EXPERIMENTAL INVESTIGATION ON START-UP PERFORMANCE OF A 315 KW ORGANIC RANKINE CYCLE SYSTEM

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ABSTRACT

The experimental study of a 315 kW organic Rankine cycle (ORC) system using a radial-flow turbine, brazed plate heat exchangers (BHPE) and R134a has been investigated. An ORC system start-up mode of matching R134a flux with heat source temperature is introduced in this paper. In order to maintain the stable operation of each device of the ORC system, R134a flux should be gradually increased with the rise of the heat source temperature. Experiments were conducted for R134a flux ranging from 5.1 kg/s to 19.0 kg/s with the hot source temperature from 65 ℃ to 95 ℃, cold source temperature from 5.2 ℃ to 12.1 ℃.The effects of electrical power, turbine back pressure, heat exchangers pressure drop and exergy loss during the process of system start-up are examined. The experimental results show that the temperature of cold source and the R134a flux have great influence on the turbine back pressure, thus affecting the turbine output power. The lower the temperature of the cold source, the smaller the flux of R134a required for the generator to achieve the full power. Under the condition that the temperature of cold source is 5.2 ℃, the minimum R134a flux required for the electrical power to reach 315 kW is 17.7 kg/s, and the corresponding net power generation efficiency is 6.5%.

1. INTRODUCTION

Energy is an important resource guarantee for the prosperity and development of human society. It is also a prominent problem that restricts the development of social civilization for a long period of time. Tartiere *et al*. (2017) and Mazzic *et al*. (2015) concluded that the recovery of industrial waste heat by the use of organic Rankine cycle (ORC) technology was a powerful way to relieve the energy constraints. Experimental investigation is the most effective and direct method to make clear the operation law of each device in the system, providing guidance for the control operation of the whole system. Bracco *et al*. (2013) built a 1.5 kW ORC prototype and its numerical model to use the results obtained from one of them to improve the other accuracy. The speed assumed by the expander varies between 4500 and 3000 rpm against an increase of the expansion ratio from 5 to 6-6.5. Yang *et al*. (2017) used an open-drive scroll type expander and R245fa to make experimental research of pressure drop, degree of superheating and condenser temperature on a 3 kW ORC system. During the operation of the system, with the increase of pressure drop, the thermal efficiency and power generation efficiency of the system show a similar trend of rapid increase first and then stable change, while the power is constantly rising. The maximum expander shaft power and electrical power are 2.64 and 1.89 kW. The experimental studies of Steven *et al*. (2018) revealed an 11 kW ORC system performance with a steady state detection algorithm to validate an off-design model. Zhang *et al*. (2019) tested the impacts of the evaporating and condensing temperatures on the performances of main components in a 600 W ORC system. The condensing temperature has less impact on the expander shaft power when the evaporating temperature is greater than or equal to 100 ℃ .In addition to the experimental study of low-power units, there are many commercial application tests of high-power units. A heat source with temperature ranging 80 ℃ to 95 ℃ from ships engine jacket water was recycled by Sellers (2017) using 125 kW ORC unit. Operation data of unit from north latitude to equatorial latitude show that the condenser pressure decreases with cooler cooling water and increases

with warmer cooling water. Increasing the condenser pressure decreases this enthalpy change and thus decreases the turbine's power output. Mohamad *et al*. (2018) used a recuperative organic Rankine cycle recovered the waste heat of a low temperature proton exchange membrane fuel cell with R245fa, R245ca and R123. The system has the highest efficiency with 44.3% and R123 is the best working fluid. Lee *et al*. (2017) used 200 kW ORC unit to recycle 82 ℃ industrial waste heat in Taiwan. The output power of this unit is 193.75 kW with a thermal efficiency of 4.7%.
Shao *et al*. (2017) and Landelle *et al*. (2017) concluded that it was important to study the influence of heat source temperature and cold source temperature on the stable and efficient operation of ORC system. The objective of the paper presented here is to explore a 315 kW ORC apparatus start-up method of matching R134a flux with heat source temperature. An experimental apparatus was set up to measure and calculate the electrical power, turbine back pressure, heat exchangers pressure drop and exergy loss during the start-up process. Through the analysis of the change of system thermodynamic parameters, a better knowledge of the ORC system operation mode can be achieved and a more suitable control strategy during the start-up process for the apparatus can be developed.

