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A study evaluating the ability to recover cooling water waste heat using organic Rankine cycle on marine engines

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ABSTRACT

Waste heat recovery (WHR) technology is an effective way to reduce fuel consumption and CO_2 emissions, and is currently used in some ships, converting up to 8% of main engine braking power into electric power. In this paper, a 4-stroke small marine diesel engine with a nominal capacity of 60kW at 2200 rpm is used for experimental research. The main parameters of waste heat from the engine include the exhaust heat and the cooling water waste heat used under operating conditions at a fixed speed at 2000 rpm at 100%, 75%, and 50% load respectively. Three system configurations were studied, including configuration (a) (recovering waste heat from cooling water to preheating the substance and recovering all waste heat from waste gas to evaporate the substance), configuration (b) (recover all waste heat from cooling water for preheating properties and recover waste heat from waste gas to further heat the substance) and configuration (c) (only waste heat recovery is performed by cooling water). The system activities are evaluated for thermal efficiency and waste heat recovery efficiency with R245fa. At the same time, the improved efficiency of ORC systems and generating capacity are presented to clarify the ability to utilize waste heat of the designed ORC system.

KEYWORDS

Waste heat recovery, cooling water, Organic Rankine Cycle, marine diesel engine

INTRODUCTION

The main engine is installed on large-capacity ships, the exhaust gas emitted by the main engine has a large flow, the pressure and temperature are quite high, about 0.35 MPa and 400°C, carry a large amount of energy discharged. This energy source accounts for about 20% to 25% of the total heat fed to the engine, and the heat released by cooling water accounts for about 10% to 16% of the total heat generated in the combustion chamber [1][2]. If making full use of this energy source, will contribute to saving fuel and increasing the efficiency of the ship's propulsion system [3][4]. To save fuel as well as reduce environmental pollution, not only seek to improve the thermal efficiency of the boiler by reducing the heat loss but also find a way to make full use of the waste heat from waste diesel engines into the environment [5][6]. According to the statistics of the world environmental protection organizations, the amount of toxic emissions caused by water transport vehicles annually accounts for about 18% to 20% of the total amount of harmful gases worldwide [7].

The main source of air pollution is the exhaust gas discharged from ship diesel engines to the environment when using fossil fuels such as heavy fuel (HFO), diesel fuel (DO), and lubricating oil when partially burned [8][9][10]. Efficient use of waste heat energy can improve the efficiency of the driving system and reduce emissions, by using the dedicated Waste Heat Recovery System (WHRS) to generate electricity or Used for warming and drying needs. For a conventional vessel, the heat load is negligible compared to the available waste heat, leaving a large volume of thermal energy unused [11]. WHRS can use the residual waste heat to convert heat energy into mechanical/electrical energy, which can then meet the needs for propulsion equipment and auxiliary engines without additional fuel costs and no CO2 emissions related to [12]. MAN Diesel sees a potential total efficiency of 60% for fuel energy used on onboard diesel main engine uses. Other studies, mostly forecasts based on energy analysis, can achieve 4-16% fuel savings for a mid-range tanker using WHRS.

In addition, the Cooling System functions to dissipate heat from hot components (piston, cylinder, cylinder cap, cylinder, etc.) so that they are not overheated. Besides, engine cooling maintains the lubricating oil temperature within a certain range to maintain the lubricant specifications. The substance that acts as an intermediate in the heat transfer process from the hot engine parts out is called the coolant. The coolant can be water, air, oil, or some special liquid. Air is used as the main cooling medium for small-capacity engines. Most of today's urban engines, especially marine engines, are cooled by water because of their high cooling efficiency [13][14]. During the working process of the engine due to the very high temperature of the combustion gas, the parts of the engine are exposed to the combustion gas at the same time by friction with each other, so their temperature is very high. In order to avoid deformation of the parts and to ensure the quality of the lubricating oil, to ensure the intake air volume is guaranteed, the engine must be cooled. The ingredients used to cool the internal combustion engine are water, air [15][16]. For marine engines, only water is used for cooling.

