Transient response of a 50 kW organic Rankine cycle system

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ABSTRACT

This study examines the transient responses of a 50 kW ORC (Organic Rankine Cycle) system subject to change of the water coolant in the condenser with R-245fa as the working fluid. With a moderate increase or decrease of water coolant flow rate, all the major quantities such as the output power, condensing pressure, evaporation pressure show mild transition. The mass flow rate of the R-245fa remains roughly the same during the transient. For a sharp rise of the water coolant flow rate, the ORC system undergoes a rather unusual behavior. The output power is first slightly increased, followed by a sharp decline to barely any output power and remains there until the end of the transient. The output power increased back right after the transient and exceeded its original state. There is almost no R-245fa mass flow rate during the power outage period. Yet the evaporation pressure also experienced a gigantic falloff during the transient period. This peculiar surge phenomenon is related to tremendous change of the total void when condensation takes place that momentarily reduces the R-245fa mass flow rate. The surge effect caused by the water coolant is associated with the rate of variation in the overall heat transfer coefficient.

1. Introduction

The needs for the low grade heat recovery had attracted many attention and became more mature in the past decades. Some new solutions had been proposed to generate electricity from the low temperature heat sources and are now applied to many applications, including solar thermal power, biological waste heat, engine/vehicle exhaust gases, domestic boilers, and the like. Among the proposed solutions, the Organic Rankine Cycle (ORC) system is regarded as the most potential candidates for its simplicity and the availability of its components [1] and is mostly implemented in practice [2]. The ORC is basically a Rankine cycle utilizing an organic fluid as the working medium. In such a system, the working fluid is better adapted than water to the lower heat source temperatures and ORC can efficiently produce shaft-work from medium temperature heat sources up to 370 °C [3]. In contrast to conventional power cycles, the ORC fluids fit perfectly in local and small scale power generation applications [4].

A wide variety of ORC researches were conducted during past years, including applications such as waste heat recovery [5—7], solar energy utilization [8—10], combined heat and power [11—13], geothermal systems [14—16], or engine exhaust gases [17]. However, despite appreciable studies were reported, the system performance reported the field operation were comparatively rare. Only relatively few experimental system performance data were reported (e.g Refs. [7,8,18].). Yet these data normally reported test results that were conducted in a controlled ambient under steady state. The system operation data provides valuable information in balancing the components, working fluids, heating medium, and cooling medium. However, in real operation, the ORC system is subject to change in operational conditions, and may exhibit transient behaviors. For instance, the water coolant flow rate in the condenser may vary due to some operational needs such as unloading or overloading. Moreover, the coolant flow rate may also subject to change during breakdown or startup. It is therefore imperative to investigate the system response pertaining to these transient changes. However, the only studies associated with the transient responses of an ORC system are mainly focused on the development of theoretical models [19,20]. There are virtually no systematic data reporting the associated influence. As a result, the objective of this study is to provide some preliminary experimental results concerning the transient responses of a 50 kW ORC system, and some physical explanations are made to address some observed peculiar characteristics.

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Nomenclature

CW	coolant water flow rate (LPM)
H	height of the plate evaporator (mm)
L	length of the plate evaporator (mm)
$\dot{m}_{R-245fa}$	mass flow rate of R-245fa (kg/s)
P	pressure (kPa)
T	temperature (°C)
t	time (s)
U	overall heat transfer coefficient (W/m^{2}K)
W	width of the plate evaporator
h	heat transfer coefficient (W/m^{2}K)

Greek letters

ρ	density (kg/m^3)

Subscripts

cond	condenser
cw	cold water (water coolant at the condenser)
eva	evaporator
hw	hot water (heating water into the plate evaporator)
i	tube side of the condenser
in	inlet
o	shell side of the condenser
original	original state before the transient starts
out	outlet
L	liquid phase
V	vapor phase

2. System construction and measurements

The schematic diagram of the 50 kW ORC system is shown in Fig. 1. The major components for the ORC include a multi-stage pump, a plate evaporator, a shell-and-tube heat exchanger 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 multi-stage centrifugal pump having 12 impellers with a nominal rating flow rate of 2.1 m^3/hr and 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/h. The counter-currently arranged plate evaporator is fully welded type (Alfa Lava) with a total of 100 plates. The overall size is 289 mm (L) × 390 mm (W) × 1250 mm (H) and the plate thickness is 0.4 mm. The nominal heat transfer capacity is up to 1000 kW.

The condenser is of shell-and-tube configuration having a total of 300 condensing tubes and its detailed schematic is shown in Fig. 2. The nominal outer diameter of the condensing tube is 19.05 mm with a low fin configuration. The shell diameter and the tube length are 558.8 mm (22″) and 2300 mm, respectively. A four-pass design is incorporated in the waterside. For effective driving the ORC system, additionally auxiliary components include a 1.8 Ton/h cross flow steam boiler and a 200 cooling tons cooling tower. The cross flow steam boiler provides the pressurized hot water around 115–125 °C to simulate the heat source which then exchange heat with the plate evaporator. The cooling water from the condenser is cooled by an air-cooled cooling tower. The cooling tower is an air-cooled forced draught having counter flow arrangement. An inverter is used to regulate the capacity of the cooling tower.

