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Experimental investigation on an ORC twin-screw expander with an emphasis on its suction process

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ABSTRACT

Organic Rankine Cycle (ORC) is an effective and promising technology to recover low-grade waste heat and output electricity. As a key component in an ORC system, the expander's performance significantly affects the whole system's efficiency. Twin-screw expander is widely employed for its compact structure, reliability, two-phase tolerance and high efficiency. To investigate the characteristics of twin-screw expander, a test bench was set up in a laboratory. R245fa was selected as the working fluid. Pressure sensors with high sensitivity and accuracy were installed at appropriate locations in the expander casing to monitor the p - V indicator diagrams. The expander's p - V indicator diagrams and operating parameters were recorded under different operating conditions. The effects of rotational speed, suction and discharge pressure on the expander's suction pressure drop and filling factor were studied in this paper. The suction pressure drop is as large as 54.5 kPa, which is 12.3% of the suction pressure at 1500 RPM. And the filling factor is 0.939. Results show that rotational speed and suction pressure affect the suction pressure drop altogether. As rotational speed increases, suction pressure drop increases almost linearly and filling factor decreases. Meanwhile, higher suction pressure leads to large suction pressure drop and lower filling factor. However, discharge pressure has little effect on suction process.

Keywords: ORC; Twin-screw expander; p - V indicator diagram; suction pressure drop; filling factor

1. INTRODUCTION

All over the world, waste heat is produced during all kinds of energy processes, bringing out heat pollution problems and energy losses. According to literature (Forman, Muritala, Pardemann, & Meyer, 2016), about 72% of the global consumed primary energy is lost. And most of them are exhausted as waste heat, among which 63% is low grade and the temperature is below 100°C. Under that circumstance, efficient waste heat recovery technology is in urgent demand. Organic Rankine Cycle (ORC) has shown great energy-saving potential and drawn much attention in low grade waste heat recovery applications (Imran, Haglind, Asim, & Zeb Alvi, 2018).

Plenty of research work have been performed on ORC systems. Chintala et.al (Chintala, Kumar, & Pandey, 2018) reviewed ORC applied in compression ignition engines waste heat recovery. The maximum thermal efficiency of engine-ORC systems can reach about 10%-25%. It also indicated that R245fa is the better working fluid for engine-ORC application for better performance, availability, economic and environmental aspects. Murgia et.al (Murgia, Valenti, Colletta, Costanzo, & Contaldi, 2017) experimentally studied an ORC system recovering waste heat from hot oil in air compressor. Tang (Tang, Wu, Wang, & Xing, 2015) investigated the performance of twin-screw expander applied in geothermal ORC power generator. It was claimed that the onsite ORC system's efficiency can reach 7.5%.

In an ORC system, the expander's performance has a significant influence on the whole system efficiency. Xiaochen Hou et.al (Hou et al., 2018) investigated the effect of external load resistance on the free piston expander-linear generator for ORC waste heat recovery systems. Guoqiang Li et.al (Li et al., 2018) performed an experimental research on the performance of high pressure single screw expander under varied inlet pressure and rotational speed. The volumetric efficiency and isentropic efficiency are 80.57% and 60.55% respectively. It was conclude that high rotational speed is effective to reduce expander leakage in large pressure difference operating conditions.

Screw expander stands out for its high efficiency and good performance under varying operating conditions, low requirement for working fluid, and high reliability (Pantano & Capata, 2017). In literature (Bianchi et al., 2018), a model for two-phase screw expander for trilateral flash cycle allocation is proposed. Tian (Tian, Xing, He, & Wu, 2017) also proposed a thermodynamic model to simulate the performance of twin-screw steam expander. The expander isentropic efficiency is estimated to be about 83%. Little work was found to investigate the experimental characteristics of twin-screw expander used in ORC waste heat recovery applications.

As known, an expander's volume flow rate is related to its suction process. Varying suction operating conditions result in different expander performance (Papes, Degroote, & Vierendeels, 2015). According to Tang (Tang et al., 2015), suction pressure drop is mainly caused by throttling loss when the working fluid flows into the expansion chamber through the small suction port. Papes et al. (Papes, Degroote, & Vierendeels, 2016) developed a numerical model to simulate the pulsations in twin-screw expander inlet pipelines. Through 3D CFD simulation, flow coefficient was obtained. The maximum deviation between the proposed model and CFD calculation is around 5% for the mass flow rate and output power of the twin-screw expander.