The temperature of water in and out of the engine depends on the engine type and cooling method. If the temperature of the cooling water is high, the quality of the combustion is good, reducing the amount of heat transferred out, reducing thermal stress can increase engine economy, but poor lubricating oil quality, reduced oil life, and reduced intake efficiency [17]. If the temperature of the coolant is low through the heat loss, which increases the thermal stress of the parts in contact with the coolant, the poor mixing process should affect the engine performance but the charge factor [18][19], resulting in increased lubrication and broken lubricant quality. Therefore, when designing a cooling system, it is necessary to rely on a specific engine type and experience data to choose the appropriate cooling water temperature [20]. This temperature depends on the thermal strength of the material, on the thermal stability of the lubricating film, on the conditions under which the working process is most beneficial, on the reliability of the parts [21]. Therefore, the installation of an additional system to utilize waste heat on the cooling system will overcome the shortcomings in the design and maximize the advantages and the economics of saving and using energy efficiently [22][23].

The ORC cycle generates electricity from a low-temperature waste heat source, so it is possible to expand its application and convert waste heat into electricity [24]. This is a simple but effective solution to take advantage of the abundant but unused waste heat to convert it into electricity without emitting CO_2, helping manufacturing businesses reduce energy costs, bring economic benefits, and contribute to environmental protection, towards sustainable development [6][25]. Therefore, the integration of equipment systems that convert waste heat from cooling water of ship diesel engines into electrical energy on the basis of the Rankin cycle using organic work agents with low ODP, GWP, in order to improve energy efficiency and economics is essential. This experimental study aims to evaluate the performance and performance of a small ship diesel engine when a cluster of equipment to convert waste heat from cooling water is installed. Furthermore, compare and evaluate the utilization of waste heat of the ORC system when set up with different case studies (only utilize waste heat of cooling water and combine the waste heat of cooling water with heat. emissions according to 2 priority levels).

MATERIALS AND EXPERIMENTAL SETUP

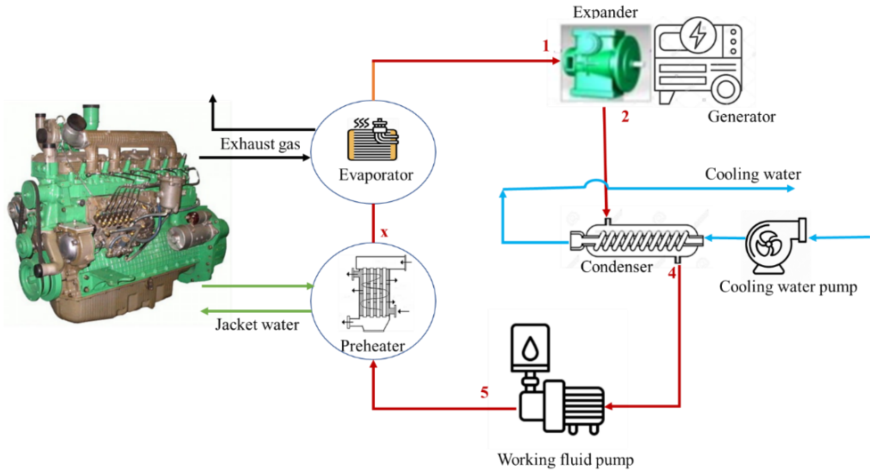

Figure 1. Layout diagram of waste heat recovery equipment by ICE-ORC system

Systems (a) and (b) include pre-heater, evaporator, expansion unit, generator, condenser, and pump. For system (c), the working medium is only heated to the cooling water. Figure 1 shows a schematic diagram of the ICE-ORC system. In systems (a) and (b), the cooling water first releases the heat to the pre-heater and then returns to the DC, while the heat-emitting exhaust gas in the evaporator is then released to the atmosphere. First, the substance is pumped to high pressure (4–5) and then preheated with cooling water (5-x) and further heated by the exhaust gas in the evaporator (x-1). The generated steam then flows into the expansion unit for useful work (1–2), then the low-pressure steam enters the condenser, where it turns into a saturated liquid (2–4) by water as cooling.

