ABSTRACT
The present work focuses on a thermodynamic analysis and feasibility study of ORC Waste Heat Recovery System (ORC-WHRS) for a marine diesel engine. ORC-WHRS with an engine was simulated and its performance was theoretically estimated under various engine operation conditions and cooling water conditions. The working fluid, R245fa, was selected for consideration of the heat source temperature, system efficiency and safety issues. The result shows electric power output of the ORC-WHRS was about 4% of the mechanical power output of the considering Marine Diesel engine. According to thermodynamic analysis, about 9~13% of system efficiency was performed with below 250 °C of low temperature heat source.

KEY WORDS
Organic Rankine Cycle (ORC), Waste heat recovery system (WHRS), Diesel Engine, Energy efficiency, Air Cooler, Economizer, Low grade heat

NOMENCLATURE
MAT : Minimum Approach Temperature
P : Pressure (kPa)
\( m_{\text{dot}} \) : Mass Flow Rate (kg/s, kg/h)
Q : Heat Capacity (kWe)
T : Temperature (°C)
\( \eta \) : Efficiency (%)

SUB-SCRIPT
CW : Cooling Water
Exh : Exhaust Gas
Sea : Scavenge Air
p: pump

1. Introduction

Because of IMO MEPC (International Maritime Organization Marine Environmental Protection Committee) 62nd Session, emission control and efficiency improvements of ships became more important issue for current marine business. Many shipyards and machinery makers focuses energy saving or efficiency improving technologies. One of the ways to achieve the efficiency improvement in the ships is recovering unused source of energy. Fig 1 shows the heat balance of the typical marine engines. Only 50% of fuel combustion energy is converted into the shaft power of the ships. The remaining of fuel combustion energy is dissipated by the exhaust gas, cooling system, and radiation from engine block. Nearly 40% of heat energy is wasted with the exhaust gas and scavenge air cooling. Using this waste heat will allow to enhance the overall fuel efficiency of the ship and to reduce green house gas. Conventionally, technology for the recovery of unused heat has been limited to the high-temperature grade waste heat and the recovered heat is used for the steam production and electric power generation by high pressure steam turbine. However, the exhaust gas temperature of the current marine engine is below 250°C because the current marine engine must satisfy IMO Tier II and emission control regulations. The Organic Rankine Cycle (ORC) is one of promising heat recovery power generation cycle for the low grade waste heat. (1) The ORC is named for its use of an organic, high molecular mass fluid with a liquid-vapor change, or boiling point, occurring at a lower temperature than the water-steam phase change. The Organic fluid allows Rankine cycle heat recovery from lower temperature heat source.

The low temperature heat is converted into useful work that can be converted into electricity.(2,3)

The present work focuses on a thermodynamic analysis and characteristics of ORC-WHRS for a marine diesel engine. This paper also discusses the feasibility of applying ORC-WHRS to the ship.
2. Engine and Working Fluid

2.1 Ship type and Marine Engine

In this work, subject ship type is select to Suez-Max tanker. Suez-Max is a naval architecture term for the largest ship measurements capable of transiting the Suez Canal in a laden condition. Suez-Max tanker is selected because it offers the relative economies of scale that can be achieved with VLCCs (Very Large Crude Carrier) and it is one of the main categories of tanker type. Man Diesel & Turbo 6S70ME-C8.1-TII Marine diesel engine is installed in this Suez-Max ship. Outputs of this engine are NCR (Normal Continuous Rating) 16.4MW and SMCR (Specified Maximum Continuous Rating) 18.2MW.

To maximize the heat recovery amount, the temperature of exhaust gas out to the ambient needs to be set as low as possible. However, the present work set the temperature of exhaust gas out to the ambient as 165 ℃. This is because considerable amount of sulfur acid in the exhaust gas may cause economizer corrosion at certain temperature point. Fig. 1 shows 14.1% of the heat is wasted to scavenge air cooling water and this is the second largest heat loss term in the engine. This heat also needs to be recovered to maximize the heat recovery in the ship.

The waste heat conditions of 6S70ME-C8.1 TII Marine diesel engine at NCR are shown in Table 1.

