DEVELOPEMENT AND DEMONSTRATION ON SINGLE SCREW EXPANDER IN ORGANIC RANKINE CYCLE

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ABSTRACT

Single screw expander is a machine which can realize volume change by means of a screw and two gaterotors. Single screw expander was recognized as one of the best volumetric expanders for the advantages of ideal force balance, low leakage, low noise, low vibration, long life, low maintenance cost, high pressure ratio, etc.

Based on the gear theory and spatial relationship between single screw rotor and gate rotor, mathematical models on the profile of CP-type, PP-type, CC-type and PC-type structure are established. The groove volumes of the four types of structure are derived. And the unwrapped helix of single screw rotor deciding the suction size and discharge position were obtained. Moreover, the changing rules of groove volume and volume ratio are quantitatively analysed. A generating processing technology and 2 sets of special machine tools to massive manufacture screw rotors from Φ20 to Φ450mm at high precision and low cost were developed. The cutting tool and moulds for machining the gate rotor have been successfully designed and machined.

Thermo- fluid dynamic models and performance testing system of single screw expander were established. Influences of clearance height, lubrication oil, rotating speed, pressure and temperature on single screw expander were investigated by experiments and numerical simulations. Six module single screw expander prototypes in wide power range from 5kW to 172 kW were developed. A double-stage single screw expander by utilizing the discharge velocity of screw grooves was developed. Experimental results indicate that the developed single screw expander performed well under different expansion ratio conditions. The coefficient of discharge velocity utilization achieved 0.42.

An optimized single screw expander integrated into ORC system working with R123 was developed, and the maximum efficiency of the system achieved 9.3%. Four demonstration projects were established respectively with solar and internal combustion engine waste heat.

1. INTRODUCTION

Steam Rankine cycle is widely used in the field of heat-power conversion. However, when the temperature of heat source is below 250℃, steam Rankine cycle is not favourable because the high specific volume of steam at low pressure requires larger installation and mandatory air removal in condensing mode. In order to address this issue, organic fluids with low boiling point, such as R123 and R245fa, were proposed to substitute water as the working fluids. The Rankine cycle adopting organic fluids instead of water turns into an Organic Rankine Cycle (ORC). ORC has attracted a lot of attention in recent years, and it is one of the most promising technologies in the practice of converting low grade heat into power. The low grade heat can be solar energy, geothermal energy and industrial waste heat, which are all widely available [1-3].

One of the key components in ORC system is expander. There are two types of expanders. One is the turbo type, and the other is the positive-displacement type[4]. Large scale ORC systems normally adopt turbo expanders. However, for small scale ORC unit, turbo expander might not be favourable[5]. Previous investigations have revealed that the rotational speed of turbo expanders increases with the decrease in turbine output power. The rotational speed of turbo expanders of small scale becomes very high, and the experimental data are normally between 17000-65000 r/min[6]. In this condition, positive-displacement expanders, such as rolling piston expander [7], scroll expander[8] and single screw expander[9], are good substitutes for turbo machines due to their relatively high efficiency, high pressure ratio, low rotational speed and tolerance of two-phase fluids. Scroll expander is a hotspot in the research on small scale ORC systems. Most of the scroll expander reported in literatures were modified from scroll compressors, and the obtained power of scroll expander is normally smaller than 3.5 kW[8]. When the output power is larger than 3.5 kW, single screw expander seems more promising. Compared to scroll expander and rolling piston expander, it has many advantages, such as balanced loading of the main screw, long working life, high volume efficiency, high partial loading, low leakage, low noise, low vibration and simple configuration.

A few investigators performed theoretical analyses on single screw expanders. Ziviani et al.[10] reported a comparison between single screw and scroll expander under part-load conditions for low-grade heat recovery ORC systems. It was found that the single screw expander presented higher power output and led to higher ORC overall efficiency although a lower maximum isentropic efficiency was obtained due to the limited expansion ratio. In another paper of Ziviani et al.[11], they reported a geometry-based modelling of single screw expander for ORC systems for low-grade heat recovery.

The high-efficiency single-screw expander technology (5-172 kW) has been developed by our team for over 10 years. The paper reviews the research progresses on the development of single screw expanders for Organic Rankine Cycle.

2. PRINCIPLE AND ADVANTAGES OF SINGLE SCREW EXPANDERS

The single screw engine is a special kind of rotary displacement expander with one rotor and two gaterotors. In an action cycle, there are three working processes: air admission, air expansion, and air discharge. The configuration and working principle is shown in Fig. 1. When the engine starts to work, the inlet gas with a certain pressure pushes rotor running in revolution, and the gaterotors go round and round with the rotor at the same time. The inlet gas expands in the closed volume formed by spiral groove, gaterotor tooth and body shell as the rotor rotates. During the expansion process, compressed gas in the closed volume expands and in the meantime a decrease in temperature and pressure is observed, which determines the output power.

