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Article

Improvement and Experimental Study of Scroll Expander for Organic Rankine Cycle

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Abstract: The scroll expander used in organic Rankine cycle (ORC) system is improved, and its performance is analyzed experimentally. The modified profile and inlet hole of the scroll expander are enhanced, and the performance of the scroll expander before and after the improvement is analyzed. The results show that when the inlet pressure exceeds 0.7 MPa, the waist-shaped hole with a larger area is preferable. The scroll expander with a waist-shaped hole has a larger output power and wider optimal pressure range, and when the inlet pressure is 1.6 MPa, the maximum output power increases by 230 W. The output power and isentropic efficiency of the scroll expander can be improved by modifying the profile. When the inlet pressure is 1.6 MPa and the rotational speed is 1750 r/min, the maximum output power of the scroll expander is 1235 W, which is 120 W higher than that before the improvement.

Keywords: Scroll expander; organic Rankine cycle; improvement; performance analysis

Nomenclature

h:	enthalpy, kJ kg^{-1}
S:	inlet hole area, mm^2
W:	output power, W
P:	pressure, MPa
N:	torque, N·m
n:	rotational speed, r/min
A:	symmetrical arc and straight-line modification
B:	symmetrical arc modification
η:	isentropic efficiency

Subscripts

s:	isentropic process
loss:	loss
e:	evaporation process

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in: inlet
out: outlet

1 Introduction

The utilization of crude energy results in less efficient energy use, as low-grade energy cannot be fully utilized. During the process of energy utilization, thermal energy is the most widely used form of energy in human production activities. However, in conventional thermal energy utilization, approximately 50% energy is wasted, and approximately 67% energy is directly discharged in industrial production, most of which is low-grade thermal energy [1,2]. Consequently, there is an urgent need to improve energy utilization efficiency. Organic Rankine cycle (ORC) is a Rankine cycle that utilizes organic fluid instead of water as the working medium [3]. Due to the low boiling point of organic fluid, the fluid can be used to recover low-temperature waste heat, converting low-grade waste heat into electricity for a broader range of use without consuming other fossil fuels. Therefore, the application of ORC in power generation systems is an effective way of enhancing energy efficiency and reducing environmental pollution.

In ORC power generation systems, the expander is the core component. Generally, expanders are classified into two types: velocity-type and volume-type. The velocity-type expander converts the kinetic energy of the fluid into shaft work, such as the turbine expander, whereas the volume-type expander uses the pressure difference generated during fluid expansion to do work, such as the scroll and screw expanders [4–6]. The volume expander is mainly used in ORC small power generation systems. The scroll expander has the advantages of low rotational speed, large pressure ratio, and few moving parts, particularly suitable for small (power < 10 kW) low-temperature waste heat recovery systems. For example, Yanagisawa et al. [7] studied the performance of an oil-free scroll expander with compressed air as the working fluid. In their study, the scroll expander was converted from an oil-free scroll air compressor with a rated power of 2.4 kW. The experimental results showed that the maximum volumetric efficiency of the expander was 76%, and the maximum adiabatic efficiency was 60% at 2500 r/min and 0.65 MPa. They reported that the most significant factor that affects the efficiency of the scroll expander is the friction mechanical loss between the dynamic and static scroll disks.

Song et al. [8] carried out three-dimensional computational fluid dynamics (CFD) simulation on the effect of different inlet positions on a scroll expander used in a small ORC system. The distribution of asymmetric flow field in the cavity of the crescent cavity, the transient change of the effective area of the entrance, and the torque of each segment of the scroll disk were analyzed. Zhang et al. [9] investigated the effect of different geometric parameters on the average mass flow rate, average output power, and efficiency of scroll expanders through experiments and simulations. It was found that when the clearance size of the scroll expander increased from 0.005 mm to 0.1 mm, the mass flow rate increased by 65 kg/h, while the isentropic efficiency decreased from 80% to 50%. Garg et al. [10] developed a general framework for the most efficient geometric model of scroll expanders used in an ORC system by calculating the leakage loss, inlet pressure drop loss, and mechanical loss. They found that the scroll expander has a distinct height or aspect ratio under a fixed operating condition, which maximizes its isentropic efficiency. Chu et al. [11] improved the performance of a scroll expander by modifying the combined profile and adjusting the inlet area. The experimental results showed that the total efficiency of the prototype reached up to 53%, and the maximum output power increased by 360 W.

