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Experimental investigation of the pipeline pressure losses effect on ORC system performance

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ABSTRACT

Organic Rankine cycle (ORC) is an important technology to convert low and medium temperature heat source into work. The irreversible loss results in the fact that the actual performance of the ORC system is much lower than the theoretical value. Pipeline is an indispensable part of the ORC system to connect system components. In this work, the effect of pipeline pressure loss on ORC system power output and thermal efficiency is studied experimentally. The results show that the pressure losses of pipeline reduce the ORC system power output, which is 27.04% lower than the theoretical value under experimental conditions. Pipeline pressure losses also reduce the thermal efficiency of the ORC system, which is 33.04% lower than the theoretical value. Under the same pressure losses, the effect of the pipeline connecting expander and condenser on the ORC system power output and thermal efficiency is about 2.47 times larger than that of the pipeline connecting evaporator and expander.

Keywords: organic Rankine cycle, experiment analysis, pipeline pressure losses, system performance

1. INTRODUCTION

In recent years, the research on energy conservation and emission reduction has attracted extensive attention to cope with global warming and energy crisis. Waste heat utilization is an important technical approach for energy conservation and emission reduction. Organic Rankine cycle (ORC) has great application prospects in the field of waste heat research due to its simple structure, wide range of application scenarios, strong adaptability and high efficiency [1-3].

Reducing the big gap between the actual and theoretical cycle performance of ORC system is one of the key problems to be solved urgently. Irreversible loss leads to the difference between the actual and theoretical cycling performance of the ORC system [4]. At present, many scholars have studied the irreversible loss of ORC system components. Wang et al. studied the influence of heat dissipation on the performance of single screw expander by means of numerical simulation and experiment (a 10-kW scale expander, the temperature of working fluid at the inlet of expander were 83 °C, 93 °C, 103 °C, 113 °C, 123 °C, respectively.) [5]. It showed that the heat transfer influence for power output was 1.91%–4.51% and the heat transfer influence for shaft efficiency was 2.72%–5.78%. Pressure loss is an important factor of irreversible loss, some researches have been done. Zhang et al. conducted an experimental investigation to study the flow pressure drop performances of R134a, R1234yf and R1234ze at high saturation temperatures in a plate heat exchanger. The experimental data were tested with saturation temperatures of 60 °C, 70 °C and 80 °C (with corresponding reduced pressures of 0.35–0.74), mass fluxes of 86–137 kg/s and outlet vapor qualities of 0.5–1 [6]. They found the frictional pressure drop increases with the increase of the mass flux and vapor quality and the decrease of saturation temperature. Meng et al. analyzed the effect of the key pump parameters on the ORC performance [7], they found low pump efficiency affected the increase of the thermal efficiency and power output of the ORC system.

Pipeline is an indispensable part of the ORC system to connect system components. The pressure losses of pipeline could reduce the ORC system performance. Only a few scholars have studied the effect of ORC pipeline pressure loss on system performance. Lei et al. examined the influence of pressure losses on ORC thermal efficiency [8], and found that the adverse impacts of pressure losses on ORC thermal efficiency are very different, mainly depending on the characteristic specific volume of working fluid in a certain state.

It can be concluded form above analysis that there are few experimental investigations regarding the influence of pipeline pressure losses on ORC thermodynamic performance. In this work, the effect of pipeline pressure losses on ORC system power output and thermal efficiency were experimentally studied based on the first law of thermodynamics. It could provide guidance for study the effect of the pipeline irreversible losses on ORC performance.