To investigate the effects of operating conditions on suction process and expander performance, an experimental test bench was set up in our laboratory. Pressure sensors with high sensitivity and accuracy were installed at appropriate locations in the expander casing to monitor the p - V indicator diagrams. The expander's p - V indicator diagrams and operating parameters were recorded under different operating conditions. The effects of rotational speed, suction pressure and discharge pressure on the expander's suction performance were studied in this paper, including suction pressure drop and filling factor.

2. EXPERIMENTAL SET-UP

2.1 ORC system test bench

The investigated twin-screw expander is tested in a complete ORC system, whose overall layout is shown in Figure 1. Two commercial electric water heaters were used to provide hot water as the heat source. Hot water was then pumped into the evaporator and released heat for the working fluid cycle. The working fluid absorbed the energy provided by hot water and flows into the twin-screw expander. The expanded vapor then cooled and condensed by cool water from a cooling tower. The working fluid pump then provides pressure needed for completing the cycle. R245fa is selected as working fluid in this system. The marker "T" represents a temperature measurement point, while the marker "P" represents a pressure measurement point. Also a Coriolis flow meter is used to measure the mass flow rate of the working fluid R245fa, marked as "F". All these elements are well integrated into a system shown in Fig. 2.

The system's operation conditions are listed in Table 1. Hot water from the electrical heaters is 60-80°C. And the nominal capacity of the ORC system is 7 kW. The rotational speed of the expander is designed at 1500 RPM. The built-in volume ratio is 2.3. According to the temperature of heat source, the evaporating pressure varies from 330-470kPa.

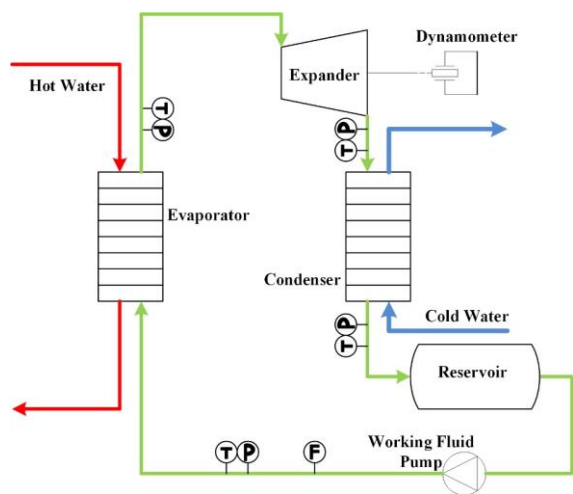


Figure 1 Overall layout of the ORC system test rig



Figure 2 Photograph of the ORC system test rig

Table 1 Operating conditions

Parameter	Value
ORC system designed capacity, kW	7
Hot water temperature, °C	60-80
Evaporation pressure of the working fluid, kPa	330-470
Evaporation temperature of the working fluid, °C	65 – 78.4
Condensation pressure of the working fluid, kPa	140
Designed speed of the expander, rpm	1500
Designed volume ratio of the expander	2.3

2.2 Recording p - V indicator diagram

The twin-screw expander is adapted from an open-drive refrigeration compressor. The flow direction is reversed as well as the rotational direction. Inner valves and filter are rearranged to fit for such change. The basic geometrical properties are listed in Table 2.

Table 2 Geometry parameters of the screw-expander

Parameter	Value
Length of the rotors, mm	140
Volume ratio of discharge port, V_i	2.3
Center distance between the male and female rotors, mm	108
Outer diameter of the male rotor, mm	143
Outer diameter of the female rotor, mm	123
Lobes of the male rotor	5
Lobes of the female rotor	7

Several Kulite pressure sensors are selected to record a twin-screw expander's indicator diagram. They are embedded in the case of expander and each sensor can record one section of the indicator diagram. The arrangement of pressure sensors depend on the variation of the working chamber volume with the rotating angle of the male rotor in the studied twin-screw expander, as is shown in Figure 3. Each sensor can record pressure data in 72° range because the studied expander's male rotor has 5 lobes. Four suction sensors should be installed with positions expressed as angle in Figure 3. Due to structural limitation, the initial suction stage's data is missing, only the final stage of the suction process is recorded.

