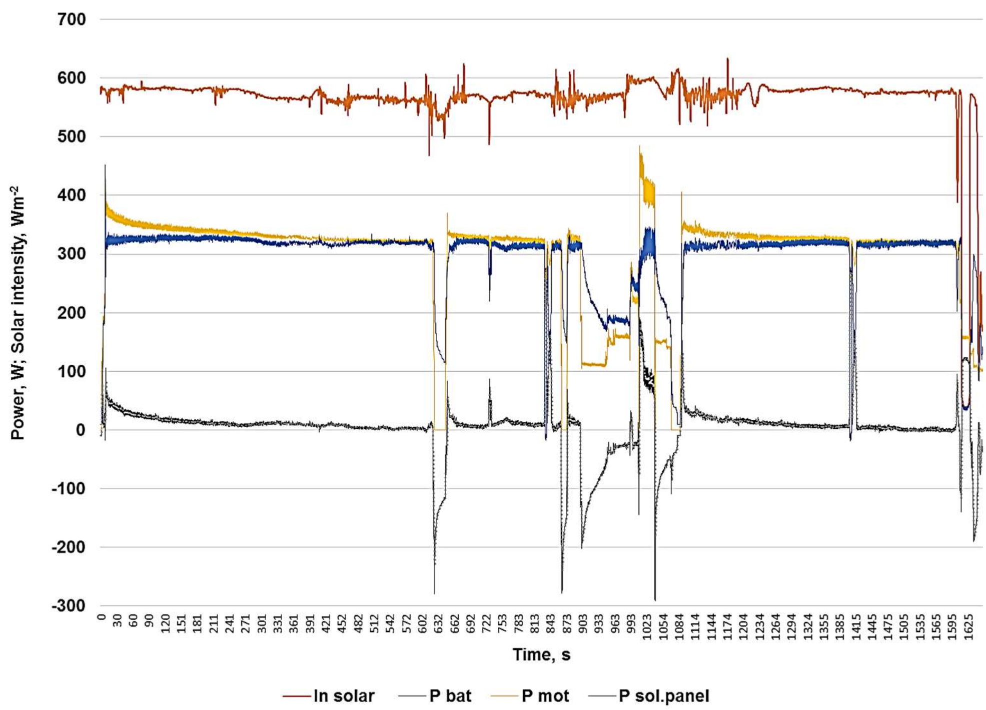

Figure 4. Power balance of the catamaran at power setting 5 and solar radiation.

During the entire experiment, almost the entire power output consumed by the motor could be provided by the solar cell, and a deficit of power was on average 3–4%. Motor power output peaks, which reached 450 W, could be explained by a significant increase in the load on the motor when waterweeds were wound on the propeller. Under this regime, additional energy was consumed from the battery. The temperature of the solar cell was not measured during the experiment; however, due to the fact that the average air temperature during the experiment was 22–26 °C, the efficiency of the solar cell might decrease because the solar panel overheated. During the replication, an average power output of the electric motor was 298 W, while the power output of the solar cell was 294 W, which means that the insignificant deficit of power was offset by the battery. At this stage of the experiment, the solar cell was fully able to provide the catamaran with the energy needed for its movement.