Detailed locations of the measurements are depicted in Fig. 1. The sensors for measuring the pressure, temperatures, flow rate and electric power are installed in the ORC system accordingly. The pressure transducers are made by Danfoss (model MBS 3200), with
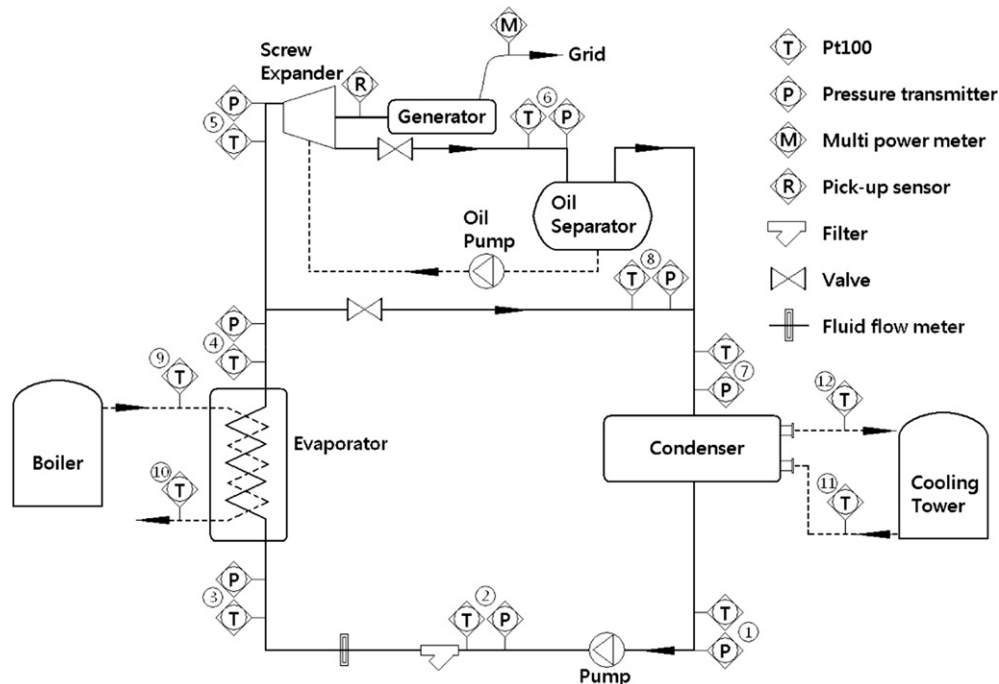

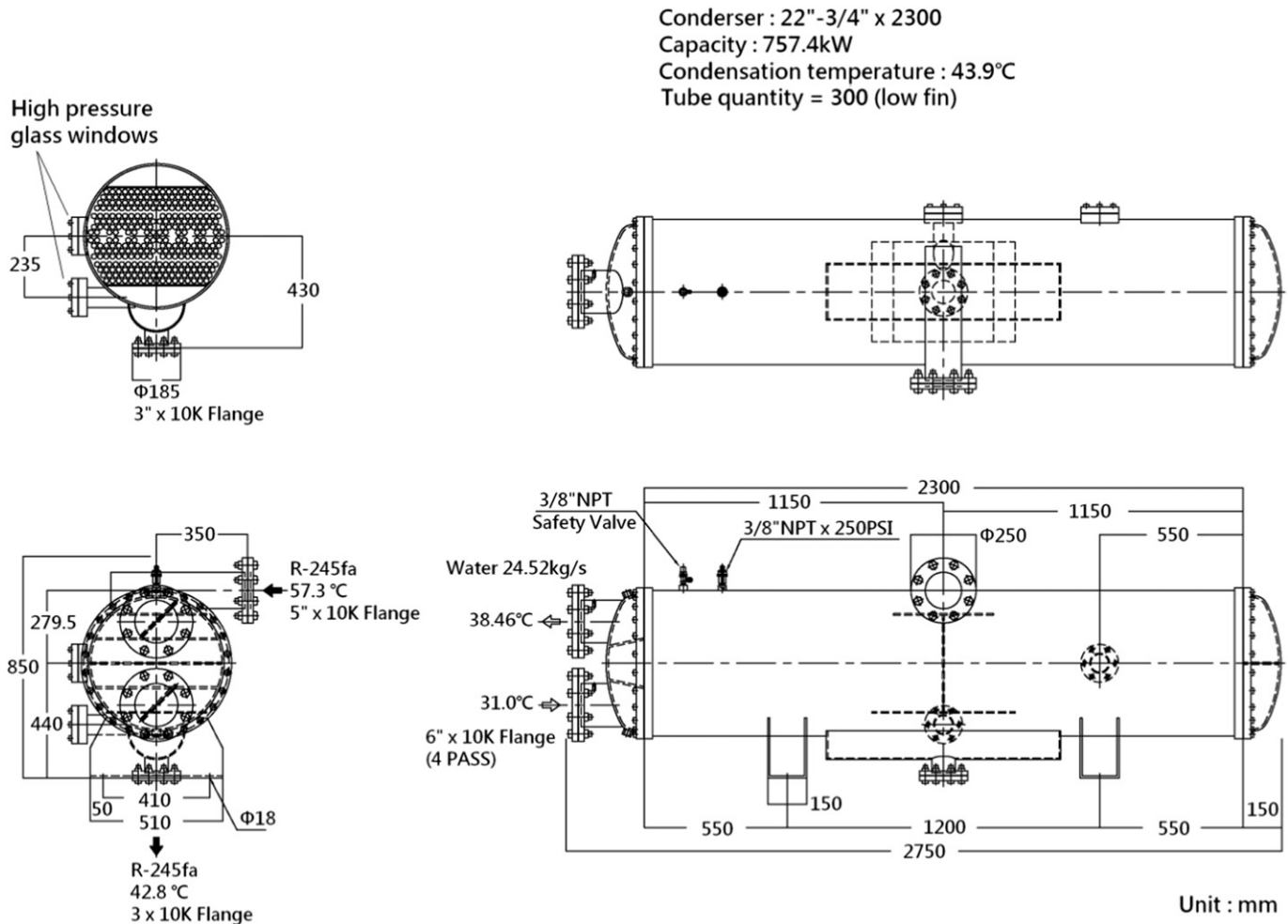**Fig. 1.** Schematic of the test facility and measurement location.