It should be pointed out that the difference between (a) and (b) is the preferred recovery of waste heat from exhaust gas (a) or cooling water (b). On this basis, the heat energy of the exhaust gas is completely recovered in the system (a), bringing the temperature of the exhaust gas at the outlet of the evaporator to the minimum value allowed in this study (393 K). In contrast, the heat energy of the coolant is completely recovered in the system (b), meaning that the temperature of the coolant at the outlet of the pre-heater is equal to that of the return temperature (353 K). In this study, the D243, 4-stroke diesel engine with a nominal capacity of 60kW at 2200 rpm is used for experimental research. The main parameters of waste heat from the engine, which have a constant rate of 2000 rpm under 100%, 75%, and 50% load respectively, are listed in Table 1.

Table 1. Waste heat properties from engines with different load levels

Parameters	100% load	75% load	50% load
The thermal energy of the exhaust gas, Q_{ex} [kW]	29.4	24.1	18.2
The thermal energy of cooling water, Q_w [kW]	30.1	23.9	18.4
The temperature of the exhaust gas, T_{ex} [K]	717	740	766
Exhaust air flow, m_{ex} [kg/s]	0.9	0.68	0.47
Cooling water flow, m_w [kg/s]	7.2	5.7	4.4

A working substance with a positive slope is defined as a dry liquid, while a liquid with a negative slope is a wet liquid, with a longitudinal slope considered as the isotropic liquid. Dry and isotropic liquids are generally recommended as they can avoid liquid droplets causing damage to the device. On the other hand, the safety and environmental characteristics (ODP value <0.20, GWP value <1500) should also be taken into account when choosing a reagent. The working substance selected is R245fa. The expander admission and discharge valves are mechanically driven by the crankshaft rotation. The expander is directly coupled to a permanent magnet electric generator in a hermetical sealed case.

Since no transmission is interposed, the expander and generator work at the same rotational speed, which can vary in the range from 400 rpm to 1800 rpm. The external surface of the machine has been thermally insulated by means of mineral wool panels, in order to reduce heat transfer losses, which have been demonstrated not negligible in analogs applications [21]. The ORC circulation pump is a prototypal volumetric external gear pump, driven by a three-phase motor that can work at a rotational speed between 250 rpm and 900 rpm by means of an inverter. The system is also provided with a by-pass line at the outlet of the evaporator, which allows the working fluid to flow through the external casing of the expander, by-passing the cylinders; this expedient is used during start-up operation, in order to warm up the expander body and avoid possible thermal stresses due to a cold start-up.

RESULTS AND DISCUSSION

The thermal efficiency of 3 ORC configurations

For an established substance R245fa, when the evaporation pressure is determined, the thermal efficiency depends only on the system configuration. In fact, the thermal efficiency becomes independent of the performance of the system and the properties of the heat source because the flow rate of the substance can be reduced in the calculation. As shown in Figure 2, the thermal efficiency increases for all three configurations with an increase in the evaporation pressure. The high thermal efficiency means greater output power can be obtained with the same amount of heat absorbed by the ORC. In which, configuration (a) can achieve the highest thermal efficiency

(21.53%) at 1.6 MPa, while the highest values of configuration (b) and configuration (c) were 18.85% at 1.36 MPa and 15.76% at 1.47 MPa, respectively.