NONMENCLATURE

Abbreviations	
ORC	Organic Rankine cycle
Variables	
T	Temperature [°C]
P	Pressure [bar]
m	Mass flow [kg/s]
W_P	Circulation pump consumption [kW]
Symbols	
η	Thermal efficiency [-]
W	Power output [kW]
h	Enthalpy [kJ/kg]
a, b, c, d	The position of sensors[-]

2. METHODOLOGY

2.1 Experimental description and design

This work is performed based on a set of 10 kW scale ORC experimental system, which is mainly composed of three subsystems: conductive oil system, ORC system and cooling water system. The conductive oil system provides heat for the ORC system evaporator. The cooling water system can take away the heat from the ORC system condenser. The ORC system can realize the conversion of heat energy into electric energy. Fig. 1 presents the schematic diagram of the ORC experimental system. In the schematic diagram, the red line represents the connection pipeline between evaporator and expander (pipe 1), and the blue line represents the connection pipeline between expander and condenser (pipe 2). The positions of points a, b, d and d represent the outlet of the evaporator, the inlet of the expander, the outlet of the expander and the inlet of the condenser, respectively. Fig. 1 also shows the position distribution of temperature sensors and pressure sensors in the ORC experimental system. R123 is selected as working fluid in this ORC experimental system. The parameter and uncertainty analysis of each main component of the system can be referred to our previous work [9-10]. The specific parameters of each pipeline are listed in Table 1.

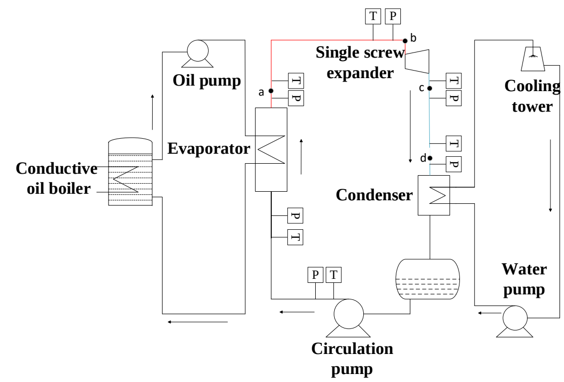

Fig. 1. A schematic diagram of the ORC experimental system.

Table 1
Main parameters of the pipes.

	Material	Length (m)	Diameter (mm)
Pipe 1	Steel	4.66	20
Pipe 2	Steel	5.69	50

Considering that the grid frequency is 50 Hz, the speed of the expander is controlled within the range of 3000±20 rpm during the experiments. The variation of state parameters of the working fluid not only affects the performance of ORC system, but also changes the pressure loss of pipe 1 and pipe 2. Therefore, in order to obtain the effect of pipeline pressure loss on ORC system performance, it is necessary to obtain the ORC system performance index and pipeline pressure loss under different working fluid state parameters.

After the ORC experimental system warm-up is completed, adjusting the working conditions of the thermal oil system and the circulation pump to make the working fluid parameters at the inlet of the expander reach the predetermined initial state (T=110 °C, P=8.5 bar). Then, the working fluid parameters at the inlet of the expander were increased to the predetermined ending point (T=127 °C, P=11.3 bar). During the experimental process, the power output of the expander, the power consumption of the circulation pump and the data of each sensor are recorded in real-time.

2.2 Thermodynamic model

The resistance of the working fluid in the pipeline inevitably cause the pressure losses, which increase the irreversible losses in the ORC system. The existence of pressure losses of working fluid results in the deviation operation of the ORC system from the ideal state. Fig. 2 shows the *T*-s diagram of the ORC system. As can be seen in Fig. 2, process 1-2-3-4-5-6-1 represents the ideal ORC operation process without pipeline pressure losses, while process 1-1'-2'-2-3-4-5-6-1 represents the actual ORC system operation process with pipeline pressure losses. During the experiment, it was found that the pressure losses of the connecting pipeline between the circulation pump and the evaporator and the connecting pipeline between the condenser and the circulation pump were very small, thus the influences of these pipeline pressure losses on the ORC system performance were ignored. During the operation of the actual ORC system, the pressure losses of pipe 1 between the circulation pump and the evaporator will cause the working fluid's state shift from point 1 to the actual state point 1'. The pressure loss of the working fluid in pipe 2 will offset the state point 2 to the state point 2'.

