The ship was built in the "Kvaerner Masa" shipyard (Turku, Finland) in the "Voyager" class. With a length overall of 311 m, a beam of 38.6 m at the waterline (48 m max), draft of 8.6 m and 139,570 BT today is among the largest passenger vessels in the world.

The concept of a "fully integrated electrical system" was applied to the ship. The six diesel generators (6 × Wärtsilä 12V46; 6 × 12,600 kW) producing high-voltage electricity (11 kV) that is being distributed to consumers. It is used primarily for propulsion engines, bow and stern thrusters, and through 11 kV / 440 V transformers for power supply of engine room and other ship requirements (in ex.hoteling).

The ship has built-in waste heat recovery system utilizing the excessive heat from diesel generator water cooling and charged air from turbo-chargers (scavenging air) and it is consisting of:

- sanitary hot water heating system
- fresh water generator heating system
- air-conditioning water heating system

Use of waste heat of cooling water of diesel engine improves thermal efficiency and reduces fuel consumption.

**Waste heat recovery system**

Modern large cruise ships have large energy needs to be used for various technological processes on board. Table 1 shows typical values, depending on the operational conditions, i.e.:
1. maximum consumption – all diesel generators at 100 % load
2. winter time in port – one diesel generator at 80 % load
3. winter time at sea – four diesel generators at 80 % load
4. summer time in port – one diesel generator at 80 % load
5. summer time at sea – four diesel generators at 80 % load
6. summer time at sea, cruising speed of 16 knots – three diesel generators at 72 % load.

It is almost commonly known that modern marine four stroke diesel engines transform into mechanical work only about 45-48% of total energy contained in the fuel while the rest of 52-55% is heat loss (exhaust gases, scavenging air cooling, cylinders cooling, lubrication oil cooling, cooling and radiation in the engine room).

In order to prevent such loss waste heat recovery systems (WHRS) are widely in use in modern vessels. In that manner the heat of exhaust gases is recovering in exhaust gas boilers to produce the steam for different purposes onboard. On this particular type of passenger ship the heat produced from scavenging air and from high temperature (HT) cooling system are recovering for:
- Distilled water production (evaporator)
- Heating of sanitary hot water
- Heating of air conditioning system (AC re-heating).

HT water cooling system on board particular vessel is used for cooling of cylinder liner, cylinder heads, turbo chargers (TC), scavenging air cooler (1st stage) and then to heating of evaporator, sanitary hot water and AC re-heater). Finally, the water is returning to engine or mixed with low temperature (LT) cooling system depending on outlet temperature after waste heat recovery. LT cooling water system is used for cooling of generators, scavenging air (2nd stage), lub-oil cooling and cooling of HT water system over mixing valve.

Although some heat is recovering in that systems it can be seen that automatic temperature control parameters in the diesel engine cooling system might be optimized to increase energy efficiency and fuel economy.

**Methodology**

The cooling system of each of the six Wärtsilä 12V46 diesel engines consists of the following components (Fig. 1):
- Red line – HT water cooling system
- Violet line – preheating
- Blue line – LT water cooling system
- Light blue line – connections to expansion tank

<table>
<thead>
<tr>
<th>Operational condition</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tank heating</td>
<td>kW</td>
</tr>
<tr>
<td>Fuel trace (piping) heating</td>
<td>kW</td>
</tr>
<tr>
<td>Diesel engine fuel heating</td>
<td>kW</td>
</tr>
<tr>
<td>Boiler fuel heating</td>
<td>kW</td>
</tr>
<tr>
<td>High temp. water heating</td>
<td>kW</td>
</tr>
<tr>
<td>Fuel oil purifier heating</td>
<td>kW</td>
</tr>
<tr>
<td>Lub-oil purifier heating</td>
<td>kW</td>
</tr>
<tr>
<td>Air conditioning (pre-heating)</td>
<td>kW</td>
</tr>
<tr>
<td>Air conditioning (re-heating)</td>
<td>kW</td>
</tr>
<tr>
<td>Hot water heating (sanitary)</td>
<td>kW</td>
</tr>
<tr>
<td>Evaporator 1</td>
<td>kW</td>
</tr>
<tr>
<td>Evaporator 2</td>
<td>kW</td>
</tr>
<tr>
<td>Galley</td>
<td>kW</td>
</tr>
<tr>
<td>Laundry</td>
<td>kW</td>
</tr>
<tr>
<td>Spa</td>
<td>kW</td>
</tr>
<tr>
<td>Swimming pools</td>
<td>kW</td>
</tr>
<tr>
<td>Total</td>
<td>kW</td>
</tr>
<tr>
<td>Steam consumption</td>
<td>kg/h</td>
</tr>
</tbody>
</table>

Table 1: The power load needs of a modern cruise ship for different operational conditions [3]
Figure 1: Diesel engine fresh water cooling system (Source: authors - adopted from [4], [5])