Conderser : 22"-3/4" x 2300
Capacity : 757.4kW
Condensation temperature : 43.9°C
Tube quantity = 300 (low fin)

High pressure glass windows

235
430
Φ185
3" x 10K Flange

350
279.5
850
440
410
510
50
Φ18
R-245fa
57.3 °C
5" x 10K Flange
R-245fa
42.8 °C
3 x 10K Flange

3/8"NPT Safety Valve
3/8"NPT x 250PSI
Water 24.52kg/s
38.46°C
31.0°C
6" x 10K Flange
(4 PASS)
2300
1150
1150
550
Φ250
550
1200
550
2750
150
150

Unit : mm

Fig. 2. Detailed dimension of the shell-and-tube heat exchanger.

an accuracy of ±1.0% of the full scale range (2500 kPa). Temperatures were measured with RTD Pt100 (3 wires) made by MorShine with a calibrated accuracy of ±0.25 °C. The flow rate of the cold water was measured using an electromagnetic flow meter made by SeaMetric (model EX80) with an accuracy of ±1.0%. The flow rate of working fluid (R-245fa) was measured using a vortex flow meter made by BNC (model BV-F080-4K1-A1NC-N) with an accuracy of ±0.7%. The electric power of the induction generator was measured using a power analyzer made by HIOKI (model 3169-20 with 9661 clamp on sensor), with an accuracy of ±0.1%. All the signals were collected by using AB MicroLogix 1400 programmable logic controller and the measured data were then transmitted to the host computer for further analyzing.

3. Results and discussion

For studying the dynamic response of the present 50 kW ORC, a total of four experiments are carried out. The controlled conditions are given as follows:

(1) Case 1, the coolant water flow rate in the condenser is suddenly raised from 400 L/min to 600 L/min.
(2) Case 2, the coolant water flow rate in the condenser is suddenly raised threefold from 400 L/min to 1200 L/min.

(3) Case 3, the coolant water flow rate in the condenser is suddenly decreased from 800 L/min to 400 L/min.
(4) Case 4, the coolant water flow rate in the condenser is suddenly decreased from 1200 L/min to 400 L/min.

Fig. 3 shows the transient variation in case 1. With a 50% rise of coolant flow rate, the condenser performance is improved moderately. In fact, one can see a steady increase of the ORC power from 21 kW to 27 kW as shown in Fig. 3(c). The results are in line with the common knowledge that a better condenser performance results in higher ORC power output. Notice that there is no appreciable change of the R-245fa mass flow rate as appeared in Fig. 3(b) where the mass flow rate is around 2.0–2.2 kg/s. The condensing pressure is slightly decreased when the transient starts, and the evaporation pressure holds quite steadily during the transient period. Hence, the moderate increase of ORC power is mainly from the slightly rise of pressure difference between the evaporator and the condenser as shown in Fig. 3(c).