2. EXPERIMENTAL APPARATUS OF ORC SYSYEM

2.1 Description of the ORC apparatus

Figure 1 shows the design chart of the updated ORC apparatus and the layout of the system is given in the Figure 2.

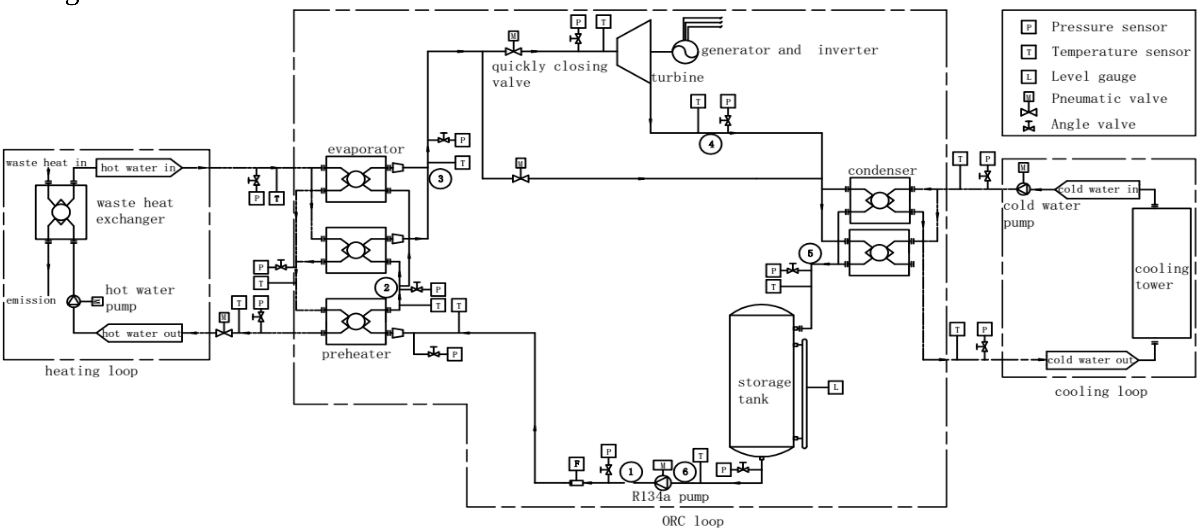

Figure 1: Design chart of the updated ORC apparatus

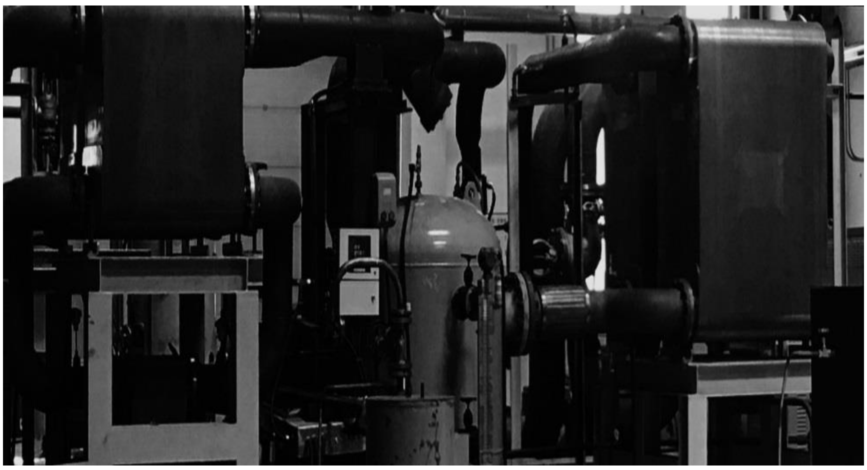

Figure 2: Layout of the updated ORC apparatus

The 315 kW ORC apparatus is designed for low temperature(between 90 ℃ and 150 ℃) waste heat and uses R134a as working fluid on the basis of the system initial optimization design. The ORC apparatus consists of the ORC loop generating electricity, the heating loop simulating the waste heat and the cooling loop condensing turbine outlet R134a gas. The ORC loop consists of a variable frequency pump, a preheater, two evaporators, a radial-flow turbine, two condensers, a storage tank, tubes, valves and sensors. The heating loop consists of a waste heat shell and tube exchanger, absorbing the heat of water vapor at 100-200 ℃ from a boiler in our laboratory, to offer 150-250 t/h hot water with the range of temperature between 90 ℃ and 150 ℃.The cooling loop consists of an open cooling tower to offer 300-500 t/h cooling water with the range of temperature from 5 ℃ to 20 ℃ depending on the ambient temperature.

2.2 Control strategy and measurement

The updated ORC apparatus has realized the function of one-key to start and stop depending on the change of heat source. On the premise of ensuring the safety of all equipment in the system, R134a flux should be gradually increased with the rise of the heat source temperature. In the automatic control program of the system, the most important thing is that the R134a superheat of the evaporator outlet should be maintained within a safe range from 10 ℃ to 20 ℃. The placement position of the measuring equipment is shown in Figure 1. A data logger with a 2 Hz acquisition frequency was used to compute all sensors data, transmitted to the system PLC. The measuring range and accuracy of the measuring equipment of the ORC apparatus are shown in Table1.

Table 1. The measuring range and accuracy of the measuring equipment used in the experiment

	Pressure Sensor	Temperature Sensor	R134a flowmeter	Water flowmeter
Range	0-2.5 MPa	0-100 ℃	0.08-1.237 m^3/min	0-10 m^3/min
Accuracy	±0.25%	±0.25%	±0.963%	±1%

3. THERMODYNAMIC ANALYSIS

