PRESENT AND FUTURE OF RENEWABLE ENERGY SOURCES ONBOARD SHIPS. CASE STUDY: SOLAR – THERMAL SYSTEMS

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Abstract: In recent years, sustainability in a climate and an environmental perspective has become an issue of highest priority. This is an agenda that cannot and should not be ignored. The financial crisis has revealed a vulnerable global society. Fortunately, the latest developments have shown signs of recovery thanks to deliberate and well-coordinated global political actions which have created new confidence among companies and consumers. This political commitment can be seen as recognition that global production and trade create wealth for all of us, with shipping and associated maritime industries as the primary enablers. In order to keep focus on the important agenda of sustainable and green shipping attention must turn towards innovation and efficient regulation. Nowadays, shipping industry is dependent on fossil fuels. As oil price is constantly increasing, solutions must be found in order to ensure industry sustainability. Developing and implementing energy efficient and environmentally friendly technologies for energy production and propulsion of the ship will conduct to a valid non-fossil future. In this context, present paper makes a review of alternative sources of energy used in shipping and also reveals concepts of future ships. The novelty is represented by authors vision regarding implementing solar thermal systems onboard, in order to comply with thermal need of the ship.

Keywords: shipping industry, renewable energy, solar thermal

INTRODUCTION
Approximately 80% of world trade by volume is carried by sea [1]. In 2007 international shipping was responsible for approximately 870 million tonnes of CO₂ emissions, or 2.7% of global anthropogenic CO₂ emissions [2]. Domestic shipping and fishing activity bring these totals to 1050 million tonnes of CO₂ or 3.3% of global anthropogenic CO₂ emissions. Despite the undeniable CO₂ efficiency of shipping in terms of grams of CO₂ emitted per tonne-km, it is recognized within the maritime sector that reductions in these totals must be made. Shipping is responsible for a greater percentage share of NOx (37%) and SOx (28%) emissions [3] and recent legislation is aimed at reducing these emissions through the introduction of emission control area and requirements on newly built marine diesel engines [4]. The base scenarios regarding CO₂ emissions from shipping from 2007 to 2050, modeled by International Maritime Organization (IMO), indicate annual increases of CO₂ emissions in the range 1.9–2.7% with the extreme scenarios predicting changes of 5.2% and -0.8%, respectively. If global emissions of CO₂ are to be stabilized at a level consistent with a 2°C rise in global average temperature by 2050 it is clear that the shipping sector must find ways to stabilize, or reduce, its emissions - or these projected values will account for 12–18% of all total permissible CO₂ emissions.

The European Union (EU), in the strategy described in [5], marks a turning point in the protection policy against atmospheric pollution from vessels. 42% of the EU’s domestic shipping and 90% of its trade with non-European countries is transported by sea. The energy consumption and CO₂ emissions per ton and mile traveled by ship is approximately 25% of fuel consumption by road. Therefore, the EU has established as a fundamental strategic objective the reduction of polluting and greenhouse gas emissions by transferring the transport of goods by road to motorways of the sea. Despite these measures, it is estimated that, by 2020, vessel emissions of sulphur oxides (SO₂), nitrogen oxides (NOₓ) and particulate matter (PM2.5) in EU waters will increase by 40%, 50% and 55%, respectively, compared with 2000 levels.

Studies made by the International Council on Clean Transportation [6] and IMO [2] concur on the range of technological and operational strategies available to the current global fleet [7]. In 2010, IMO introduced “Technical measures”, “Operational measures” and “Economic instruments” as instruments for reducing CO₂ emissions. IMO also introduced the Energy Efficiency Design Index (EEDI), as the index for evaluating the technical measures [8]. It is expressed in grams of CO₂ per ship’s capacity mile, and a smaller EEDI value indicates a more energy-efficient ship design. The far more complex EEDI formula itself may be roughly simplified as: EEDI = CO₂ Emission/Transport Work; broadly then, EEDI may be thought of as a ship’s carbon dioxide output divided by its cargo-carrying capacity. From the EEDI equation, it appears that the main categories of EEDI reduction technologies and opportunities include the following:

- Policy issues on shipping logistics;
- Modified hull form (reduction in propulsion resistance);
- Modified propeller (enhanced propulsion efficiency);
- Energy-saving appendages on hull;
- Increase in deadweight capacity by increasing the hull size;
- Use of energy from exhaust heat recovery;
- Use of renewable energy (wind, solar, etc.).