In this work, the ideal ORC system is defined to ignore the pressure losses of pipe 1 and pipe 2 ($P_b = P_a$, $P_c = P_d$). When only the impact of pressure losses of pipe 2 on the ORC system performance is considered, the pressure losses of pipe 1 is ignored and the pressure losses of pipe 2 is retained ($P_b = P_a$). When only the influence of pipe 1 pressure losses on ORC system performance is considered, the pressure losses of pipe 2 is ignored and the pressure losses of pipe 1 is retained ($P_c = P_d$). The power output of the expander is calculated by referring to the theoretical model of literature [11].

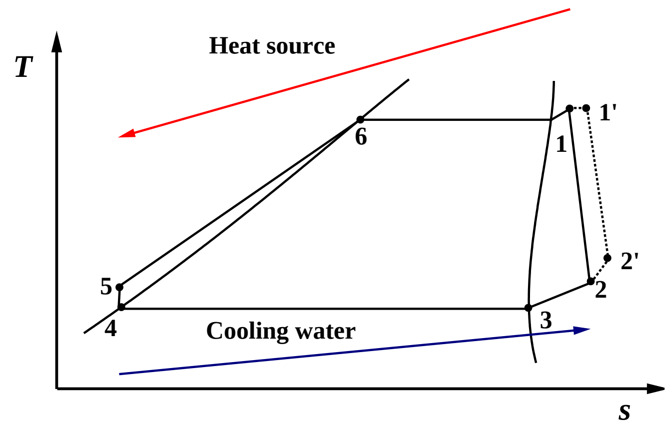

Fig. 2. *T-s* diagram of the ORC experimental system.

The ORC experimental performances are evaluated as follows.

(1) The power output of the actual ORC system is calculated according to the following formula:

$$\dot{W}_0 = \frac{T \cdot n}{9550} \quad (1)$$

(2) The power output of the ideal ORC system in this work is calculated according to the following formula:

$$\dot{W}_{\mathrm{THEORY}} = f(P_a, T_b, P_d, T_c) \quad (2)$$

(3) The power output of ORC system considering the pressure losses of pipe 1 is calculated according to the following formula:

$$\dot{W}_{\mathrm{pipe1}} = f(P_b, T_b, P_d, T_c) \quad (3)$$

(4) The power output of ORC system considering the pressure losses of pipe 2 is calculated according to the following formula:

$$\dot{W}_{\mathrm{pipe2}} = f(P_a, T_b, P_c, T_c) \quad (4)$$

(5) The thermal efficiency of the actual ORC system is calculated by the following formula:

$$\eta_0 = \frac{\dot{W}_0 - \dot{W}_P}{\dot{m}(h_1 - h_5)} \quad (5)$$

(6) The thermal efficiency of the ideal ORC system is calculated by the following formula:

$$\eta_{\mathrm{THEORY}} = \frac{\dot{W}_{\mathrm{THEORY}} - \dot{W}_P}{\dot{m}(h_1 - h_5)} \quad (6)$$

(7) The thermal efficiency of the actual ORC system considering the pressure losses of pipe 1 is calculated by the following formula:

$$\eta_{\mathrm{pipe1}} = \frac{\dot{W}_{\mathrm{pipe1}} - \dot{W}_P}{\dot{m}(h_1 - h_5)} \quad (7)$$

(8) The thermal efficiency of the actual ORC system considering the pressure losses of pipe 2 is calculated by the following formula:

$$\eta_{\mathrm{pipe2}} = \frac{\dot{W}_{\mathrm{pipe2}} - \dot{W}_P}{\dot{m}(h_1 - h_5)} \quad (8)$$

3. RESULTS AND DISCUSSION

(1) The effect of pipeline pressure losses on ORC system power output.