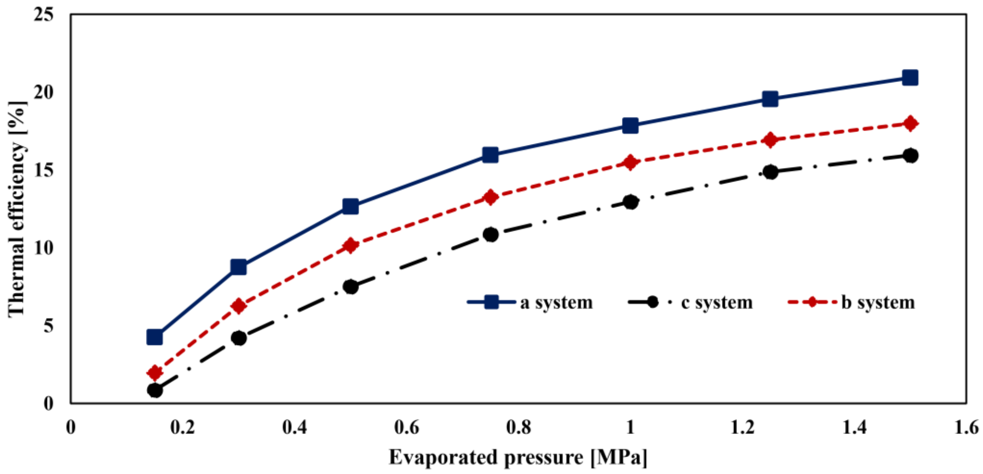

Figure 2. Relationship between thermal efficiency and evaporating pressure of 3 configurations

Obviously, the thermal efficiency of R245fa with (a) configuration is the best, with using this configuration the thermal efficiency of the ORC system can reach from 18% to nearly 22% when the vapor pressure change from 1.2MPa to 1.8MPa. Meanwhile, configuration (c) gives the lowest thermal efficiency, with steam pressure from 1 Mpa to 1.5 Mpa, the thermal efficiency increases from 12% to nearly 16%.

Waste heat recovery efficiency

At a given evaporation pressure, the flow rate of the substance decreases with an increase in the transition point temperature difference. This downtrend stops when the outlet temperature of the waste heat from the heat exchangers meets the limitations of each system. As a result, the efficiency of waste heat recovery obtained under these conditions is maximum at each evaporation pressure. Figure 3 shows the change of the waste heat recovery efficiency as a function of the evaporation pressure for the three working solvents when the engine is operating at rated load. For all three configurations, the weight increases with evaporative pressure.

With R245fa, maximum evaporation pressure of 1.8 Mpa for (c), followed by 1.58 Mpa for (b) and 1.57 Mpa for (a), which match the results for thermal performance, while the system's maximum evaporation pressure (b) is limited to a low value due to the system configuration. During this cycle, the heat energy of the cooling water is completely recovered by the working medium and thus increases its entanpi. Since the enthalpy increases slightly in the liquid phase but increases dramatically in the gas phase or biphasic state, the thermodynamic state of the working medium at the outlet of the pre-heater should be in the two-phase or gas-phase zone.

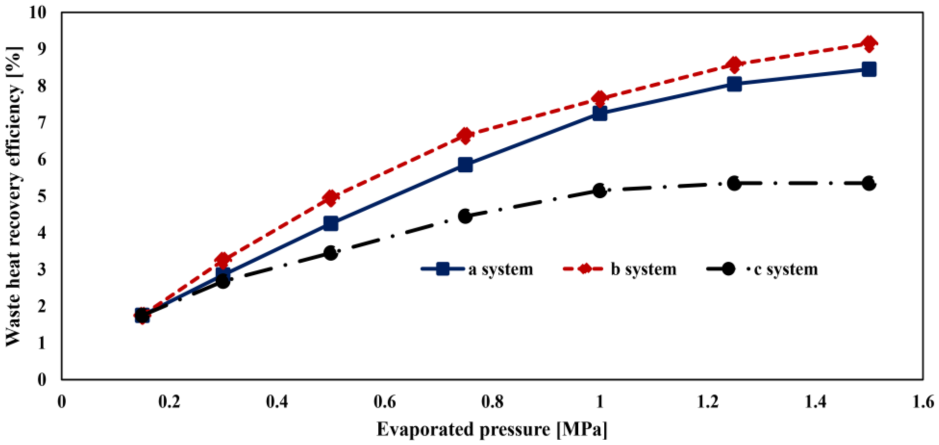

Figure 3. Relationship between waste heat recovery efficiency and vapor pressure

In system (b), the maximum evaporation pressures of the three working solvents are 0.42 MPa, 0.49 MPa, and 0.79 MPa, respectively. It is clear that at a certain low evaporation pressure, system (c) showed the lowest of all three candidate properties due to its unique cooling water heat recovery, which also proves the benefits of cascading use of exhaust gas and cooling water. The highest heat recovery efficiency values appear in the system (a), namely 10.19%, 9.47%, and 8.68%. From the above results, it can be concluded that R245fa exhibits the best overall performance out of the three working solvents. Therefore, only R245fa will be used in the remainder of this work as an operating fluid to evaluate system performance when the engineered load changes.

