



1st International Conference on Energy and Power, ICEP2016, 14-16 December 2016, RMIT University, Melbourne, Australia

## Experimental investigation on the performance of a twin-screw expander used in an ORC system

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### Abstract

Organic Rankine Cycle (ORC) is an effective and promising technology to convert low-grade thermal energy to electricity. As a key component in an ORC system, the expander plays a significant role in energy conversion efficiency in the ORC system. In this paper, an ORC experimental system is developed to investigate the performance of a twin-screw expander under various working conditions. Pressure sensors with high sensitivity and accuracy are installed at appropriate locations in the expander casing to monitor the  $p$ - $V$  (pressure-volume) indicator diagrams which indicates the performance of the expander. The effect of the key parameters such as expander rotating speed, the suction pressure on the expander performance is studied using the experimental data. The results show that high expander rotating speed leads to large suction pressure loss, low volumetric and indicated efficiencies. As the rotating speed increases from 900 rpm to 1900 rpm, the volumetric efficiency decreases by up to 17.2% from 1.004 to 0.831 and the indicated efficiency reduces by up to 27.1% from 0.846 to 0.617. Furthermore, as the suction pressure increases from 550 kPa to 750 kPa the indicated efficiency rises up to a peak value of 0.815 and then falls. The volumetric efficiency does not show significant change as the suction pressure varies.

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Peer-review under responsibility of the organizing committee of the 1st International Conference on Energy and Power.

*Keywords:* Organic Rankine Cycle; Heat Recovery; Twin-screw Expander.

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## 1. Introduction

Due to energy crisis and worldwide environmental problems such as CO<sub>2</sub> emission and global warming, it is essential to improve energy utilization efficiency by generating useful power from low-grade heat sources, such as industrial waste heat, solar thermal and geothermal sources. Organic Rankine Cycle (ORC) is an effective technology to convert the low-grade thermal energy to effective power. This ORC technology has attracted extensive research interest as it is progressively adopted in the application of low-grade heat sources [1]. The ORC system uses organic working fluid instead of water in a traditional steam Rankine Cycle to cater for different temperature ranges and uses different types of expanders to fit various power capacities. Two main types of expanders are normally used in ORC systems: dynamic expanders [2-5] and volumetric expanders. As a main type of positive displacement type expander, twin-screw expanders are widely used in small-to-medium scale ORC units [6].

Much research work has been carried out to investigate the performance of the twin-screw expander in ORC systems. Tang et al. [7] studied the performance of a twin-screw expander and investigated the effect of expander speed and suction pressure. Subiantoro et al. [8] compared the performance of the four new revolving vane expanders. Results showed that some revolving vane expander performance is much better than others. Wang et al. [9] demonstrated that it was possible to apply the single screw technology in the expander field, which had good part load characteristics. Yang et al. [10] performed experimental investigation on the internal leakage of a rotary vane expander prototype to replace the throttling valve to improve the COP of the CO<sub>2</sub> refrigeration cycle.

The  $p$ - $V$  indicator diagram is often used by researchers to evaluate the performance of compressors and expanders. Wu et al. [11] investigated the effect of super-feed pressure with an economizer on the performance of a twin-screw refrigeration compressor experimentally by analysing the indicated diagrams. Wu et al. [12] further developed a theoretical model to illustrate the  $p$ - $V$  indicator diagrams and validated the model using experimental data. The results showed that the theoretical model could be used as a powerful tool to evaluate the performance of a twin-screw refrigeration compressor. However, only little research used the  $p$ - $V$  indicator diagrams to investigate the performance of different positive displacement type expanders. In this paper, the performance of the twin-screw expanders used in the ORC system is studied by using the  $p$ - $V$  indicator diagrams.

## 2. Experimental facilities

### 2.1. The ORC system test rig

Fig. 1(a) shows the schematic drawing of the twin-screw expander experimental system. It consists of a boiler, a twin-screw expander, a condenser, a reservoir, a pump and a lot of piping and valves. Hot water is pumped into the evaporator as heat source. R245fa is used as working fluid due to its safety, stability and high efficiency at a medium heat source temperature [13]. The working fluid R245fa absorbs energy from the hot water in the boiler and expands in the twin-screw expander. The expanded vapor is then cooled and condensed in the condenser by the cold water from a cooling tower. The working fluid pump pumps the condensate from the condenser to the boiler and then next cycle starts. The operating conditions of the ORC system are listed in Table 1.

