Considerations of the energy balance of an internal combustion engine and the recovery of heat lost through the cooling water

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Abstract: The thermal balance of an engine expresses the distribution of available heat, between the equivalent energy of effective mechanical work and the various losses. From the analysis of the thermal balance, it results if the thermal energy is used efficiently, corresponding to the economic work of the engine, helping to find and remove the causes that lead to the non-economical use of thermal energy. The thermal balance is useful in calculations for the design of the cooling system and the calculation of the exhaust gas recovery system. The heat flow lost through the cooling fluid is determined by measuring the flow of cooling water and also its inlet and outlet temperature. The heat flow lost through the exhaust gases is determined by the difference between the enthalpy of the exhaust gas and the enthalpy of the fresh entry load. The heat flow lost due to incomplete chemical burn is determined by analyzing the exhaust gases and determining the components that contain chemical energy. The parameters necessary for the thermal balance at a certain operating regime are obtained from direct measurements. The paper presents an analysis of thermal balance for ICE in the maritime domain and the possibilities of cooling system recovery for a ship engine of a tanker ship.

1. Introduction
The energy balance is set for a certain engine operating characteristic, typically for the speed, load and regulator characteristic.

Energy efficiency development must be a combined some portion of the procedure. Energy efficiency is not just a presentation of certain computation, file or innovation. The encounter has demonstrated that in mind the end goal to guarantee best outcomes, improvement of energy efficiency should be a steady procedure inside the new building project, beginning from the meaning of key performance indicators and finishing with appointing of on board performance management system and preparing for installed team at ship conveyance, [1].

This paper comprises in ideas studying the cooling system thermal balance of a diesel generator engine of a VLCC tanker ship of 305000 dwt. The main attributes of VLCC ships are described in table 1.
2. Description of the tanker ship energy system

The energy system of the ship is provided by 2 YANMAR diesel generators shown in figure 1 with a nominal power of 1840 running with a speed of 720rpm, 1 turbo generator with a nominal power of 1100kW running with a speed of 11730 rpm and 1 CUMMINS emergency generator with a nominal power of 620kW running with a speed of 1800rpm [1].

The main characteristics of the main diesel generator engine are [1]:

- type: YANMAR 6EY26L;
- 4 stroke engine;
- cylinders: 6 in line;
- bore: 260mm;
- stroke: 385mm;
- injection pressure: 34MPa;
- power: 1840kW;
- speed: 750rpm;
- cylinders cooling: fresh water;
- open system cooling with sea water.

![Diesel generator YANMAR 6EY26L, [1].](image)

Turbogenerator characteristics shown in figure 2 are [1]:

- type: MITSUBISHI MULTI STAGE/1;
- power: 1100kW;
- speed: 11730rpm.

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Table 1. VLCC tanker ship dimensions, [1].

| Characteristics                  | Value    |
|----------------------------------|----------|
| Length overall                   | 333.00 m |
| Length between perpendiculars   | 324.00 m |
| Draft                            | 20.83 m  |
| Deadweight                       | 305301 MT|
Emergency generator characteristics shown in figure 3 are, [1]:
- type: KTA 19 DM CUMMINS;
- 4 stroke engine;
- power: 620kW.

Figure 2. Turbo - generator MITSUBISHI MULTI STAGE, [1].

Figure 3. Emergency diesel generator type KTA 19 DM CUMMINS, [1].

3. Thermal energy balance for diesel engine
In section 2 was calculated the energy balance for the reference engine started from the initial data. Then was calculated waste heat for cylinders cooling according to equation (1), waste heat for oil cooling according to equation (2) and the residual heat according to equation (3).