<table>
<thead>
<tr>
<th></th>
<th>T (℃)</th>
<th>(m_{\text{dot}}) (kg/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exhaust gas</td>
<td>227</td>
<td>150,300</td>
</tr>
<tr>
<td>Scavenge air</td>
<td>182</td>
<td>147,600</td>
</tr>
</tbody>
</table>

2.2 Selection of Working Fluid

The selection of the working fluid is key importance in low temperature rankine cycles because heat transfer inefficiencies are highly prejudicial at the low temperature rankine cycle. To select appropriate refrigerant for marine ORC-WHRS system, the heat source temperature, system efficiency and safety are needed to be considered. Calculation was carried out for simple Rankine Cycle with the five different refrigerants at the same heat source temperature. The simple Rankine Cycle consists of evaporator, turbine, condenser and pump as shown in Fig. 2.

Fig. 2 Schematic of Rankine Cycle

Fig. 3 T-S diagram of various refrigerant

Five different refrigerants were R245fa, Pantane, Isopentane, Isobutane, and R124a. These refrigerants are selected because of those thermal characteristics as shown in Fig 3.

The system efficiencies were evaluated under the same condition. The calculation conditions were heat source...
temperature of 170°C, inlet cooling water temperature of 36°C and heat exchanger pinch point of 10°C.

The evaluation results show that R245fa, Pentane and Isobutene have the highest system efficiency as shown in Table 2.

<table>
<thead>
<tr>
<th>Refrigerant</th>
<th>Efficiency (%)</th>
<th>Eff. Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>R245fa</td>
<td>11.1</td>
<td>1</td>
</tr>
<tr>
<td>Pentane</td>
<td>11</td>
<td>2</td>
</tr>
<tr>
<td>Isopentane</td>
<td>8.8</td>
<td>4</td>
</tr>
<tr>
<td>Isobutene</td>
<td>11</td>
<td>2</td>
</tr>
<tr>
<td>R134a</td>
<td>4.8</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 2. Evaluation Results of Refrigerants

The safety and environmental issues are also considered to select the refrigerant. Most class societies prohibit the refrigerants that have more than 2000GWP (Global Warming Potential). Even the refrigerant that has low enough GWP to satisfy the class society restriction, high flammable refrigerants are not allowed in the ship. The safety and environmental characteristics of refrigerants are shown in Table 3.

<table>
<thead>
<tr>
<th>Refrigerant</th>
<th>GWP</th>
<th>Safety Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>R245fa(6)</td>
<td>950</td>
<td>Inert, Chemically stable</td>
</tr>
<tr>
<td>Pentane</td>
<td>11</td>
<td>Highly Flammable, Explodable</td>
</tr>
<tr>
<td>Isobutene</td>
<td>11</td>
<td>Highly Flammable, Explodable</td>
</tr>
</tbody>
</table>

Table 3. Characteristics of Refrigerants

The study shows that R245fa is the most suitable for marine ORC-WHRS refrigerant with consideration of heat source temperature, system efficiency and safety issues.

3. Simulation

<table>
<thead>
<tr>
<th>$P_{\text{Crit}}$</th>
<th>$T_{\text{Crit}}$</th>
<th>Boiling pt.</th>
<th>Molecular wt.</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.651kPa</td>
<td>154°C</td>
<td>15.11°C</td>
<td>134</td>
</tr>
</tbody>
</table>

Table 4. Properties of R245fa

R245fa is selected for the working fluid of ORC-WHRS and its properties are shown in Table 4. The assumptions made for cycle calculation are as follows:

(1) Working fluid inlet condition to Turbine or Expander: Saturated Vapor
(2) Working fluid outlet condition from Turbine or Expander: Superheated Vapor
(3) Working fluid outlet condition from condenser: Saturated liquid
(4) Recuperator is not considered in the system
(5) Evaporator maximum pressure: limited to 30 bar Also, isentropic efficiencies of turbine/expander and pump are assumed as 82% and 75% respectively. Efficiencies of generator and motor are assumed as 95% and 80% respectively. The system is calculated and analyzed with HYSYS Software. The working fluid properties in the calculation are taken from the HYSYS database as shown in Table 4.

The cycle efficiency ($\eta_{\text{cycle}}$) and system efficiency ($\eta_{\text{system}}$) of ORC-WHRS can be expressed as (1) ~ (3).

$$W_{\text{out,net}} = W_{\text{turbine}} - W_{p,\text{ORC}}$$ (1)

$$\eta_{\text{cycle}} = \frac{W_{\text{out,net}}}{Q_{\text{evap}}}$$ (2)

$$\eta_{\text{system}} = \frac{(W_{\text{out,net}} - W_{p,\text{loop}} - W_{p,CW})}{Q_{\text{evap}}}$$ (3)

To assure performance and safety of Marine Diesel engine, indirect type heat transfer loop is needed for marine ORC-WHRS. The heat transfer medium is water. The pressure of the medium is set to greater than boiling
pressure at the highest temperature of the heat transfer loop to avoid phase change in the loop. Schematic diagram of the system is shown in Fig. 4.