For case 2, the operation condition is similar but the coolant mass flow rate is abruptly raised from 40 L/min to 120 L/min. Contrast to that in case 1, the transient response of the ORC reveals some unexpected peculiar phenomena as seen in Fig. 4. Firstly, one can see that the ORC output power is slightly increased from 23 kW to 26 kW, and followed by a tremendous surge to barely any output power as shown in Fig. 4(c). The power outage lasts about 70 s and subsequently a sharp rise of power output emerges. Eventually the
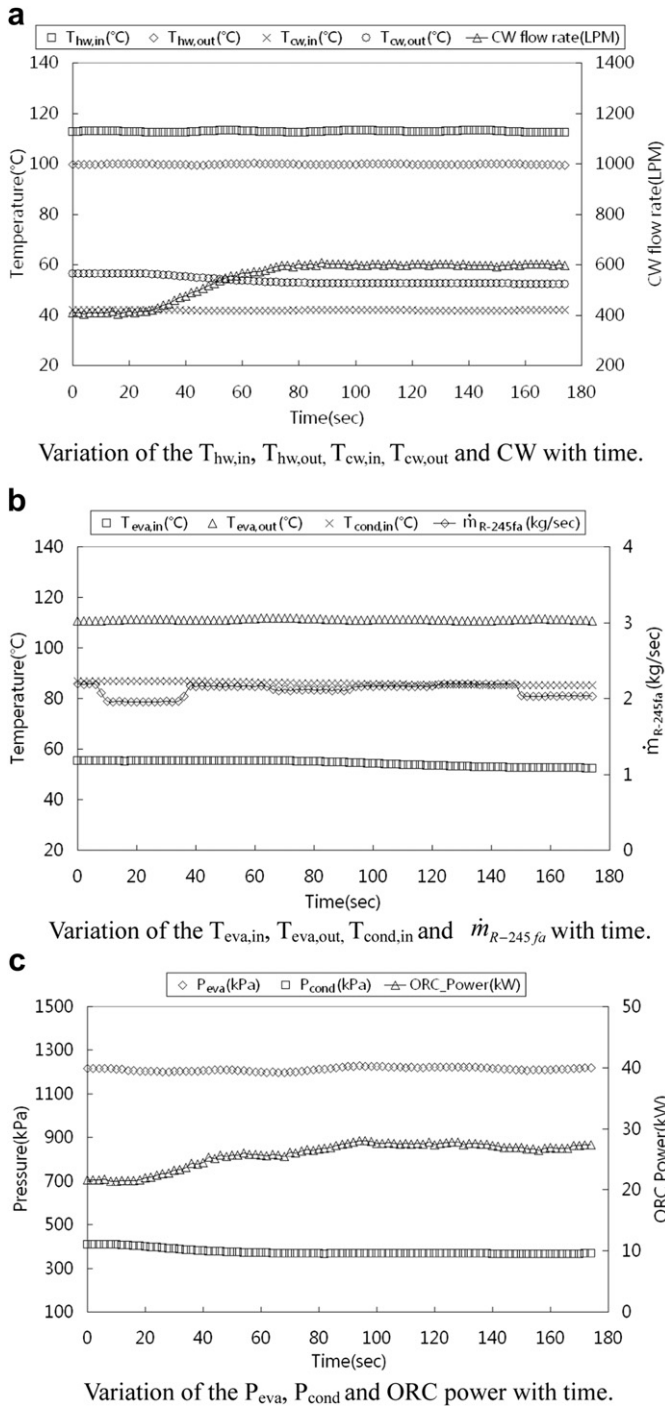
a

Variation of the $T_{hw,in}$, $T_{hw,out}$, $T_{cw,in}$, $T_{cw,out}$ and CW with time.

b

Variation of the $T_{eva,in}$, $T_{eva,out}$, $T_{cond,in}$ and $\dot{m}_{R-245fa}$ with time.

c

Variation of the P_{eva}, P_{cond} and ORC power with time.

Fig. 3. Transient response for the 50 kW ORC system when the water coolant is increased from 400 LPM to 600 LPM.

a

Variation of the $T_{hw,in}$, $T_{hw,out}$, $T_{cw,in}$, $T_{cw,out}$ and CW with time.

b

Variation of the $T_{eva,in}$, $T_{eva,out}$, $T_{cond,in}$ and $\dot{m}_{R-245fa}$ with time.

c

Variation of the P_{eva}, P_{cond} and ORC power with time

Fig. 4. Transient response for the 50 kW ORC system when the water coolant is increased from 400 LPM to 1200 LPM.