The current thermodynamic analysis of the 315 kW ORC system follows the basic laws of thermodynamics to calculate the measurement parameters of the inlet and outlet of each device in the system. The main research parameters of this study are electrical power, turbine back pressure, heat exchangers pressure drop and exergy loss in the system start-up process.

The electrical power is the power output from the frequency converter to the power grid, which is directly measured by the power analyzer.

Because the turbine back pressure has a very important influence on the system power generation, it is an important parameter in the system, using the turbine outlet pressure sensor to measure its value.

Pressure drop of the heat exchanger can be calculated from side by pressure sensors at the inlet and outlet of evaporator and condenser, which is conducive to the follow-up optimization design of heat exchanger in the system.

Thermodynamic analysis of the irreversible energy loss of each device in the system is helpful to understand the operation status of each device and to insulate the large energy loss equipment to reduce the exergy loss. When calculating the exergy loss, it is considered that the system is stable flow, neglecting the exergy loss caused by other factors such as pressure drop of pipeline, and only considering the exergy loss caused by heat transfer with temperature difference and friction.

The formula for calculating the exergy loss of main equipment is as follows:

$$\mathrm{I}_{pp} = T_0 \cdot \dot{m} \cdot (s_1 - \mathrm{s}_6) \tag{1}$$

$$\mathrm{I}_{ev} = T_0 \cdot \dot{m} \cdot (s_3 - \mathrm{s}_1 - \frac{\mathrm{h}_3 - h_1}{\mathrm{T}_H}) \tag{2}$$

$$\mathrm{I}_{\mathrm{tb}\&qv} = T_0 \cdot \dot{m} \cdot (s_4 - \mathrm{s}_3) \tag{3}$$

$$\mathrm{I}_{cd} = T_0 \cdot \dot{m} \cdot (s_5 - \mathrm{s}_4 - \frac{\mathrm{h}_5 - h_4}{\mathrm{T_L}}) \tag{4}$$

The total exergy loss of the system is:

$$I_{\mathrm{sys}} = I_{\mathrm{pp}} + I_{ev} + I_{\mathrm{tb}\&qv} + I_{cd} \tag{5}$$

Exergy loss rate of each device is:

$$i_j = \frac{I_j}{I_{sys}} \tag{6}$$

The net power generation efficiency is:

$$\eta_{sys} = \frac{W_G - W_{pp}}{Q_{ev}} \tag{7}$$

4. RESULTS AND DICUSSIONS

The experimental results are summarized in this section. Variation of the ORC loop thermodynamic parameters during the system start-up process analyses is carried out.