The temperature difference of the condenser inlet and outlet decides the cooling capacity. The temperature of cooling water effect to the ORC-WHRS performance because the condensing temperature and pressure of condenser is decided with MAT (Minimum Approach Temperature). A pinch point is the closest approach point between hot and cold heat change curves and this pinch decides the performance of heat exchanger and ORC. Next section shows the effects of the MAT and pinch point of ORC-WHRS.

4. Discussions and Results

4.1 Effects of Cooling Water

Fig. 5 and Fig. 6 show the maximum cycle efficiency and system efficiency at T_{\text{loop,in}} = 170°C. Different combinations of pinch and MAAT (Minimum Allowable Approach Temperature) were simulated to see the effect of cooling water temperature. Because of the internal condenser pressure effects on the expansion ratio of turbine, the temperature of C.W is the most influential factor to the efficiency.

The case of P5°C-M10°C and P10°C-M5°C combinations show the equivalent maximum cycle efficiency because the condensing temperature is decided by condition of pinch and MAAT. However, Fig. 6 shows the pinch is more dominant to the system efficiency. It is because the more C.W and pump power are needed for the smaller MAAT even though the smaller MAAT causes the lower condensing temperature and the higher system efficiency at the same pinch.

4.2 ORC performance curve

The ORC-WHRS performances are evaluated with different T_{\text{mid}}, inlet temperature of exhaust gas heat exchanger from 1^{st} stage scavenge air cooler, as shown in the Fig. 4. The calculation assumes C.W = 25°C (ISO ambient condition), and 10°C of pinch and MAAT for the 1^{st} scavenge air cooler, ORC condenser and ORC evaporator. Fig. 7 shows the net power output of ORC-WHRS with different T_{\text{mid}} and T_{\text{Loop,out}}. Results show that as T_{\text{mid}} increases the power output of ORC-WHRS increases. The maximum power output of the ORC-WHRS is 667kWe at T_{\text{mid}} = 150°C and T_{\text{Loop,out}} = 80°C.

Fig. 8 shows the net power output and the system efficiency of ORC-WHRS with respect to the T_{\text{Loop,out}}. The results show that the system efficiency is 12.3% at the maximum net power output of the ORC-WHRS.

However, the optimum net power output of ORC-WHRS and system efficiency are calculates as 650kWe and 13.1% respectively. The system efficiency increases as T_{\text{Loop,out}} increases until it reaches to the maximum point. It is because T_{\text{Loop,out}} controls the evaporation pressure of ORC-WHRS evaporator. However, increasing of T_{\text{Loop,out}} causes more pump power consumption to supply the same heat capacity. The system efficiency decreases after the maximum point because power consumption of the
circulation pump is more dominant to the system efficiency.

Because of the temperature limitation of heat source from marine diesel engine, the turbine inlet pressure is fixed to the certain point even though $T_{\text{Loop,out}}$ increases. At the same condition, the net power output decreases because heat recovery amount of 1st scavenge air cooler decreases.

5. Conclusion

In this work, several candidates of organic working fluids were evaluated and selected for the marine diesel engine ORC-WHRS application. The cycle efficiency and system efficiency were evaluated with C.W temperature. The net power output of ORC-WHRS was investigated with the temperature conditions of HTL. The 9–13% of system efficiencies were performed with the waste heat of the marine diesel engine. Thermal dynamic analysis showed approximately 650kWe of additional electric power can be produced from waste heat recovery through the scavenge air and exhaust gas. The 650kWe of electric power is about 4% of the mechanical power output of the 6S70ME-C8.1-TII marine diesel engine.

The present work was performed with the basic thermodynamic theory to see feasibility of ORC-WHRS for the marine diesel engine. Additional works are required to carry this work to the real state. Additional works are as follows:

1. Establish the control logic, operate & run logic of HTL & ORC-WHRS
2. Design of air cooler under consideration of its size and pressure drop
3. Arrangement plan under consideration of ship design

Acknowledgement

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References