output power exceeds that before the transient starts due to a better condenser performance. Secondly, as shown in Fig. 4(c), the pressure in the evaporator remains unchanged that is similar to case 1 during the initial 10 s, and followed by a sharp decline which is completely opposed to that in case 1. The power outage occurs when the sharp decline emerges. This is expected since the pressure difference between the evaporator and condenser is too small to generate any useful work. On the other hand, there is barely any R-245fa flow rate during power outage period as shown in Fig. 4(b). The foregoing results show an extraordinary phenomenon when
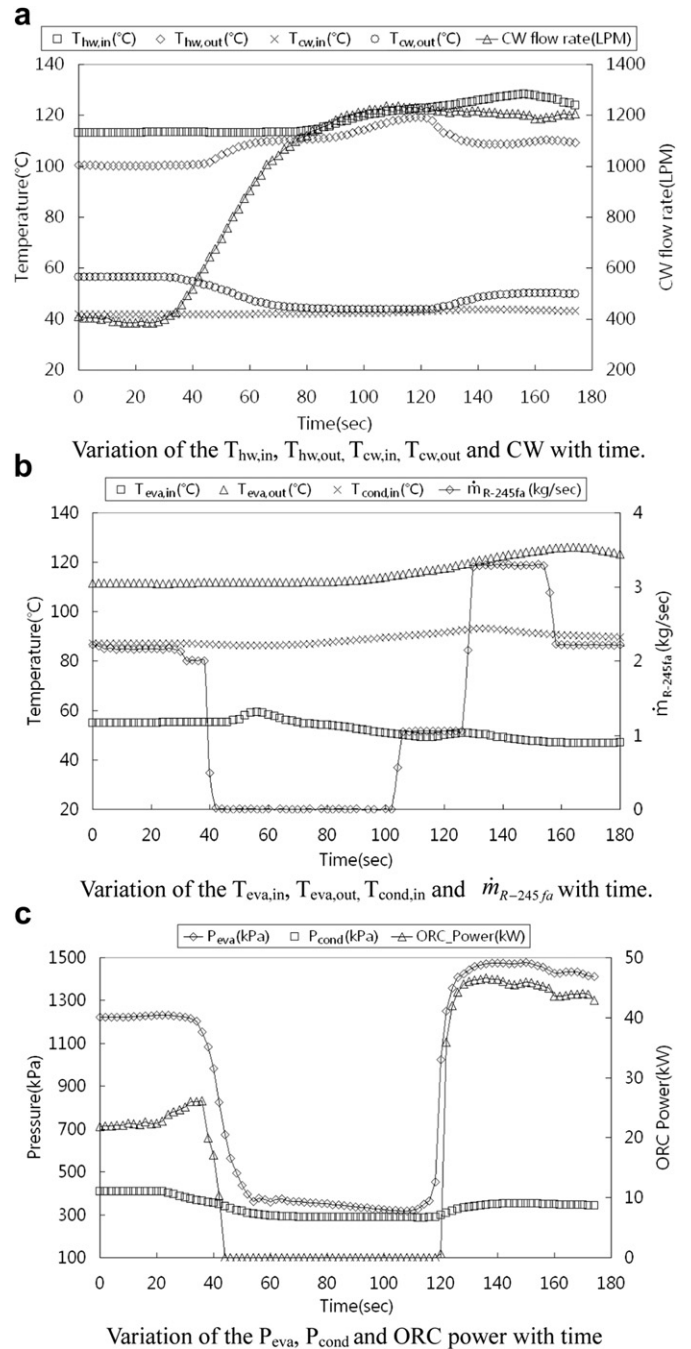
compared with case 1. The initial rise of output power is analogous to that in case 1 where the condensing pressure is reduced when the transient starts, the higher pressure difference between the inlet and out of screw expander leads to a rise of power output. Notice that there are two effects that compete with each other during the transient subject to change of the water coolant flow. This phenomenon had been experimentally verified by Wang and Liao [21]. They showed that the condensing pressure is decreased during the transient period of increasing the water coolant flow rate. Fig. 5 depicts a schematic showing the effect of substantial rise of water coolant flow rate on the surge phenomenon. Firstly, a lower condensing pressure results in a lower vapor density, indicating
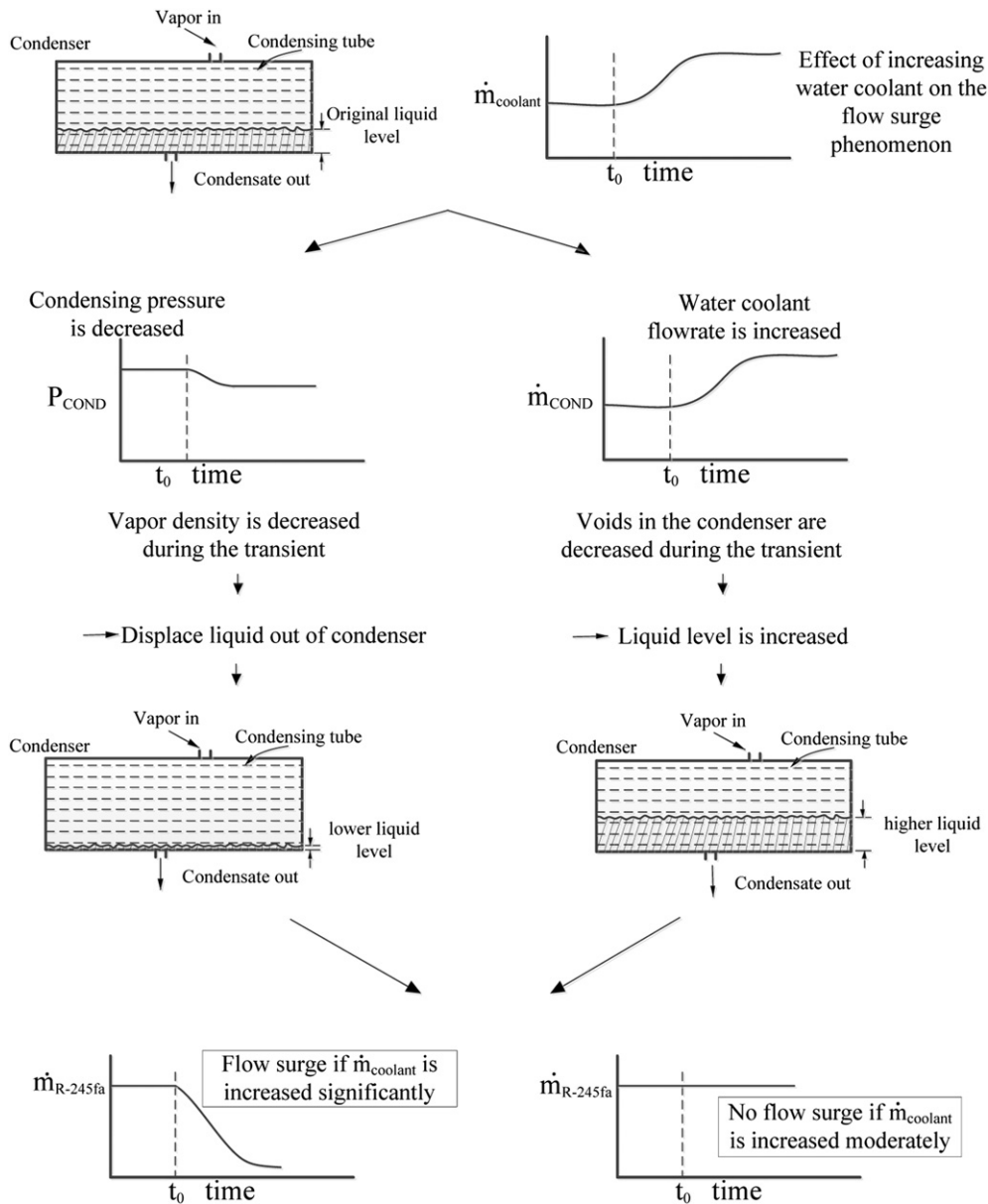
Fig. 5. Schematic showing the flow surge phenomenon subject to sudden rise of coolant flow rate.