The scroll expander is mostly refitted from the scroll compressor. At the opening of the structure of the scroll, the profile modification (such as PMP profile modification, symmetrical arc modification, and symmetrical-arc and straight-line modification) is adopted in this study. For the compressor, these modifications can cause the dynamic and static scroll disks to be fully meshed, increase the compression ratio of the compressor, and reduce the clearance volume [12]. However, for the expander, these modifications can cause the dynamic scroll disk to periodically block the inlet hole and increase the inlet resistance, thus reducing the energy conversion efficiency. Based on previous studies, the modified profile and inlet hole of the scroll expander are improved, and the inlet hole is not blocked [13–17]. The performance of the scroll expander before and after the improvement is compared experimentally.

2 Design and Improvement of Scroll Expander

Based on the 1.2 kW output power of the scroll expander and the gas parameters of the inlet and outlet under the rated working condition, the scroll expander is improved. The positions of the dynamic and static scroll disks and the inlet hole are shown in Fig. 1. During the process of revolution and translational motion, the end of the dynamic scroll disk periodically blocks the inlet hole. The static and dynamic scroll disks engage in a fixed eccentricity with a phase difference of 180°. The gas entering through the inlet hole expands in the crescent-shaped gap formed by the dynamic and static scroll disks, pushing the dynamic scroll disk to cause revolution and translational motion. The dynamic scroll disk transfers this movement through the eccentric axis and output power. Thus, the inlet hole is not covered by the dynamic scroll disk, and the inlet resistance is reduced.

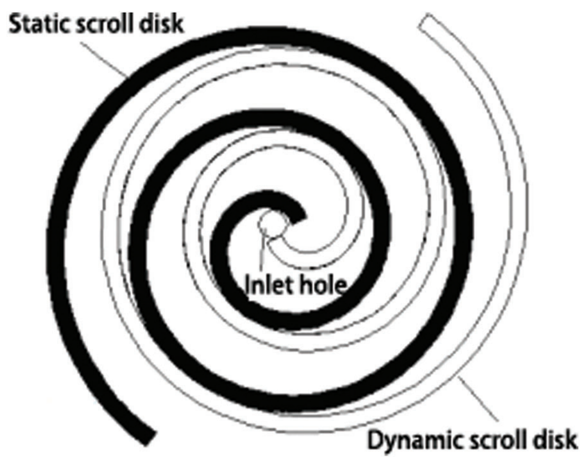


Figure 1: Positions of the dynamic and static scroll disks and the inlet hole

The profile of the dynamic scroll disk is directly truncated and modified, as shown in Fig. 2. Compared with the traditional method, the volume of the first expansion chamber is increased by pushing the initial expansion angle backward [18–20]. The parameters of the two modification methods are shown in Tab. 1.

The circular inlet hole of the static scroll disk was milled into a waist-shaped hole with an area changed from 77.56 to 108.58 mm^2, as shown in Fig. 3. According to the thermodynamic model and the literature, when the inlet pressure changes, the output power and isentropic efficiency of the scroll expander with the waist-shaped inlet hole are more stable and have a broader optimal pressure range [21,22]. When the inlet pressure is high, the larger inlet flow area can effectively reduce the gas flow resistance and increase the air inlet volume. The effect of reducing the resistance and increasing the flow is more significant when the pressure reaches a certain value, thus increasing the output power.

