OPERATING CHARACTERISTICS OF WORKING FLUID PUMP IN A 315 KW ORGANIC RANKINE CYCLE SYSTEM

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ABSTRACT

In the organic Rankine cycle (ORC) power generation system, the working fluid pump, as a boosting component, determines the stability, efficiency and safety of the system. This paper is based on ORC power generation test of 315kW, which uses R134a as the working fluid and variable frequency multistage centrifugal pump as the working fluid pump. In order to explore the effect of the cold source on the operating characteristics of the working fluid pump, the system load and the pump speed (960~2960rpm) are all increased at different cooling water temperatures (279K, 283K, 287K, 291K) while maintaining the evaporator outlet superheat degree at 20±1K. The parameters such as the temperature, pressure and flow rate were measured, and the performance curve, the output power, the Net Positive Suction Head available (NPSHa) and the efficiency of the pump under off-design conditions were studied. The experimental results show that the rotational speed of the working fluid pump has a significant effect on the NPSHa. As the pump speed increasing, the temperature and pressure of the working fluid at the pump inlet are affected, leading to NPSH rising first and then decreasing.. When the cooling water temperature is 291K and the pump speed is 2250 rpm the NPSHa reaches the maximum value of 10.8m water head. In addition, at the same speed, the increase of the temperature of the cooling water increases the flow rate and the pump outlet pressure, at the same time, the NPSHa of the pump increasing. The research results could provide guidance and reference for the efficient operation and cavitation protection of the working fluid pump in the ORC system.

Keywords: organic Rankine cycle; multistage centrifugal pump; Net Positive Suction Head available; variable working condition

1. INTRODUCTION

Weng et al. (2014) said there is a large amount of waste heat with low temperature. This kind of heat energy has the characteristics of huge amount, various kinds, wide distribution and low energy density. It is generally believed that waste heat temperature above 250 ℃ is the possibility of power conversion. The flue gas temperature <250 ℃ heat resources can be used for drying materials, refrigeration, heating, or supplying domestic hot water, etc., summarized by SAC/TC20 (2009) . Johnson, I. et al. (2008) concluded that medium and low temperature thermal energy is widely distributed and the total amount is very large. Taking industrial waste heat as an example, more than 50% of the energy is emitted directly in the form of medium and low temperature (<230 ℃) waste heat. Organic Rankine cycle power generation is a small power station system that uses organic matter with low boiling point as working fluid to achieve power output through Rankine cycle. Therefore, this low-temperature waste heat power generation technology greatly expands the temperature range of waste heat power generation. Bao et al. (2013) and Quoilin et al. (2010) said that organic Rankine cycle system is relatively simple, high reliability, easy to maintain and so on, and has received more and more attention in recent years.

Working fluid pump is the key equipment in the organic Rankine cycle system, which plays a role of cyclic pressurization to the working fluid and is the source of the cyclic power of the system.The efficient, safe and stable operation of the working fluid pump cannot be ignored. Therefore, it is

