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# Response of a 50 kW Organic Rankine Cycle System Subject to Influence of Evaporators

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## Abstract

The variations of the evaporator on the system responses of a 50 kWe ORC system using R-245fa are investigated. The effect of exit superheat on the ORC system depends of the types of the evaporator. For the plate evaporator, an exit superheat less than 10 °C may cause ORC system unstable due to liquid entrainment. For maintaining stable operation, the corresponding Jakob number of the plate heat evaporator must be above 0.07. On the other hand, no unstable oscillation of the ORC system is observed for an exit superheat of 0~17 °C when the shell-and-tube heat exchanger is used as the evaporator.

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Keywords: *dynamic response; organic Rakine cycle; evaporator; plate heat exchanger; shell-and-tube heat exchanger*

## 1. Introduction

The Organic Rankine Cycle (ORC) is similar to a conventional Rankine cycle except it uses organic fluids as a working fluid rather than water. Since the specific vaporization heat of organic fluids are generally much lower than that of water [1], the ORC is especially viable for low grade heat recovery. It had been statistically estimated that the low-grade waste heat accounts for more than 50% of the total amount of heat generated in industry [2], therefore exploitation of ORC for harvesting low grade energy becomes quite promising for the past few decades. This is because that the ORC can efficiently produce shaft-work from medium temperature heat sources up to 370 °C [2]. In contrast to the conventional power cycles, the ORC fluids fits perfectly in local and small scale power generation applications [3-7]. In practice both shell-and-tube heat exchanger and plate heat exchanger can be used as the evaporator, and apparently different system response may occur. Therefore the present study focuses on the associated influence.

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## 2. System Construction and Measurements

The schematic diagram of the 50 kWe ORC system is shown in Fig. 1. The major components of the ORC include a multi-stage pump, an evaporator, a shell-and-tube condenser with four-pass design, a screw expander and a generator, and an oil separator. The working fluid is R-245fa. The 7.5 kW pump is a multistage centrifugal pump having 12 impellers with a nominal rating flow rate of 2.1 $m^3/hr$ equipped with a maximum discharge pressure of 2500 kPa. The power input to the R-245fa is from an external power source. The screw expander is a semi-hermetic twin screw (made by Hanbell Precise Machinery Co., model RC2-410AF). The electrical generator is coupled with the expander and is enclosed in the same housing. The corresponding expansion ratio is 4.8 with a nominal volumetric flow rate of 480 $m^3/hr$. In this study, both plate heat exchanger and shell-and-tube heat exchangers are used as the evaporator for further comparison. Some other detailed experimental setup and measurements be seen from Lee et al. [8].

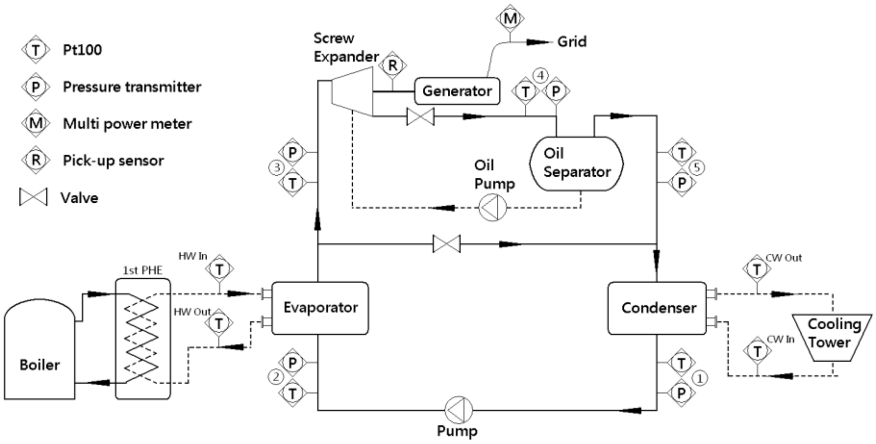

Fig. 1 Schematic of the test facility and measurement location.

## 3. Results and Discussion

In a typical ORC system, both plate and shell-and-tube heat exchanger can be used as the evaporators. In this study, we have compared the associated system response for these two different heat exchangers subject to influence of exit superheat. The working fluid, R-245fa, is placed at the shell side of the shell and tube heat exchanger. For plate heat exchanger, the associated exit superheat level at the outlet is 10, 12, and 14 °C. Adjustment of the exit superheat is made by regulating the hot water flowrate at the evaporator. As shown in Fig. 2, for the plate evaporator, change of exit superheat level from 14 to 12 °C does not pose detectable influence on the system response. However, unstable oscillation emerges as the exit superheat is reduced to 10 °C. Both the inlet and outlet pressure of the expander reveals an unstable fluctuation. Causes of this phenomenon are associated with the presence of liquid entrainments at a low superheat condition. This can be elaborated from the study of Barnhart and Peters [9] who had conducted the entrainment measurement for a serpentine evaporator. They found that the entrainment is related to exit superheat, inlet quality, and mass flowrate of the evaporator. Among the aforesaid effects, the exit superheat plays the most critical role on the entrainment flowrate. Their experiments showed that the entrainment fraction is mainly related to the dimensionless Jakob number, $C_p\Delta T/i_{fg}$. Where $\Delta T$ represents the exit superheat ($T_g - T_s$), $C_p$ is the specific heat, and $i_{fg}$ is the corresponding latent heat. Barnhart and