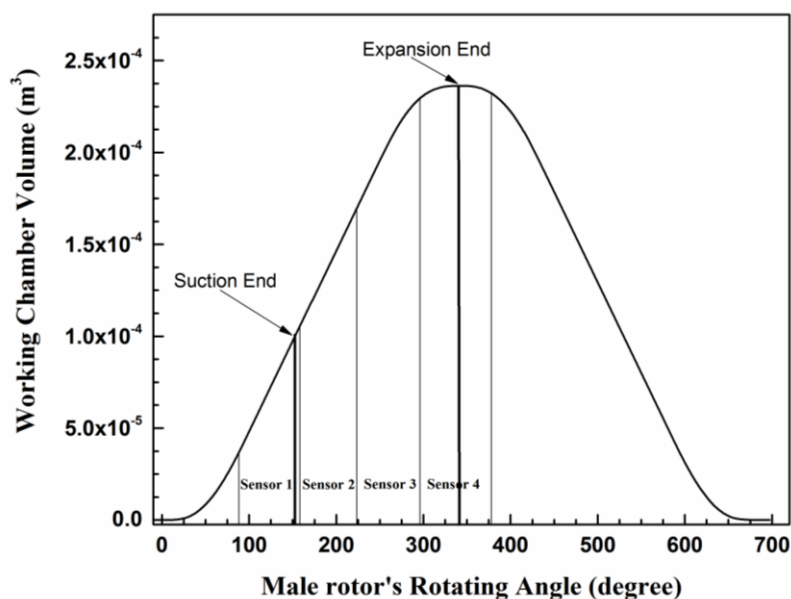


Figure 3 Arrangement of pressure sensors

2.3 Performance Parameters

The performance parameters can be calculated from the measured pressures, temperatures, flow rates and the power consumptions. The suction pressure drop is defined as the pressure drop at the suction end point and it can be calculated as follows:

$$\Delta p = p_s - p_{s_{\text{suc_end}}} \quad (1)$$

The filling factor represents the performance of suction process and is defines as the ratio of mass flow rate in the suction end point and mass flow rate in isentropic process.

$$\text{Filling factor} = \frac{m_{\text{suc_end}}}{m_{\text{iso}}} \quad (2)$$

In the above equations, p_s is suction pressure and m is mass flow rate. Subscript 'iso' is isentropic process and 'suc_end' is suction end point.

3. RESULTS AND DISCUSSION

3.1 Effect of rotational speed

Rotational speed is an important operating parameter of the expander. To better design and optimize the expander, it's essential to study the effect of rotational speed on the expander performance, especially the suction process.

Figure 4 shows p - V indicator diagrams in suction process under different rotational speed. The suction and discharge pressure is 442.4 kPa and 200.4 kPa, respectively. The grey dash line stands for the isentropic process, during which there is no pressure loss in the suction process. The green line, yellow and red line represents different suction process at different rotational speed. That is 1400 RPM, 1500 RPM and 1600 RPM respectively. From Figure 4, it can be seen that there is suction pressure drop in the real suction process, which cannot be neglected. Such pressure drop in the suction process will definitely result in lower mass flow rate and lower volumetric efficiency of the expander.

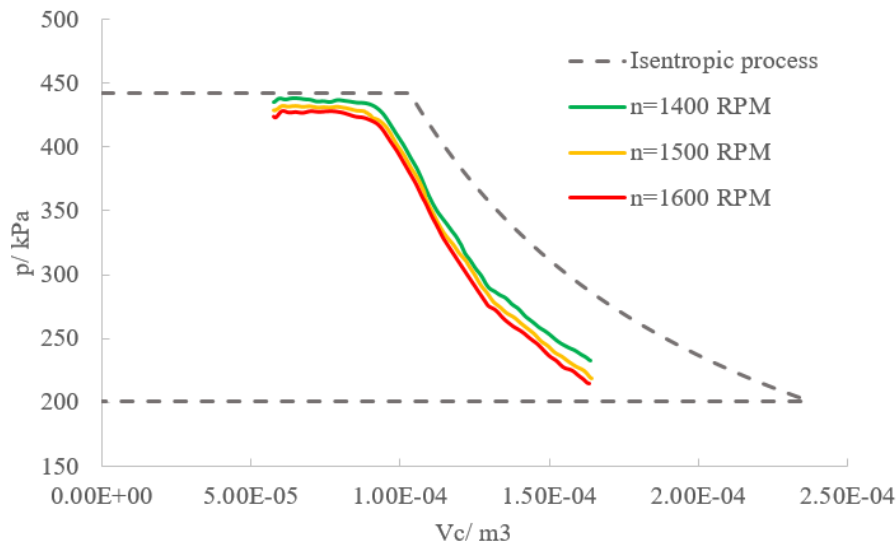
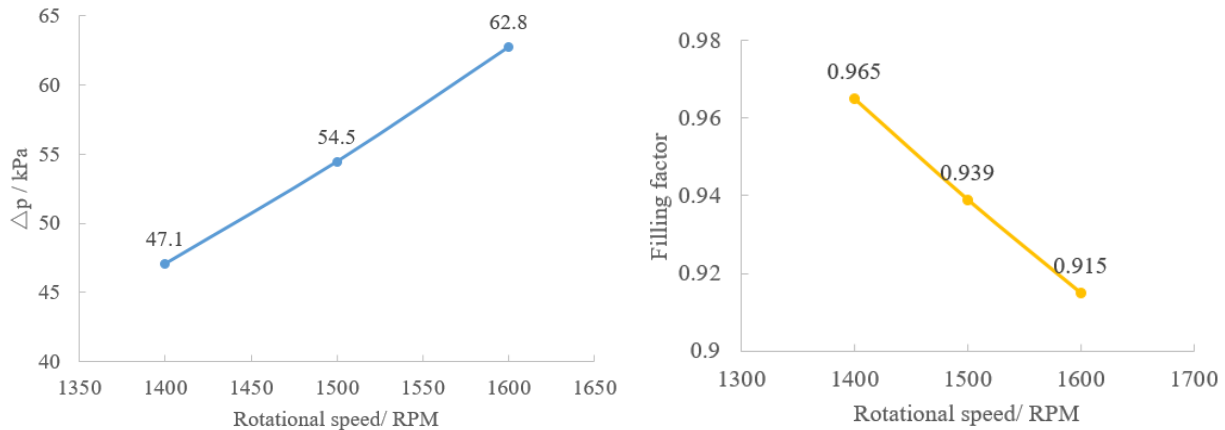