necessary to study the operation rule of the working fluid pump in the organic Rankine cycle system.
Yang et al. (2019) analyzed the variation law of the operating parameters of two different types of working fluid pumps (multistage centrifugal pump and hydraulic diaphragm metering pump) under variable working conditions, by using R245fa as the working fluid and under condensing temperature 303 K, and then researched the influence of the operating parameters of the working conditions on the performance of ORC system. The maximum thermal efficiency of the two types of pumps could reach up to 11.66% and 10.35%. The hydraulic diaphragm metering pump was more suitable to the low mass flow ORC system. Ye et al. (2016) established a small organic Rankine cycle system with R245fa working fluid. The efficiency of the volumetric working fluid pump was studied under the conditions of evaporation temperature of 75 °C and condensation temperature of 11 °C. In this test, the actual isentropic efficiency of the working fluid pump ranges from 15% to 47%, which is lower than the theoretical value of the previous simulation. The paper points out that more accurate pump efficiency should consider the working fluid flow change and obtained through experiments. Zhang et al. (2017) constructed a test bench of multistage centrifugal pump using R123 as working fluid, and the characteristic curve of multistage centrifugal pump was obtained by controlling pump speed (870~2900rpm) and working flow (0.20~5.00 $m^3 \cdot h^{-1}$). The results showed that the overall pump efficiency of multistage centrifugal pump was between 15.00% and 65.70%. With the increase of the evaporation temperature of the ORC system, the practical back work ratio was up to 0.45. When the speed of multistage centrifugal pump is 2900 $r \cdot min^{-1}$, the thermal efficiency of the vehicle ORC waste heat recovery system could reach up to 10.5%. Wu et al.(2018) constructed the power generation system using R245fa as the working fluid. The systematic performance was analyzed and calculated with the change of working condition when the working fluid pump was taken into account under different working fluid pump efficiency. The results showed that the increase in evaporation temperature also increases the effect of the working fluid pump on the efficiency of the first law, while the change in condensation temperature has less effect.

In summary, it can be concluded that the research on the characteristics of the working fluid pump combined with the cold source conditions of the ORC system is little, especially the effective NPSHa(Net Positive Suction Head available). On the other hand, the ORC system built by most researchers is only a few kilowatts power generation, limiting reference for engineering applications. In this paper, the 315kW ORC power generation system was tested in combination in different seasons with various cooling water conditions. The pressure, flow rate, NPSHa, efficiency of the working fluid pump and system output power were studied. It can provide reference for high efficiency operation and anti-cavitation protection.

2. TEST METHODOLOGY

The test bench is divided into two parts: one is the organic Rankine cycle system and the other is the data acquisition system. The organic Rankine cycle system uses R134a as the circulating fluid. The system, as shown in Figure 1, includes evaporators, expanders, condensers, a storage tank, a working fluid pump and valve piping accessories. The expander uses a single-stage radial turbine, and the maximum output power is 333 kW. The evaporators and condensers use brazed plate heat exchangers that can withstand a maximum pressure of 3.1 MPa. The working fluid pump is a multi-stage centrifugal pump with variable frequency and adjustable speed, the specifications of which are shown in Table 1. Figure 2 shows the ORC data acquisition and test rig. The data acquisition system mainly includes temperature sensors, pressure sensors, flow meters, power meters and so on. The measuring range and accuracy of the measuring equipment are shown in Table 2. The error bars caused by the accuracy of the sensor are shown in the figure.

Table 1: Specifications of the working fluid pump

Rated power	Maximum speed	Rated flow	Maximum pressure difference
45 kW	2960 rpm	70 m^3/h	2.02MPa

Table 2: The measuring range and accuracy of the measuring equipment used in the experiment

	Pressure Sensor	Temperature Sensor	R134a flowmeter	Water flowmeter	Power meter
Range	0-2.5MPa	0-125 ℃	0.08-1.237 m^3/min	0-10 m^3/min	0-1MW
Accuracy	±0.25%	±0.25%	±0.963%	±1%	±0.1%

