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Investigation on a small-scale pumpless Organic Rankine Cycle (ORC) system driven by the low temperature heat source

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Abstract: A small-scale pumpless Organic Rankine Cycle (ORC) system driven by the low temperature heat source is established to investigate the overall performance. Hot water temperature from 75°C to 95°C is adopted for performance analysis whereas the environmental temperature is about 25°C. Refrigerant R245fa is selected as working fluid, and scroll expander is employed for power generation. One worth noting fact is that pumpless ORC system shows great potential for low temperature heat recovery. Experimental results indicate that the maximum power output is 232 W, which is obtained at 95°C hot water inlet temperature. Correspondingly, the average power output is 204 W which is lasted for 6.6 min, revealing the high stability for power generation. For different hot water inlet temperature, the highest energy and exergy efficiency of the system are 2.4% and 13.7%. Besides, performance of novel pumpless ORC system is compared with that of our previous prototype. It shows a remarkable improvement in terms of power output, energy efficiency and exergy efficiency. Power generation process is able to keep constant for 95% of the cycle time. As a result, pumpless ORC may become an alternative solution to low grade heat utilization when compared with conventional small-scale ORC.

Keywords: Pumpless Organic Rankine Cycle (ORC); Scroll expander; Energy efficiency; Exergy efficiency.

Nomenclature

C	specific heat, kJ/(kg·K)
E	exergy, kW
h	specific enthalpy, J/kg
M	total mass, kg
m	mass flow rate, kg/s
N	torque, N·m
n	rotational speed, rpm
Q	heat transfer rate, kW
T	temperature, K
T_0	environment temperature, °C
t	time, s
W	power, W
η	efficiency

Subscripts

ave	average
eva	evaporator
ex	heat exchanger
exp	expander
h	heat
hw	hot water
ref	refrigerant
m	metal
w	water

1. Introduction

Thermal driven power generation is one major technology for low grade heat utilization, which has drawn a burgeoning number of attentions in recent years[1]. Organic Rankine Cycle (ORC), characterized as simple structure, flexible adjustment and relatively low driving temperature, is considered to be one effective approach to recover the low temperature waste heat [2, 3]. In order to improve the overall performance of ORC systems, innovation of the working fluid and optimization of the main components have become two major research fields.

As for innovation of the working fluid, different applications and thermal driving temperature have been investigated by various researchers. Vivian et al. proposed and designed four different ORC configurations, which were operated with twenty-seven working fluids for recovering heat from sensible heat source ranging from 120°C to 180°C. The different guidelines were evaluated and summarized for each system configuration[4]. Kaska et al. [5] performed energy and exergy analysis on an ORC driven by industrial waste heat when R245fa was selected as working fluid. Simulation results indicated that the energy efficiency and exergy efficiency of the system were 10.2% and 48.5%, respectively. Apart from the normal refrigerant, several tentative researches were investigated by selecting Alkanes as working fluid for recovering waste heat of engine exhaust gas. Results demonstrated that Alkane-based ORCs may be more attractive than conventional steam cycles[6]. Also various mixtures based on siloxanes applied in the dual-loop ORC system were proposed and analyzed by Tian et al, and it was indicated that the largest net power and the highest thermal efficiency could reach 21.66 kW and 22.84%, respectively[7].

With regard to optimization of the components, the expander usually plays the leading role for ORC systems, which has been extensively investigated. Different kinds of expanders such as scroll

expander[8], single and twin screw expander [9, 10] and radial turbines[11] have been analyzed and utilized to convert the thermal energy to the mechanical shaft power. Among them, the scroll expander, characterized as high efficiency and compact structure, is often applied for the small-scale ORC systems [12, 13]. Besides, with respect to the evaporator, quite a lot of novel models have been established for optimization. Imran et al.[14] employed hydraulic and thermal design model of chevron type plate evaporator. It was demonstrated that the optimal value of allowable pressure drop was 30-40 kPa, corresponding to net power of 73-74 kW for the ORC system. Later, a novel design which is related to a shell and louvered fin mini-tubes heat exchanger was introduced. Results indicated that the overall system efficiency could be improved by 9% [15]. Last but not the least, the working fluid pump plays the role of pressurizing the refrigerant from the condensing pressure to the evaporating pressure. Therefore, considering small ORC systems, working fluid pump as a main component will consume a large part of electricity resulting in the loss of both energy efficiency and system compactness [16]. One innovative idea is to eliminate the pump which will lead to the improved system efficiency for small ORC systems. One solution is to utilize the gravity of working fluid to drive small ORC systems. Although working fluid pump was able to be removed through this method, the required height of the system was the bottleneck of this novel design[17]. Li et al.[18] proposed a naturally-controlled ORC without negative work. It was indicated that the performance is 0.9% higher than that of ORC with the pump, and the minimum required height was about 20.9 m. Compared with the gravity driving ORC, Yamada et al. developed a pumpless ORC prototype, which was considered to be an alternative solution[19]. Experimental results demonstrated that the pumpless ORC had the capability of producing the power. Later, the concerning experimental rig was established, and the maximum shaft work output was quite small and fluctuated, which was lower than 50 W[20]. Recently, a novel