Figure 4 p - V indicator diagrams in suction process under different rotational speed

From the measured p - V indicator diagrams in suction process, the suction pressure drop and filling factor can be calculated via the measured data. Figure 5 illustrates the effects of rotational speed on suction pressure drop and filling factor. In Figure 5 (a), suction pressure drop increases almost linearly with rotational speed. When the rotational speed increases from 1400 RPM to 1600 RPM, the suction pressure drop increases 15.7 kPa from 47.1 kPa to 62.8 kPa. The suction pressure drop is as large as 54.5 kPa, which is 12.3% of the suction pressure at 1500 RPM. Larger suction pressure drop leads to lower density of the sucked gas, lower mass flow rate and filling factor. At 1500 RPM, the filling factor is 0.939. That means nearly six percent of expander mass flow rate is reduced in the

suction process. As shown in Figure 5 (b), filling factor decreases linearly with rotational speed. As the rotational speed increases from 1400 RPM to 1600 RPM, the filling factor decreases from 0.965 to 0.915.



(a) Suction pressure drop versus rotational speed

(b) Filling factor versus rotational speed

Figure 5 Effects of rotational speed on suction pressure drop and filling factor

3.2 Effect of suction pressure

In an ORC system, the evaporating temperature is decided by the temperature of heat source. Thus the suction pressure is affected by the heat source, which might be varying all the time. Suction pressure is another important operating parameter of the expander. Knowing the influence of suction pressure on expander performance is a prerequisite for the performance optimization of expander.

Figure 6 shows p - V indicator diagrams in suction process under different suction pressure. The rotational speed and discharge pressure is 1600 RPM and 220.4 kPa, respectively. The green line, yellow and red line represents different suction process at different suction pressure, 497.4 kPa, 471.4 kPa and 442.4 kPa respectively. Effects of suction pressure on suction pressure drop and filling factor are shown in Figure 7. Higher suction pressure leads to large suction pressure drop and lower filling factor. As the suction pressure rises from 442 kPa to 497 kPa, suction pressure drop increases from 52.8 kPa to 55.8 kPa, while filling factor decreases from 0.915 to 0.905.

