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Analysis of the opportunity to implement solar-thermal systems on ships. Case study: The voyage of a cruise ship in the Black Sea

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Abstract. The global energy consumption is steadily increasing, thus increasing the greenhouse gas emissions from the energy-consuming processes reaching the atmosphere. The main consequences are the accelerated decrease of the raw materials resources and the environmental pollution with direct effect on the population quality of life. One applicable solution is represented by the use of renewable energy sources, to replace fossil fuels used as main input in energy production. This paper analyzes the possibilities to implement renewable sources on board of ships, the main objective being to reduce the fossil fuel consumption required for the transportation activity with direct effect on reducing the polluting emissions. One solution consists of implementing solar-thermal collectors on board ships and identifying the opportunities for using the thermal energy obtained. The case study presented outlines the benefits of installing a solar thermal system on a cruise ship during a voyage in the Black Sea.

Keywords: cruise ship, solar-thermal conversion, fossil fuel economy.

1. Introduction

The extensive use of fossil fuels as main energy resource leads to the natural resources depletion and to adverse effects on the environment (climate change and global warming) and on the population. Thus, air pollution, largely due to the energy production processes required for various activities, is responsible for 18,000 daily deaths or 6.5 million annually [1]. To prevent and counteract these negative effects, environmentally friendly solutions are required and this paper focuses on ensuring the thermal energy on board commercial vessels by identifying a sustainable

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solution, meeting the following main objectives: (1) to reduce the dependence on traditional (fossil) fuels and (2) to reduce greenhouse gas (GHG) emissions. Currently, international shipping accounts for about 80% of the global trade (in volume) and over 70% of its value. Consequently, the CO_2 emissions in this sector were 870 million tons in 2007, representing 2.7% of the global CO_2 emissions. In 2012, the share dropped to 2.2% mainly as a result of the global economic crisis, but it is supposed to increase by 50-250% till 2050 as result of developing the global economic exchanges [2].

The main directions for improving energy efficiency and reducing CO_2 and other GHG emissions in shipping have been established by the International Maritime Organization (IMO) and are assessed through the Energy Efficiency Design Index (EEDI). These includes developing naval logistics policies, modifying the shape of the ship, developing the propeller, increasing the total load capacity by increasing the size of the ships, the use of recovered energy from exhaust gas and the use of energy from renewable sources. Solutions based on renewable sources mainly focus on the use of solar and wind energies and, in the future, on wave energy [3]. Considering the use of solar energy, there are certain developments related in particular to its conversion into electricity, while the conversion to thermal energy is limited approached [4, 5] so far. Thus, this paper analyzes the opportunity of installing solar-thermal systems on board a cruise ship during a voyage in the Black Sea, providing information about the thermal energy obtained, the fuel savings, as well as the effect on reducing the impact at communities level in the neighborhood of the ports by assessing the amount of CO_2 that is no longer released in the atmosphere.

2. Methodology

The evaluation of the thermal energy obtained from solar-thermal systems implemented on ships has certain specifics compared to fixed (land-based) systems. Among these are the following: the variable latitude (due to the ships movement between different points), the orientation of the collectors towards the Sun (influenced by the movement direction), the influence of other marine parameters (humidity, salinity, degree of pollution, etc.).

To assess the opportunity of using solar-thermal systems on board installed on a vessel, the following methodology was followed:

- The voyage of the ship is designed, considering the ship's specifics, the travel route and the period of the year when the voyage is done;
- The thermal energy produced using the solar-thermal systems is evaluated, by estimating the solar radiation and the parameters on which it depends and the solar-thermal system efficiency;
- The output thermal energy is correlated with the fuel savings and with the amount of CO_2 that no longer reaches the atmosphere because of this savings.

Fig. 1. Cruise ship highlighting the available surfaces for implementing solar-thermal collectors.

Table 1. Main characteristics of Spirit of Chartwell (www.douroazul.com)

Passengers	30
Crew	10
Tonnage [t]	485
Maximum length [m]	63.87
Maximum width [m]	6.72
Installed power [HP]	2 X 350
Maximum speed	11 knots (≈20 km/h)

The *Spirit of Chartwell* cruise ship (Fig. 1) was selected as reference vessel; its main characteristics are inserted in Table 1. The ship is equipped with two Scania engines of 350HP each (257 kW), with the specific power consumption of 203 g/kWh at maximum to ¾ load and 207 g/kWh at ½ load.

The voyage of the ship was considered in the Black Sea area as presented in Fig. 2; the time interval needed to visit the main touristic sites in the area during the favorable period of the year when the voyage is recommended was estimated and are included in Table 2. Thus, the first day of the voyage was considered the 1st of August, the stationing time length in each port is about two days, and the speed of the ship during the voyage was considered 10 knots.