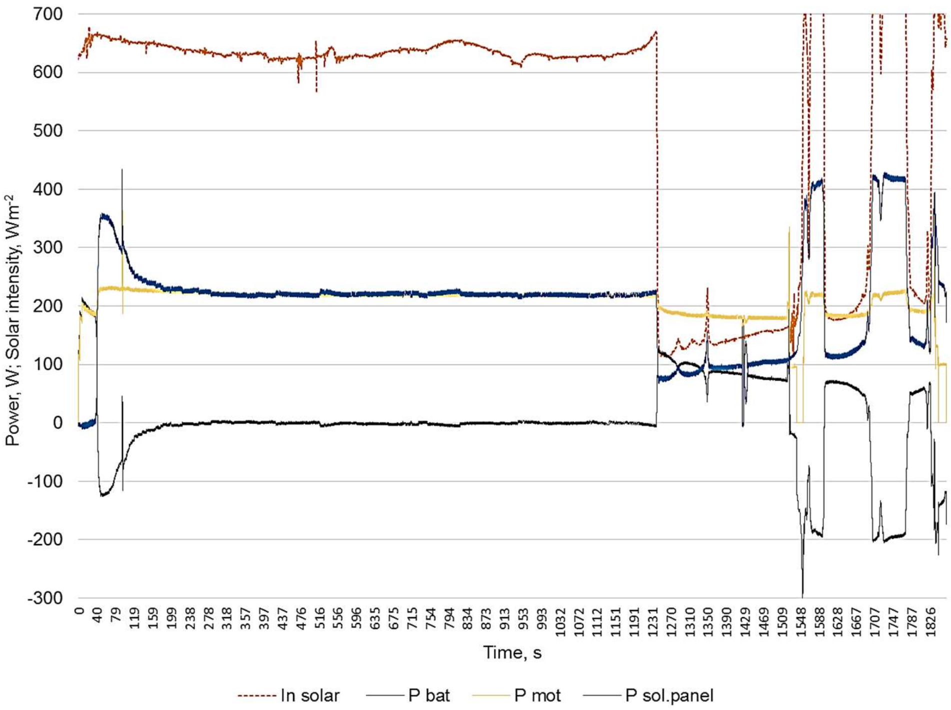

Figure 5. Power balance of the catamaran at power setting 4 and solar radiation.

During the replication at power setting 4, the intensity of solar radiation varied (Fig. 5). The replication lasted for 1,862 seconds, and the catamaran reached an average speed of 3.13 km h^{-1}. During this replication, the average height of the sun above the horizon was in the range of 56.07–55.94°. At the initial stage, the solar radiation intensity reached an average of 660 W m^{-2}; however, with the appearance of clouds at the 1,240th second, the solar intensity decreased rapidly to 115 Wm^{-2}. At this stage, the power output of the solar cell decreased from 223 W to 75 W. At this moment, the MPPT controller switched the power supply for the motor to the battery that provided the missing average power output of 110–115 W. At this stage, a decrease in the motor's power output was also observed because when the motor was powered from the solar cell, an average voltage of 14.05−14.10 V was supplied to the motor, but when powering it from the battery, the voltage decreased to 12.80−13.00 V.

According to a subjective assessment of the operators of the catamaran, a decrease in its speed due to a decrease in the motor's speed was also observed during this period. After the previous replication of the experiment, the battery was slightly discharged, as evidenced by an increase in the power output of the solar cell to 348 W at the 46th s of the replication. The battery charging power ranged from 126 W at the highest discharge rate, gradually decreasing to 0 after 140 seconds. Similar periods of battery charging could also be observed after solar intensity decreased at the 1,525th and 1,697th seconds. During the replication analyzed, the average power output of the motor was 207 W, while the power output generated by the solar cell was 205 W. At the maximum solar intensity, the solar cell could fully provide the energy required for running the catamaran. When the solar intensity decreased, the energy was supplied from the battery, but when the solar intensity increased, the battery was charged for a short period.