a larger vapor volume that will displace more R-245fa condensate out of the condenser. Secondly, in contrast, increased flow rate of water coolant leads to condensing more vapor in the condenser, thereby reducing the effective voids in the condenser. This eventually will slow down or even reveals a flow reversal. For a gigantic rise of the water coolant flow rate, the latter influence may surpass the former and the condensate may be momentarily pulled back from the condenser exit, and results in a flow surge phenomenon. Notice that change of the condensing pressure usually precedes the thermal response caused by the water coolant. Thus, one can see a slight rise of output power when the transient starts.

The flow surge phenomenon is caused by a significant reduction in vapor void fraction in the condenser. Notice that the density ratio (ρ_V/ρ_L), for R-245fa at $p = 300$ kPa is about 76.8. According to a prior analysis (Kuo et al. [22]), the thermal resistance is comparable between the shell side (R-245fa) and tube side (water) since the low fin tube had been employed in the present condenser. In this regard, a threefold increase of water coolant flow rate would result in about 140% increase of the water coolant heat transfer coefficient $(h_i \sim V^{0.8})$, and it corresponds to about 41% increase in overall heat transfer coefficient $(U \sim (1/h_i + 1/h_o)^{-1})$. In contrast, a 50% increase of water coolant flow rate (case 1) only results in about 38% increase of the waterside heat transfer coefficient, and it corresponds to about 15% increase in overall heat transfer coefficient. With a significant density difference in liquid and vapor, the decrease of effective voids in the shell-side volume is much more pronounced when the coolant flow rate is increased above certain threshold value. In fact, the flow surge phenomena in a double-pipe condenser had been thoroughly investigated by Wang and Liao [21], Liao et al. [23], and Liao and Wang [24]. Their analysis and experimental results in a double-pipe condenser clearly showed that the abrupt change of condensate mass flow rate is associated with tremendous change of the total void when condensation takes places. The flow surge phenomenon can be understood by considering the variation of the void fraction during the transient process subject to heat addition or removal. For instance, an

appreciable rise of water coolant flow rate will augment the performance of the condenser, and the sufficient amount heat removal results in an appreciable reduction in total vapor volume within the heat exchanger, thus causing the outlet liquid flow rate to be momentarily lowered, and the outlet flow rate may be even pulled back to the condenser. In essence, appreciable condensation removes considerable void in the condenser, and momentarily reduces the refrigerant mass flow rate. It is worth noting that the shell-side volume in a shell-and-tube heat exchanger is much larger than that in a double-tube condenser. Therefore the effect of increasing water coolant flow rate on the transient surge may be even more severe. However, the apparent drop in condensing