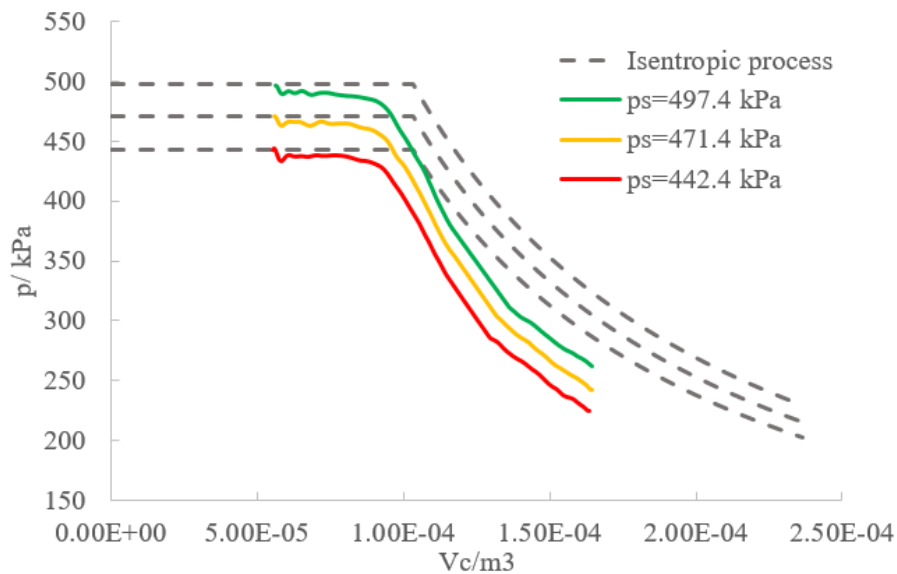
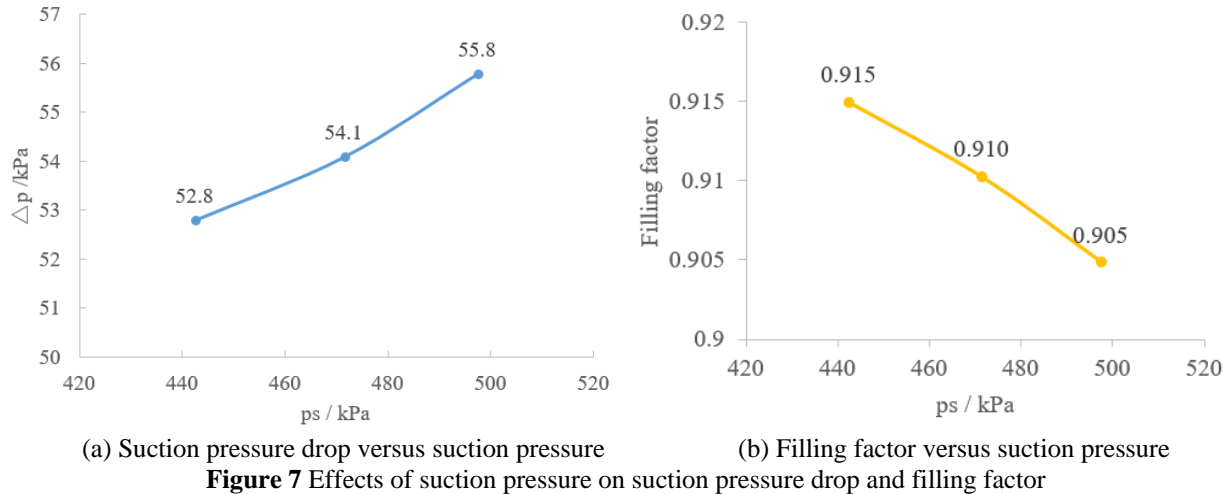


Figure 6 p - V indicator diagrams in suction process under different suction pressure



3.3 Effect of discharge pressure

In an ORC system, the condensing temperature is decided by the cooling system. As the ORC system operating condition is confirmed, the discharge pressure is set. In the following section, the effect of discharge pressure on expander suction process is studied.

Figure 8 shows p - V indicator diagrams in suction process under different discharge pressure. The rotational speed and suction pressure is 1400 RPM and 458.4 kPa, respectively. The green line, yellow and red line represents different suction process at different discharge pressure, 246.4 kPa, 231.4 kPa and 177.4 kPa respectively. Effects of discharge pressure on suction pressure drop and filling factor are shown in Figure 9. Both suction pressure drop and lower filling factor changes slightly with discharge pressure. At the selected operating condition, the suction pressure drop is about 50 kPa and filling factor is around 0.956.