pumpless ORC system was investigated by our previous work to accomplish a higher electricity output[21]. Despite of the achievement of higher output, the unstable power generation and relatively low efficiency of this system had great potentials to be further improved. In addition, other similar cycles are also investigated for power generation. Sorption cycles could theoretically realize the power and refrigeration cogeneration. So far the continuous power output couldn't be realized due to the unstable sorption rate [22, 23]. Resorption cycle was also considered to generate power since it had the better cogeneration performance than the sorption cycle [24, 25]. However, the performance was no better than that of the sorption system[26]. Therefore, the unstable output has become the common problem of the pumpless power generation system.

In this paper a small-scale pumpless ORC system is established and expected to gain the improved stability for the power output. The same refrigerant R245fa with zero Ozone Depletion Potential (ODP) is selected so that the performance could be compared with that of the previous system. Hot water temperature from 75°C to 95°C and 25°C environmental temperature are adopted to investigate the overall efficiency.

2. Cycle description

Fig.1a demonstrates the schematic diagram of the pumpless ORC, and the system is mainly composed of two high-efficient heat exchangers i.e. heat exchanger 1(HX1) and heat exchanger 2(HX2), one expander, one generator, eight water valves for hot water and cooling water, four refrigerant valves and other auxiliary components. For the pumpless ORC system, fluid pump is replaced by controlling the valves at intervals. Additionally hot water/cooling water is used as the heat transfer fluid for evaporation /condensation processes. The expander and generator are connected

coaxially.

Fig.1b indicates the T - S thermodynamic diagram with a series of isochoric curves when R245fa is selected as the refrigerant. The working procedure of the pumpless ORC system is composed of two processes. One is pre-expansion process. The other is power generation process. The details are described as follows:

(a) Pre-expansion process. In this process, HX1 acts as an evaporator while HX2 works as a condenser. Water valves V2, V4, V5 and V7 are open, and all other valves i.e. both water and refrigerant valves are closed. The evaporator that is full of the working fluid with very slight of vapour quality undertakes isochoric heating through hot water (5-1 in Fig.1b). The pressure of the HX1 will increase gradually until it becomes constant, which is close to R245fa saturation pressure in accordance with the hot water temperature. Meanwhile, the working fluid in the condenser is assumed to start as saturated vapour at high temperature as well as high pressure, and it undergoes isochoric cooling process (2-4 in Fig.1b) as the liquid gradually appears.

(b) Power generation process. When the pressure of the HX1 reaches a higher constant value and HX2 achieves a cooler level, RV1 and RV4 are opened. Then R245fa with high temperature and pressure from the HX1 flows into the expander and generates the power (2-3 in Fig.1b). The power is generated until there is no pressure difference between the HX1 and HX2. During this process the high pressure working fluid in the evaporator is isobaric heated (1-2 in Fig.1b). The exhaust enters the HX2 and is isobarically condensed into the saturated liquid (3-5 in Fig.1b). When the generator doesn't produce power, RV1, RV4, V2, V4, V5 and V7 are closed.

Then HX1 and HX2 swap their roles as evaporator and condenser. Water valves V1, V3, V6 and V8 are opened, so hot water begins to heat HX2 and cooling water begins to cool HX1. A new cycle starts,

which is similar to the previous pre-expanding and power generation processes.

(a)

(b)

Fig. 1. Schematic diagram (a) pumpless ORC system; (b) T - s diagram of pumpless ORC.

