Recovery of Engine Waste Heat Using the 100-kW Class ORC "Heat Innovator®"

RAI Yasuhiro : Doctor of Engineering, New Products Incubation Center, Corporate Research and Development

SHIBATA Naruyasu : Section Manager, Design Department, Plant Division, IHI Plant Construction Co., Ltd.

WADA Daisuke : New Products Incubation Center, Corporate Research and Development

MIYOSHI Kazuo : Senior Researcher, New Products Incubation Center, Corporate Research and Development

AKIYOSHI Ryo : Doctor of Engineering, Manager, Design Department, Plant Division, IHI Plant Construction Co., Ltd.

The Organic Rankine Cycle (ORC) is a thermodynamic cycle in which a low-boiling-point fluid is used to generate power from low-grade waste heat in factories, engine systems and geothermal plants. IHI has developed the "Heat Innovator," a 100-kW class ORC power generation system that consists of an ORC module, a boiler for recovering heat from the exhaust gas of an engine, heat input and rejection cycles, and an overall control system. A test has been conducted for over a year and the results have shown that the stable and automatic operation of the "Heat Innovator" is possible. Also the cost of the maintenance of this system is reduced considerably by the use of magnetic bearings in the turbo-generator, which leads to the system being free of wear, reduces mechanical loss, and avoids the risk of the refrigerant being contaminated by lubricant. This article describes the system integration and some of the test results obtained through using this 100-kW class ORC in an engine power plant.

1. Introduction

In light of the global trend to reduce CO_2 emissions, industrial facilities urgently need to introduce more energy efficient equipment and adopt more renewable energy resources. This requirement has promoted the development of ways of utilizing low-grade heat sources. One of the solutions to this requirement is an Organic Rankine Cycle (ORC) power generation system that can utilize low-grade waste heat (below 200°C), and this has received attention from various fields in the industry. The ORC uses an organic fluid that has a lower boiling point than water, such as a fluorocarbon or hydrocarbon liquid. Due to its low boiling point, the organic fluid can drive an expander (e.g., a turbine) in a thermodynamic process even if the temperature of the heat source is relatively low.

IHI launched a 20-kW class ORC system called the Heat Recovery (HR) Series in August 2013, and it has already confirmed this system's performance at several customers' sites, which range from industrial factories to hot springs.(1) In addition to the HR Series, IHI has introduced a 100-kW class ORC system called the "Heat Innovator," which can utilize much larger-scale heat sources at industrial factories and power plants. In its development of the 100-kW class ORC system, IHI integrated an ORC module manufactured by Verdicorp Inc. (USA, IHI's contracted ORC module supplier) into an ORC power generation plant, which includes a waste heat recovery system, heating and cooling systems and a comprehensive integrated control system. Based on its long-term experience in engineering and the construction of various plant systems, IHI is able to propose optimal systems that are individually designed according to the customer's heat source and operating situations.(2)

The strength of IHI's ORC power generation system lies in the potential for it to be integrated into various industrial products. For example, one of the gas engines in IHI's engine lineup has an electric efficiency of up to 47.8% at the maximum operating point,(3) which means that an overall efficiency of more than 50% can be reached by integrating the ORC into the exhaust gas and jacket water system.

This article describes and presents some of the test results for a 100-kW class ORC power generation system that utilizes the exhaust gas heat from a diesel engine.

2. ORC power generation system

2.1 Overall design

Figure 1 shows a schematic flow diagram of the present ORC power generation plant, and **Table 1** summarizes the specifications for the system. The heat source used in the ORC system is the exhaust gas from a 5-MW diesel engine. An exhaust gas boiler that produces hot water is installed in the exhaust gas line between the engine and the stack. The boiler heat input is controlled by the exhaust gas flow rate, which is in turn controlled by valves installed both at the boiler inlet and in the by-pass line. Since the temperature of the heat source for the ORC is more than 100°C, the hot water line is pressurized to more than the atmospheric pressure (hot water pressure: 0.8 MPa). Hot water produced by the boiler flows through the evaporator to vaporize the refrigerant, after which it flows back to the pump for circulation in the hot water cycle.