Fig. 2. Scheme of the voyage.

The voyage starts in Odessa (Ukraine) and continues to Constanta (Romania), Varna (Bulgaria), Istanbul (Turkey), Batumi (Georgia), Novorossiysk (Russia) and ends in Odessa.

As Table 2 shows during the voyage the ship sails 1595 nautical miles, and at the speed of 10 knots this distance is traveled in 160 hours (about 7 days). The remaining 12 days are allocated to sightseeing activities in the ports. The voyage is runs between 46°28'N (Odessa) and 41°14'N (Istanbul) for latitude, respectively 27°58'E (Varna) and 38°21'E (Batumi) for longitude. The positioning during voyage (especially through latitude) is relevant for estimating the available solar radiation, and small differences as in this case lead to predictability in estimating solar radiation and the recommended tilt angle of solar-thermal collectors.

Table 2. Main characteristic features of the voyage

Point	Port	Position		Arrival	Departure	Distance on sea between ports [Nautical miles]
		Latitude	Longitude			
1	Odessa	46°28'N	30°49'E	-	01.08 / 08.00	-
2	Constanta	44°05'N	28°43'E	02.08 / 04.00	04.08 / 08.00	173
3	Varna	43°11'N	27°58'E	04.08 / 16.00	07.08 / 08.00	76
4	Istanbul	41°14'N	29°07'E	07.08 / 21.00	10.08 / 08.00	149
5	Batumi	41°39'N	38°21'E	12.08 / 17.00	15.08 / 08.00	586
6	Novorossiysk	44°38'N	37°52'E	16.08 / 10.00	18.08 / 08.00	249
7	Odessa	46°28'N	30°49'E	19.08 / 22.00	-	362

To evaluate the thermal energy that can be produced by converting the solar energy, it is necessary to assess the global solar radiation, by in situ measurements or by generated analytical data. As there was no possibility of continuous measurements on sea, the use of empirical methods derived from statistical data processing was used to obtain the values corresponding to the global solar radiation. There are certain reliable computational models in literature [6-8], and this paper uses a model developed and tested during the Danish Galatea III expedition [9], an expedition that run between August 2006 and April 2007. According to this model, the direct irradiance on the horizontal plane at sea level is:

$$B_H = I_0 \cdot \sin\alpha \cdot e^{-0.8662 \cdot T_R \cdot m \cdot \delta_R} \qquad (1)$$

where I_0=1367 W/m^2 is the solar constant, α is solar elevation angle, T_R is Linke factor (or turbidity factor), m is the air mass defined by equation (3) and δ_R is optical transparence defined by equation (2).

$$\delta_R = \left[\left(6.6296 + 1.7513 \cdot m - 0.1202 \cdot m^2 + 0.0065 \cdot m^3 - 0.00013 \cdot m^4\right)\right]^{-1} \qquad (2)$$

$$m = \frac{1.002432 \cdot \sin^2\alpha + 0.148386 \cdot \sin\alpha + 0.0096467}{\sin^3\alpha + 0.149864 \cdot \sin^2\alpha + 0.0102963 \cdot \sin\alpha + 0.000303978} \qquad (3)$$

or $m = \frac{1}{\sin\alpha}$ for α > 25°.

Diffuse irradiance on the horizontal plane is defined by:

$$D_H = \left(49.04 \cdot T_R - 42.32\right) \cdot \left(1 - e^{0.1 \cdot T_R - 0.0908\alpha}\right) \qquad (4)$$

Based on the direct and diffuse solar radiation in the horizontal plane, global radiation was calculated in the plane of the collector surface, using eq. (5), (6) and (7).

$$B_\chi = \frac{B_H}{\sin\alpha} \cdot \cos\nu \qquad (5)$$

$$D_\chi = D_H \cdot \frac{1 + \sin(90 - \chi)}{2} \qquad (6)$$

$$G_\chi = B_\chi + D_\chi \qquad (7)$$

where: ν is solar incident angle, χ is tilt of collector, and B_χ, D_χ and G_χ are direct, diffuse and global radiation in the plane of the collector surface.

The main unknown is the turbidity factor T_R (Linke factor) that needs to be adopted based on available online resources (www.soda-pro.com) when the ship is in the harbor and based on the mathematical model developed for the voyage period [10]. Attention must be paid when considering Linke factor for land and for the sea, because its variability over sea is much lower compared to the land.

