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A REVIEW OF LOW-GRADE HEAT RECOVERY USING ORGANIC RANKINE CYCLE

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Abstract: Many industrial processes and conventional fossil fuel energy production systems used in small-medium industries, such as internal combustion engines and gas turbines, provide low or medium temperature (i.e., 200–500^{0}C) heat fluxes as a by-product, which are typically wasted in the environment. The possibility of recovery-wasted heat from internal combustion engines using organic Rankine cycle is investigated in this article.

Keywords: internal combustion engine, waste heat recovery, organic Rankine cycle, configurations

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1. INTRODUCTION

In recent years, there has been a great deal of waste heat energy being released into the environment, such as exhaust gases from turbines and engines and waste heat from industrial plants, which lead to serious environmental pollution. In addition, there are also abundant geothermal resources and solar energy available in the world. These heat sources are classified as low-grade heat sources. Therefore, more and more attention has been paid to the utilization of low-grade waste heat nowadays for its potential in reducing fossil fuel consumption and alleviating environmental problems.

Since conventional steam power cycles cannot give a better performance to recover low-grade waste heat, the organic Rankine cycle (ORC) is proposed to recover low-grade waste heat. There are several advantages in using an ORC to recover low-grade waste heat, including economical utilization of energy resources, smaller systems and reduced emissions of CO, CO2, NOx and other atmospheric pollutants. The main advantage of the ORC is its superior performance in recovering waste heat with a low temperature.

Besides the ORC, researchers have proposed various thermodynamic cycles, such as Kalina cycle, Goswami cycle, and trilateral flash cycle, to convert this low-grade heat sources into electricity. Although there is more power output for the same heat input with Kalina cycles compared to ORCs, the ORC system is much less complex and needs less maintenance.

2. ORGANIC RANKINE CYCLE

The ORC system represents a simple Rankine cycle in which the water is replaced by organic mediums that boil at low temperatures. The layout of an ORC simple cycle layout and typical T–s diagrams of both subcritical and transcritical cycles are reported in Figure 1. Over the years, the ORC systems have gained a moderate level of maturity and reliability, allowing heat recovery from different sources.

One of the main challenges of the ORC is represented by the choice of the appropriate working fluid, in order to achieve the maximum efficiency for given hot and cold sources. Many analyses of the influence of the working fluids on system efficiency have been reported in the literature, as for instance [8,10]. However, the selection of the optimal working fluid is considered not fully addressed. In fact, recent research works focus on analyzing multi- component mixtures of working fluids in order to better match the heat sources.

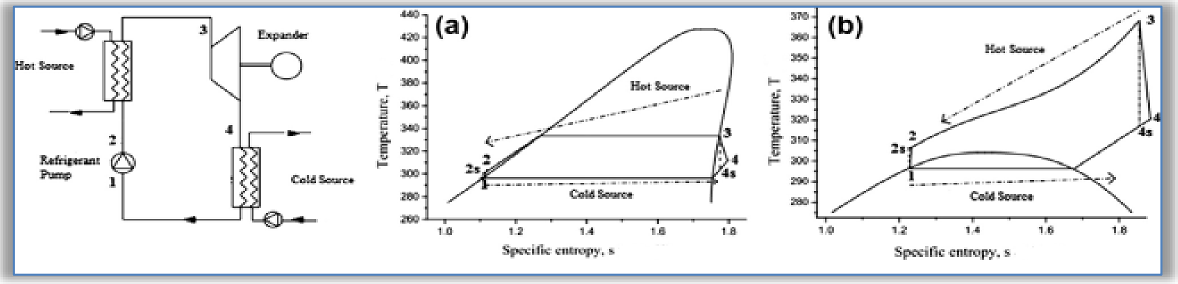

Figure 1 – ORC simple cycle layout and T–s diagrams of subcritical (a) and transcritical (b) cycles [13]

The technical feasibility of ORC applications for LGTE recovery has already been investigated and validated [3,9]. In fact, ORC cycles are successfully used in several applications, such as geothermal resources, waste thermal energy recovery from gas turbines or internal combustion engines [15] and biomass-based CHP plants.