4.1 System start-up process

Industrial waste heat is characterized by intermittent, large temperature span and instability. In order to maintain the stable operation of each device of the ORC system, R134a flux should be gradually increased with the rise of the heat source temperature. On the premise of ensuring the superheat at the outlet of evaporator and the effective cavitation margin of working fluid pump, PID control method is adopted to adjust the frequency of working fluid pump according to the temperature of heat source so as to make the system run steadily.

The test of the ORC apparatus were performed on January 30, February 18, March 21, 2019.The corresponding experimental conditions for each tests are listed in Table 2. The heat source in this section refers to the hot water entering the evaporator. The cold source in this section refers to the cooling water entering the condenser.

Table 2: The apparatus experimental condition

experimental condition	Test1 (1.30)	Test2 (2.18)	Test3 (3.21)
average temperature of cold source at condenser inlet(℃)	11.9	5.6	9.0
average flux of cold source at condenser inlet(t/h)	365.6	333.2	391.1
average flux of hot source at condenser inlet(t/h)	201.8	203.1	206.3

Under the condition of little fluctuation of flow rate of the heat and cold source and the sable temperature of cold source, the variation of R134a flux and electrical power with heat source temperature during the test3 (3.21) start-up of ORC system is shown in Figure 3.

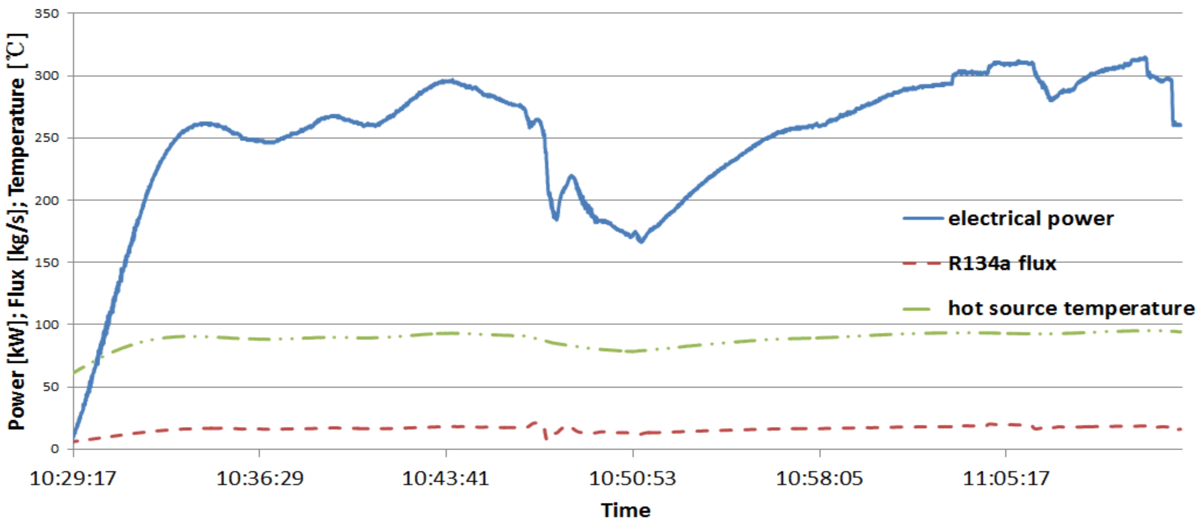

Figure 3: ORC system start-up process

At the beginning, the temperature of heat source rises gradually, and the motor starts to generate electricity when the frequency of working fluid pump increases. In this process, the working fluid pump aims to control the superheat of R134a at the evaporator outlet within a certain range, and adjusts with the change of heat source temperature.

4.2 Effect of cold source temperature on system performance during the start-up performance

Under the influence of different cold source temperatures, the apparatus experimental parameters of the ORC apparatus system are shown in Table 3 when the rated output power is 315 kW.