3 Performance Experiment System

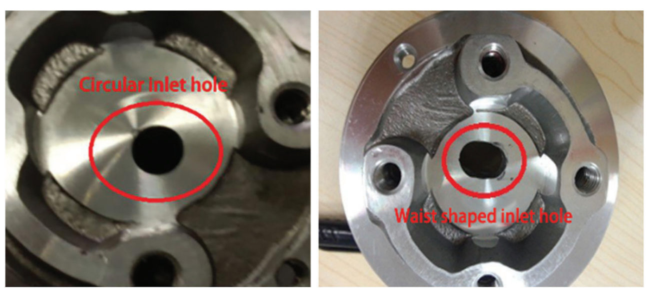
The performance experiment system of the scroll expander is depicted in Fig. 4. The system is composed of a nitrogen supply device, pressure sensor, temperature sensor, scroll expander, alternator, electrical power meter, laser tachometer, and adjustable load. The scroll expander was connected with the alternator through the aluminum alloy plum blossom coupling to form the energy conversion component of the experimental system.

a b

Figure 2: Modifications of the end profile of the dynamic scroll disk. a) Symmetrical-arc and straight-line modification. b) Symmetric arc modification

Table 1: Modification parameters of the profile

Parameters	Symmetrical arc modification	Symmetric-arc and straight-line modification
Modification angle β	67.37°	117.23°
Connection radius R	6.32 mm	6.67 mm
Modified arc radius r	2.06 mm	2.41 mm
Connection line length L	0 mm	7.52 mm



a b

Figure 3: Improvement of the inlet hole of the static scroll disk. a) Circular inlet hole. b) Waist-shaped inlet hole

During the experiment, sufficient gas reserves and stable pressure were required. The gas supply device adopted in the experiment was composed of a 30 m^3 liquid nitrogen storage tank, gas self-pressurizing system, carburetor, pressure regulating valve, and flow control valve. Under the action of the self-pressurizing system, liquid nitrogen continuously flowed into the carburetor to vaporize the nitrogen at 2.5 MPa, and then after decompression, entered the scroll expander through the pressure regulating valve.

4 Experimental Results and Analysis

To investigate and compare the performance of the scroll expander before and after improvement, the performance test process and purposes are as follows:

1. By changing the inlet pressure with the pressure reducing valve, the curve of the output power and efficiency of the scroll expander is obtained. The effect of the inlet pressure on output power and efficiency of the scroll expander is analyzed.