Although ORCs are characterized by rather low efficiencies (8–12 %) [11], they are particularly viable for small-scale power generation systems. Absence of fuel cost, improved reliability and low maintenance may also contribute to making ORCs commercially attractive.

3. ENGINE WASTE HEAT EVALUATION

Huge amounts of energy are consumed by internal combustion engines in all types of vehicles, but much of this energy is wasted through the exhaust and the cooling system. Exacerbating this problem is the fact that these combustion products also cause serious environmental issues. Engine waste-heat recovery could improve the fuel thermal efficiency, minimize fuel consumption, and reduce engine emissions. Using an organic Rankine cycle (ORC) to recover the low-grade wasted heat from these systems is the technology that is the closest to being suitable for mass production.

The efficiency of an internal combustion engine refers to the percentage of the energy resulting from the combustion that actually is applied to moving the car or running the accessories. For current ICEs, the proportion of fuel energy converted into effective work at medium and high loads is about 30% - 45% for the diesel engine or 20% - 30% for the gasoline engine, and the rest is mainly brought into the environment by the exhaust gas and cooling system.

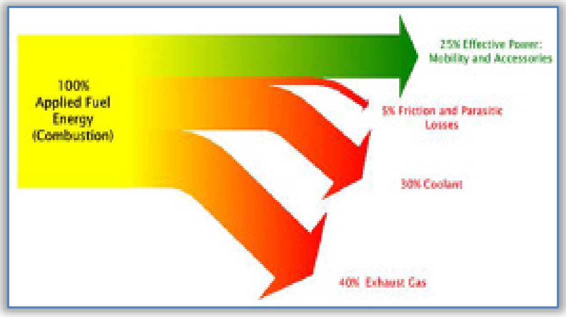

Figure 2 - Energy losses in gasoline engine and effective power [1]

To design a reasonable ORC system to utilize various waste heats from the diesel engine with high efficiency, studying the energy distribution in the running process of the diesel engine is necessary. When an engine is running, the energy and energy quantities of the exhaust and the coolant are significantly different. Because of this, it is very difficult to design a system that can comprehensively recover waste heat from both the exhaust and the coolant of that system. A six-cylinder in-line diesel engine is used as the object of analysis. The main technical performance parameters are listed in Table 1.

Table 1. The main technical performance parameters of the diesel engine

Items	Parameters	Units
Model	Diesel	[-]
Cylinder number	4	[-]
Stroke and cylinder bore	80.5x76	[mm]
Displacement	1461	[cm^3]
Compression ratio	15.7:1	[-]
Air intake type	Turbocharged and Intercooled	[-]
Fuel injection system	High pressure common rail	[-]
Rated power	80	[kW]
Rated speed	4000	[rpm]
Maximum torque	240	[Nm]
Speed at maximum torque	1750	[rpm]

When a vehicle is running, the engine speed and load can vary through a wide range. Therefore, the engine performance test was conducted in an engine test cell in order to obtain the thermodynamic parameters of the exhaust and coolant systems overall possible engine operating regions as defined by the engine speed and output torque. For our measurements, the minimal and maximal engine speeds were set to 1000 rot/min and 4500 rot/min, respectively. The intermediate speeds were selected using a step increment of 250 rot/min, starting from the minimum engine speed. At each selected engine speed, different load values were selected, ranging from a 100% load to a minimal stable load value. The values for the output torque, the output power, the engine speed, the mass flowrate of the intake air, the injected fuel quantity, the exhaust gas temperature, and the coolant temperatures at the outlet of the engine's water jacket were all recorded for each load and speed configuration.