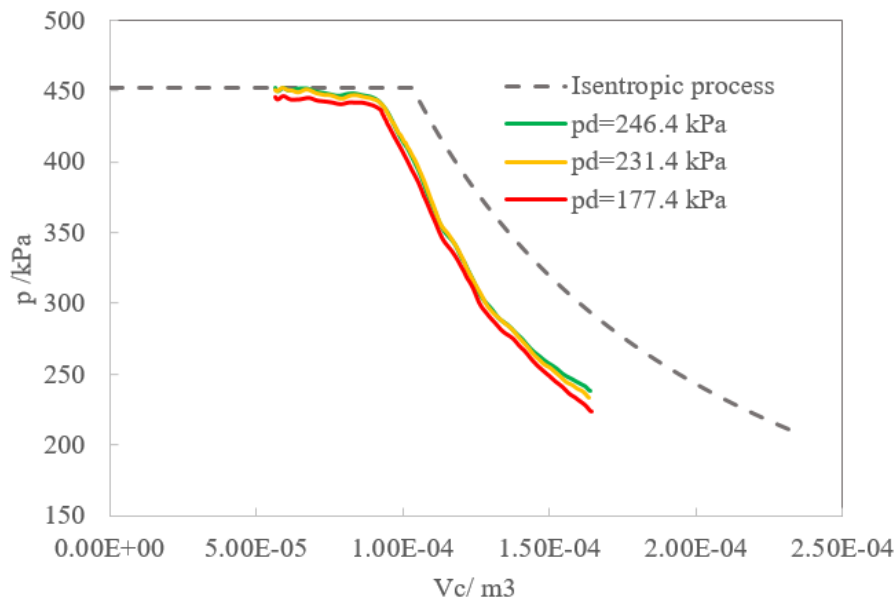


Figure 8 p - V indicator diagrams in suction process under different discharge pressure

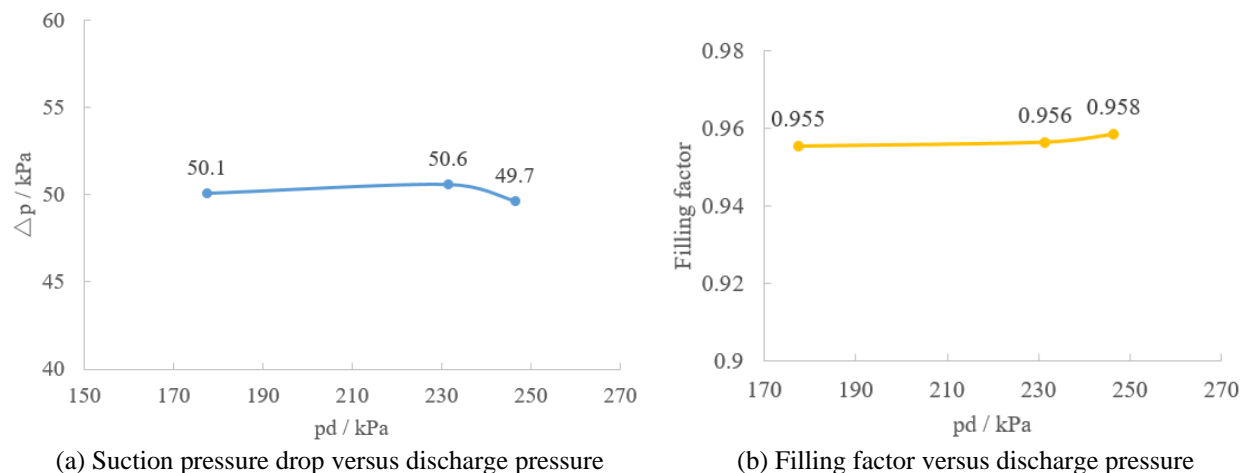


Figure 9 Effects of discharge pressure on suction pressure drop and filling factor

4. CONCLUSIONS

A comprehensive experimental investigation is carried out to evaluate the suction process characteristic of a twin-screw expander used in an ORC system under various conditions. The p - V indicator diagram is recorded to analyze the expander suction process. The effects of rotational speed, suction pressure and discharge pressure on the expander suction performance are evaluated. The following conclusions can be obtained from the discussion and analysis:

- The suction pressure drop is as large as 54.5 kPa, which is 12.3% of the suction pressure at 1500 RPM. And the filling factor is 0.939.
- Suction pressure drop increases almost linearly with rotational speed. Meanwhile filling factor decreases linearly with rotational speed.
- Higher suction pressure leads to large suction pressure drop and lower filling factor. As the suction pressure rises from 442 kPa to 497 kPa, suction pressure drop increases from 52.8 kPa to 55.8 kPa, while filling factor decreases from 0.915 to 0.905.
- Both suction pressure drop and lower filling factor changes slightly with discharge pressure.

NOMENCLATURE

V	volume	(m ³)
p	pressure	(kPa)
m	mass flow rate	(kg/s)
n	rotational speed	(RPM)
filling factor	filling factor	(-)

Subscript

c	expander
s	suction
iso	isentropic process
d	discharge
suc_end	suction end point

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