1. expansion tank
2. automatic three-way valve for regulation of LT water temperature 1
3. fresh water (FW) cooler
4. air vent tank
5. LT water circulation pump for scavenging air and lubricating oil cooling (attached to the engine)
6. automatic three-way valve for regulation of LT water temperature 2
7. LT scavenging air cooler (2nd stage)
8. lubricating oil cooler
9. LT water circulation pump for generator cooling (driven by electromotor)
10. LT generator cooler
11. automatic three-way valve for regulation of HT water temperature 1
12. automatic three-way valve for regulation of WHRS
13. HT water circulation pump (attached to the engine)
14. HT scavenging air cooler (1st stage)
15. automatic three-way valve for regulation of HT water temperature 2
16. evaporator (1st stage of WHRS)

The thermal efficiency of the diesel engine cooling system is (Fig. 1):

\[ \eta_{WHR} = \frac{\dot{m}_{WHR} \cdot c_w \cdot \Delta t_{WHR}}{\dot{m}_{ECW} \cdot c_w \cdot \Delta t_{ECW}} \]  

where:
- \( \dot{m}_{WHR} \) – mass flow through waste recovery system
- \( \dot{m}_{ECW} \) – mass flow through engine cooling system
- \( c_w \) – specific heat capacity of cooling water
- \( \Delta t_{WHR} \) – temperature difference WHR system
- \( \Delta t_{ECW} \) – temperature difference HT/LT cooling system

Due to equal mass flow (\( \dot{m}_{WHR} = \dot{m}_{ECW} \)) the relevant formula is:

\[ \eta_{WHR} = \frac{\Delta t_{ECW}}{\Delta t_{WHR}} = \frac{t_6 - t_5}{t_6 - t_5} \]  

Useful power (P) or thermal heat recovered (THR):

\[ P = THR = P_{HT} \cdot \eta_{WHR} \]  

Where \( P_{HT} \) is power from engine HT cooling system (jacket water and charge air HT circuit).

The waste heat in the HT cooling water can be used for fresh water production, central heating, fuel tank heating etc. The heat available from HT cooling water is affected by engine load and ambient conditions. Recoverable heat is reduced by circulation to the expansion tank, radiation from piping and leakages in temperature control valves. Data provided by the manufacturer for heat bal-
Temperatures recorded on board:

- Temperature before cylinders: \( t_1 \) = 72 °C
- Temperature after cylinders: \( t_2 \) = 83 °C
- Temperature after HT charge air cooler: \( t_3 \) = 93 °C
- Temperature before WHRS: \( t_4 \) = 92 °C
- Temperature after WHRS: \( t_5 \) = 84 °C
- Temperature after LT charge air cooler: \( t_6 \) = 40 °C
- Temperature after lubricating oil cooler: \( t_7 \) = 45 °C
- Temperature before engine: \( t_8 \) = 37 °C

\( P_H \) = 12645 kW

Calculated values:

- Thermal efficiency: \( \eta_{WHR} \) = 0.38
- Heat recovery at 100% load per DE: \( \text{THR}_1 \) = 1770 kW
- Heat recovery at 72% load per DE: \( \text{THR}_2 \) = 1274 kW
- Heat recovery for three DE at 72% load: \( \text{THR}_3 \) = 3822 kW

Table 2: Thermal efficiency calculated before optimization (only 1st stage of WHRS in use)

Temperatures recorded on board:

- Temperature before cylinders: \( t_1 \) = 72 °C
- Temperature after cylinders: \( t_2 \) = 83 °C
- Temperature after HT charge air cooler: \( t_3 \) = 93 °C
- Temperature before WHRS: \( t_4 \) = 92 °C
- Temperature after WHRS: \( t_5 \) = 84 °C
- Temperature after LT charge air cooler: \( t_6 \) = 40 °C
- Temperature after lubricating oil cooler: \( t_7 \) = 45 °C
- Temperature before engine: \( t_8 \) = 36 °C

\( P_H \) = 12645 kW

Calculated values:

- Thermal efficiency: \( \eta_{WHR} \) = 0.52
- Heat recovery at 100% load per DE: \( \text{THR}_1 \) = 2433 kW
- Heat recovery at 72% load per DE: \( \text{THR}_2 \) = 1752 kW
- Heat recovery for three DE at 72% load: \( \text{THR}_3 \) = 5256 kW

Table 3: Thermal efficiency calculated before optimization (1st and 2nd stage of WHRS in use)

Optimization

It is common practice on board that there is no any intention of the engine crew to optimize waste heat recovery system of scavenging air cooling or HT/LT fresh water cooling. With correct selection of parameters ("set points") in automated control of automatic three-way valve (11,12 and 15), (Fig. 2) it is possible to optimize the system.