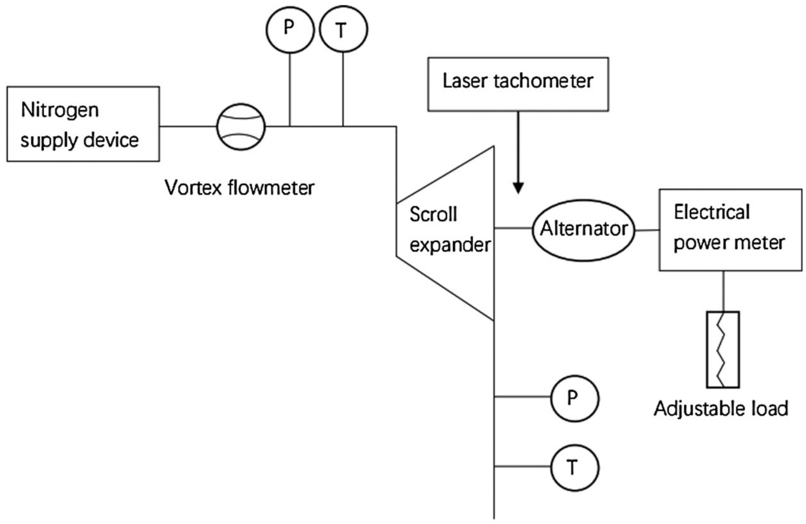


Figure 4: Performance test system of the scroll expander

2. The rotational speed and output power of the scroll expander are obtained by varying the inlet flow rate through the flow control valve, and the effect of the inlet flow rate on the performance of the expander is analyzed.
3. By adjusting the load to control the rotational speed, the performance curve of the scroll expander is obtained when the speed changes, and the optimum speed under different inlet pressures are determined.
4. By comparing the performance differences of two different inlet holes of the scroll expander using the same parameters under the same conditions, the effects of inlet area and hole shapes on the output power and efficiency of the scroll expander are determined.
5. Under the conditions of the same inlet parameters, the effects of different profile modifications on the performance of the scroll expander are compared and analyzed.

The output power and isentropic efficiency are the objective functions to be determined from the experiment, and the mechanical loss mainly includes the bearing loss and the friction loss between dynamic and static scroll disks [23]. The torque loss can be calculated as follows.

$$W = W_{in} - W_{loss} = W_{in} - 2\pi n N_{loss} \tag{1}$$

In analyzing the performance of the scroll expander, it is assumed that the expansion process in the scroll expander is a reversible adiabatic process, also called isentropic process.

The experimental analysis is carried out based on the isentropic efficiency of the scroll expander, which can be calculated using Eq. (2) [24].

$$\eta = \frac{h_1 - h_2}{h_1 - h_{2s}} \tag{2}$$

4.1 Effect of Different Inlet Holes

The shape and area of the inlet hole affects the output power and isentropic efficiency of the scroll expander. The circular inlet hole of scroll compressor was modified to a waist-shaped hole, and the area was changed from 77.56 to 108.58 mm^2. Experiments were performed on the scroll expander before and after improvement. When the load is constant, the inlet pressure gradually increases from 0.3 to 1.6 MPa, and the output power and isentropic efficiency are obtained, as displayed in Figs. 5 and 6. Fig. 5 shows

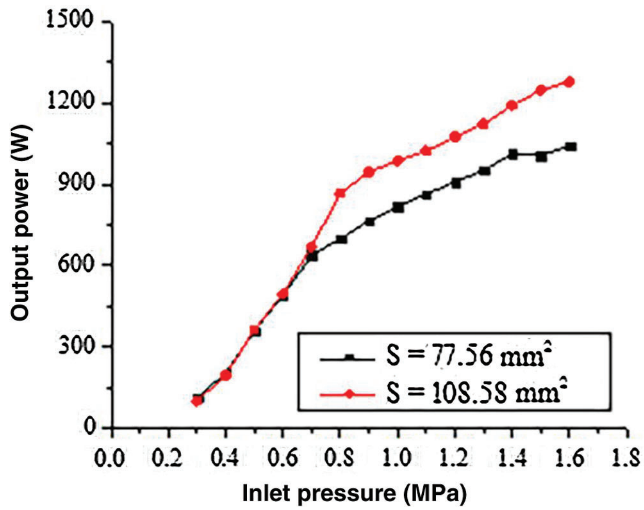


Figure 5: Output power of the scroll expander with different inlet shapes

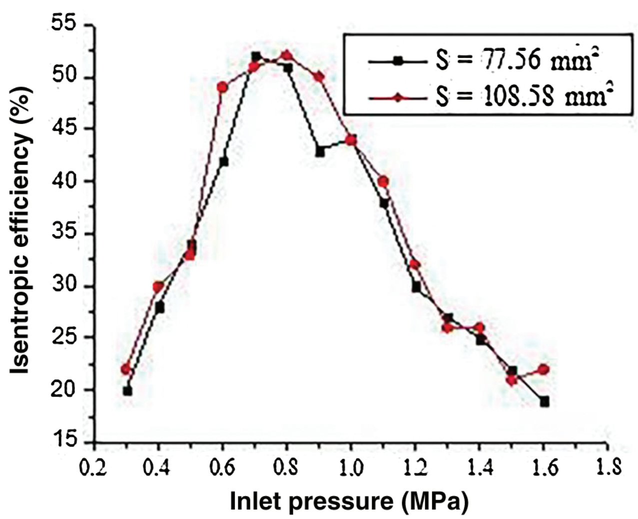


Figure 6: Isentropic efficiency of the scroll expander with different inlet shapes