Fig.2 displays the photo of the pumpless ORC system. Fig.2a shows the pumpless ORC system with heat exchanging part whereas Fig.2b indicates the system with auxiliary equipment, which includes hot water tank, cooling tower, power generation part and control units. Pumpless ORC is placed in the higher position of the system while the lower part is another thermal driven system which is not

operated at the moment. In this experiment, pumpless ORC is the only research subject. Besides, the hot water tank heated by the electric heater is used to simulate the low temperature heat source. The cooling water from a cooling tower is adopted to compensate the condensing heat of the R245fa. The system is filled with about 17 kg liquid R245fa. Four refrigerant valves and eight water valves are employed to change the flow direction of the refrigerant and water. The refrigerant R245fa is selected as the working fluid, and scroll expander is employed for power generation. Besides, performance of the novel pumpless ORC system is compared with our previous prototype in terms of power output, energy efficiency and exergy efficiency.

Fig. 2. Photos of the pumpless ORC system (a) pumpless ORC; (b) pumpless ORC with auxiliary equipment.

With regard to the main auxiliary equipment, the maximum heating power of hot water tank is about 20 kW, and the flowrate of the hot water in the experiment is about $2 \text{ m}^3 \cdot \text{h}^{-1}$. The cooling tower has the cooling capacity of 8 kW, and the flowrate of the cooling water is about $3 \text{ m}^3 \cdot \text{h}^{-1}$.

An oil-free scroll expander (E15H22N4.25, designed and produced by Air Squared Company) with nominal output of 1 kW is adopted for power generation, which is attached with an AC generator via

magnetic coupling. The expander has an expansion ratio of 3.5:1, and displacement of 12 cc/rev. 10 electrical bulbs with a total nominal power around 950 W (each nominal power is 95W) act as the electric loads, which are used to consume the power output. One dynamometer (full scale from 0 to 3 kW with accuracy of $\pm 0.1R$) is connected between the bulb and load bank to test the power output. Two high efficient heat exchangers are designed and manufactured as the evaporator and condenser, respectively. Four spiral pipes are used for better evaporation of the refrigerant. All the welding points are checked periodically to prevent the leakage caused by the continuing expansion and contraction of the heat exchangers.

All the measurement points have been marked as P, T, m, W in Fig.1a, and the main testing apparatus for the pumpless ORC system are provided in Table 1. Pressure sensors (full scale from 0 to 2.5 MPa with accuracy of $\pm 0.1\%$) are placed at the inlet and outlet of the expander and two heat exchangers. Temperature sensors of PT100 are fixed at the positions as shown in Fig.1a, and their testing accuracies are $\pm 0.1^\circ\text{C}$. A vortex flowmeter with tolerance of $\pm 1\%$ is placed along the straight pipeline before the expander. The water flowrate is measured by the turbine flowmeter with 0.5% accuracy. A pocket tachometer is adopted for measuring rotation speed of the expander with 0.1% accuracy. The experimental data are monitored and logged by an Agilent 34972A, which is fixed in the control unit.

Table 1. The main testing apparatus for the pumpless ORC system.

Apparatus	Type	Testing scope	Accuracy
Dynamometer	HP9800	0-3kW	$\pm 0.1R$
Temperature sensor	PT100	-50°C-200°C	$\pm 0.1^\circ\text{C}$
Pressure sensors	YSZK-311	0-2.5MPa	$\pm 0.1\%$
Flow meter	LWGY-B15L	0.1-90°C	$\pm 0.5\%$

3. Performance evaluation

Since the heat exchanger is maintained at a constant temperature, heat source supplying for the conventional ORC system is only concerned with the heat transferred to R245fa for evaporation if the heat loss transferred from heat exchanger to surroundings can be neglected under stable working conditions. Different from the conventional ORC system, the heat input Q_h for the pumpless ORC system is composed of two parts, i.e. the heat Q_{ref} transferred to R245fa for evaporation and the heat to warm up the heat exchanger.

Total heat input of the pumpless ORC system:

$$Q_h = Q_{ref} + \frac{1}{t_{cycle}} M_{ex} C_m \cdot \Delta T_m = \frac{\int_0^{t_{cycle}} C_w m_w (T_{hw,in} - T_{hw,out}) dt}{t_{cycle}} \quad (1)$$

where t_{cycle} is the cycle time which includes both pre-expansion and power generation processes.

