Article

Considerations of the exploitation parameters of the lost heat recovery systems for a VLCC tanker ship

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Abstract: Nowadays, the shipbuilding industry is trying to improve the energy performance. This paper treats a crude oil super tanker ship of 305000 dwt studying the possibility of improving efficiency through heat recovery. Waste heat is heat, which is created by fuel burning or chemical response, and then "dumped" into nature despite the fact that it could, in any case, be reused for some helpful and financial reason. The basic nature of heat is not the same, but instead its "value". The system of how to recuperate this heat depends partially on the temperature of the waste heat fluid and the financial matters included. An extensive amount of hot flue gases is created from boilers, ovens, stoves and heaters. On the off chance that a specific measure of this waste heat could be recouped, a lot of essential fuel could be spared. Main engine exhaust gas energy is by far the most attractive among the waste heat sources of a ship because of the heat flow and temperature. It is possible to generate an electrical output of up to 11 % of the main engine power by utilizing this exhaust gas energy in a waste heat recovery system comprising both steam and power turbines and combined with utilizing scavenge air energy for exhaust boiler feed-water heating.

Keywords: heat; recovery; engine; Very Large Crude Carriers; parameters;

1. Introduction

VLCC (Very Large Crude Carriers) are among the biggest working freight vessels on the planet. With a capacity, more than 250,000 dwt, these big vessels are equipped for conveying an immense measure of crude oil in a single voyage. Known as supertankers, these vessels are essentially utilized for whole deal rough transportation from the Persian Gulf to Europe, Asia and North America. This paper comprises in ideas studying of a VLCC of 305000 dwt. Main characteristics of VLCC ship are described in table 1.[1]

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lenght overall</td>
<td>333.00 m</td>
</tr>
<tr>
<td>Lenght between perpendiculars</td>
<td>324.00 m</td>
</tr>
</tbody>
</table>

Table 1. VLCC tanker ship characteristics.
2. Description of VLCC main engine

The propulsion of the ship is provided by a MITSUBISHI-UE MDE 7UEC85LSII, two-stroke, slow and reversible engine, with a constant overcharging pressure that develops a rated output of 27020 kW at a speed of 76 rpm, the ship shifting with a maximum speed of 15.38 Nd. MAN B&W two-stroke engines from the 30 to 95-cm bore sizes have a total power range from 1,560 kW to 82,440 kW, with units that vary in height from 5,912 to 16,156 mm.

This covers the ME (40 to 95 bore), ME-GI (40 to 95 bore), ME-B (30 to 50 bore) and MC (35 to 70 bore) series.[1,2]

Table 2. Main engine characteristics.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bore</td>
<td>850 mm</td>
</tr>
<tr>
<td>Stroke</td>
<td>3150 mm</td>
</tr>
<tr>
<td>Number of cylinders</td>
<td>7</td>
</tr>
<tr>
<td>MCR power</td>
<td>27020 kW</td>
</tr>
<tr>
<td>NCR power</td>
<td>22965 kW</td>
</tr>
<tr>
<td>Speed</td>
<td>76 rpm</td>
</tr>
</tbody>
</table>

Figure 1. VLCC main engine: (a) side picture; (b) top picture.

3. Exhaust gas recovery system

Exhaust gas energy recovery is more likely than the energy contained in the cooling water. This is determined by the higher exhaust gas temperature, from 250 °C to 400 °C. The simplest and cheapest system consists of an exhaust gas turbine, the so-called power turbine, installed on a bypass of the gas exhaust, and connected in turn with an electric generator to provide electrical power on board the ship. On the other hand, the most common system to meet over 90% of transport ships is the gas economizer.

The Mitsubishi Dual Steam Pressure Exhaust Gas Economizer is designed incorporating the latest heat exchanger technologies which Mitsubishi Heavy Industries Ltd has nurtured through its
long experience with the manufacture of exhaust gas economizer and main and auxiliary boiler. The dual steam pressure exhaust gas economizer has a low-pressure evaporating section, high-pressure evaporating section and superheating section each independently arranged with inlet and outlet headers and also casing supports and low-pressure steam separator which is appurtenant to the low-pressure evaporating section. The high-pressure evaporating section and superheating section which generates high-pressure and high-temperature steam for driving the generator turbine is located in the high-temperature gas zone while, on the other hand, the low-pressure evaporating section which generates low-pressure saturated steam for heating fuel and other services is situated in the low-temperature gas zone. With the heat-absorbing elements arranged in this manner, the dual steam pressure exhaust gas economizer offers far greater heat recovery than the conventional installations and thus makes it possible to have an economical steam turbine power generating system even for ships are powered by medium or small size diesel engines.[2]