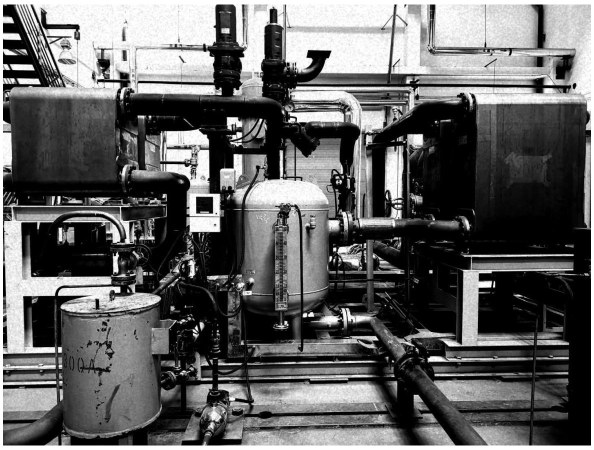

Figure 1: ORC test rig photograph

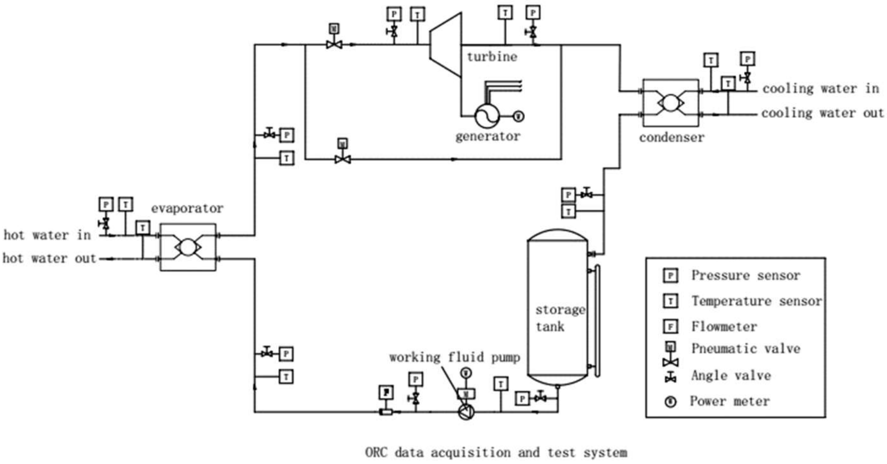

Figure 2: ORC data acquisition and test system

The ORC system test was conducted in different seasons (corresponding to different cooling water temperatures). The test adjusts the speed of the working fluid pump through the frequency converter, while maintaining the evaporator outlet superheat at 20 °C, so as to research the variation of the system parameters when the temperature of the cooling water changes. The cooling water conditions are listed in Table 3.

Table 3: The cooling water conditions

Case	Temperature	Pressure
1	279K	0.2MPa
2	283K	0.2MPa
3	287K	0.2MPa
4	291K	0.2MPa

The cooling water temperature, pump outlet pressure, pump flow rate, system output power, and working fluid pump power consumption are directly measured by sensors. The pressure difference between the inlet and outlet of the pump, NPSHa, the output of the working fluid pump and the efficiency of the working fluid pump are calculated by the measured data.

3. TEST RESULTS AND ANALYSIS

3.1 Outlet pressure of working fluid pump

The inlet and outlet pressure difference of Working fluid pump, given by:

$$dp = p_{out} - p_{in} \tag{1}$$

Where dp is the inlet and outlet pressure difference of Working fluid pump, Mpa; p_{out} and p_{in} indicate the pressure at the pump outlet and pump inlet, respectively, MPa.

Figure 3 shows the change of the outlet pressure of the working fluid with the working fluid pump speed and the cooling water temperature. The results show that at the same cooling water temperature, the outlet pressure of the working fluid pump increases with the rotation speed. The higher the temperature of the cooling water, the higher the outlet pressure of the working fluid pump, which means that the pressure of the entire system will increase. As the speed approaches the rated speed, the effect of the cooling water temperature is reduced. At a rotation speed of 1500 rpm and the cooling water temperature difference is 12 K, the outlet pressure difference is 0.18 MPa, and at the rotational speed of 2500 rpm and the same 12 K temperature difference, the outlet pressure difference is 0.13 MPa.

3.2 Pressure difference between the inlet and outlet of the working fluid pump

Figure 4 shows the variation of the inlet and outlet pressure difference of the working fluid pump with the working fluid pump speed and the cooling water temperature. The results show that the pressure difference between the inlet and outlet of the working fluid pump increases with the increase of the working fluid pump speed, and the pressure difference is close to the square of the rotational speed, which is consistent with the theory of the variable frequency pump. The pressure difference between the inlet and outlet of the working fluid pump is negatively correlated with the cooling water temperature. Under the same working fluid pump speed, the higher the cooling water temperature, the smaller the pressure difference between the inlet and outlet of the working fluid pump is. However, the absolute value of the influence is small. When the temperature changes by 4 K, the pressure difference changes only 0.02~0.03 Mpa.