Fig. 3 presents the variation of $\dot{W}_{\mathrm{THEORY}}$、$\dot{W}_0$、$\dot{W}_{\mathrm{pipe1}}$ and $\dot{W}_{\mathrm{pipe2}}$ with the increase of T_{b}. By comparing $\dot{W}_{\mathrm{THEORY}}$ with $\dot{W}_0$ in Fig. 3, it can be found that the pressure loss of the pipeline could decrease the ORC system output power significantly. With the increase of T_{b}, the gap between $\dot{W}_{\mathrm{THEORY}}$ and $\dot{W}_0$ is going up slowly. That is to say, the effect of pipeline pressure losses on ORC system power output increases with increasing T_{b}. When T_{b} is 126.9 °C, the difference value between $\dot{W}_{\mathrm{THEORY}}$ and $\dot{W}_0$ reaches the maximum value of 2.10 kW. When T_{b} is 110.8 °C, the power output losses caused by pipeline pressure losses accounted for the maximum 27.04% of $\dot{W}_{\mathrm{THEORY}}$. By comparing the difference between $\dot{W}_{\mathrm{THEORY}}$ and $\dot{W}_{\mathrm{pipe1}}$ with the difference between $\dot{W}_{\mathrm{THEORY}}$ and $\dot{W}_{\mathrm{pipe2}}$, the effect of working fluid pressure losses of pipe 1 on ORC system power output is greater than that of pipe 2. Fig. 4 presents the results of the different effect of pipe 1 pressure losses and pipe 2 pressure losses on ORC system power output with increasing T_{b} under the same pressure losses value. It shows that $\Delta\dot{W}_{pipe2}$ is almost 2.46 times higher than $\Delta\dot{W}_{pipe1}$. In another words, with the same pressure losses, the effect of pipe 2 pressure losses on ORC system power output is more obvious than that of pipe 1. The pressure losses of pipe 2 should be reduced as much as we can.

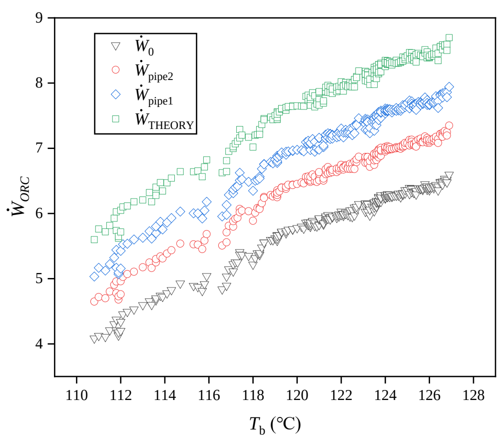

Fig. 3 Variation of the ORC system power output with increasing T_{b}.

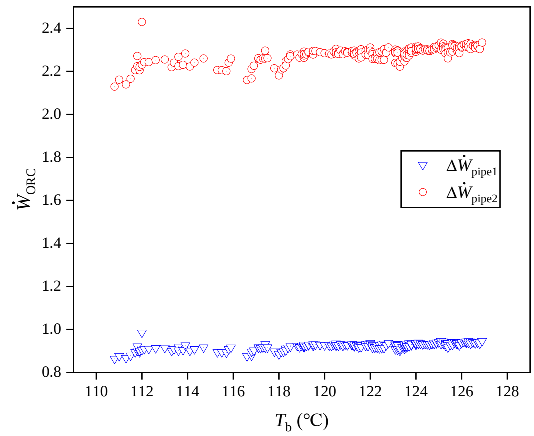

Fig. 4 Variation of the ORC system power output with increasing T_{b} under same pressure losses.

(2) The effect of pipeline pressure losses on ORC system thermal efficiency.