Further on, there are presented some alternative sources of energy used in shipping industry, some innovative solutions identified by researchers and our vision regarding technical solution that is not yet taken into consideration in review literature. These efforts are made for reducing emissions from ships and, as ultimate goal, obtaining a zero emission vessel.

ALTERNATIVE SOURCES OF ENERGY IN SHIPPING
Several alternatives are proposed to reduce or to replace fossil fuels onboard a ship: sails, kites, receive electricity in ports, use of biodiesel, wind turbines, photovoltaic modules and hydrogen fuel cells. They can be used on their own or in conjunction with what are called hybrid systems for power generation onboard a ship. These are green energy generation systems that use renewable or clean energies.

Sails and Kites
The sole function of sails and kites will be to assist the propulsion of the vessel. Both systems, through the use of wind power, will provide savings in the fuel consumed by the ship’s main engine.

In 1995, the Danish Department of Environment and Energy subsidized a study by the consultancy firm, Knud E. Hansen A/S, to look into sail propulsion for merchant vessels. As a result, the company between 1995 and 1999 developed a model tanker of 200 m length and 50,000 dwt designed to transport oil products, with sail-assisted propulsion in the form of wing sails. The feasibility studies for this project reached to the following conclusions
s-rbines energy from the wind acts on it. Electricity produced by wind turbines will have advantages to a scale: less conventional diesel consumption; a neat deck. The main function of this group of alternative sources will be to generate electrical power for auxiliary systems, although they will also be able to provide propulsion. Biodiesel is a fuel derived from biomass for diesel engines. Taking into account that almost all propulsion and power generation systems for merchant ships now consist of diesel engines, it is clear that biodiesel can play a role in this sector. As advantages can be mentioned: significant reduction in the pollutants emitted into the air; it biodegrades in watery solutions, degrading between 85% and 88% in a 28-day period; it can be used in any conventional diesel engine and can be stored in the same tanks as diesel. Without any additional modifications or investment; the energy balance is positive, with a ratio of 1 (input/2.5/output). Disadvantages consist in: high production costs, about twice that for diesel oil; market price is higher than that of conventional diesel for ships; it has harmful effects on the environment: destruction of forest and jungles for this type of crop and increased emissions of nitrogen oxides (NOx); the refueling infrastructure for ships at port is still in the early stages of development; the current production of biodiesel is around 10% of the global market of diesel; problem of space: producing one tonne of biodiesel requires three hectares of cropland.

The wind turbines energy from the wind acts on the blades, making a generator spin. This in turn converts rotational mechanical energy into electrical energy. Their characteristics are: use of wind’s clean and renewable energy, installation is made on the vessel’s open deck and energy production is not continuous owing to the random existence of adequate wind conditions. Their most significant application in vessels is as part of a hybrid energy system, working in combination with hydrogen fuel cells. Thus, the electricity produced by wind turbines will be used to generate hydrogen through the electrolysis of water and this is used to charge the cells.

The most developed wind turbines are those of the Horizontal Axis Wind Turbines (HAWT) type, an excellent method of generating electrical energy. Their application on merchant ships is very attractive considering that the wind force is greater at sea than on land and, hence, a better performance is yielded. The technical feasibility of onboard installation can be analyzed based on their main dimensions: blade diameter, the axis rotation height, base diameter and weight.

Vertical Axis Wind Turbines (VAWT) performs better than HAWTs with air turbulence, changes in wind direction and high-speed winds. Owing to their low altitude they also have less impact on the ship’s stability, and this in turn makes their maintenance easier. However, they produce 50% less energy than HAWTs. This means that, to produce similar power, VAWTs require significantly larger power and energy density, enable a navigation time that is unmatched to date. Another example is Nichio Maru, a massive roll-on-roll-off coastal transporter ship, equipped with 281 photovoltaic solar modules mounted above deck. Producers, Nissan, state that the ship will lower its fuel bill by 1,400 tonnes of diesel per year, and lower carbon emissions by 4,200 tonnes [20].

Hydrogen fuel cells are electrochemical devices that can convert the chemical energy contained in hydrogen into electrical energy, yielding water as the only by-product. They are similar to batteries, except that they are designed to produce electricity continuously, provided that hydrogen and oxygen are supplied from an external source. Batteries, on the other hand, have a limited capacity [9].