The heat Q_{ref} :

$$Q_{ref} = \frac{1}{t_{cycle}} \left[M_{ref} (h_{eva,mid} - h_{liq,sat}) + \int_0^{t_{power}} m_{ref} (h_{eva,out} - h_{eva,mid}) dt \right] \quad (2)$$

where $h_{eva,mid}$ is the enthalpy of the fluid at the point 1 in Fig.1b; $h_{eva,out}$ is the enthalpy of the fluid at the point 2 in Fig.1b; $h_{liq,sat}$ is the enthalpy of the saturated liquid at the point 5 in Fig.1b; t_{power} is the time of the power generation process.

The average power output of the generator:

$$W_{ave} = \frac{1}{t_{cycle}} \int_0^{t_{cycle}} \frac{2\pi \times n \times N}{60} dt = \frac{1}{t_{cycle}} \int_0^{t_{cycle}} W dt \quad (3)$$

where W is the instantaneous power output; n is the rotation speed of the expander; N is the torque meter of the expander.

The energy efficiency of the pumpless ORC system:

$$\eta_{energy} = \frac{W_{ave}}{Q_h} \quad (4)$$

The heat exergy of the pumpless ORC system:

$$E_{heat} = Q_h \times \left(1 - \frac{T_0}{T_{hw,ave}} \right) \quad (5)$$

where $T_{hw,ave}$ is average temperature of the hot water.

The exergy efficiency of the pumpless ORC system is

$$\eta_{\text{exergy}} = \frac{W_{\text{ave}}}{E_{\text{heat}}} \quad (6)$$

4. Experimental results and discussions

4.1 Temperature and pressure

In order to investigate the overall performance of the pumpless ORC system, different hot water inlet temperature from 75°C to 95°C is employed with 5°C increment while cooling water inlet temperature is 25°C which is corresponding to the environmental temperature. Fig.3 indicates hot water inlet temperature, cooling water inlet temperature, and expander inlet and outlet pressure with the variation of time. Hot water inlet temperature and cooling water inlet temperature are exemplified as 95°C and 25°C, respectively. As the figure shows, pressure and temperature trends of two heat exchangers are similar, which indicate the good operational stability. When the pre-expansion process happens, the inlet pressure of expander climbs remarkably to a constant value of 1.046 MPa in 1.16 min. As the refrigerant valve is open, power generation process starts. The inlet pressure of expander jumps to 0.98 MPa suddenly and keeps constant for about 6 min. Meanwhile, the expander outlet pressure soars from 0.12 MPa to 0.21 MPa and increases gradually. Finally, the inlet and outlet pressure of the expander tends to be approaching, and the expander stops revolving. At this time, the inlet pressure decreases to a constant value of 0.5 MPa and the outlet reaches 0.4 MPa. Different from the theoretical T-S diagram of Fig.1b, the real working processes are not always stable because of heat exchanging between the R245fa and hot water in the heat exchanger. After the pre-expansion process, heat transfer temperature difference is less than 1°C. When the power generation process starts i.e. open the refrigerant valve, the refrigerant R245fa need a large quantity of heat for evaporation. However, the heat transfer area of the heat exchangers are limited as its design, which will lead to the heat transfer temperature difference. This is

the main reason why the inlet pressure of expander suddenly declines from 1.046 MPa to 0.98 MPa. Similarly, the same explanation can be applied for the outlet pressure, which increases suddenly from 0.12 MPa to 0.21MPa.

Fig.3 also demonstrates that two heat exchangers are almost symmetrical. Several switch points of operation match well with each other in different working cycles when the power generation process starts or pre-expansion process starts. This repeatable phenomena will lead to the stable power generation and experimental reliability.

Fig. 3. Hot water inlet, cooling water inlet temperature, expander inlet and outlet pressure vs. time.

4.2 Power generation

Fig.4 reveals the evaporation pressure and power output of the pumpless ORC system under the condition of 90°C and 95°C hot water inlet temperature. It is worth noting that the power generation process can be separated into three phases. In the first phase, the power output increases to be constant, which takes a very short period. This is mainly because the rotating speed of generator is not high enough to achieve the constant output. After that, it goes through a very stable power generation phase. Eventually, with time elapsing, the power output declines sharply because the mass flow rate of the

refrigerant R245fa in one heat exchanger decreases gradually, and simultaneously the other heat exchanger obtains more refrigerant. The pressure ratio between two heat exchanger tends to become small. Similarly, the evaporation pressure shows the same trend with the variation of time.