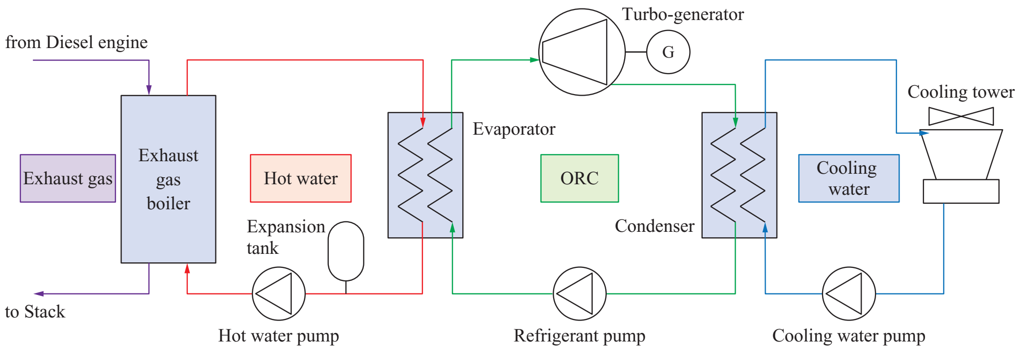

Fig. 1 Schematic of the system

Table 1 Specifications for the 100-kW ORC "Heat Innovator"

System cycle	Organic Rankine cycle
Generator	Magnetically levitated single radial turbine/ Synchronous permanent magnet generator
Working fluid	R245fa (inert gas)
Heat source	80-200°C
Max. power output	113 kW (gross)

It should be noted that although only the exhaust gas is used as a heat source in the present plant, the jacket cooling water used for the engine could also be utilized as a secondary heat source to increase the recovery of heat from the engine.

2.2 Diesel engine

The exhaust gas produced by the 16V32CX diesel engine, which is manufactured by Niigata Power Systems Co., Ltd. is used as the heat source. The temperature of the exhaust gas reaches 400°C and a single engine produces 1 500 kW of thermal energy, which has the potential to drive two 100-kW ORC systems.

2.3 Exhaust gas boiler

Heat recovery from the exhaust gas is realized by means of the exhaust gas boiler shown in **Fig. 2**, which is manufactured by IHI Packaged Boiler Co., Ltd. The heat exchange between the exhaust gas and the water takes place at the finned tubes fitted in the boiler casing. During the design of the boiler, the size and configuration of the finned tubes were set so as to ensure that any pressure loss in the exhaust gas that the boiler may cause is limited to a maximum of 1.5 kPa, thereby avoiding excess back pressure for the diesel engine. In addition, two soot blowers were installed in the upper and lower parts of the boiler in order to remove soot and ash from the exhaust gas and prevent them from accumulating on the finned tubes, which would cause a deterioration in the heat transfer coefficient for the boiler.

2.4 ORC system

The ORC module consists of a refrigerant pump, an evaporator, a turbo-generator, and a condenser. The working fluid used for the Rankine cycle is R245fa. **Figure 3** shows a picture of the ORC power module. The turbo-generator is composed of a single radial turbine connected to a permanent magnetic generator directly inside a hermetic casing. Magnetic bearings are used to keep the shaft levitated, so no lubricant is needed to drive the turbo-generator. Also, the hermetic casing eliminates concerns about the refrigerant leaking. These features make the system easy to maintain. The ORC module and related equipment are located inside the enclosure shown in **Fig. 4**. The enclosure also includes the grid-connect panel, the control panel, and a transformer.