According to the model during the analyzed period (August, warm season), the turbidity factor during the voyage between harbors is:

$$T_{R_{rel}} = 0.8516 \cdot \varphi_{rel}^5 + 0.6180 \cdot \varphi_{rel}^4 - 1.1190 \cdot \varphi_{rel}^3 - \\ - 0,8947 \cdot \varphi_{rel}^2 + 0.3973 \cdot \varphi_{rel} + 0.7337 \tag{8}$$

where: $T_{R_{rel}}$ is the relative turbidity factor, considered as the value of the turbidity factor divided by 5 (5 being the maximum factor for sea); φ_{rel} is the relative latitude obtained by the ratio between the real latitude and the maximum possible value, 90°.
The evaluation of the solar-thermal energy also depends on other parameters that were considered in this case as follows:

- System efficiency, considered $\eta = 50\%$ (since the efficiency of the collectors generally exceeds 80%);
- Collector tilt angle relative to the horizontal plane, chosen according to the geographical position and the period of the year, hourly;
- The orientation of the solar collectors towards the Sun; the collectors tracking aims at hourly following the Sun in the East-West direction.

The variability of the turbidity factor and of the tilt angle during the voyage are presented in Fig. 3.
As expected, the turbidity factor has higher values in ports than on the sea (with a maximum of 4.5 in Batumi) due to pollution and humidity.

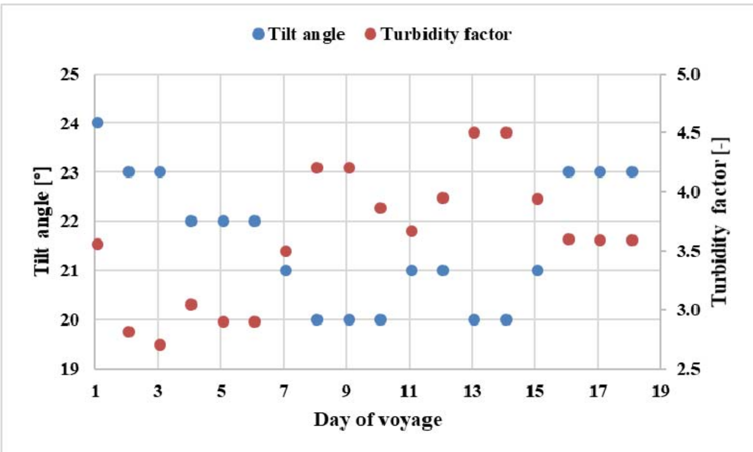

Fig. 3. Turbidity factor and tilt angle during voyage.

The analysis also considered the case when the collectors are horizontally positioned. The thermal energy of the solar-thermal system resulting from the solar energy conversion was calculated based on eq. (9).

$$E_{STS} = E \cdot A_{abs} \cdot \eta \tag{9}$$

where: E is solar energy (Wh/m^2), A_{abs} is the absorber area (m^2) and η is the efficiency of the solar-thermal system.

3. Results and discussions

Based on the solar radiation model and considering the parameters and their specifics (the location, period of the year, land or sea, etc.), as well as the characteristics of the solar-thermal system (with 50% efficiency and an absorber area of 40 m^2, 1 m^2 for each person on board), the thermal energy delivered by the system, its possible uses on board, the amount of fuel saved by using this energy and the amount of CO_2 not reaching atmosphere were calculated. In Fig. 4 there are presented the daily average global radiation and the daily average thermal energy for the case of tracked collectors.

The daily average energy value in Fig. 4 was calculated by dividing the daily sum of hourly global radiation and hourly thermal energy by 24, or less for the first and last day of the voyage. Analyzing the values, it results that the difference between minimum and maximum of parameters (except the first day) is about 19%. This percentage is influenced mainly by the day of the year (through the angles that characterize the solar radiation), and by latitude. Thus, the thermal energy that can be obtained during the entire duration of the voyage is 3580 kWh when using tracked collectors and 2835 kWh when using horizontally mounted collectors. Thus, at least for the chosen voyage period, the solar thermal collectors using tracking systems generates with about 20% thermal energy more compared to the horizontally mounted ones.