Since the infrastructure needed in ports for ships to refuel hydrogen is not even in the design phase, ships carrying hydrogen fuel cells will need a short and medium term means of producing and storing hydrogen onboard. An interesting application on ships is by means of water electrolysis, a process in which electric current passing through water produces a dissociation of its molecules into hydrogen and oxygen. This is a clean hydrogen generation system. The electricity required can be provided using renewable energy, such as wind or solar power (power generation hybrid systems).

Some of advantages of hydrogen fuel cells onboard ship are: high yields result from the process of obtaining electricity (two to three times that of an internal combustion engine); hydrogen stocks are limitless; when operating the hydrogen fuel cell, water is the only waste (this is a zero emission, clean energy); low levels of noise are produced, less than a quarter of those produced by diesel generators; easy to use and maintain, working at low temperatures and having very few moving parts; versatile in that it can be part of hybrid systems in combination with other renewable energies, such as wind, solar or photovoltaic. As aforementioned, the estimated investment cost to produce a hydrogen fuel cell system is about 6,000 Euros per kW; the technology has not undergone sufficient testing.
PROSPECTS FOR FUTURE

By considering the development of the technologies, we can imagine that future ships will produce less emission of pollutants into atmosphere. However, taking into account the large amount of energy used by a ship, it is obvious that only by design of hybrid systems based on alternative sources of energy there can be reduced environmental impact of shipping industry. Further, there are reviewed some innovative concepts that aim nearly zero emission ships by 2050.

One of these, the Aquarius MRE system will use array of rigid sails and solar modules to form a ship based renewable energy system. On large ships up to twenty rigid sails could be installed whereas on smaller vessels just one or two sails would be needed. The system is not intended to be a ship’s primary source of propulsion. Instead, the system is being designed to work alongside other technologies in order to reduce fuel consumption and harmful gas emissions for a variety of ships such as bulk carriers, oil tankers and cargo ships. Depending on the number, size, shape and configuration of the rigid sails it is estimated that the system will reduce vessels annual fuel consumption by up to 20%.

Another concept is developed by Eco Marine Power [22] which is leading a project of an eco-friendly solar vessel specifically designed to operate as a commuter ferry in urban areas. The vessel design is known as Medaka and will be one of the first of a new class of green passenger ferries which will incorporate a range of technologies to minimize fuel consumption and emissions of noxious gases. In addition the sails will use a simplified hybrid electric marine propulsion system that will be easy to maintain and make the overall vessel a cost effective alternative to vessels powered by diesel engines alone. The solar modules mounted on the roof will use a concept which will allow them to be raised or lowered. In normal operation the modules are at a slight angle. It can also be configured to use a variety of power sources in addition to the solar modules such as an LNG or biofuel.

Solar Sailor, an Australian company specializing in renewable energy technologies, will install its solar and wind power systems on a massive dry cargo ship that could be used to haul iron ore from Australia to China. The equipment is likely to be similar - but on a larger scale - to the zero-emission systems the company has installed on four dual-fuel passenger ferries operated by the Hong Kong Jockey Club. Solar Albatross is a 24 meter 100 passenger carrying catamaran ferry with its stow able Solar-Sails [23].

Finally, a concept that gathers all the renewable sources available on sea is E/S Orcelle produced by Wakenshims. The E/S Orcelle will have an optimum cargo capacity of 85,000 m³ of cargo deck stowage area, roughly equivalent to 14 football fields. This is up to 50% more space than today’s modern car carriers, which are capable of transporting 6,500 vehicles. Primary energy sources include solar, wind and wave energy.

The main design considerations include [24]: a) Using the sun, wind and waves to employ multiple energy generators that include fuel cells; b) Optimizing cargo capacity and lowering energy consumption per transported unit; c) Taking into consideration other environmental challenges, such as completely eliminating the problems related to ballast water, thanks to the new hull design.

Solar energy will be utilized through photovoltaic modules located in the vessel’s sails. When not in use for wind propulsion, the sails may be tilted, laid down or in other ways directed for maximum solar energy collection. The solar energy will then be transformed into electricity for immediate use, or for storage.

CASE STUDY: SOLAR THERMAL SYSTEM ONBOARD SHIP

As it can be seen from above, the solar thermal solution is not even the optimal option when consider alternative sources of energy in shipping. Reviewed literature reveal some concern related to usage of additional thermal energy onboard vessels, especially those which are involved in short maritime transportation [21]. Identified solutions rely mostly in storage of thermal energy produced onshore and transfer to ship before going on sea.