Fig. 2 Exhaust gas boiler

Fig. 3 ORC power module

Fig. 4　Enclosure for the ORC and control

2.5　Cooling tower

Low-pressure refrigerant gas emitted from the turbine flows into the condenser located atop the enclosure. Cooling water is supplied to the condenser, which rejects the heat to condense the refrigerant gas. The condensed refrigerant then flows back to the refrigerant pump.

2.6　Control panel and remote monitoring system

With the exception of the diesel engine, all of the ORC power generation system is controlled from the control panel in the enclosure. All of the data sent by the equipment is collected and analyzed collectively by the main control unit. The collected data is then uploaded to an external server via a mobile communication line. As a result, it is possible to monitor the plant online in real time, thereby enabling engineers to detect any faults and preliminary warnings from a distant location.

Since the diesel engine is equipped with its own control panel, the ORC system receives several types of data from the engine, which enables the condition of the engine to be monitored. This data includes the exhaust gas temperature and pressure, as well as the status of the main breaker for the engine. This data exchange between the engine and the ORC system makes it possible for the system to be automatically started or shut down according to the status of the engine. Due to this function, the ORC generates power automatically without the on-site operator needing to be involved at all times when the engine is operating. Moreover, the refrigerant pump and the turbine speed are controlled in accordance with the thermal conditions of the heat source and other related factors. This enables the ORC to generate the maximum power that can be extracted from the heat source, even though the heat load of the engine fluctuates over time.

Figure 5 shows the operational patterns recorded during actual instances of when the engine fluctuated and tripped. If the engine load drops, the temperature of the hot water produced by the exhaust gas boiler falls, which causes the ORC to reduce the refrigerant flow rate and the turbine speed. As a result, the power output decreases accordingly. If the engine trips, the ORC shuts down immediately to protect the turbine and magnetic bearings. When the engine resumes normal operation, the ORC automatically resumes operation when the start-up conditions have been met.

3.　Results and discussion

3.1　Rated operational conditions

Table 2 lists the test results for the present ORC power generation plant. It has been confirmed that the ORC system can produce a gross output of 113 kW, which is the rated specification. The net output of the ORC is about 100 kW after the power input to the refrigerant pump has been subtracted (**Fig. 6**). The gross power generation efficiency reaches up to 13.9%, which is relatively high considering that the ideal Carnot efficiency with the same heat source condition is about 25%. This high efficiency is a result of the high performance of the magnetic bearings and the suitability of the plant design.

Table 2　Performance test results

Item	Unit	Testing result
Exhaust gas temperature	°C	396
Hot water temperature	°C	154 (in)/124 (out)
Cooling water temperature	°C	23 (in)/26 (out)
Turbine speed	rpm	36 530
Gross power output	kW	113