Fig. 5 presents the variation of η_{THEORY}、η_0、η_{pipe1} and η_{pipe2} with the increase of T_{b}. By comparing η_{THEORY} and η_0 in the Fig. 5, it can be concluded that the pressure loss of the pipeline could decrease the ORC system thermal efficiency significantly. With the increase of T_{b}, the gap between η_{THEORY} and η_0 is going down slowly. In other words, with the increasing T_{b}, the effect of pipeline pressure losses on ORC system thermal efficiency decreases. When T_{b} is 110.8 °C, the difference value between η_{THEORY} and η_0 reaches the maximum value of 2.42%. When T_{b} is 110.8 °C, the thermal efficiency losses caused by pipeline pressure losses accounted for the maximum 33.04% of η_{THEORY}. By comparing the difference between η_{THEORY} and η_{pipe1} with the difference between η_{THEORY} and η_{pipe2}, the effect of working fluid pressure losses of pipe 1 on ORC system efficiency is greater than that of pipe 2. Fig . 6 presents the results of the different effect of pipe 1 pressure losses and pipe 2 pressure losses on ORC system thermal efficiency with the same pressure losses value under the increasing T_{b}. It shows that $\Delta\eta_{\mathrm{pipe2}}$ is almost 2.47 times higher that $\Delta\eta_{\mathrm{pipe1}}$. In another words, with the same pressure losses, the effect of pipe 2 pressure losses on ORC system thermal efficiency is more obvious than that of pipe 1.

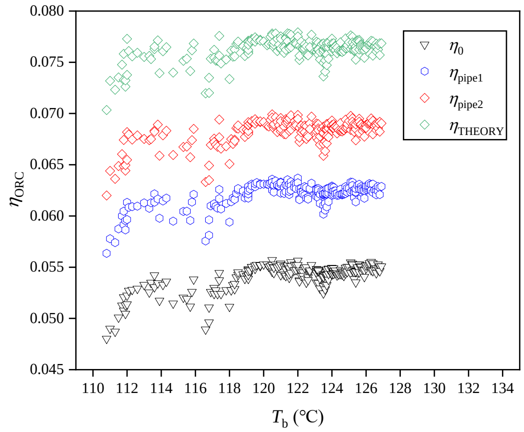

Fig. 5 Variation of the ORC system efficiency with increasing T_b.

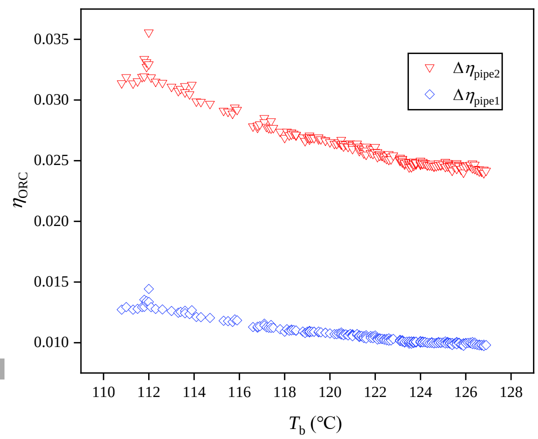

Fig. 6 Variation of the ORC system thermal efficiency with increasing T_b under same pressure losses.

4. CONCLUSION

In this work, the effect of pipeline pressure losses on ORC system performance is studied by experiment with the increase of inlet temperature of the expander. Based on the experimental conditions (T_b=110-127 °C, P_b=8.5-11.3 bar), the following conclusions are obtained.

(1) Pipeline pressure losses could reduce ORC system power output significantly. Mostly, the actual ORC system power output is 27.04% lower than the theoretical value. Pipeline pressure losses will also reduce the thermal efficiency of ORC system significantly. Mostly, the actual ORC system thermal efficiency is 33.04% lower than the theoretical value. Therefore, to improve the ORC system performance, the pipeline pressure should not be neglected.

(2) The pressure losses of pipeline connecting evaporator and expander has a greater impact on the power output and thermal efficiency of the ORC system than that of the pipeline connecting expander and condenser.

(3) The pressure losses of pipeline connecting expander and condenser has a greater impact on the power output and thermal efficiency of the ORC system than that of the pipeline connecting evaporator and expander with same pressure losses value. The pressure losses of pipeline connecting expander and condenser should be paid more attention.

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