3.1. Initial data

Initial data for diesel engine balance are:
- cylinders cooling flow: \( Q_{cyl} = 120 \ \text{m}^3/\text{h} \)
- fresh water specific heat: \( c_{cyl} = 4.2 \ \frac{kJ}{kg K} \)
- sea water pump flow for oil cooling: \( Q_{woil} = 38.7 \ \text{m}^3/\text{h} \)
- sea water specific heat: \( c_{woil} = 4 \ \frac{kJ}{kg K} \)
- fresh water density: \( \rho_{FW} = 1000 \ \frac{kg}{m^3} \)
- sea water density: \( \rho_{SW} = 1025 \ \frac{kg}{m^3} \)
- fresh water temperatures:
  - inlet: \( t_{incyl} = 75 \ ^\circ C \)
  - outlet: \( t_{outcyl} = 82 \ ^\circ C \)
- sea water temperatures:
  - inlet: \( t_{inwoil} = 35 \ ^\circ C \)
  - outlet: \( t_{outwoil} = 40 \ ^\circ C \)

3.2. Waste heat for cylinders cooling

The heat flow lost through the cylinders coolant fluid is determined by measuring the flow of cooling water in \( \frac{kg}{s} \) and its inlet and outlet temperature in the engine in \( ^\circ C \), obtaining:

\[
Q_{cyl} = G_{cyl} \rho_{FW} c_{cyl} (t_{incyl} - t_{outcyl}) \left[ \frac{kJ}{h} \right]
\]

\[
Q_{cyl} = 3.528 \cdot 10^6 \left[ \frac{kJ}{h} \right]
\]

3.3. Waste heat for oil cooling:

The heat flow lost through the oil coolant fluid is determined by measuring the flow of cooling sea water in \( \frac{kg}{s} \) and its inlet and outlet temperature in the heat exchanger in \( ^\circ C \), obtaining:

\[
Q_{woil} = G_{woil} \rho_{SW} c_{woil} (t_{inwoil} - t_{outwoil}) \left[ \frac{kJ}{h} \right]
\]

\[
Q_{woil} = 6.3468 \cdot 10^5 \left[ \frac{kJ}{h} \right]
\]

3.4. Waste residual heat

Waste residual heat includes all other losses that have not been taken into account, for example the thermal energy corresponding to the mechanical friction work that does not flow into the cooling fluid, the energy consumed for putting auxiliary mechanisms into operation, the environmental losses in the outer surface of the engine.

\[
Q_{waste} = Q_{in} - (Q_u + Q_{cyl} + Q_{woil} + Q_{gex}) \left[ \frac{kJ}{h} \right]
\]

\[
Q_{waste} = 7.34 \cdot 10^5 \left[ \frac{kJ}{h} \right]
\]

3.5. Relative energy balance

Relative thermal balance is used when it comes to analysing how to use thermal energy at a particular engine, while specific and relative heat balances are used both to analyse how to use thermal energy and to compare it from in terms of effective efficiency, various types of engines.

\[
q_u' = 100 \cdot \frac{Q_u}{Q_{intr}} \ [%]
\]
\[ q'_u = 39.60[\%] \]
\[ q'_u = 30 \ldots .45[\%] \]

\[ q'_{cool} = 100 \cdot \frac{Q_{cycl}}{Q_{in}} + 100 \cdot \frac{Q_{woil}}{Q_{in}} = 24.93[\%] \] (5)

\[ q'_{cool} = 20 \ldots .30[\%] \]

\[ q'_{gex} = 100 \cdot \frac{Q_{gex}}{Q_{intr}}[\%] \] (6)

\[ q'_{gex} = 31.06[\%] \]

\[ q'_{gex} = 25 \ldots .50[\%] \]

\[ q'_{waste} = 100 \cdot \frac{Q_{waste}}{Q_{in}}[\%] \] (7)

\[ q'_{waste} = 4.39[\%] \]

\[ q'_{waste} = 2.5 \ldots 8[\%][2] \]

4. Waste heat recovery for sea water cooling

The cooling fluid eliminates an important fraction of the thermal energy introduced by combustion of the fuel as shown in equation (4) to equation (7). In closed-circuit cooling systems, the cooling water temperature is around 75 ... 85°C, favourably affecting the process of transformation in the engine cylinder and increasing the relative heat recovery rates. Hot water from the closed-circuit cooling systems can be used for the following purposes:

a) for distilling plant as heat agent shown in figure 4;
b) for HVAC system;
c) for the auxiliary boiler.

In the figure below is a schematic diagram of a heat recovery system for distilling plant, [2, 3].