Fig. 4. Evaporation pressure and power output (a) 90°C hot water inlet temperature; (b) 95°C hot water inlet temperature.

Table 2 shows the main parameters of power generation when hot water inlet temperature ranges from 75°C to 95°C. It can be noted that the maximum power output and average power output are able to reach 232 W and 204 W, respectively when the hot water inlet temperature is 95°C. For different hot water inlet temperature, the maximum power output ranges from 103 W to 232 W while the average power output ranges from 83 W to 204 W. When the hot water inlet temperature increases, the evaporation pressure will accordingly increase, which leads to the higher power output of the system. For different hot water inlet temperature, the highest inlet pressure ranges from 0.65 MPa to 1.01 MPa, which is a little lower than the evaporation pressure due to the pipe pressure drop. Besides, the higher power output accompanies the less time lasted. This is mainly because the higher temperature accelerates the heat transfer process, and the fast heat transfer process of the refrigerant R245fa causes a larger mass flow rate. Since the total quantity of the refrigerant in the heat exchanger is certain value, the larger mass flow rate will lead to less time lasted. In the experiment, the time for the pre-expansion process is

controlled as 70 s. The lasting time of power generation is related with several factors such as volume of the exchanger, electric loads and temperature of the heating and cooling water. Under different working conditions, the time lasted for the power generation process ranges from 6.33 min to 10.66 min.

Table 2. Main parameters of power generation vs different hot water inlet temperature.

Hot water inlet temperature/°C	Maximum power output/W	Average power output/W	The highest inlet pressure/MPa	Time lasted for power generation/min
75	103	83	0.65	10.66
80	144	122	0.728	9
85	179	148	0.797	8.3
90	204	166	0.9	7.4
95	232	204	1.01	6.33

4.3 System performance

Fig.5 shows the hot water inlet and outlet temperature with the variation of time under the condition of 90°C and 95°C hot water inlet temperature. At the beginning of the heating process the hot water outlet temperature declines remarkably. Taking 95°C hot water inlet temperature as an example, the hot water outlet temperature drops from 95°C to 57°C. The reasons are analyzed as follows: when the pre-expansion process starts, the cooling water originally inside HX2 needs to be flowed away. Then the heat is consumed for heating the metal part of heat exchanger from low temperature to high temperature. Another certain amount of heat is consumed for heating the sub-cooled refrigerant liquid of R245fa to saturated state. Also noted in Fig.5a and 5b, when the power generation process starts, the hot water outlet temperature declines slightly again. This is mainly because most of the refrigerant R245fa has enough heat transfer area and begins to evaporate.

Fig. 5. Hot water inlet and outlet temperature vs. time (a) 90°C hot water inlet temperature; (b) 95°C hot water inlet temperature.

For the pumpless ORC system, it is of great importance to investigate the interactive correlation among power output, rotation speed, electric load, voltage and current. Therefore, the different electric loads and rotation speed are investigated for comparison. Fig.6 reveals the maximum power output and rotation speed under the condition of different electric load number, i.e. the number of bulb, when the hot water inlet temperature are 90°C and 95°C. The maximum power output and rotation speed are both investigated in the stable conditions. As the Fig.6 shows, the maximum power output increases with the increment of the electric loads. It is worth noting that the maximum power output is initially increased by increasing the number of electric loads. Gradually, the value will tend to be stable, which means that keeping adding the number of electric loads will not result in the increase of the power output. In other word, it is the most suitable load number for this hot water temperature. Compared with the power output, the rotation speed shows the reverse trend with the electric load. This is mainly because the increasing number of electric loads will inevitably lead to the large requirement of the torque for the scroll expander. The larger torque is required, the less rotation speed becomes. For different number of electric loads, the maximum power output and the rotation speed range from 120 W to 232 W and from 1800 rpm to 2281 rpm, respectively.

Fig. 6. The maximum power output and rotation speed vs. electric load number (a) 90°C hot water temperature; (b) 95°C hot water temperature.

Based on the results of Fig.6, the control strategy of the pumpless ORC system is to seek for the maximum power output under the condition of each hot water inlet temperature. For different hot water inlet temperature, several electric bulbs will be tried for the initial experiment, and then more bulbs will be connected into the system. When the maximum power output don't increase with the increment of the load number, the working condition will be further investigated. Under this scenario, the rotation speed of the expander, voltage and current of the power generation as well as the energy and exergy efficiency of the pumpless ORC system will be evaluated.