Table 3: The apparatus experimental parameters at 315 kW

experimental parameters	Test1 (1.30)	Test2 (2.18)	Test3 (3.21)
temperature of cold source at condenser inlet(℃)	12.1	5.2	8.6
R134a flux(kg/s)	19.0	17.7	18.6
frequency of working fluid pump(Hz)	50	48	49
system power consumption(kW)	45.0	39.8	42.4
temperature of hot source at evaporator inlet(℃)	96.9	94.2	95.2
net power generation efficiency(%)	6.3	6.5	6.2

The changes of electrical power and turbine back pressure during start-up process of the system with different cold sources are respectively shown in Figure 4 and Figure 5. Error bars account for measurement uncertainties.

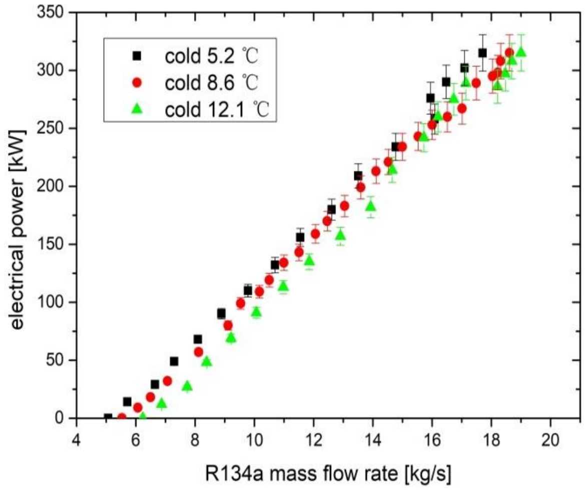

Figure 4: Effect of cold source temperature on electrical power

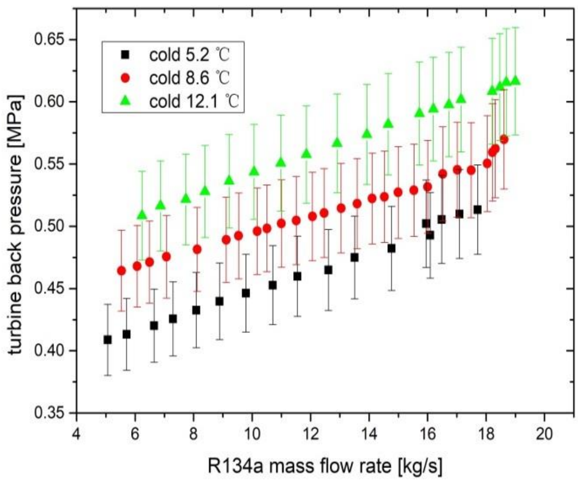

Figure 5: Effect of cold source temperature on turbine back pressure

The back pressure and electrical power increase gradually as the mass flow rate increases with the temperature of the heat source. The lower the cold source temperature is, the lower the turbine back pressure is, and the less fluid flow is needed to reach the rated power 315 kW. In the three tests, the lowest temperature of the cold source is 5.2 ℃, the required working fluid flow rate is 17.7 kg/s, and the net power generation efficiency of the system is 6.5%, deducting system power consumption. When the R134a flux is constant, the average temperature of cold source increases by 1 ℃, the average back pressure of turbine increases by 0.015 MPa, and the average power generation decreases by 3.6 kW. The lower the temperature of the condensation source leads to the higher condensation efficiency of the condenser, so the liquid level of R134a stored in the condenser decreases, which leads to the lower condensation pressure. When the pressure loss of condenser is very small, the reduction of condensation temperature directly leads to the reduction of turbine back pressure and the electrical power increases.

The changes of pressure drop of evaporator and condenser during start-up process of the system with different cold sources are respectively shown in Figure 6 and Figure 7.