Thermal energy obtained through conversion of solar energy can be used onboard ships in domestic hot water and steam generation processes. In turn, steam is used in firefighting system, ship’s heating plant, for heating marine heavy fuel and oil and for heating of fresh water required in starting procedures of main engine.

Research will focused upon reduction of fuel demand used for heating water, oil and marine heavy fuel oil by adapting solar thermal technologies for onboard operation. At this point, there are considered options like plane and vacuum tube collectors. Further is presented a CFD simulation [14] of a tube collector. The study has been carried with the ANSYS CFX as input values of solar radiation from previous research [13].

The following section presents a study of a stationary solar – thermal collector, in order to assess its main operational features before considering it’s implementation onboard ships.

In order to assess the operational differences between the various exposure angles, there were developed two 3D models of a tube solar collector [25], corresponding to the two tilt angles of 0° and respectively 48°. Turbulent flow is simulated by solving the incompressible Reynolds-averaged Navier-Stokes equations (RANS), based on the finite volume method to build the spatial discretization of the transport equations. The velocity field is obtained from the momentum conservation equations and the pressure field is extracted from the mass conservation constraint, or continuity equation, transformed into a pressure-equation. In the case of turbulent flows, additional transport equations for modeled variables are discretized and solved using the same principles. The gradients are computed with an approach based on Gauss’s theorem.

Non-orthogonal correction is applied to ensure formal first order accuracy. Second order accurate result can be obtained on a nearly symmetric stencil. Inviscid flux is computed with a piecewise linear reconstruction associated with an upwinding stabilizing procedure which ensures a second order formal accuracy when flux limiter is not applied. Viscous flux is computed with a central difference scheme which guarantees a first order formal accuracy. We have to rely on mesh quality to obtain a second order discretization for the viscous term. Implicit scheme is applied for time discretization. Second order three-level time scheme is employed for time-accurate unsteady computation.

Several turbulence models, ranging from one-equation model to Reynolds stress transport model are implemented in Ansys CFX [16]. Most of the classical linear eddy-viscosity based closures like the Spalart-Allmaras one-equation model, the two-equation k-ω, SST model by Menter [10], for instance are implemented. Wall function is implemented for two-equation turbulence model.

During the simulation were especially observed the radiative heat transfer process, described for a particle of known dimensions \(d_p\), with uniform temperature \(T_p\) and emissivity \(\varepsilon_p\), by applying the following equation:

\[
Q_R = \varepsilon_p \cdot \pi \cdot d_p^2 \cdot \left( 1 - \sigma \cdot \varepsilon_p \cdot T_p^4 \right) \]

36
where \( I \) is the radiation intensity on the particle surface at the location of the particle, \( n \) is the refractive Index of the fluid, and \( \sigma \) is the Stefan-Boltzmann constant. An equivalent amount of heat can be removed from the radiation field.

**The solar collector geometry**

For developing the 3D geometry used in the simulations, there were chosen an existing solar collector type, with a 1.5 m² absorbing area, consisting in 30 tubes of 1500 mm long and 47 mm in diameter, disposed at a distance of 20 mm. The storage tank has a volume of 230 liters (figure 1) [26].

![Fig. 1. The arrangement of the tube solar collector [26]](image)

Simulation settings

Initially, for developing the simulation, it was developed an unstructured mesh, with 307369 nodes and 1404607 elements (figure 3).

Table 1. Domain Physics

<table>
<thead>
<tr>
<th>Domain - Default Domain</th>
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<tbody>
<tr>
<td>Materials</td>
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<tr>
<td>Gravity X Component</td>
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</tr>
<tr>
<td>Gravity Y Component</td>
<td>9.8100e+00 [m s⁻²]</td>
</tr>
<tr>
<td>Gravity Z Component</td>
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<td>Domain Motion</td>
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<tr>
<td>Reference Pressure</td>
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<td>Heat Transfer Model</td>
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<td>Thermal Radiation Model</td>
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<td>Gray</td>
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<tr>
<td>Turbulence Model</td>
<td>SST</td>
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<tr>
<td>Turbulent Wall Functions</td>
<td>Automatic</td>
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</table>

The initial conditions were determined for two tilt angles of 0 and 48 deg. The energy flux used at the boundary conditions is of 156 W/m², which corresponds to the radiation value determined as an average for 27th of October, between 10.00 and 13.00 hours [13]. The physics used in the simulation are described in table 1.