Fig.7 reveals the voltage and current with different rotation speed under the condition of 90°C and 95°C hot water inlet temperature. It is indicated that the voltage shows a linear increasing relationship with the rotation speed whereas the current reveals a linear decreasing. This is because the power output is almost constant in the power generation process. Therefore, the voltage and current fit the inverse proportional function. For the different rotation speed, the voltage and current range from 90 V to 146 V and 0.87 A to 2.35 A, respectively.

Fig. 7. Voltage and current vs. rotation speed (a) 90°C hot water temperature; (b) 95°C hot water temperature.

On the basis of Fig.4 and Fig.5, the total power output and the average heat input of the pumpless ORC system are analyzed under the condition of different hot water inlet temperature, which is shown in Fig.8. Results show that the power output and heat input increase with the increment of hot water inlet temperature. For the different hot water inlet temperature, the total power output ranges from 53.1 kJ to 73.1 kJ while heat input ranges from 4.2 kW to 7.16 kW. Fig.9 indicates the energy efficiency and exergy efficiency of the pumpless ORC system. It is demonstrated that both energy and exergy efficiency increase at first, then decrease gradually and continue to increase at the end. The maximum energy efficiency is able to reach 2.4% on the condition of 95°C hot water inlet temperature. The maximum exergy efficiency can reach 13.7% when hot water inlet temperature is 80°C. For different hot water inlet temperature, the energy and exergy efficiency range from 1.8% to 2.4% and 12.2% to 13.7%, respectively.

Fig. 8. Heat input and total power output of the pumpless ORC vs. hot water inlet temperature.

Fig. 9. Energy efficiency and exergy efficiency of the pumpless ORC vs. hot water inlet temperature.

The errors of the experiments are analyzed by the parameters as shown in Table 1. Assuming that the testing results are unrelated, the errors of energy and exergy efficiency of the pumpless ORC system can be calculated according to the equation 7 and 8. The largest error of energy and exergy efficiency for the pumpless ORC system are 5.2% and 11.6%, respectively.

$$\Delta\eta_{\text{energy}} = \sqrt{\left(\frac{\partial\eta_{\text{energy}}}{\partial W_{\text{ave}}} \Delta W_{\text{ave}}\right)^2 + \left(\frac{\partial\eta_{\text{energy}}}{\partial T_{\text{hw,in}}} \Delta T_{\text{hw,in}}\right)^2 + \left(\frac{\partial\eta_{\text{energy}}}{\partial T_{\text{hw,out}}} \Delta T_{\text{hw,out}}\right)^2 + \left(\frac{\partial\eta_{\text{energy}}}{\partial m_w} \Delta m_w\right)^2} \quad (7)$$

$$\Delta\eta_{\text{exergy}} = \sqrt{\left(\frac{\partial\eta_{\text{exergy}}}{\partial W_{\text{ave}}} \Delta W_{\text{ave}}\right)^2 + \left(\frac{\partial\eta_{\text{exergy}}}{\partial T_{\text{hw,in}}} \Delta T_{\text{hw,in}}\right)^2 + \left(\frac{\partial\eta_{\text{exergy}}}{\partial T_{\text{hw,out}}} \Delta T_{\text{hw,out}}\right)^2 + \left(\frac{\partial\eta_{\text{exergy}}}{\partial m_w} \Delta m_w\right)^2} \quad (8)$$

4.4 Performance comparison between novel pumpless ORC and previous version

In order to have a comprehensive analysis, performance of this novel pumpless ORC system is compared with that of our previous version which can be referred to the reference [21, 27]. The scroll expander used in the previous pumpless ORC system is modified from compressors of the automobile air-conditioner as shown in Fig.10. Since only the shaft power is obtained in the previous version, performance for both systems should be compared with the same scale. Therefore, the power to electricity efficiency should be provided to transfer the electricity into shaft power of the novel pumpless ORC system. Fig.11 shows the work to electricity efficiency and electricity based on the air compressed power generation testing unit, which is used for testing the performance of the scroll expander. The details of our testing rig can be referred to the reference[28]. As Fig.11 shows, when the expander inlet pressure varies from 0.6 MPa to 1 MPa, the work to power efficiency of the expander maintains at about 78.6%. Therefore, the electricity can be transferred into the shaft power under different working conditions. Fig.12 shows the difference of energy efficiency between novel version and previous version. When the hot water inlet temperature is 95°C, the highest energy efficiency of novel version for shaft power output can reach 3.2% which is improved by 43% when compared with 2.2% of the previous version. Even the lowest hot water inlet temperature 75°C, the novel pumpless ORC system shows a 23% increment. Another significant improvement lies in the power output stability. Fig.13 indicates the power output difference between the maximum and average value. It can be found that the fluctuation of power output of the novel pumpless ORC system is no more than 21% while the fluctuation of previous one is as high as 143.5%. In fact, after several seconds of power generation, the power output of the novel version keeps almost constant.