the variation curves of the output power of the scroll expander with the inlet pressure. By comparing the two curves, the output power of the scroll expander with the waist-shaped hole exceeds that of the circular hole after 0.7 MPa. When the inlet pressure is 1.6 Mpa, the maximum output power of the expander reaches 1260 w and increases 230 W at the same flow rate. When the inlet pressure is less than 0.7 MPa, the output power values of the expander with different hole shapes are the same. Therefore, in the design of a scroll expander, it is unnecessary to select the complex waist-shaped hole when the inlet pressure is less than 0.7 MPa. However, the output power of the expander can be increased by choosing a larger inlet hole shape when the inlet pressure exceeds this value. The larger inlet flow area can effectively reduce the gas flow resistance and increase the air inlet volume, thereby increasing the output power.

Fig. 6 displays the curves of isentropic efficiency of scroll expander variation with the inlet pressure. Compared with the circular inlet-hole expander, the isentropic efficiency of the waist-shaped hole does not increase significantly, and its variation trend is the same as that of the circular inlet hole. However, the scroll expander with a waist-shaped inlet hole has a broader optimum pressure range. When the load is constant, the optimum pressure range of the scroll expander with a waist-shaped inlet hole is 0.6–0.9 MPa, while that of the circular inlet hole is 0.7–0.8 MPa. Within this range, the maximum isentropic efficiency of the expander reaches 51%.

4.2 Effect of Different Profile Modifications

Different modification methods of the profile will influence the meshing state between the scroll disks, thus affecting the performance of the scroll expander [25]. For convenience, the symmetrical-arc and straight-line modification is called "A modification," and the symmetrical arc modification is called "B modification." Under the same load, the output power of the two modified scroll expanders increase with inlet pressure, as shown in Fig. 7. It can be seen from Fig. 7 that the output power of the B-modified expander exceeds that of the A-modified expander within the entire pressure range. When the inlet pressure ranges from 0.4 to 0.9 MPa, the output power of the B-modified scroll expander is approximately 20% higher than that of A-modified scroll expander. When the inlet pressure is higher than 0.9 MPa, the output power is between 5.7%–11.8% higher. These results are due to the change in the expansion-starting angle by B modification, which increases the volume of the central inlet chamber, thus increasing the output power.

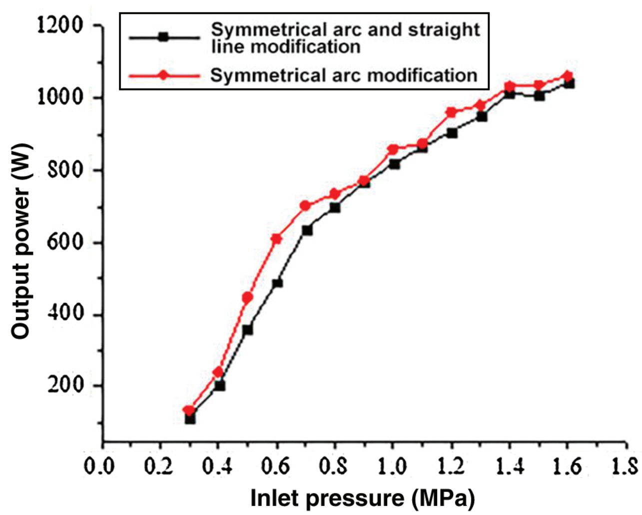


Figure 7: Output power of the scroll expander with different profile modifications

The analysis of the experimental data shows that the isentropic efficiency of the B-modified expander exceeds that of A-modified expander, as depicted in Fig. 8. The maximum isentropic efficiency is similar under the two profile modification modes, but the average isentropic efficiency of the B-modified expander is approximately 4% higher than that of the A-modified expander.