4. ALTERNATIVES FOR HEAT RECOVERY USING AN ORGANIC RANKINE CYCLE

In this study, three alternatives were considered for the heat recovery from an internal combustion engine:

≡ Exhaust gases: It utilizes the waste heat that leaves the engine whit exhaust gases.
≡ Combined Exhaust gases and Engine Coolant System: The engine coolant system is used to preheat the heat-transfer fluid that also captures energy form the exhaust gases.
≡ Combined Engine and Exhaust gases: This system replaces the engine coolant system and utilizes the heat-transfer fluid as the engine coolant.

The total heat recovered from the exhaust is carried by the working fluid into the heat power cycle. The configuration of the power cycle and the total heat recovered from the exhaust are used to calculate the mass flow rate of working fluid needed in the cycle.

The energy recovery system proposed in Figure 3 here is based on the implementation of a heat-power cycle using the exhaust gases as the heat source.

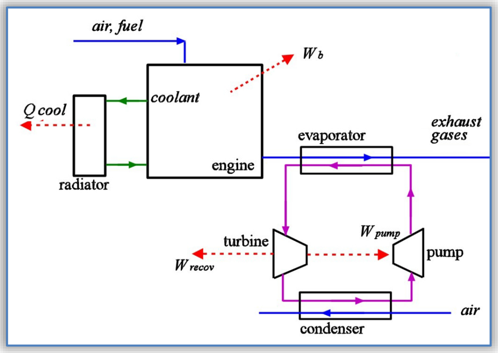

Figure 3 - Heat recovery system from the exhaust gases [2]

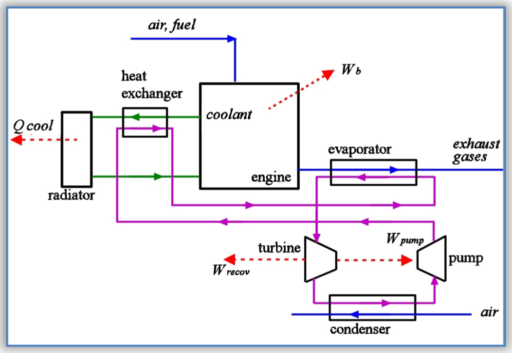

Figure 4 - Heat recovery from the combined exhaust gases and engine coolant system [2]

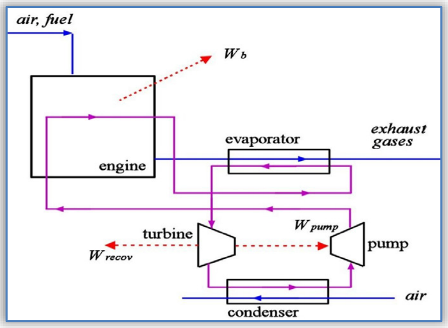

Figure 5 - Heat recovery from the engine waste heat and exhaust gases [2]

Figure 4 shows the proposed system that recovers heat from the exhaust gases and the engine coolant system. This system uses the same parts of the energy recovery system from the exhaust gases and an additional heat exchanger with the engine coolant system. The objective of this heat exchanger is to pre-heat the working fluid before it enters the evaporator. By doing this, it is possible to recover some waste heat from the engine cooling system. There are many parameters that must be known for the incorporation of this heat exchanger in the engine cooling system: the amount of heat that is rejected by the engine through the engine cooling system, as well as the coolant mass flow rate and coolant temperature.

A third system, shown in Figure 5, was proposed to take advantage of both the engine waste heat and the exhaust gases. In this system, the conventional engine coolant system was eliminated and as a replacement, the engine block was used as the heat exchanger for the Rankine cycle. This strategy has the advantage of using the waste heat from the engine at a higher temperature than the one that would be achievable by using the conventional engine coolant system. The engine block is used to raise the temperature of the working fluid. The exhaust gases are used to complete the boiling process and then to superheat the vapor.

5. RESULTS

One common way to present the operating characteristics of an internal combustion engine over its full load and speed range is to plot brake specific fuel consumption contours on a graph of brake mean effective pressure (or engine torque) versus engine speed. The measured engine performance map is displayed in Figure 6.