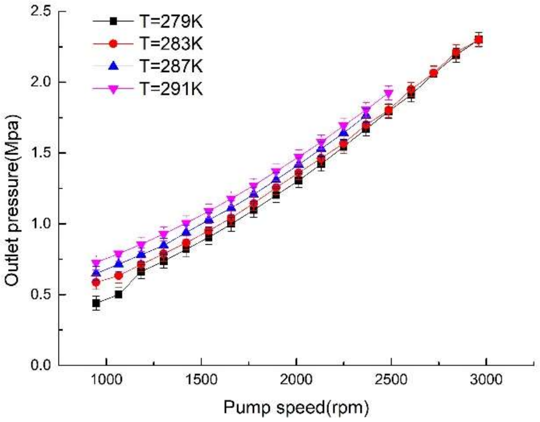

Figure 3: Outlet pressure

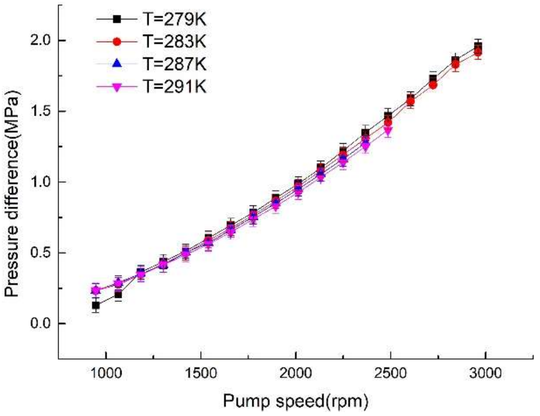

Figure 4: Pressure difference

3.3 Mass flow

Figure 5 shows the change of the working fluid flow with the working fluid pump speed and the cooling water temperature. The results show that the flow rate of the working fluid pump increases with the increase of the working fluid pump speed. The flow rate and the speed are close to linear relationship, which is consistent with the theory of the variable frequency pump. The working fluid flow is positively correlated with the cooling water temperature. Under the same working fluid pump speed, the higher the cooling water temperature, the larger the working fluid pump flow rate is. As the speed approaches the rated speed, the pump flow is more susceptible to the temperature of the cooling water. At a speed of 1200 rpm,with the temperature difference of 12 K, the flow difference is only 0.2881 kg/s.At the 2500 rpm, with the same 12 K temperature difference, the flow difference is 1.7 kg/s.

3.4 NPSHa

NPSHa, available net positive suction head, is a measure of how closing the fluid at a given point is to boiling, and so to cavitation, given by：

$$NPSH_a = p_{in} - p_{in,sat} \tag{2}$$

Where p_{in} is the pump inlet pressure, Mpa; $p_{in,sat}$ is the saturation pressure corresponding to the pump inlet temperature, Mpa.

Figure 6 shows the variation of NPSHa with the working fluid pump speed and the cooling water temperature. The results show that NPSHa is positively correlated with the temperature of the cooling water, and the higher the cooling water temperature, the larger the NPSHa is. This is because the temperature of the cooling water affects the pressure of the condenser, and the pressure and temperature together determine the NPSHa. This result means that when the ORC system is operated under the conditions of low cooling water temperature in winter, more attention needs to be paid to the protection of the working fluid pump. At the same cooling water temperature, as the rotational speed increasing, NPSHa increases first and then decreases. As the external load increasing, the working fluid pump increases the rotational speed, and the inlet temperature and inlet pressure of the working fluid pump both increase. Increasing the inlet temperature, NPSHa will decrease. While increasing the inlet pressure, NPSHa will increase. Therefore, when the working fluid pump speed is less than a certain value, the influence of the pressure is greater than the temperature, so the NPSHa increases first; and when the rotational speed is greater than a certain value, the influence of the pressure is less than the temperature, and thus the NPSHa decreases. When the cooling water temperature is 291K and the working fluid pump speed is 2250 rpm, the NPSHa reaches the maximum value of 0.108 Mpa, equivalent to 10.8 m water head.