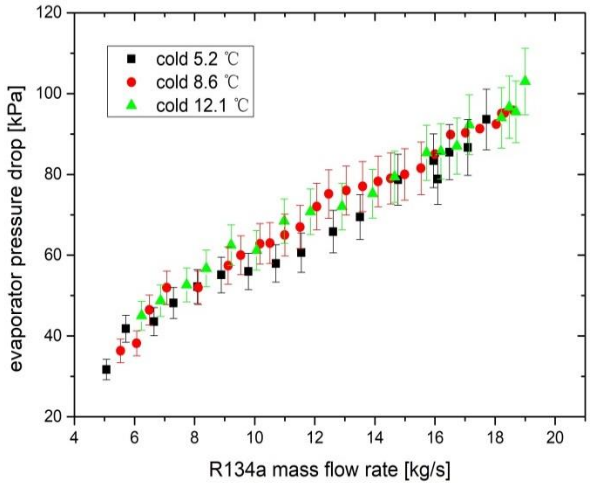

Figure 6: Effect of cold source temperature on evaporator pressure drop

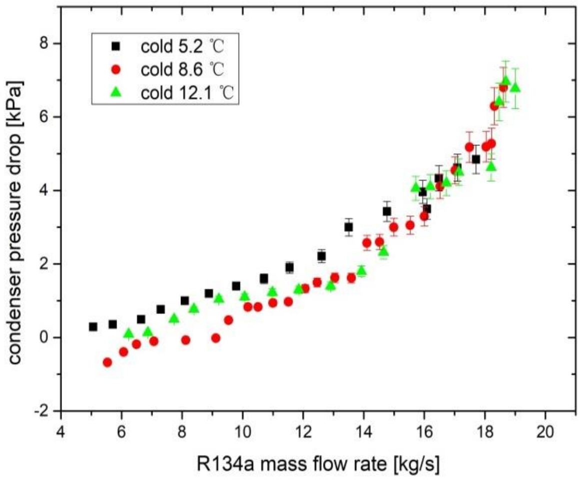

Figure 7: Effect of cold source temperature on condenser pressure drop

All heat exchangers in the ORC loop are brazed plate heat exchangers and the evaporator described in this chapter includes one preheater and two evaporators in the ORC apparatus. For every 1 kg/s increase of R134a flow rate, evaporator pressure drop increases by 4.9 kPa on average and condenser pressure drop increases by 0.5 kPa on average. The pressure drop of R134a in the evaporator and the condenser increases with the increase of R134a flux, and the pressure drop in evaporator is much larger than that in condenser. Under the same flow rate of R134a, the average flow velocity of working substance in the evaporator is higher than that in the condenser, which results in a large pressure loss in the evaporator. In addition, the evaporation system is divided into two evaporators and a preheater. The layout of the evaporator results in a large pressure loss.

The results of these three tests show that there is no obvious correlation between the temperature of the cold source and the pressure drop of the condenser, which may be caused by the fluctuation of the sensor measurement with smaller pressure drop in the condenser. It is noteworthy that the pressure difference between the inlet and outlet of the condenser is negative when the mass flow rate is low (5-8 kg/s). When the pressure loss caused by the flow of refrigerant in the condenser is very small, it is less than the pressure generated by the liquid level in the condenser, which results in the pressure of R134a at the outlet of the condenser being greater than the pressure at the inlet.