Improvement in the thermal efficiency and reduced fuel consumption might be achieved through temperature adjustment as shown in the following tables (Table 2, 3 and 4).
Temperatures recorded on board:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value 1</th>
<th>Value 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature before cylinders</td>
<td>t₁</td>
<td>75 °C</td>
</tr>
<tr>
<td>Temperature after cylinders</td>
<td>t₂</td>
<td>86 °C</td>
</tr>
<tr>
<td>Temperature after HT charge air cooler</td>
<td>t₃</td>
<td>95 °C</td>
</tr>
<tr>
<td>Temperature before WHRS</td>
<td>t₄</td>
<td>94 °C</td>
</tr>
<tr>
<td>Temperature after WHRS</td>
<td>t₅</td>
<td>77 °C</td>
</tr>
<tr>
<td>Temperature after LT charge air cooler</td>
<td>t₆</td>
<td>40 °C</td>
</tr>
<tr>
<td>Temperature after lubricating oil cooler</td>
<td>t₇</td>
<td>45 °C</td>
</tr>
<tr>
<td>Temperature before engine</td>
<td>t₈</td>
<td>36 °C</td>
</tr>
</tbody>
</table>

Calculated values:

- Thermal efficiency : $\eta_{\text{WHR}} = 0.90$
- Heat recovery at 100% load per DE : $\text{THR}_1 = 3948$ kW
- Heat recovery at 72% load per DE : $\text{THR}_2 = 2843$ kW
- Heat recovery for three DE at 72% load : $\text{THR}_3 = 8528$ kW

RESULTS AND DISCUSSION

The settings of the control parameters in the automatic temperature control system before and after optimization as well as both thermal efficiencies are shown in Table 5. Although it is theoretically possible to adjust parameters in such way that there will be no heat loss at all (if $\Delta t_{\text{WHR}} = \Delta t_{\text{ECW}}$), it is obvious that such recovery cannot be achieved in practice. Due to that reason, the parameters are to be selected on highest possible level allowed by manufacturer with maximum savings.

Table 5: Automatic temperature control settings (HT cooling water) and thermal efficiencies before and after optimization

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Before Optimization</th>
<th>After Optimization</th>
</tr>
</thead>
<tbody>
<tr>
<td>HT cooling water temperature</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$t_1$</td>
<td>72 °C</td>
<td>75 °C</td>
</tr>
<tr>
<td>$t_2$</td>
<td>93 °C</td>
<td>95 °C</td>
</tr>
<tr>
<td>$t_3$</td>
<td>92 °C</td>
<td>94 °C</td>
</tr>
<tr>
<td>$t_4$</td>
<td>81 °C</td>
<td>77 °C</td>
</tr>
<tr>
<td>$\eta_{\text{WHR}}$</td>
<td>0.52</td>
<td>0.85</td>
</tr>
<tr>
<td>$\text{THR}_1$</td>
<td>5256 kW</td>
<td>8528 kW</td>
</tr>
</tbody>
</table>

The difference obtained in reused power is:

$$\Delta \text{THR} = \text{THR}_{1,b} - \text{THR}_{1,a} = 8528 - 5256 = 3272 \text{ kW} \quad (5)$$

The recovered heat as useful power can be presented through savings in daily cruising fuel consumption (FCd) when running one of engines with specific fuel consumption (SFOC) of 200 g/kWh as:

$$\text{FC}_{d} = \frac{\Delta \text{THR} \cdot 24 \cdot SFOC}{1 \cdot 10^6} = \frac{3272 \cdot 24 \cdot 200}{1 \cdot 10^6} = 15.71 \text{ t} \quad (6)$$

Considering global average bunker price [7] for Intermediate Fuel Oil 380 (IFO 380) that is 463.50 USD/t daily savings on cruising will be 7282 USD (or approximately 2.6 mil USD/year) which is quite significant for any company.

CONCLUSION

Taking into consideration development of environmental legislation as well as capital and operational expenses for ship owners to comply with it is obvious that energy efficiency of the ship becomes more important.

Traditionally, the Chief Engineer on board will keep the settings of the automatic temperature control system of the diesel generator HT/LT water cooling system at the same values (or as close as possible to the minimum deviation) as it was set during the trial run or at the values transmitted during the “Chief Engineers’ handover protocol”.

This paper shows that significant savings might be achieved through optimization of parameters in automatic temperature control of diesel engines HT/LT cooling water system. Different settings are resulting with different thermal efficiencies. Consequently, recovered heat reduce fuel consumption and increases energy and costs efficiency.

However, it is to be noted that before attempting of any parameter adjustment, the mechanical and physical condition of all elements included into system (engine, coolers, pumps, regulation valves, ...) must be carefully examined as well as operational condition in sailing area. Further research will be focused on cruising speed optimization respecting diesel electric propulsion.

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