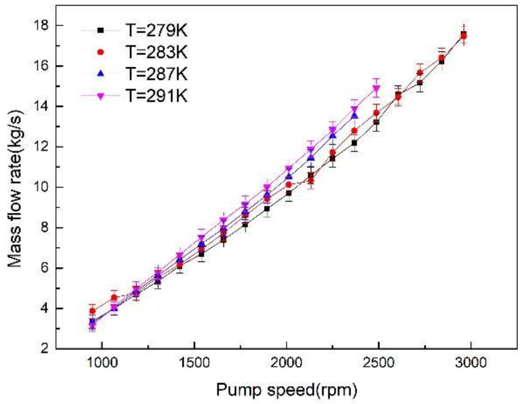

Figure 5: Mass flow

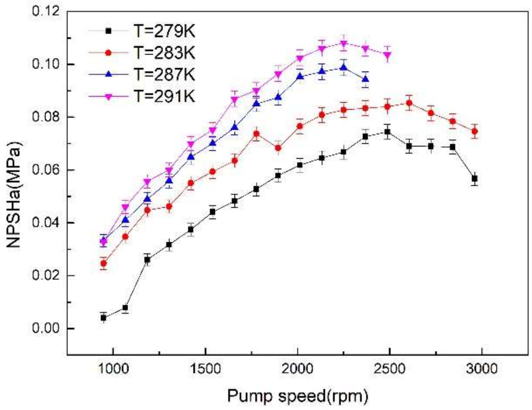

Figure 6: NPSHa

3.5 ORC system output power

Figure 7 shows the variation of the ORC system output power with the working fluid pump speed and the cooling water temperature. In particular, when the system output power is less than 0 kW, it means that the grid supplies power to the system. The results show that the ORC system output power increases as the speed increases. The system output power is inversely related to the cooling water temperature. The higher the cooling water temperature, the lower the output power of the ORC system is. This is because the cooling water temperature affects the back pressure of the turbine, and the increase in back pressure causes the turbine output to decrease. At a rated speed of 2960 rpm of the working fluid pump, the system output power reduce by about 7.5 kW for every 1 K increase in the cooling water temperature.

3.6 Output power of the working fluid pump

The working fluid pump output power is equal to the product of the pump inlet and outlet pressure difference and the volume flow, given by：

$$W_{pump} = 1000 dp \times Q_v \tag{3}$$

Where W_{pump} is the working fluid pump output power, kW; Q_v is the the volume flow, m^3/s.

Figure 8 shows the variation of the output power of the working fluid pump with the working fluid pump speed and the cooling water temperature. The results show that the output power of the working fluid pump increases with the increase of the rotational speed and is linear with the cubic of the rotational speed, which is consistent with the theory of the variable frequency pump. It is worth noting that the output power of the working fluid pump is little affected by the temperature of the cooling water. The temperature of the cooling water changes by 4 K, and the output power of the working fluid pump changes only 0.03~0.07 kW. According to the experience, the output power of the working fluid pump is proportional to the product of the flow rate and the differential pressure. According to the previous analysis, the flow rate of the working fluid pump is positively correlated with the temperature of the cooling water, and the pressure difference between the inlet and outlet of the working fluid pump is negatively correlated with the temperature of the cooling water. The interaction of the two factors causes the working fluid pump output power to be less correlated with the cooling water temperature.