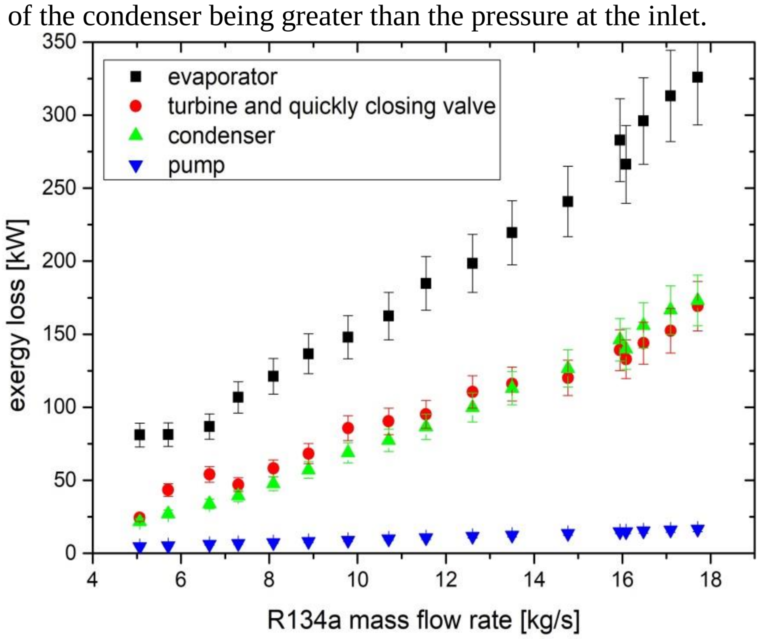

Figure 8: Effect of R134a mass flow rate on exergy loss under the cold source temperature of 5.2 ℃

Figure 8 shows the variation of the exergy loss of each equipment with the increase of R134a flux when the cold source temperature is 5.2 ℃.The total loss of the system is divided into four parts: evaporator, turbine and quickly closing valve before the turbine, condenser and working fluid pump. Exergy loss of each equipment increases gradually with the increase of R134a flux. The main reason that the influence of the quickly closing valve is taken into account in measuring the turbine exergy loss is that the quickly closing valve uses a three-eccentric butterfly valve, which has a large pressure loss. In addition, the long pipeline from the evaporator outlet to the turbine inlet also has certain pressure and temperature losses that cannot be ignored. Exergy loss of each equipment at 315 kW under the cold source temperature of 5.2 ℃ is given in Table 4.

Table 4: Exergy loss of each equipment at 315 kW under the cold source temperature of 5.2 ℃

	evaporator	turbine and quickly closing valve	condenser	pump	total ORC system
exergy loss(kW)	325.9	169.2	173.1	16.5	684.7
exergy loss rate(%)	47.6	24.7	25.3	2.4	100

The evaporator exergy loss accounts for nearly half of the system exergy loss. The turbine and the quickly closing valve and the condenser each account for about a quarter of system exergy loss. R134a temperature at the outlet of evaporator is the highest temperature and R134a temperature at the inlet of evaporator is nearly the lowest temperature in the ORC loop relatively. The heat transfer temperature difference of R134a through the evaporator is greater than that of other equipment in the system, resulting in the exergy loss of the evaporator occupying the largest part of the system exergy loss. The exergy loss of the working fluid pump occupies a small part of the system exergy loss, because the temperature of R134a passing through the working fluid pump changes little during the almost ideal adiabatic process.

5. CONCLUSIONS

A 315 kW ORC experimental apparatus was designed, established and tested under three conditions of cold source in this paper. The ORC apparatus has been able to generate 315 kW power continuously and steadily in the laboratory for hundreds of hours. The start-up process of matching R134a flux with heat source temperature is explored. Moreover, the effects of electrical power, turbine back pressure, heat exchangers pressure drop and exergy loss in the process of system start-up are examined. The main conclusions drawn from the investigation are summarized as follows:
(1) It is feasible to gradually increase the working fluid flow rate according to the change of heat source temperature during the 315 kW ORC apparatus start-up process.
(2) In the three tests introduced in this paper, the maximum net power generation efficiency is 6.5%. With the increase of cold source temperature leading to the increase of turbine back pressure at the same the flow rate of refrigerant, the R134a flux needed to reach 315 kW increases. In the case of the same R134a flux, the pressure drop of the evaporator and the condenser and the exergy loss of each device in the ORC system increase at the same time with the increase of cold source temperature.
(3) The evaporator exergy loss accounts for nearly half of the system total exergy loss in the tests during the start-up process.

NOMENCLATURE

I	exergy	(kW)
T	temperature	(K)
m	mass flowrate	(kg/s)
s	specific entropy	(kJ/kg/K)
h	specific enthalpy	(kJ/kg)
W	power	(kW)
Q	heat power	(kW)

Greek symbols

η	energetic efficiency

Subscript

pp	pump
ev	evaporator
tb	turbine
qv	quickly closing valve
cd	condenser
sys	ORC system
G	generator
0	reference

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