Fig. 10. Photo of the scroll compressor of the automobile air conditioner.

Fig. 11. Work to electricity efficiency and electricity based on the scroll expander.

Fig. 12. Comparison of energy efficiency between novel version and previous version.

Fig. 13. Power output difference between the maximum and average value.

In the end of the reference[21], two main shortcomings have been remained. One is the relatively low efficiency of the system, which still has the space to be improved. The other is fluctuation of power output, i.e. the larger gap between the maximum and average value. These two shortcomings have been solved in the novel pumpless ORC system. Without the metering pump, the stable power output could be achieved by three two-position four-way valves manually. For the real application, three electric four-way valves will be used, and the power consumed can be neglected when compared with the power output for the cycle time. In addition, the unstable phase at the beginning and end of the cycle cannot be avoided since the valves need to be switched from one cycle to the other. Actually, the switching period only takes less than 5% of the whole power generation process. Also worth nothing that quite a lot of researches utilize the shaft power to analyze the performance of small ORC systems. This novel pumpless ORC system accomplishes the real electricity output in a small-scale ORC system with low temperature heat source. It provides an alternative method to recover the low temperature heat source.

Based on the experimental results, the real scaling application could be conceived in the future, and two main problems are bound to be solved. One is the discontinuous power output for the

pumpless ORC system. It could be solved by using three heat exchangers for circulation of power output. The other is the unstable power output in the beginning and end of the power generation process, which also happens in the conventional ORC systems. To keep power output constant in the whole cycle, good capacitance and battery technologies must be used in the unstable period. Also the scroll expander will be replaced with turbine or screw expander for the larger power output, and volume of heat exchanger will be increased for more refrigerant. Besides, it is acknowledged that the pumpless ORC technology should mainly aim at the middle or small-scale applications with the relatively low heat source temperature e.g. below 100°C. Under the condition of great electricity demands as well as enough heat source with relatively high temperature, advantages of the pumpless ORC is not so obvious when compared with the conventional ORC since the pump consumption becomes relatively small.

5. Conclusions

In this paper, a small-scale pumpless ORC system is established to investigate the overall performance with low temperature heat source below 100°C. The refrigerant R245fa is selected as the working fluid, and scroll expander is employed for power generation. Conclusions are yielded as follows:

- (1) Different hot water temperature from 75°C to 95°C are adopted to drive the pumpless ORC system. The maximum power output and average power output are 232 W and 204 W, respectively when the hot water inlet temperature is 95°C. For different hot water inlet temperature, the maximum power output ranges from 103 W to 232 W while the average power output ranges from 83 W to 204 W. When the inlet temperature increases, the

evaporation pressure will correspondingly increases, which leads to the higher power output of the system.

- (2) For different hot water inlet temperature, the total quantity of the power output ranges from 53.1 kJ to 73.1 kJ while heat input ranges from 4.2 kW to 7.16 kW. Both energy and exergy efficiency increase first, then decrease gradually and continue to increase at the end. The maximum energy efficiency is able to reach 2.4% while the maximum exergy efficiency could reach 13.7%. For different hot water inlet temperature, the energy and exergy efficiency range from 1.8% to 2.4% and 12.2% to 13.7%, respectively.
- (3) Additionally, performance of this novel pumpless ORC system is compared with that of our previous version. When hot water inlet temperature is 95°C, the highest energy efficiency of novel pumpless ORC system for shaft power output can reach 3.2% which is improved by 43% when compared with 2.2% of the previous version. Even the lowest hot water inlet temperature 75°C, the novel pumpless ORC system shows a 23% increment. The fluctuation of power output of the novel pumpless ORC system is no more than 21% while the fluctuation of previous one is as high as 143.5%. Pumpless ORC system shows great potential for low temperature heat recovery, and the real application could be conceived in the future

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