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Low-pressure evaporator</th>
<th>Steam separator</th>
<th>High-pressure evaporator</th>
<th>Superheater</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evaporating Kg/h</td>
<td>2420</td>
<td>2420</td>
<td>5710</td>
<td>5410</td>
</tr>
<tr>
<td>Designed pressure MPa</td>
<td>0.98</td>
<td>0.59</td>
<td>2.65</td>
<td>2.16</td>
</tr>
<tr>
<td>Steam temperature °C</td>
<td>Sat</td>
<td>Sat</td>
<td>Sat</td>
<td>245</td>
</tr>
<tr>
<td>Gas flow at 85% MCR Kg/h</td>
<td>179800</td>
<td>179800</td>
<td>179800</td>
<td>179800</td>
</tr>
<tr>
<td>Inlet gas temperature at 85% MCR °C</td>
<td>263</td>
<td>263</td>
<td>263</td>
<td>263</td>
</tr>
</tbody>
</table>

4. Thermal energy balance

Any energy transformation process is characterized by the energy balance equation:

$$W_{int} = W_u + W_p$$  (1)

Therefore, in each transformation process, part of the energy introduced $W_{int}$ turns into useful energy $W_u$, and one part is lost $W_p$. 

Figure 2. VLCC recovery system: (a) recovery system[7]; (b) gas economiser [8].
Figure 3. Main engine energy diagram;

Figure 4. Main engine performance report;
Main engine performance report shows parameters that influence the heat flow:

- turbocharger exhaust gas temperatures
- air cooler temperatures
- freshwater jacking cooling temperature
- exhaust gas economizer temperatures

Figure 4 show parameters of main engine at 70.6 rpm and 81.3 % load.

<table>
<thead>
<tr>
<th>Table 4. Engine temperatures.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
</tr>
<tr>
<td>Exhaust gas temperature °C</td>
</tr>
<tr>
<td>Exhaust gas economizer °C</td>
</tr>
<tr>
<td>Air temperature °C</td>
</tr>
</tbody>
</table>

We have a set of formulas on which the main engine power is based, along with recovery systems. The absolute thermal balance is used when it comes to analyzing the use of thermal energy on a particular engine, while the specific and relative heat balances are used both for the analysis of the use of thermal energy and to compare it from in terms of effective efficiency, various types of engines.

\[ Q_{\text{intr}} = Q_u + Q_{\text{rac}} + Q_{\text{ex}} + Q_{\text{rez}} \text{ [kJ/h]} \]  
\[ Q_{\text{heat}} = m_{eg} \cdot c_p \cdot \Delta T \text{ [kW]} \]
\[ d'_{eg} = m_{air} \cdot \alpha \cdot C_e \text{ [Kgair/kWh]} \]
\[ m_{eg} = m_{air} + m_{fuel} \text{ [Kg / s]} \]

where:
- \( Q_{\text{intr}} \) – introduced heat
- \( Q_u \) – used heat
- \( Q_{\text{rac}} \) – cooling energy
- \( Q_{\text{ex}} \) – exhaust gas heat
- \( Q_{\text{rez}} \) – the residual heat
- \( Q_{\text{heat}} \) – heat flux
- \( m_{eg} \) – exhaust mass flow
- \( cp \) – specific gas heat
- \( \Delta T \) – temperature difference
- \( d'_{eg} \) – airflow for gas exchange [Kgair / kWh]
- \( m_{air} \) – theoretical air mass for 1 Kg fuel burn [Kg air / Kg fuel]
- \( \alpha \) – air excess coefficient
- \( C_e \) – specific fuel consumption [Kg / kWh]
### Table 5. Engine energy flows.