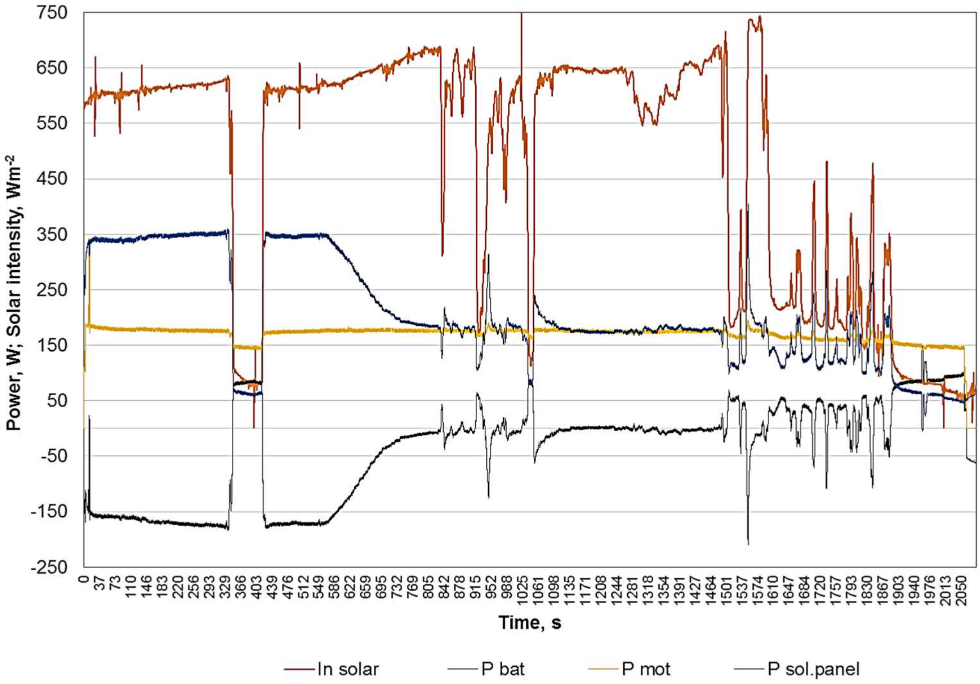

Figure 6. Power balance of the catamaran at power setting 3 and solar radiation.

During the replication at power setting 3, solar intensity was very variable and varied from 685 to 60 W m^{-2} (Fig. 6). During this replication, the average height of the sun above the horizon was in the range of 52.84−54.97°. The replication lasted for 2,084 seconds and the average speed of the catamaran was 2.80 km h^{-1}. A relatively high battery discharge rate was characteristic of this trip. The average power output consumed by the motor during the trip was 171.1 W. Unlike other replications, the average battery charging power was 35.7 W during the trip. At the early stage, the replication was started with a semi-discharged battery. The solar cell generated a power output of 335−360 W from the 25th to 336th second of the replication and could provide both the motor with a power output of up to 175 W and charged the battery at a power of 161−184 W. There was a significant decrease in solar intensity at the 340th second. The motor's power output decreased to 143.6 W because the battery supplied only an average voltage of 12.1 V. After the solar intensity increased at the 417th second, the battery charging resumed, which continued at a constant rate up to the 570th second; the charging rate gradually began decreasing, and at the 830th second it decreased to 0. Proportionally, the controller also decreased the power output generated by the solar cell, which approached the power output consumed by the motor. At the next stage of the replication, the solar intensity was variable, yet the largest decrease in it was observed at the end of the experiment. Due to the relatively low power output consumed by the motor at power setting 3 even at a low solar intensity of 280−300 W m^{-2}, the solar cell could provide the motor with the energy needed to move the catamaran.

Based on the experimental data, on a sunny day with a solar intensity of more than 500 W m^{-2}, the solar catamaran could be equipped with a low capacity battery. The distance covered by the catamaran at all the highest power settings is unlimited as long as the solar intensity required is available. Solar-powered watercraft are usually used at lower latitudes than the one at which the experiment was conducted. Similar experiments are not widely available in the literature, and the experimental data are difficult to quantitatively compare with those available in other sources.

CONCLUSIONS

1. An original methodology for identifying the power parameters of slow−speed electric drive watercraft was developed and tested.

2. An analysis of the results of the experiment revealed that an average speed of the catamaran was 3.67 km h^{-1} at power setting 5, 3.13 km h^{-1} at power setting 4 and 2.80 km h^{-1} at power setting 3. The relatively low speed could be explained by the catamaran's imperfect waterline shape and high hydraulic resistance.

3. At stabilized speed, the power output consumed by the electric motor was 330−335 W at power setting 5, 220−225 W at power setting 4 and 172−175 W at power setting 3. When the intensity of solar radiation decreased, it was necessary to lower the catamaran's power setting to achieve a longer distance because it did not significantly affect the speed of the catamaran.

4. In case the power output generated by the solar panel was higher than the power output required to move the catamaran, the controller absorbed the excess power output or, in the case of the partially charged battery, charged the battery.

5. When the battery of the catamaran was fully charged and the potential power output of the solar cell was higher than that required to power the motor, the controller reduced the power output of the solar cell, which was brought closer to the power output required to run the motor. This was characteristic of power setting 4 from the 200th to the 1,200th second of the experimental trip.

6. When anchored in the port, the catamaran's solar cell can charge the battery, which allows the catamaran to start its movement with a fully charged battery, and no battery charging from the port network connection is required.

7. In cases where the battery was not fully charged and the catamaran was operated at the first three power settings, the battery was charged at a power of 170−180 W.

8. When the intensity of solar radiation decreased below 200 W m^{-2}, the motor was powered by the battery; however, the power output of the motor decreased slightly because of a voltage drop of on average 8−9%. During this period, a decrease in the motor's speed and a decrease in the catamaran's speed were also observed.

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