Based on the output power (Fig. 7) and isentropic efficiency (Fig. 8), it can be observed that the output power and isentropic efficiency can be enhanced by modifying the profile of the expander following the structural strength requirement.

4.3 Effect of Rotational Speed

Rotational speed has a significant effect on the performance of a scroll expander. This effect occurs because the increase in rotational speed increases the throttling loss of inlet and outlet holes, the flow loss, and the mechanical friction of the internal parts of the scroll expander. The most significant effect is that the rotational speed affects the gas leakage of the expansion chamber and then, influences its performance.

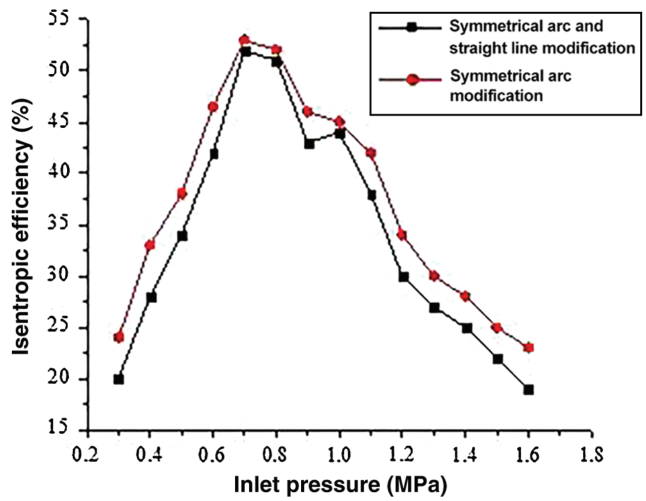


Figure 8: Isentropic efficiency of the scroll expander with different profile modifications

During the experiment, the inlet pressure was controlled at 0.6, 1.0, and 1.6 MPa. Under the preset inlet pressure, the rotational speed of the expander was varied by adjusting the load continuously, and the change in the corresponding output power and isentropic efficiency before and after improvement was analyzed after that.

Fig. 9 compares the output power before and after improvement when the rotational speed of the expander is changed under different inlet pressures. Under different inlet pressures, the increase in rotational speed will initially increase the output power and later decrease. Different inlet pressures correspond to different optimal rotational speeds, which maximize the output power of the expander. Higher inlet pressure leads to higher optimal rotational speed. When the inlet pressure is 1.6 MPa, and the rotational speed is 1750 r/min, the maximum output power of the scroll expander is 1235 W, which is 120 W higher than that before the improvement.