Peters [9] found that the entrainment fraction is considerably reduced when Ja is above 0.02. On the other hand, the present results indicate that the influence of entrainment is negligible when Ja is above 0.07. The departure between the present one and theirs is actually not surprising. Firstly, the basic configuration is quite different (horizontally arranged serpentine tube evaporator vs. vertical plate heat exchanger), the serpentine configuration with return bend inevitably reduces the amount of entrainment due to consecutive turnings. Secondly, their horizontal arrangement is also prone to the gravity influence. Therefore, in summary of these two effects, the associated Ja value shows certain departure amid the present study and those by Barnhart and Peters [9]. In spite of the quantitative difference prevails between the present one and theirs, the qualitative trend is basically the same, suggesting that the exit superheat poses a significant influence on the instability phenomenon. On the other hand, the exit superheat for shell-and-tube heat evaporator, ranging from 0 ~ 17 °C, does not result in any unstable oscillation of the ORC system. All the major parameters, like condensing pressure (temperature), evaporation pressure (temperature), and ORC system efficiency remains about the same irrespective of any exit superheat. The opposite trend between plate and shell-and-tube heat exchanger is mainly due to the inherited nature of these two kinds of heat exchanger. For the plate heat exchanger, the cross section area remains the same during the evaporation process; thereby the corresponding vapor velocity is sufficient high at the exit of the plate heat exchanger. Hence the vapor shear caused by gigantic density difference leads to liquid entrainments. The results are analogous for the serpentine heat exchanger of Barnhart and Peters [9]. However, the appreciable volume above the tube bundle of the shell-and-tube heat exchanger as shown in Fig. 3 acts as an enormous buffer for the evaporated vapor. Therefore the vapor velocity in association with various exit superheat is still too low to carry significant amount of liquid entrainment into the expander. As a result, no unstable oscillation of the ORC system occurs, yet the power output remains fairly steady in association with the exit superheat.

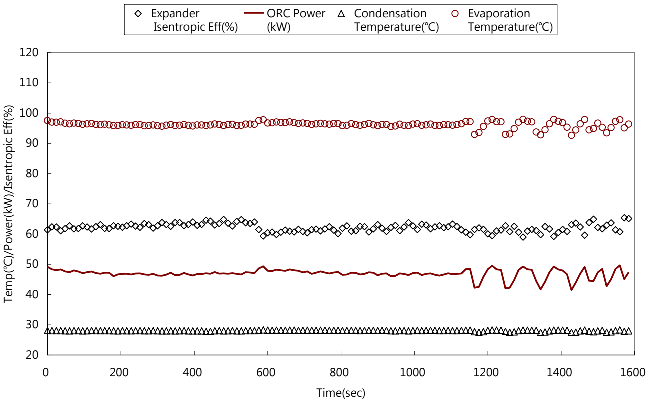

Fig. 2 System response of the 50 kWe ORC system with the plate evaporator subject to an exit superheat of 10, 12, and 14 °C.

## 4. **Conclusions.**

In this study, the variations of the evaporator on the system responses of a 50 kWe ORC system are reported. The working fluid of the ORC system is R-245fa. The effect of exit superheat for various types of evaporator, including plate and shell-and-tube heat exchanger on the system performance is also reported. It is found that the effect of exit superheat on the ORC system depends of the types of the evaporator. For the plate evaporator, an exit superheat less than 10 °C may cause the ORC system unstable. This is because the liquid entrainment may result in unstable operation of the screw expander.

For maintaining a stable operation, the corresponding Jakob number of the plate heat evaporator must be above 0.07. On the other hand, no unstable oscillation of the ORC system is observed for exit superheats ranging from 0 to 17 °C when shell-and-tube heat exchanger is employed as the evaporator. It appears that the sufficiently large buffer above the tube bundle may significantly reduce the effect vapor shear and eliminate the effect of entrainment.

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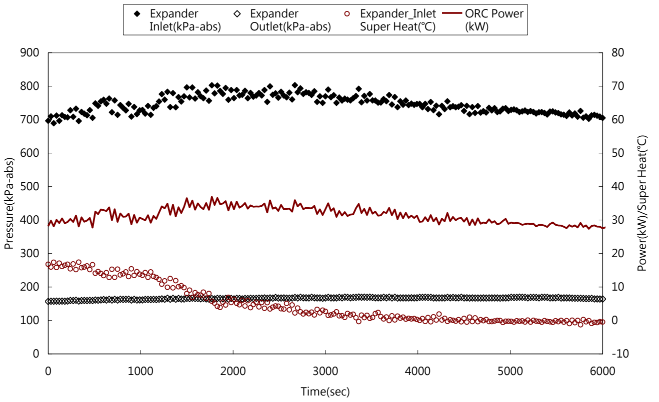

Fig. 3 System response of the 50 kW ORC system with the shell-and-tube evaporator subject to an exit superheat of 0~17 °C.