pressure from approximately 400 kPa to 300 kPa offsets the influence as depicted in Fig. 5. In summary, the condensate mass flow rate is significantly reduced. Hence the outlet temperature of R-245fa at the evaporator is elevated to the hot water temperature (~125 °C) as seen in Fig. 4(a). However, the temperature rise occurs at the end of the transient and it peaks after the transient period. This is associated with the thermal lag due to hot water heating. It should be emphasized that this unusual phenomenon occurs only when substantial change of overall heat transfer is made during some short period. In case 1, there is only moderate increase of overall heat transfer coefficient, thereby only moderate transient process is seen.
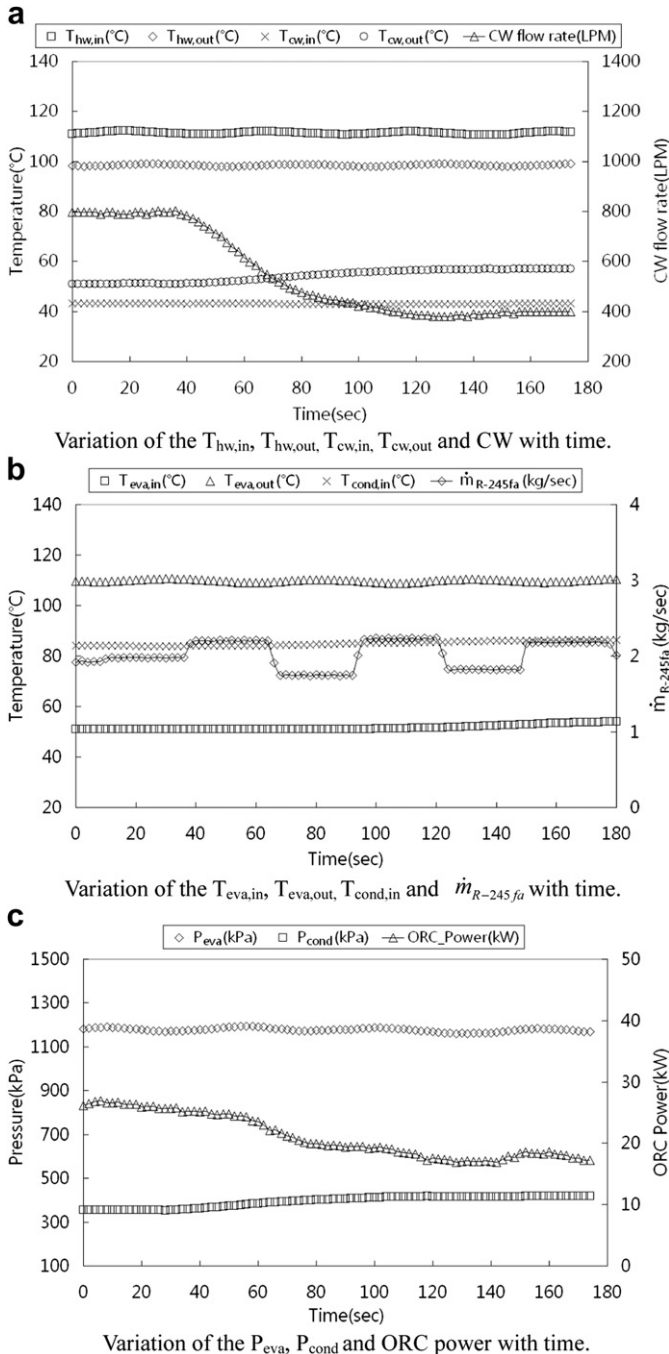