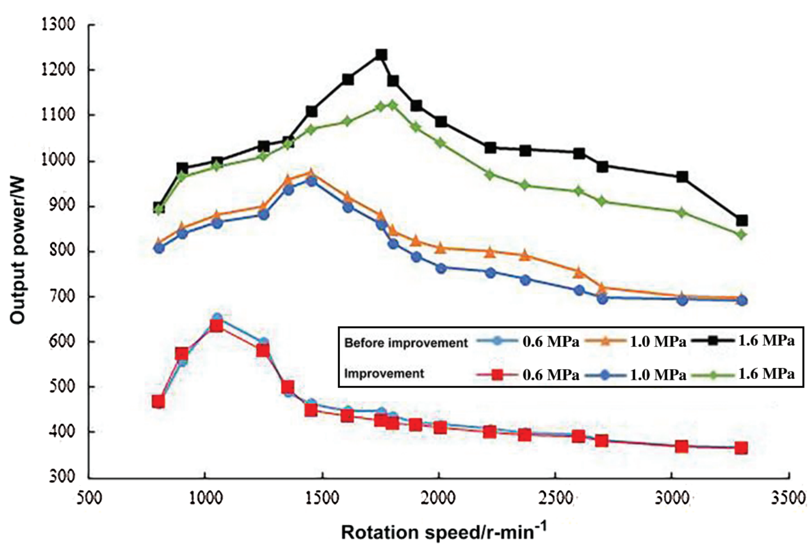


Figure 9: Rotational speed variation with output power

Under different inlet pressures, the effect of rotational speed on the isentropic efficiency of the scroll expander is shown in Fig. 10. The variation in rotational speed has a slight effect on the isentropic efficiency of the expander. When the rotational speed changes, the isentropic efficiency fluctuates around the average isentropic efficiency. The average isentropic efficiency is 44% at an inlet pressure of 0.6 MPa, 38% at 1.0 MPa, and 20% at 1.6 MPa. The isentropic efficiency is lower when the intake pressure is higher because, at the same rotational speed, the lower inlet pressure leads to smaller gas leakage during the expansion process.

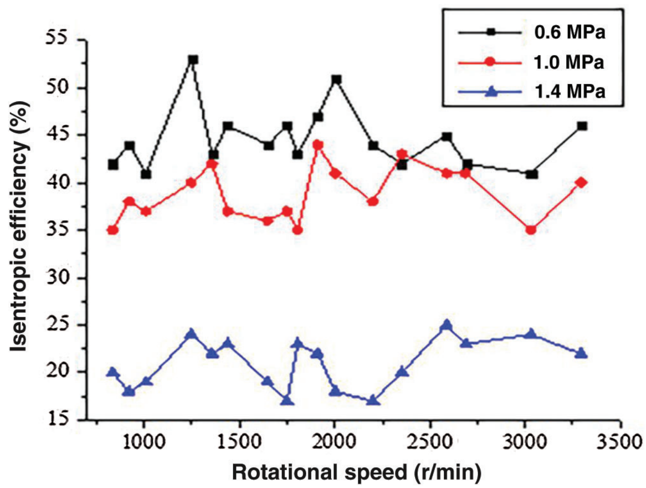


Figure 10: Rotational speed variation with isentropic efficiency

5 Conclusions

The scroll expander used in an ORC system was improved, and its performance was analyzed experimentally. The static and dynamic scroll disks engaged in a fixed eccentricity at a phase difference of 180°, such that the inlet hole was not covered. The profile of the dynamic scroll disk was directly truncated and modified. The circular inlet hole of the static scroll disk was milled into a waist-shaped hole with an larger area of 108.58 mm^2. The performance of the scroll expander before and after improvement was compared experimentally. Based on the findings of this study, the following conclusions can be drawn:

1. The shape and area of the inlet hole influences the output power and isentropic efficiency of the scroll expander. The output power of the scroll expander with a waist-shaped hole increases more than that of the circular hole after the inlet pressure exceeds 0.7 MPa. When the inlet pressure is 1.6 MPa, the maximum output power increases by 230 W. Waist-shaped hole is preferable when the inlet pressure is higher than 0.7 MPa. The scroll expander with a waist-shaped hole has a wider optimum pressure range with a maximum isentropic efficiency of 51%.
2. Comparing the performances of the scroll expander with the symmetrical-arc and straight-line modification and the symmetrical arc modification, the expander with the symmetrical arc modification has higher output power and isentropic efficiency. When the inlet pressure ranges from 0.4 to 0.9 MPa, the output power increases by 20%. When the inlet pressure exceeds 0.9 MPa, the output power increases by 5.7%–11.8%. The average isentropic efficiency of the scroll expander is improved by 4%.
3. The increase in rotational speed leads to an increase in the gas leakage of the expansion chamber. Different inlet pressures lead to different optimal rotational speeds, which maximize the output

power of the expander. When the inlet pressure is 1.6 MPa and the rotational speed is 1750 r/min, the maximum output power of the scroll expander is 1235 W, which is 120 W higher than that before the improvement.

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Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

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