![Fig. 3. a) the meshed model; b) detail of the mesh at the intersection between the tubes and the tank](image)

The settled simulation is a transient study and it was carried for 3600 seconds with a time step of 2 seconds; the chosen time step proved to be a convenient one, since the residuals values were established around the value of \( 10^{-4} \) (figure 4).
where RMS P MASS is root mean square of the calculated mass, RMS U Moment is root mean square of the calculated moment on the Ox axis, RMS V Moment is root mean square of the calculated moment on the Oy axis and RMS W Moment is root mean square of the calculated moment on the Oz axis.

Simulation postprocessing
After achieving the results of the simulation, there was determined the peak values for temperatures and fluid velocities in the tubes and the tank for the two selected tilt angles (table 2).

Table 2. Fluid temperatures and velocities by tilt angle

<table>
<thead>
<tr>
<th></th>
<th>0 deg</th>
<th>48 deg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max temperature</td>
<td>2.857e+02 [K]</td>
<td>2.842e+02 [K]</td>
</tr>
<tr>
<td>Min temperature</td>
<td>2.833e+02 [K]</td>
<td>2.835e+02 [K]</td>
</tr>
<tr>
<td>Max pressure</td>
<td>8.328e-03 [Pa]</td>
<td>5.112e-01 [Pa]</td>
</tr>
<tr>
<td>Min pressure</td>
<td>-3.241e-03 [Pa]</td>
<td>-2.770e+00 [Pa]</td>
</tr>
<tr>
<td>Max Fluid Velocity</td>
<td>2.247e-03 [m/s]</td>
<td>7.697e-03 [m/s]</td>
</tr>
<tr>
<td>Min Fluid Velocity</td>
<td>-5.990e-04 [m/s]</td>
<td>-6.151e-03 [m/s]</td>
</tr>
<tr>
<td>Min Fluid Entropy</td>
<td>-2.132e+02 [J/kg x K]</td>
<td>-2.101e+02 [J/kg x K]</td>
</tr>
<tr>
<td>Max Fluid Entropy</td>
<td>-1.791e+02 [J/kg x K]</td>
<td>-1.999e+02 [J/kg x K]</td>
</tr>
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</table>

RESULTS AND DISCUSSIONS
By studying the values obtained for the two situations that the maximum temperature in the tank raises with 12.55K in the 0 degrees tilt angle situation and with 11.05K in the 48 degrees tilt angle situation.

When studying the temperature charts in the two situations, it may be seen that in the 0° tilt angle situation, the peak values for the temperature are established at the bottom of the tubes line (figure 5a), while in the 48° angle situation, the temperature fields are more uniform, with peaks established at the intersection between the tubes and the tank (figure 5b).

When speaking about the fluid velocities in the system, it can be seen that the natural flow has better qualitative and quantitative parameters for the tilt angle of 48° (figure 6).

It may be observed that the maximum temperature, reached after 1 hour it is higher for the 0° tilt angle is bigger than the temperature reached for the 48° tilt angle. In the same time, if we are looking at the temperatures in tank, it may be observed that the temperature distribution in the figure 5 covers more space, which indicates a better overall exchange system.

At this point it can be concluded that the free flow has a better development in the 48°, when also the flow velocities are higher and evenly spread than in the first case.
This situation shows that, at least for the submitted tilt angles, the second solution may be an alternative for increasing the free stream profile.

**CONCLUSIONS**

The idea of gradually substituting conventional fuels, used in propulsion and power generation for merchant vessels, with alternative solutions that use clean or renewable energies, is becoming a reality driven by two fundamental factors. First, there is an increase in international policy aimed at eliminating the use of polluting fuels in ships, efforts being made especially by IMO. Secondly, the price of these fuels is continuously rising, because of dwindling oil reserves. In search of a “green” ship, alternative solutions identified consists in use of kites, sails, biodiesel, wind turbines (with horizontal or vertical axis), photovoltaic solar modules, hydrogen fuel cells or combined systems.

However, ship-owners are skeptical regarding implementing renewable sources of energy onboard ships, due primarily to high costs associated with these technologies. Efforts must be made, generally by policies and special facilities and benefits, for encouraging development of “greener” ships.

**REFERENCES**