![Diagram](image-url)
Where: 1 - engine; 2 - distilling plant; 3 - distillate pump; 4 - pump for high salinity water; 5 - air eductor; 6 - sea water chest; 7 - sea water filter; 8 - sea water pump; 9 - oil cooler; 10 - water cooler; 11 - fresh water pump.

To increase the water temperature in the closed-circuit cooling systems, it is used to pressurize the system so that the water temperature reaches 110 ... 130°C when leaving the engine. In this case, the cycle efficiency increases, and the engine operation becomes stable at a small difference ($\Delta t_{cool} = t_{out} - t_{in}$) of the cooling water temperature. Also, increases the relative heat flow that can be recovered from the cooling water, which leads to an increase in the overall efficiency of the internal combustion engine, [4].

5. Calculation of cooling system plate heat exchanger

5.1. Construction of plate heat exchanger
Plate heat exchangers, shown in figure 5, are used for universal heating, cooling and heat recovery processes in the most diverse fields, such as chemical industry, pulp and paper industry, food industry, heating, ventilation and conditioning, industrial mechanics, thermoelectric power stations, metallurgical industry, extractive industries, shipping industries.

The use of a heat exchanger on the large scale is illustrated by the many features on which these are presented. However, they are not used for gas-gas applications, so they are not used for air cooling and are not suitable for condensers.

The number and size of the plates are determined by the flow of fluids, the physical properties of the two fluids, the pressure drop in the system and the temperature regime. The plates form a Chevron angle. The values of Chevron angle are between 65°C and 25°C [4, 5].

![Figure 5. Plate heat exchanger fluids direction.](image)

During operation, the fluids pass through the holes in the plate covers, being routed in the alternating channels on the plates. The two fluids cannot come in direct contact, they are separated by a thin plate, through which the heat transfer is made.

The correct installation of the plates is made so that their tiles form a faggy pattern. Otherwise, the heat exchanger function is compromised.
5.2. Initial data for heat exchanger calculation

The initial data for the heat exchanger calculation are:

- thermal load: \( Q = 980 [\text{kW}] \)
- first thermal agent: \( t_{\text{out fw}} = 82[^\circ \text{C}], \ t_{\text{in fw}} = 75[^\circ \text{C}] \)
- second thermal agent: \( t_{\text{in sw}} = 35[^\circ \text{C}], \ t_{\text{out sw}} = 40[^\circ \text{C}] \)
- thermal efficiency: \( \eta = 99.7 \ [%] \)
- specific heat: \( c_1 = c_2 = 4.2 \ [\text{kJ/kgK}] \)

5.3. Thermal calculation of plate heat exchanger

In figure 6 is shown a diagram of the temperature variation with the heat exchange area for the counter current circulation.

![Figure 6. Temperature vs exchange area diagram.](image)

From the temperature range variation diagram can be calculated the maximum and the minimum temperature difference for primary and secondary fluids:

\[
\Delta T_{\text{max}} = 42[^\circ \text{C}] \\
\Delta T_{\text{min}} = 30[^\circ \text{C}]
\]

Differential logarithmic medium temperature from equation (8) for counter current circulation is:

\[
\Delta t_{\text{ml}} = \frac{\Delta t_{\text{max}} - \Delta t_{\text{min}}}{\ln(\Delta t_{\text{max}}/\Delta t_{\text{min}})} = 39[^\circ \text{C}]
\] (8)

From thermal balance equation (9) is calculated primary and secondary fluid flow:

\[
Q_{\text{ut}} = \frac{\Delta t_{\text{ml}} \cdot (t_{\text{out fw}} - t_{\text{in sw}})}{c_1} = \frac{(t_{\text{out sw}} - t_{\text{in sw}})}{c_2} = k \cdot S_0 \cdot \Delta t_m \ [\text{W}]
\] (9)

\[
G_1 = \frac{Q_{\text{ut}}}{c_1 \cdot (t_{\text{out fw}} - t_{\text{in sw}})} = 3.173 \ [\frac{\text{kg}}{\text{s}}]
\] (10)

\[
G_2 = \frac{Q_{\text{ut}}}{c_2 \cdot (t_{\text{out sw}} - t_{\text{in sw}})} = 11.744 \ [\frac{\text{kg}}{\text{s}}]
\] (11)