Table 1. Operating conditions of the ORC system

Parameter	Value
Evaporation pressure of the working fluid, MPa	0.33~0.47
Evaporation temperature of the working fluid, °C	65~78.4
Condensation pressure of the working fluid, MPa	0.14
Designed rotational speed of the expander, rpm	1500
Designed volume ratio of the expander	2.3

Two plate types of heat exchangers provided by Danfoss are used as the boiler and condenser in the studied system due to their compact size and high heat transfer coefficient. The twin-screw expander is coupled with an eddy current dynamometer which provides load automatically. The eddy current dynamometer can be set to measure torque, rotational speed and output power of the twin-screw expander. The centrifugal type working fluid pump (GRUNDFOS,

CR 1-15) is used to control the flow rate by varying the frequency. Moreover, the system is well instrumented to monitor the ORC system operation conditions. 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’.

## 2.2. Monitoring of the $p$ - $V$ indicator diagrams

In order to investigate the characteristics of the twin-screw expander,  $p$ - $V$  indicator diagrams are measured. The key technique of monitoring the  $p$ - $V$  indicator diagram of the twin-screw expander is to install the pressure sensors at a proper location in the compression chamber. Several sensors are embedded in the casing of the expander. Each sensor records a range of compression process and has an overlap with the adjacent sensor [14].

In the studied twin-screw expander, the arrangement of pressure sensors depends on the variation of the working chamber with the rotating angle of the male rotor. Four sensors are installed with positions expressed as angle in Figure 1(b). Due to structural constraints, no pressure sensor is installed to monitor the initial suction stage. Only the final stage of the suction process is recorded.

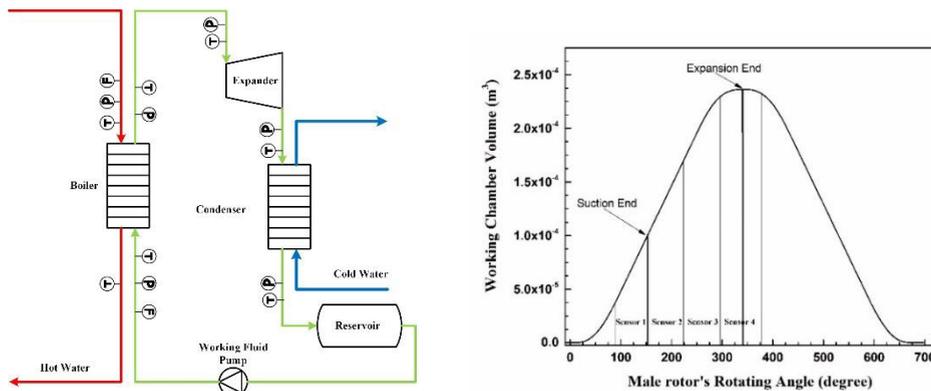


Fig. 1. (a) Schematic drawing of the ORC system test rig;

(b) Location of pressure sensors.

## 3. Experimental results and discussions

The influence of suction throttling loss and leakage on volumetric and indicated efficiency of the twin-screw expander is investigated using the experimental  $p$ - $V$  indicator diagram under different operating conditions. The effect of key parameters such as rotational speed and suction pressure on volumetric and indicated efficiency of the twin-screw expander is also studied experimentally.

### 3.1. The $p$ - $V$ indicator diagram of the twin-screw expander

Figure 2 shows experimental and theoretical  $p$ - $V$  indicator diagrams of twin-screw expander under the standard expansion process that the pressure ratio matches the designed internal volume ratio. The rotational speed, suction pressure and discharge pressure are 900 rpm, 658.2 kPa and 297.5 kPa respectively. Compared with the theoretical result, the experimental result shows that suction throttling loss  $\Delta p$  happened at the end of suction process. Suction throttling loss leads to low mass flow rate, which results in low volumetric efficiency. Meanwhile, output power decreases by suction throttling loss. Low indicated work leads to low indicated efficiency. Therefore, suction throttling loss at the end of suction process has effects on the performance of twin-screw expander.