The lowest brake specific fuel consumption (b.s.f.c.) zone is situated at the high duty range between 1500 rot/min and 3000 rot/min and the minimum b.s.f.c. value is less than 210 g/kWh.

The effective thermal efficiency is defined as the ratio of the output torque at the flywheel end to the fuel combustion energy, and the results are given in figure 7. The effective thermal efficiency reaches a peak of greater than 40% in the low b.s.f.c. region.

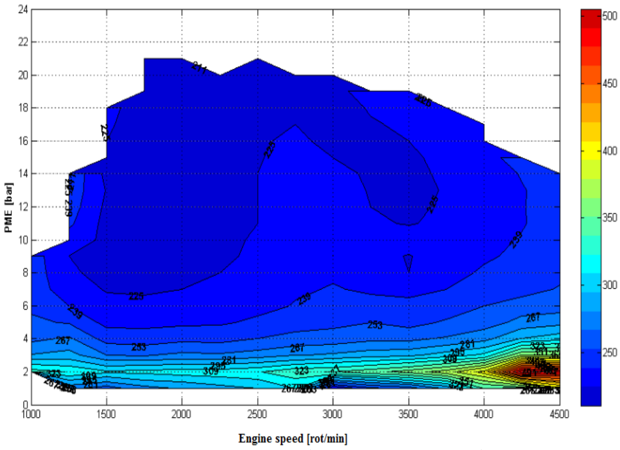

Figure 6 - Brake specific fuel consumption [g/kWh]

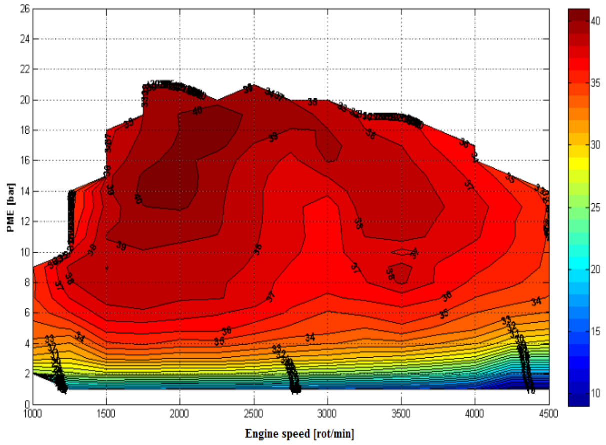

Figure 7 - Engine effective thermal efficiency [%]

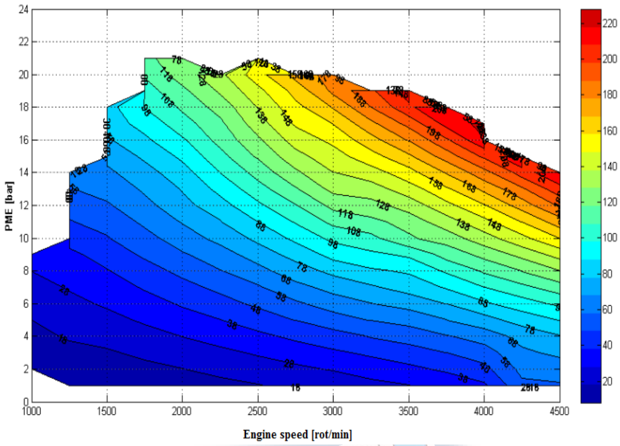

Figure 8 - Fuel combustion energy [kW]

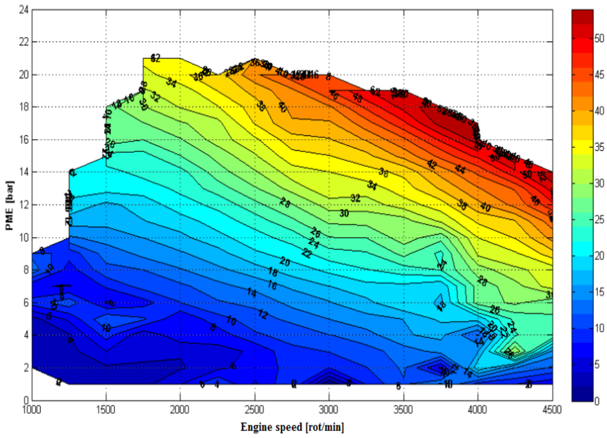

Figure 9 - Energy part of cooling system [kW]