Fig. 6. Transient response for the 50 kW ORC system when the water coolant is reduced from 800 LPM to 400 LPM.
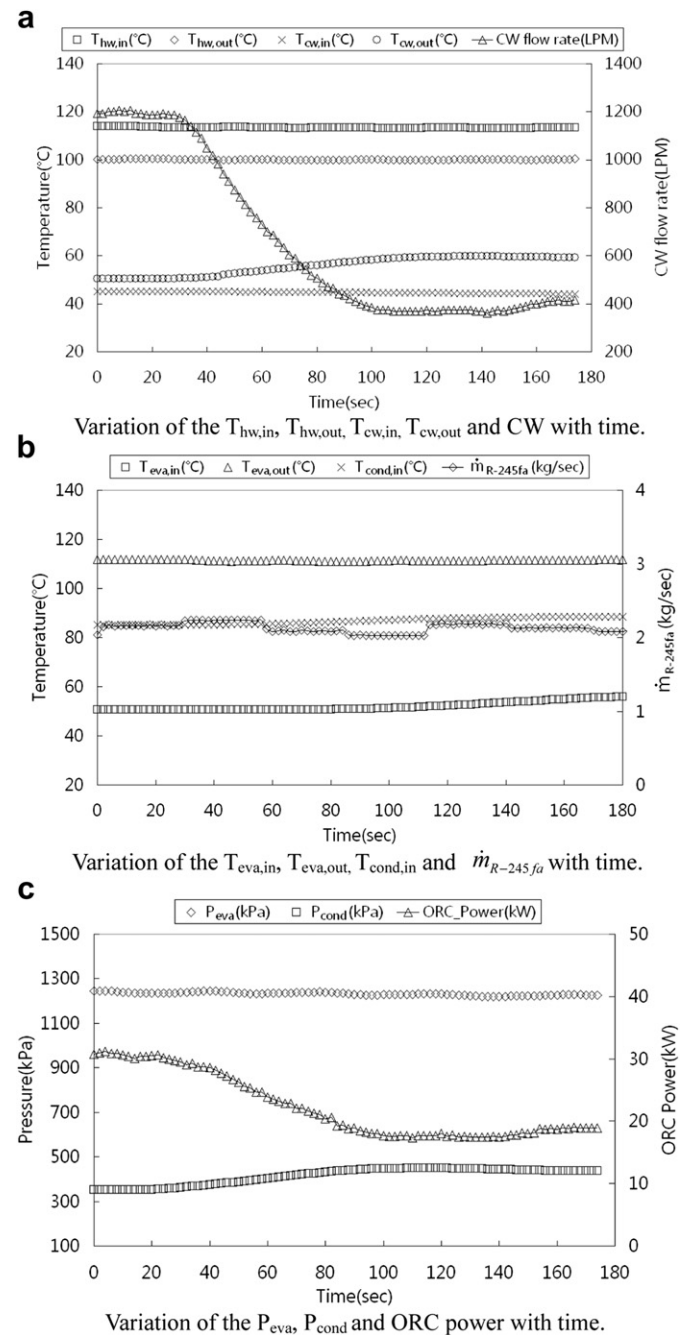

Fig. 7. Transient response for the 50 kW ORC system when the water coolant is reduced from 1200 LPM to 400 LPM.

The foregoing cases are applicable for increasing the water coolant flow rate. The opposite operation with decreasing flow rate from 800 LPM to 400 LPM is designated as case 3 and the system response is shown in Fig. 6. The transient response shows opposite trend as compared to case 1. The ORC output power is slightly reduced due to a small decrease of pressure difference amid condenser and evaporator as shown in Fig. 6(c). All the measured variables reveal some smooth variation during the transient period. There is no surge phenomenon. Analogous results are also seen in case 4 where the water coolant is abruptly reduced from 1200 LPM to 400 LPM as shown in Fig. 7. Despite a gigantic reduction of water coolant flow rate, in contrast to case 2, it appears that the no flow surge phenomenon is encountered even though the mass flow rate at the condenser exit may be temporarily increased. There are two reasons for this result. Firstly, the relative decrease in overall heat transfer coefficient is less pronounced (30% rather than 41% in case 2). Secondly, an appreciable increase of condensing pressure also lessens the influence of decreasing coolant flow as shown by Laio and Wang [24].

In summary from the foregoing observations, it appears that the surge phenomenon is associated with the rate of the transient variation. In case 2, there is a threefold increase of water coolant flow rate in about 75 s whereas a 50% reduction in water coolant flow rate in about 100 s. As a result, a rough estimation for the occurrence of surge phenomenon is suggested as follows:

$$\frac{1}{U_{\text{original}}} \frac{dU}{dt} > 0.005 \text{ s}^{-1} \qquad (1)$$

4. Conclusions

This study examines the transient responses of a 50 kW ORC system subject to change of the water coolant flow rate in the condenser. The working fluid for the ORC system is R-245fa. The effect of varying water coolant flow rate in the condenser on the system performance is reported. Based on the foregoing discussions, the following results are made:

(1) With a moderate increase of water coolant flow rate, all the major quantities such as the output power of the ORC, condensing pressure, evaporation pressure show moderate transition. The output power is slightly increased due to a better heat transfer performance in the condenser that leads to a higher pressure difference between the inlet and outlet of the screw expander. However, the mass flow rate of the R-245fa remains roughly the same during the transient.

(2) For a sharp rise of water coolant flow rate, the ORC system undergoes a rather unusual behavior. The output power is first slightly increased, followed by a sharp decline to barely any output power and remains there until to the end of the transient. The output power then shows a substantial rise sharply and is virtually higher than the original state. There is almost no R-245fa mass flow rate during the power outage period. Yet the evaporation pressure also experienced a gigantic falloff during the transient. This peculiar surge phenomenon is related to tremendous change of the total void when condensation takes place that momentarily reduces the R-245fa mass flow rate.

(3) With a moderate or significant decrease of the water coolant flow rate, all the major quantities such as the output power of the ORC, condensing pressure, evaporation pressure also show moderate transition. The output power is slightly decreased due to a worse heat transfer performance in the condenser that

leads to a smaller pressure difference between the inlet and outlet of the screw expander. However, the mass flow rate of the R-245fa remains roughly the same during the transient.

(4) In summary of the effect of water coolant on the transient response of an ORC system, it is found that the surge phenomenon is associated with the rate of the transient variation of the overall heat transfer coefficient.

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