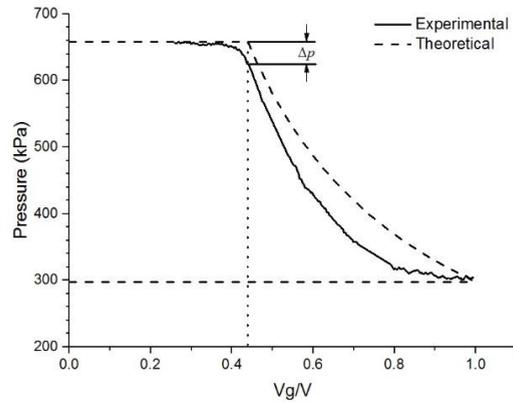


Fig. 2. The  $p$ - $V$  indicator diagram under the standard expansion process

### 3.2. The effect of rotational speed on the twin-screw expander performance

In the experiment, the suction chamber pressure and the discharge chamber pressure are remained at 658 kPa and 290 kPa, respectively. The suction process is at saturated vapor state, and suction temperature and condense temperature are 72.9°C and 44°C, respectively.

Figure 3(a) shows the effect of the rotational speed on the volumetric efficiency. As the rotational speed increases from 900 rpm to 1900 rpm, the volumetric efficiency decreases from 1.004 to 0.831. This is mainly due to the friction loss and throttling loss during the suction process. The experimental results show that the suction pressure loss increases from 26.5 kPa to 89.7 kPa due to the friction as the rotational speed increases from 900 rpm to 1900 rpm. In addition, the throttling loss of the gas also increases as the gas flows through the suction chamber. Although the leakage decreases at the high rotational speed, the effect increase in the friction loss and throttling loss are much larger than the decrease in the leakage. Therefore, the net effect of the rotational speed on the volumetric efficiency is negative in the expander.

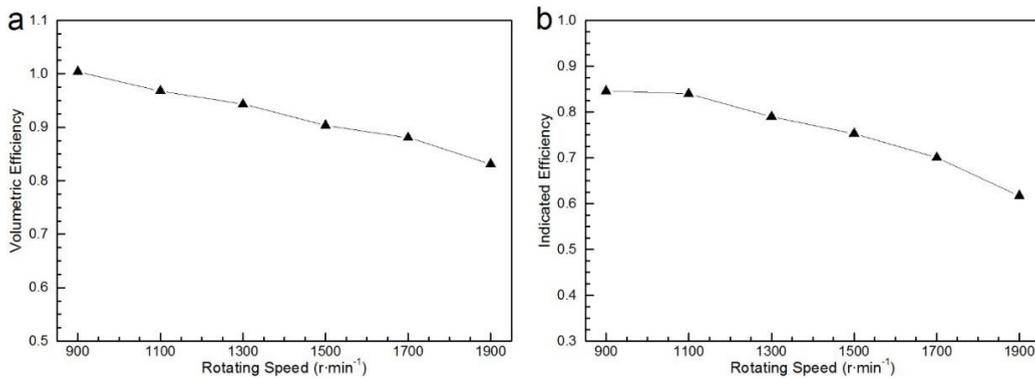


Fig. 3. (a) volumetric efficiency varying with rotational speed; (b) indicated efficiency varying with rotational speed.

Figure 3(b) shows the effect of rotational speed on the indicated efficiency. As the rotational speed increases from 900 rpm to 1900 rpm, the indicated efficiency decreases by up to 27.1% from 0.846 to 0.617. This decrease is also mainly caused by the friction loss and throttling loss at the suction. Comparing with Figure 3(a), the indicated efficiency drops much faster than the volumetric efficiency. This can be explained by the effect of rotational speed on the leakage in the working chamber. As the rotational speed of the expander increases, the leakage in the expansion

chamber decreases which improves the volumetric efficiency. However, the decrease in leakage has insignificant effect on the indicated efficiency which is mainly caused by the throttling and friction losses.