Is calculated heat exchange area from equation (12):

\[
S' = \frac{Q_{\text{ut}}}{k \cdot \Delta t_{\text{ml}}} = 9.82 \ [\text{m}^2]
\] (12)
Fluids velocity for both circuits are calculated in equations (13) and (14):

\[
\begin{align*}
    w_1 &= \frac{\dot{Q}_1}{n \rho A} = 0.4 \, [m/s] \\
    w_2 &= \frac{\dot{Q}_2}{n \rho A} = 0.7 \, [m/s]
\end{align*}
\] (13) (14)

Global heat transfer coefficient is calculated in equation (15):

\[
    k = \frac{1}{\frac{1}{\alpha_1} + \frac{1}{\sum \delta \lambda} + \frac{1}{\alpha_2}} = 2521.13 \left[ \frac{W}{m^2 K} \right]
\] (15)

6. Heat transfer simulation

6.1. Heat exchanger geometry

With the help of the Design Modeler option provided by the Ansys Fluent program, was realized the geometric construction of the heat exchanger shown in figure 7. The heat exchanger complies with the geometric characteristics of the real cooling system.

As it can be observed, were realized the following components:
- heat exchange body;
- interior plates;
- inlet and outlet holes.

6.2. Heat exchanger meshing

The following stage after the geometrical construction is the discretization shown in figure 8. This process is a structural analysis of the entire heat exchanger and is divided into a number of cells in view of the possibility of further development of the calculus on each cell, thereby determining the particle values.

Discretization was carried out with the help of the Mesh interface of the Ansys Fluent. After the structural analysis results in 933231 cells and 51355 nodes.

In the next step was established the type of fluid, the number of iterations and the flow of fluid in pipes. In this stage was also established both, the inlet and outlet fluid values for pressure and velocity.
6.3. Ansys Fluent results

The Ansys program generated a series of figures to show heat exchange in the heat exchanger. Both the temperature contour on the heat exchanger as shown in figure 9 and the temperature per unit of volume as shown in figure 10 were used.

The heat exchange in the cooler can be seen in figure 11. At the same time, heat exchange can be seen on the sides of the cooler as shown in figures 12 and 13.

Figure 8. Heat exchanger mesh, [4].

Figure 9. Heat exchanger (all body), [4].

Figure 10. Heat exchange per volume unit (all body), [4].

Figure 11. Heat exchange per volume unit (back part), [4].
7. Conclusions
Waste heat recovery systems on seagoing vessels are capable of recovering only a small portion of the residual heat, which is not enough to provide the entire amount of thermal and electrical energy required for the auxiliary equipment of the ship. They mainly recover only some of the thermal energy contained in the exhaust and cooling water of the main and auxiliary engines.

To perform the modelling of the plate heat exchanger, the Ansys program, namely Ansys-Fluent, was involved in the study of the flow of fluids.

Ansys offers a complete range of simulation solutions, engineering kits offer almost any field of simulation engineering, and a prerendering machine is required. CFD heat exchangers models are based on principles of fluid dynamics.

Was analyzed the heat exchange with the Ansys CFD program. The main results obtained were the following: output temperature contour: min 291 K, max 363 K as shown in figures from 9 to 13.

Referring to the results of the relative balance of 4.39 % for the YANMAR 6EY26L diesel generator, can be concluded that the result is halfway through the reference interval, which leads to promising results for the VLCC tanker ship. Also, considering that there are three diesel generators on board, can be installed recovery systems directly on diesel generators without integrating the main engine.

The results obtained from the modelling can be helpful for the operators in VLCC tanker ships.

8. References
[1] Mitsubishi Heavy Industries Ltd 2016- Book Horaisan I(1)
[2] Faitar C and Novac I 2017 Basic aspects and contributions to the optimization of energy systemsexploitation of a super tanker ship IOP Conf. Ser.: Mater. Sci. Eng. 227 012043
[3] www.termo.utcluj.ro, accessed at 09.10.2018
[4] www.ansys.com, accessed at 11.10.2018
[5] www.marineengineeringonline.com, accessed at 14.10.2018