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>72</td>
<td>85.0</td>
<td>22967</td>
<td>4129</td>
<td>121398</td>
<td>117268</td>
</tr>
<tr>
<td>71</td>
<td>81.8</td>
<td>22089</td>
<td>3675</td>
<td>108045</td>
<td>104370</td>
</tr>
<tr>
<td>66</td>
<td>73.2</td>
<td>19776</td>
<td>3433</td>
<td>100940</td>
<td>97507</td>
</tr>
<tr>
<td>62</td>
<td>64.2</td>
<td>17352</td>
<td>3013</td>
<td>88568</td>
<td>85555</td>
</tr>
<tr>
<td>60</td>
<td>54.2</td>
<td>14642</td>
<td>2542</td>
<td>74725</td>
<td>72183</td>
</tr>
<tr>
<td>59</td>
<td>50.2</td>
<td>13575</td>
<td>2371</td>
<td>69703</td>
<td>67332</td>
</tr>
<tr>
<td>58</td>
<td>48.9</td>
<td>13224</td>
<td>2296</td>
<td>67498</td>
<td>65202</td>
</tr>
<tr>
<td>51</td>
<td>37.1</td>
<td>10033</td>
<td>1742</td>
<td>51205</td>
<td>49463</td>
</tr>
<tr>
<td>50</td>
<td>30.8</td>
<td>8328</td>
<td>1446</td>
<td>42508</td>
<td>41062</td>
</tr>
</tbody>
</table>

**Figure 5.** The main engine flows diagram;
Figure 6 shows the Sankey diagram of VLCC tanker ship energy systems. Summaries of input and output energy flows of ship operations are shown in Tables 5, while Figure 5 presents a diagram of the ship flows analyzed. Propeller with propulsion system represents the biggest source of energy consumption, as it accounts for 67% of the ship energy demand. This also translates to the main engines consuming the largest share of the overall energy input of the system (87.7%). Hence, efforts directed towards the reduction of propulsive power are highly justified for the ship under study [4].

One quality of the technique utilized lies in the assortment of information that can be utilized as a part of the request to expand the structure of on board energy flows.

The tanker ship sea configuration according to the main engine load is the following:
- under 50% main engine load in the operating configuration of the ship are both auxiliary boiler and diesel generators
- over the 50% load of the main engine, the configuration of the ship can be with the gas economizer as well as the steam turbine generator.

5. The Quality of the thermal energy

Energy analysis is based on the first law of thermodynamics. The energy balance can be written as follows

$$\frac{du}{dt} = Q - W + \sum_i m_{in,i}(h_{in,i} + \frac{1}{2}v_{in,i}^2 + gz_{in,i}) - \sum_j m_{out,j}(h_{out,j} + \frac{1}{2}v_{out,j}^2 + gz_{out,j})$$

where U, Q, W, m, h, v, g and z represent internal energy, heat, work, mass, specific enthalpy, fluid velocity, gravitational acceleration and altitude.

The energy efficiency of a component is defined as:
\[ \eta = \frac{\Delta H_{\text{out}}}{\Delta H_{\text{in}}} \]  

(7)

where \( \Delta H_{\text{out}} \) and \( \Delta H_{\text{in}} \) represent the totality of the useful energy output and of the energy input to the system, respectively. Examples of the useful output of a system are the mechanical power (in the case of a Diesel engine) or the enthalpy content of a steam ow (for a boiler).

Electric, kinetic and potential exergy quantities coincide with their energy counterparts. The physical exergy can be calculated as follows:

\[ B_{ph} = m [(h - h_0) + T_0(s - s_0)] \]  

(8)

where \( B \), \( h \), and \( s \) respectively stand for exergy ow, speci_c enthalpy, and speci_c entropy, while the subscript 0 refers to the conditions of the reference environment.

Similarly, the exergy counterpart of a heat ow at a given temperature can be calculated as:

\[ B_{\text{heat}} = \dot{Q}[1 - \frac{T_0}{T}] \]  

(9)

where \( T \) represents the temperature at which the heat is transferred.

Differently from energy, exergy is not conserved. Any non-reversible process involves a loss of exergy. This contribution to the exergy balance, generally known as irreversibility rate, is calculated as:

\[ i = T_0 \dot{S}_{\text{gen}} \]  

(10)

where \( \dot{S}_{\text{gen}} \) stands for the entropy generation rate in the component.

Energy analysis is based on the assessment of energy quantities, where all forms of the energy are treated at the same level. This assumption is valid for most of energy forms. Given a certain amount of electric energy, this can be converted with almost 100% efficiency to any other form: using an electric motor (conversion to mechanical energy), or a resistance (to thermal energy), etc.