The electrical output from the ORC system

Working fluid enters the expander at the location having a small clearance. A rotor with moveable vanes is attached to a rotor which is in close proximity to the casing in asymmetric orientation. The rotation of the rotor allows the vanes to move outwards while trapping working fluid, as the rotation angle increases the volume bound by consecutive vanes increases, and expansion of working fluid occurs. Their reported power output ranges from few watts to 2.2 kW. As some volumetric expanders, they can be directly attached to the generator due to their low rotational speeds. They are usually preferred to reduce the system costs because of their simple design and low manufacturing costs, higher torque, and higher volumetric efficiency. In addition, they are mechanically simple and available commercially.

Besides, they are characterized by small vibration, low acoustic impact, and simple and reliable structure. However, they exhibit lower isentropic efficiencies compared to other volumetric expanders due to leakages and higher friction losses. Figure 4 presents the trend of the produced electric power as a function of the superheating degree. The electric power increases for all systems and decreases with the superheating. The system (a) and (b) obtained the best generator power; Power output values range between 1200 W and 4800 W. Baseline calculation results for a 60kW yield 5-6% of gain in power output if a bottoming ORC cycle is adapted. Thermal efficiencies of ORC systems onboard ships lie in the range from 5% to 20%, depending on the selected heat sources, working fluid, cycle configuration, and operating parameters.

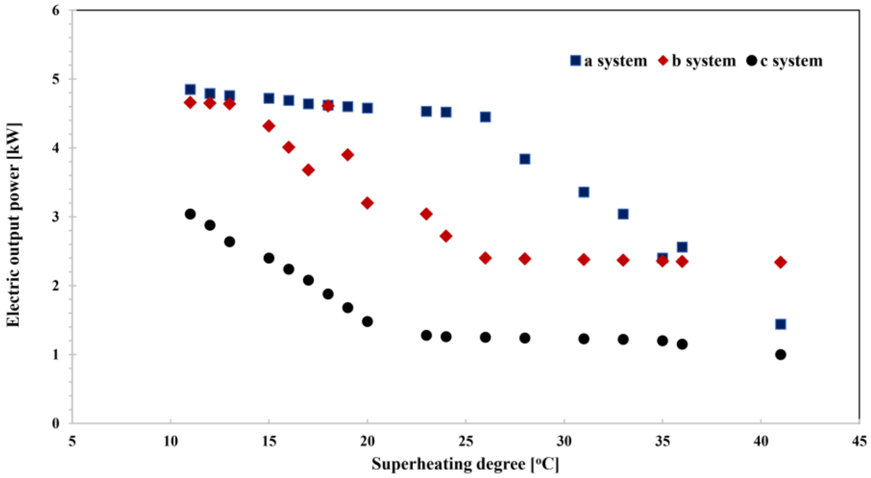

Figure 4. Electric output power

CONCLUSION

The thermal efficiency of the proposed ORC systems depends on the choice of the substance rather than on the properties of the heat source. All three candidate properties in this study show an increasing trend of thermal efficiency with an increase in evaporative pressure, where the highest efficiency (21.82%) is achieved by R245fa with the critical pressure is 4.46 MPa. Unlike thermal efficiency, the efficiency of waste heat recovery is closely related to the characteristics of the heat source. A system that recovers both the exhaust gas and engine coolant heat offers a higher recovery efficiency than a system that only recovers exhaust heat at the same evaporation pressure. The highest value of the heat recovery efficiency (10.19%) is obtained by the complete exhaust heat recovery system, which uses R245fa as the substance. The electric capacity generated from the ORC heat utilization system ranges from 1.2 kW to 4.8kW, which contributes about 2.8-4.5% to the total efficiency.

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