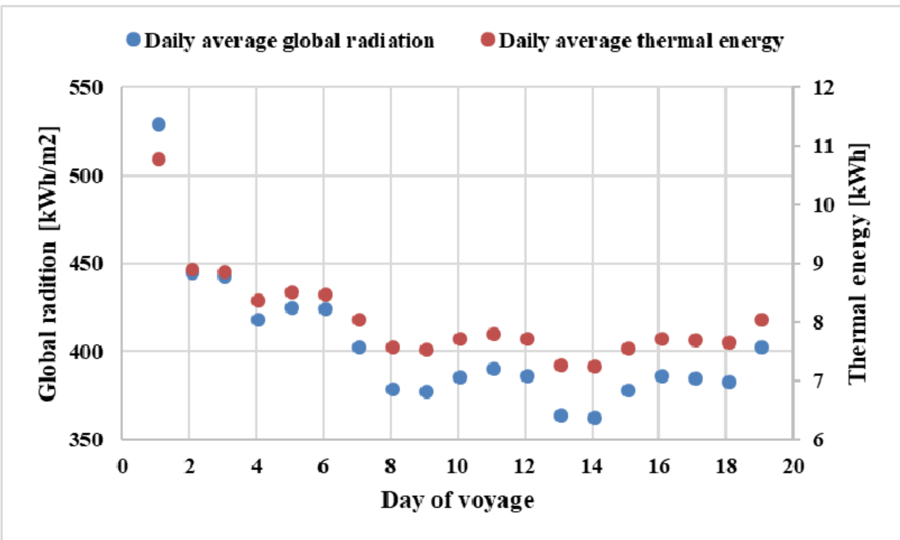

Fig. 4. Daily average global radiation and thermal energy for tracked collectors

The thermal energy delivered by the solar-thermal system corresponds to an amount of saved of fossil fuel and thus of CO_2 that does not reach the atmosphere. The fuel used on board is Diesel with a specific heat of $Q_i = 42000\left[\dfrac{\text{kJ}}{\text{kg}}\right]$. The amount of fuel m saved by using the thermal energy delivered by the solar thermal system can be calculated (considering that 1 kWh = 3600 KJ):

$$m = \frac{E_{STS} \cdot 3600}{Q_i} \text{ [kg]} \tag{10}$$

where: E_{STS} is the energy produced by the solar thermal system (in kWh), and Q_i is the specific heat of the fuel in (kJ/kg).

Using eq. (10) the amount of saved fossil fuel is $m = 306.8$ kg when using tracked collectors and $m = 243.0$ kg for the case of horizontally positioned collectors. If these amounts of fuel are not burned, 955.4 kg of CO_2 will not reach the atmosphere when using tracked collectors, respectively 756.7 kg of CO_2 when using horizontally mounted collectors. Compared to the ship's total voyage consumption of 16688 kg, at the rated speed of 10 knots, 160 hours of march and a specific consumption of the engines of 104.3 kg/h) these amounts represent a fuel saving of 1.83% and, respectively 1.45 %. Although the amounts are relatively small, it should be noted that for a ship owner with many vessels, the cumulated fuel savings may be relevant, considering that the fuel cost is the most important operating expense.

One of the uses of this energy is for DHW preparation, the water needed to meet the daily needs of the passengers and onboard staff. Based on the previously calculated values, the amount of domestic hot water that can be produced through solar-thermal conversion during the voyage is given by:

$$DHW = \frac{E_{STS}}{c \cdot \Delta t} \tag{11}$$

where: $c = 4.18\left[\dfrac{\text{kJ}}{\text{kg} \cdot \text{K}}\right] = 0.001161\left[\dfrac{\text{kWh}}{\text{kg} \cdot \text{K}}\right]$ represents the specific heat of water, $\Delta t = 40^\circ\text{C}$ is the temperature difference between the DHW temperature (50°C) and the temperature of water before preparation (10°C).

By applying eq. (11) a volume of domestic hot water of 77090 L results for the tracked collectors and 61046 L for the horizontally mounted collectors. Considering that the voyage runs for 19 days, a daily total amount of 4057 L is obtained in the first case and 3213 L in the second case. These DHW production fully meets the needs of the onboard personnel (40 people), considering a daily consumption of 50 ... 100 L/person. Also, a potential heat excess can be stored in tanks specially designed for a temperature of 90°C (e.g. as a backup during cloudy days) or can be periodically used (weekly) to rise the DHW temperature above 60°C, to prevent the development of bacteria in the distribution piping and storage tanks [11, 12].

3. Conclusions

The use of renewable energy resources on ships can contribute to reducing the dependence on fossil fuels and the impact of shipping on the environment. This study analysis the opportunity and benefits of implementing a solar thermal system on a cruise ship during a Black Sea voyage. The main conclusions of the researches are:

- The thermal energy that can be obtained from the solar thermal conversion leads to relatively low fuel savings (1.45% ... 1.83%) compared to the propulsion system consumption on the ship;
- The use of the output thermal energy for domestic hot water preparation can 100% meet the daily needs for on-board personnel during the analyzed period of the year;
- The fossil fuel savings support the reduction of the CO_2 emissions, which are important for the health of communities located in the neighborhood of ports or on the inland waters (rivers).

To further validate and optimize this study, future research will consider the implementation of a solar-thermal system onboard a vessel. To insure the energy autonomy and independence of ships and to protect the environment, it is necessary to consider the combination of more renewable energy sources. Additionally, policies are needed to encourage ship owners to implement green technologies (based on solar energy conversion) on board ships by providing financial benefits to the operation of green ships.

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