Total energy efficiency measures what fraction of the energy input to the component is not destroyed.

\[ \varepsilon_t = \frac{\sum B_{\text{out},i}}{\sum B_{\text{in},i}} \]  

(11)

Task efficiency measures the ability of the component to generate useful output.

\[ \varepsilon_u = \frac{\sum W_{u,i} + \sum W_{p,i} + \sum B_{h,i} + \sum B_{c,i}}{\sum W_{p,i} + \sum B_{c,i} + \sum B_{ch,p,i}} \]  

(12)

The efficiency loss ratio measures what fraction of the exergy input to the component is destroyed.

\[ \delta = \frac{i}{\sum B_{\text{in},i}} \]  

(13)

Relative irreversibility measures the contribution of the component to the total exergy destruction of the system.

\[ \gamma = \frac{i}{\sum i} \]  

(14)
6. Thermal energy modeling

The act of modeling can refer to many different types of actions, from verbal modeling (describing the behaviour of a system in words) to physical modelling (building a physical reproduction of the system, generally in the smaller scale, to perform tests). Computational models are extensively used for application to ship energy systems.

Ansys offers a complete range of simulation solutions, engineering kits offers almost any field of simulation engineering, and a pre-rendering machine is required. CFD boiler models are based on principles of fluid dynamics and feature the inherent ability to provide detailed geometric information on in-cylinder mass and energy own by solving the governing ow equations.

With the Ansys software, simulation of operation under the conditions of gas discharge will be made to facilitate calculation.

Enhancement with finite elements has to go through the following steps:

- defining the structure, its geometrical characteristics and the applied loads
- schematic of how the structure takes over the applied loads
- individualization of local deviations of the structure, such as: additional stiffening, cutting and consolidation of the area
- the choice of finite element types, from the program library, for modeling the structure, taking into account the deformation modes or the stresses that arise in the elements
- meshing the structure into finite elements, taking into account: the geometrical dimensions of the structure, the elastic characteristics of the material, the edge conditions, the loads and the displacements imposed on the materials
- checking input data for compatibility and accuracy
- running the calculation program
- verification of the obtained results.

7. Gas exhaust simulation for ship’s boiler

Boiler geometry was made in Design Modeler and mesh has 77859 nodes and 72760 elements. For this simulation was considered real size economizer onboard VLCC tanker ship. The analysis type is changed to Pressure Based Type, Velocity formulation is changed to absolute and time to steady state. In Models, Energy is set to “on”, a viscous model is selected as k-ε model standard. In the Cell zone Conditions, Zone type is Fluid. In Boundary Conditions for the water Inlet is set to mass flow rate 33.7 \(\frac{m^3}{s}\) and temperature 580.5 \([K]\), and for Outlet is set to pressure outlet with temperature 360 \([K]\). In Boundary Conditions for the exhaust gas Inlet is set velocity magnitude 1 \(\frac{m}{s}\), 1.5 \(\frac{m}{s}\) and 2 \(\frac{m}{s}\) and temperature 300 \([K]\), and for Outlet is set to pressure outlet with temperature 441.5\([K]\).
Figure 7. Economizer geometry in Ansys; Velocity range was between 0 and 2.219 m/s.

Figure 8. Velocity results: (a) exhaust gas velocity contour; (b) water velocity in pipes;

Figure 9. Velocity and temperature results for water pipes;
Figure 10. Temperature contour results;

Figure 11. Heat flux (a) top view; (b) bottom view;

Figure 12. Heat flux (a) bottom pipe; (b) top pipes;
6. Conclusions

The work treated the energy analysis of a VLCC tanker ship, based on a real measurement onboard ship. The energy analysis was used to calculating the potential for waste heat recovery on the tanker power demand among consumers.

The availability of measurements of total heat demand, as well as of individual heat and power consumers, would provide the possibility to discuss savings related to consumers, and not only.

Waste heat recovery is well proven onboard ships, but the potential can be variable depending on the size, numbers, usage and efficiency of the engines on board. Furthermore, these measures are usually not relevant for retrofitting, due to large costs and efforts related to redesign, steel work, extra weight, etc.

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.

The results obtained from the modeling can be helpful for the operators in VLCC tanker ships. As it seems velocity of flue gases in tube banks has higher value in the narrow section and it is considered effective in heat transfer, but velocity has the highest value in space between wall side and tubes and this may affect the erosion in tubes also this velocity respectively flow gases near the wall it’s loss of energy. The total heat transfer rate was slightly lower on the furnace wall (evaporator), but this disadvantage was offset by the increased convection in the downstream heat exchangers. Because of the low soot concentration, the contribution of convection in the BL-firing case was larger in the lower furnace.

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