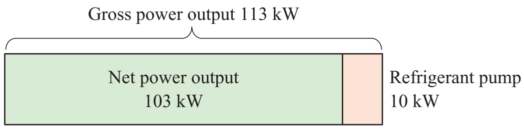

Fig. 6　Gross and net power output

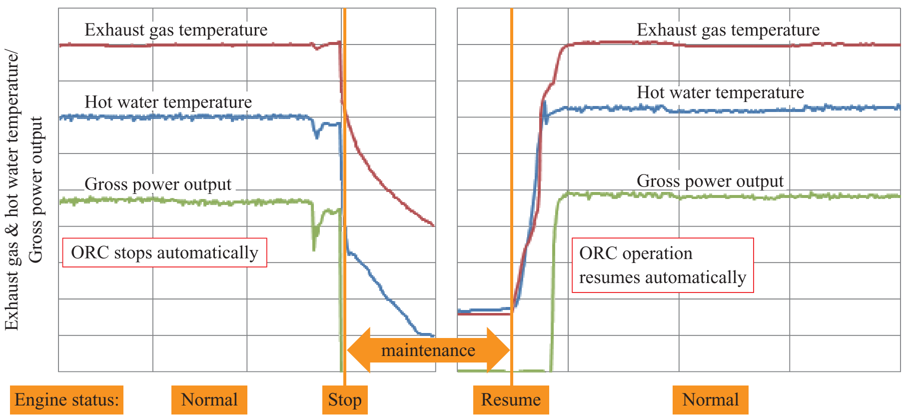

Fig. 5　Automatic ORC start/stop function

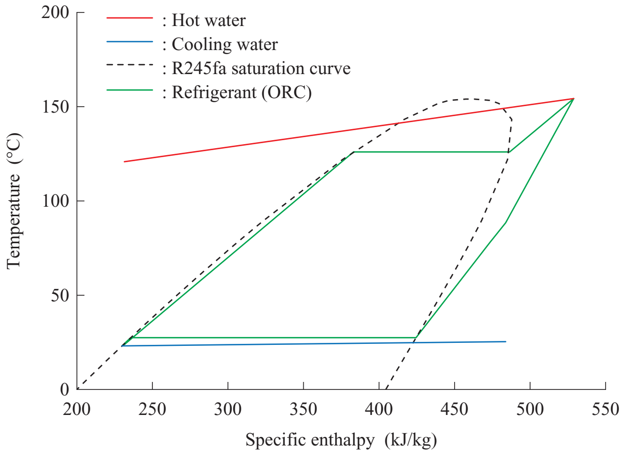

Fig. 7 T-h cycle diagram

The power output changes from summer to winter due to the condensing temperature being influenced by the ambient temperature. In general, more power can be generated during winter because of the higher cycle efficiency achieved by the lower condensing temperature. However, it was confirmed that this ORC power generation system can produce gross power of up to 95 kW even in summer.

Figure 7 shows a T-h diagram of the thermodynamic cycle at the point of maximum operation. In the present test case, the control parameter for superheating at the inlet of the turbo-generator is set to be relatively large. This is to avoid the risk of the turbine receiving a liquid slug in the event of a sudden change in the thermal condition of the heat source. This parameter will be fine-tuned based on the testing results, which may help to make the whole system more energy efficient in the future.

3.2 Degradation of the exhaust gas boiler

To avoid degradation of the heat transfer coefficient for the exhaust gas boiler as a result of an accumulation of soot and ash on the finned tubes, twin soot blowers were installed in the upper and lower parts of the boiler. An observation of changes in the overall heat transfer coefficient during the operational period revealed that a 15% degradation in the coefficient occurred. However, no further degradation has been confirmed. The effectiveness of the soot blowers was proven throughout the whole period of the operation.

4. Conclusion

This article describes the design, construction and performance testing results for the 100-kW class ORC system called the “Heat Innovator.” During the performance testing, the rated specification was achieved and the viability of each plant component was confirmed. The magnetic bearings installed in the turbo-generator enable the maintenance costs and labor requirements to be reduced. The entire project progressed smoothly, from the design and manufacturing of the exhaust gas boiler, the process design for the whole plant system, the piping construction, and the control logic development all the way through to the maintenance system that was adopted based on IHI’s long-term experience in plant engineering. IHI’s ORC system has the potential to be applied not only to the exhaust gas from various types of engines, but also to the engine jacket water, industrial exhaust heat sources, and geothermal plants. We are continuing the testing at the present plant so that we will be able to make the best use of this knowledge in future ORC plants.

REFERENCES

(1) T. Takahashi : The outline of the small Organic Rankine Cycle power generating unit ‘Heat Recovery’ HR series Journal of Gas Turbine Society of Japan Vol. 41 No. 6 (2013. 11) pp. 467-472

(2) IHI Plant Construction Co., Ltd. : Heat Innovator: The effective and simple waste heat recovery system Journal of IHI Technologies Vol. 55 No. 1 (2015. 3) pp. 18-19

(3) Niigata Power Systems Co., Ltd. : Advanced Gas Engines 28AGS Series Product Catalogue (2012)