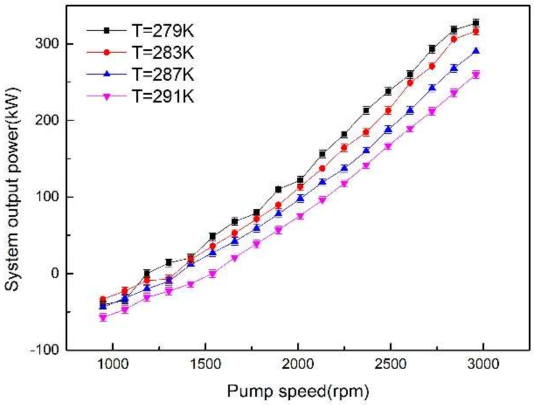

Figure 7: ORC system output power

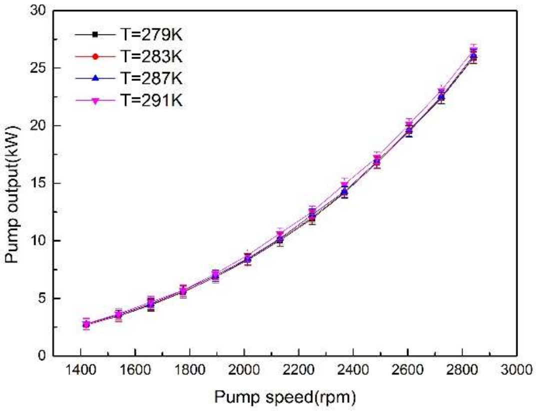

Figure 8: Output power of the working fluid pump

3.7 Power consumption of the working fluid pump

Figure 9 shows the variation of the power consumption of the working fluid pump motor with the working fluid pump speed and the cooling water temperature. The results show that the power consumption of the working fluid pump increases with the increase of the rotational speed. The power consumption of the working fluid pump is almost negligible due to the temperature effect of the cooling water. This is consistent with the variation in the output power of the working fluid pump analyzed above.

3.8 Working fluid pump efficiency

The working fluid pump efficiency is equal to the ratio of the working pump output power to the working fluid pump power consumption , given by：

$$\eta_{pump} = 100 W_{pump} / W_{consume} \qquad (4)$$

Where η_{pump} is the working fluid pump efficiency, %; $W_{consume}$ is the working fluid pump power consumption, kW.

Figure 10 shows the variation of the working fluid pump efficiency with the working fluid pump speed and the cooling water temperature. The results show that at the same speed, the higher the cooling water temperature, the higher the efficiency of the working fluid pump is. When the working fluid pump speed changes from 1400 rpm to 2960 rpm, the working fluid pump efficiency is concentrated in the range of 60%~70%. This result can provide a reference for the selection of the working fluid pump in the initial design of the ORC system.