The distribution of fuel energy released by combustion under a certain operating condition of the diesel engine is depicted using the first law of thermodynamics, which is:

$$\dot{Q}_{cb} = P + \dot{Q}_r + \dot{Q}_g + \dot{Q}_{rest}\ [kW] \quad (1)$$

Where: $\dot{Q}_{cb}$ is the heat flux received through fuel combustion; P is the amount of mechanical power produced; $\dot{Q}_r$ is the heat flux rejected through the water cooling system; $\dot{Q}_g$ is the heat rejected through the exhaust gases and $\dot{Q}_{rest}$ is the heat flux rejected through radiation and incomplete combustion that cannot be directly determined in this stage.

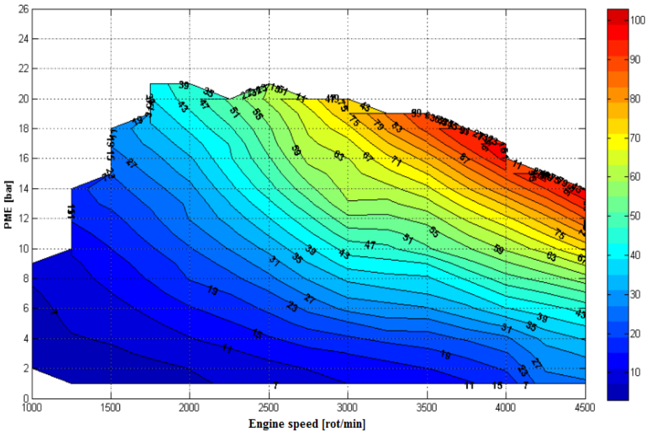

Figure 10 - Energy part of exhaust [kW]

The fuel energy released by combustion is shown in Figure 8. As the engine speed and engine load increases, the fuel energy released by combustion increases gradually. Such phenomenon is primarily caused by the increase in fuel consumption and intake air mass. The combustion energy increases almost linearly with the engine output power, achieving 220 kW at the rated power point. Note that the waste heat quantities of the exhaust and the coolant vary in a similar fashion. The variation of the waste heat quantity carried by the coolant system and exhaust gases over the whole operating range, is shown in figures 9 and 10.

6. CONCLUSIONS AND FUTURE RESEARCH

It can be concluded that, of the overall energy generated from the fuel combustion, only a relatively small proportion is used to produce useful work output, a large proportion of the energy is wasted, and the fuel energy released by combustion is far more than the effective power output of the diesel engine.

Exhaust gas and coolants of vehicles can be used to generate power by ORC. For normal cars in cruising speed this will produce 10% more power and can be used to improve its overall efficiency. In light duty cars depending on type this can cause between 5-30% reductions in fuel consumption. BMW, Honda and Researchers at Loughborough University and the University of Sussex, UK are examples of researchers in this field. Their researches shows that 62 miles/h speed of driving; using ORC will improved the thermal efficiency of the engine by 3.8%.

So far, most researches on waste heat recovery of the engine using ORC are theoretical researches and simulations [4,5,14], and only a few experiments are developed, especially in engine field [6,7]. What's more, most simulations are based on simple thermodynamic models, i.e., ignoring detailed structures and operating characteristics of system components including heat exchangers and expanders. So models like that are too ideal to precisely reflect the real performance of the ORC. To optimize the performance of ORC systems flexible and reliable simulation models are required.

Future developments could involve using an exergetic analysis to show the ability of the ORC to generate electricity from the recovered heat. An efficiency improvement and lower fuel consumption of the overall system is expected.

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