### 3.3. The effect of suction pressure on the twin-screw expander performance

Figure 4 shows the effect of the suction pressure on the expander performance. The rotational speed is maintained at 1100 rpm. The discharge pressure is 290 kPa. The designed suction chamber pressure is 658 kPa which matches the designed internal volume ratio of the twin-screw expander. Increasing or decreasing the suction pressure will cause the expander under-expansion or over-expansion. As shown in Figure 4(a), the volumetric efficiency does not show significant change as the suction pressure increases from 550 kPa to 750 kPa. As the suction pressure increases, the suction volume increases. However, the increase in suction volume is offset by the suction pressure loss and increase in leakage in the working chamber. In the experiment, it was found that the suction pressure loss increases by 32.5% from 31.1 kPa to 41.2 kPa as the suction pressure increases from 550 kPa to 750 kPa. Meanwhile, the leakage also increases in the working chamber due to the high pressure difference. Therefore, the volumetric efficiency remains almost constant as the suction pressure increases.

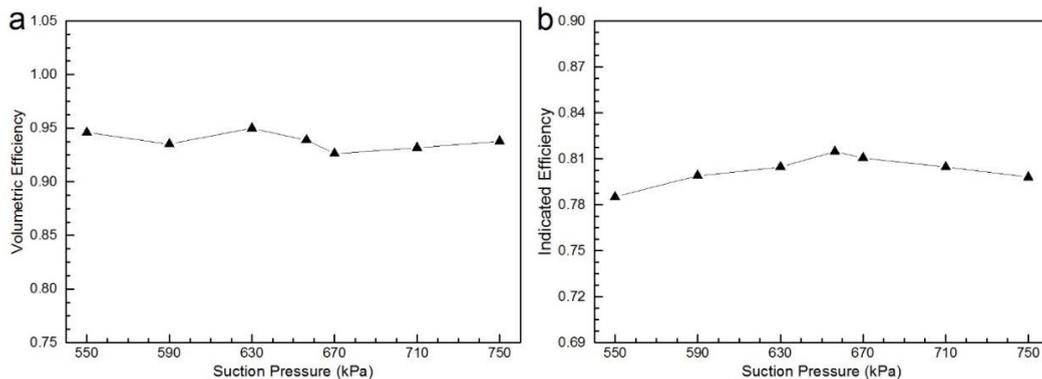


Fig. 4. (a) volumetric efficiency varying with suction pressure; (b) indicated efficiency varying with suction pressure.

Figure 4(b) shows the change of the indicated efficiency under different suction pressures. It is found that there exists an optimal suction pressure. This optimal suction pressure is the same as the designed suction pressure which is associated with the designed internal volume ratio of the expander. When the suction pressure is apart from this designed suction pressure, the expander will under either over-expansion or under-expansion process. Both over- or under-expansion causes the energy loss which leads to decrease in indicated efficiency. As the suction pressure decreases from 658 kPa to 550 kPa, the indicated efficiency drops from 0.849 to 0.784 due to the over-expansion. As the suction pressure increases from 658 kPa to 750 kPa, the indicated efficiency drops from 0.849 to 0.789. This indicates that the energy loss caused by over-expansion is higher than that cause by under-expansion. Furthermore, in the whole experimental suction pressure range, the indicated efficiency of the expander is always higher than 0.78. This stable high indicated efficiency indicates that the twin-screw expander is very promising in the application in the ORC power system.

## 4. Conclusions

In this paper, the performance of a twin-screw expander used in an ORC system is experimentally studied. The effect of key parameters such as rotational speed and suction pressure on the performance of the twin-screw expander is investigated. Some conclusions were drawn as detailed below:

- When the internal volume ratio of the twin-screw expander matches pressure ratio well. Suction throttling loss at the end of suction process has effect on the performance of twin-screw expander.

- The expander rotational speed shows large effect on both volumetric and indicated efficiency. As the rotational speed increases from 900 rpm to 1900 rpm, the volumetric efficiency and indicated efficiency decreases by 17.2% and 27.1%. The effect of rotational speed on the indicated efficiency is greater than volumetric efficiency due to the leakage in the working chamber.
- The suction pressure is found to have insignificant effect on the volumetric efficiency while it has huge effect on the indicated efficiency. The variation of suction pressure leads to either under-expansion or over-expansion. Both have led to the decrease in indicated efficiency.

## Acknowledgements

The authors would like to acknowledge the financial support from the National Science Foundation of China (Grant No.51276134).

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