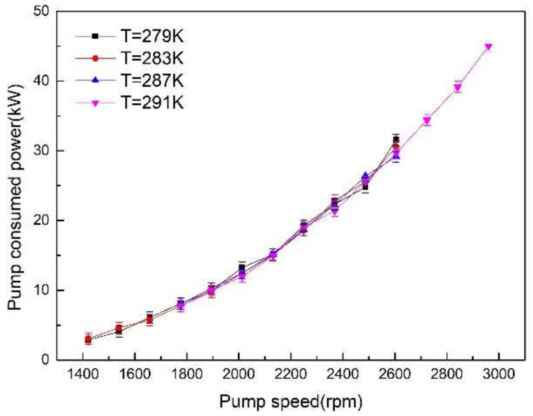

Figure 9: The power consumption of the working fluid pump

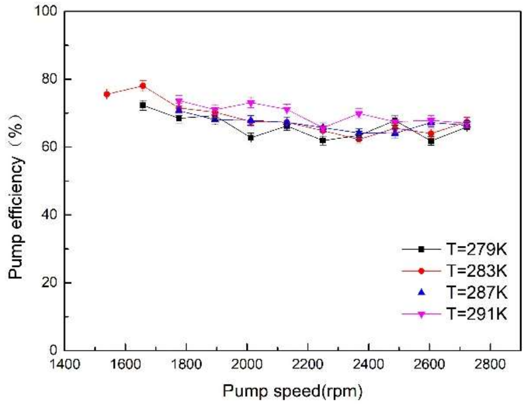

Figure 10: The working fluid pump efficiency

4. CONCLUSIONS

The ORC system uses R134a as a cycle fluid and has been tested in different seasons. By analyzing the operating data of the working fluid pump, the operating law of the working fluid pump in the ORC system is obtained, which provides a realistic reference for the efficient operation and protection of the ORC working fluid pump. The main conclusions are as follows:

(1) The pressure difference between the inlet and outlet of the working fluid pump is negatively correlated with the cooling water temperature, while the flow rate is positively correlated with the cooling water temperature. However, the output power of the working fluid pump is hardly affected by the cooling water temperature, and is only the cubic linearity of the working fluid pump speed.

(2) NPSHa increases with the increase of cooling water temperature, and increases first and then decreases as the speed of the working fluid pump increases. When the working pump speed is 2250 rpm, NPSHa reaches the maximum value.

(3) At a rated speed of 2960 rpm of the working fluid pump, the output power of the ORC system is reduced by about 7.5 kW for every 1 K increase in the cooling water temperature.

(4) When the ORC system is running stably, the efficiency of the working fluid pump is concentrated between 60% and 70%.

The experimental results are helpful for the selection of ORC working fluid pump and optimization of working fluid pump control. In the next step, the ORC system will be optimized on the basis of the selection and control optimization of the working fluid pump to ensure that the net output power of the ORC system is the largest under different external conditions.

NOMENCLATURE

T	temperature	(K)
p	pressure	(Mpa)
Q	mass flowrate	(kg/s)
W	power	(kW)
Greek symbols		
η	energetic efficient	
Subscript		
sat	saturated	
v	volume	

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REFERENCES

Bao, J., Zhao. L., 2013, A review of working fluid and expander selections for organic Rankine cycle. *Renewable & Sustainable Energy Reviews*, vol. 10, no. 24: p. 325-342.

Quoilin, S., Lemort, V., Lebrun, J., 2010, Experimental study and modelling of an Organic Rankine Cycle using scroll expander. *Applied Energy*, no. 87: 1260-1268.

SAC/TC20., 2009, Calculation method and utilization guides for waste heat resource's quantity of industrial boiler's and flame heating furnace's exhaust gas: GB/T17719—2009, Beijing: China Standards Press, 003 p.

Johnson, I. , Choate, W. T. , & Davidson, A. ,2008, Waste heat recovery. technology and opportunities in US industry. US Department of Energy.

Weng, Y.Y., 2014, Conversion Process and Utilization of Low Grade Heat Energy, Shanghai Jiao Tong University Press, 001 p.

Wu, T. M., Liu, J. H., Xu, X. J., Liu, Q., 2018,Influence of Working Fluid Pump on System Performance in Organic Rankine Cycle. *Fluid machinery*, vol. 2,no. 46: p. 68-73.

Yang, Y. X., Zhang, H. G., Zhao, R., 2019, Effects of variable operating conditions of working fluid pumps on the performance of organic Rankine cycle system. *Chemical industry and engineering progress*, vol. 38, no. 2: p. 851-857.

Ye, J. Q., Zhao, L., Deng, S., Wang, X. D., Su, W., 2016, Efficiency of working fluid pump in a small-scale organic Rankine cycle System. *Chemical industry and engineering progress*, vol. 35, no. 4: p. 1027-1032.

Zhang, H. G., Yang, Y. X., Meng, F. X., Zhao, R., Tian, Y. M., Liu, Y., 2017, Running performance of working fluid pump for organic Rankine cycle system. *CIESC Journal*, vol. 68, no. 9: p. 3573-3579.