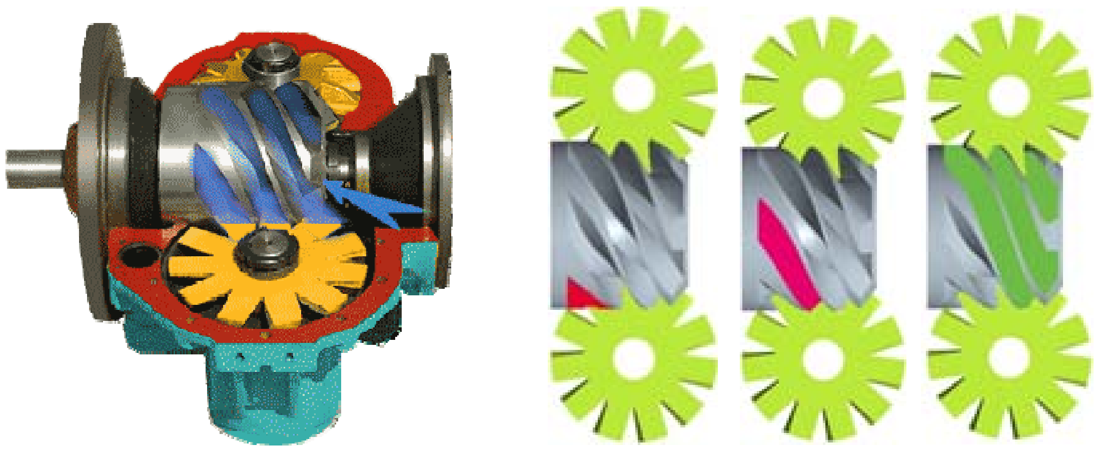


Fig.1: Configuration and principle of Single Screw Expanders

The main axis of the single screw expanders is operated in a completely balanced state, no axial force nor a radial force, which greatly improve the reliability. By comparison, there is a huge axial force and the radial force with the screws of the twin-screw expanders. The gaterotors can form the reasonable friction fairs by metal and special nonmetal materials which make the work more reliable and the vibration noise lower, the force balance reduces the requirements for lubrication. The vibration is not obvious when the single-screw expander running. However, there are big scope and low frequency vibration for piston expander and there are small scope and high frequency vibration for twin-screw expander. Under the same output power and the same circumstances, the noise of single screw expander is 10-15 decibels lower than that of twin-screw expanders. The single screw expanders have the longer service life than other types. It is the double of twin-screw ones. It can serve more than 100,000 hours (20 years). Single screw expanders without a triangular leakage have a higher volumetric efficiency which can reach a maximum 96%. According to a triangular leakage, the highest volumetric efficiency of the twin-screw compressors can only achieve 88%.

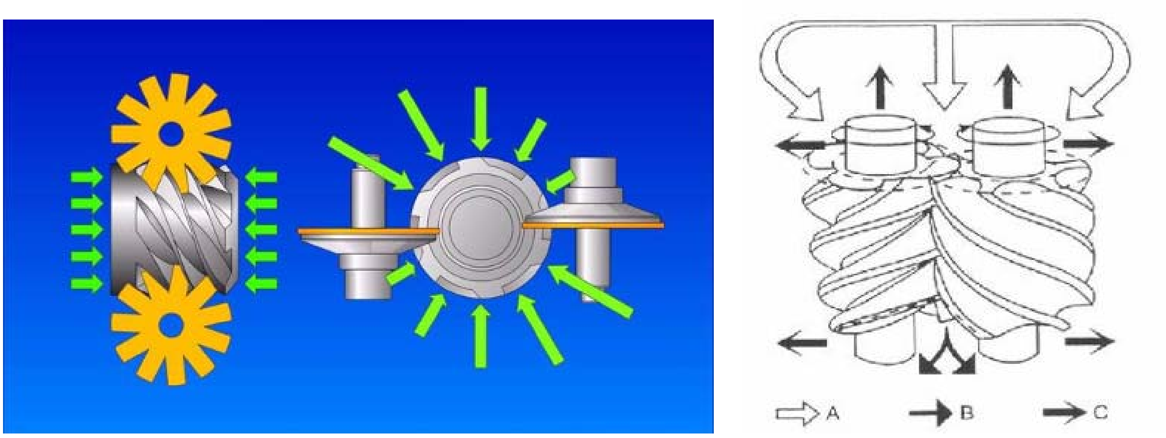


Fig. 2: Comparison between Single Screw and Twin Screw Expander

3. MANUFACTURE OF ROTOR AND GATEROTOR

Based on the gear theory and spatial relationship between single screw rotor and gate rotor, the profile of CP-type, PP-type, CC-type and PC-type structure are established. The single tooth of gate rotor is working as cutting tool, and the profile of gate rotor is given. By gear theory, the profiles of four- type single screw rotor are obtained. And then the groove of single screw rotor is used as a tool of machining the gate rotor tooth.

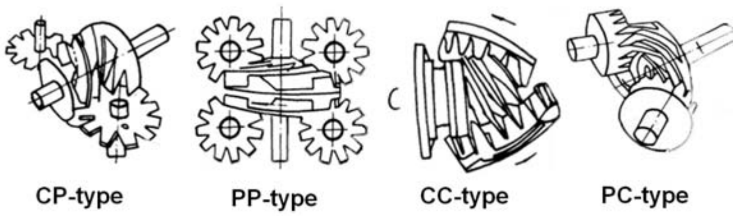
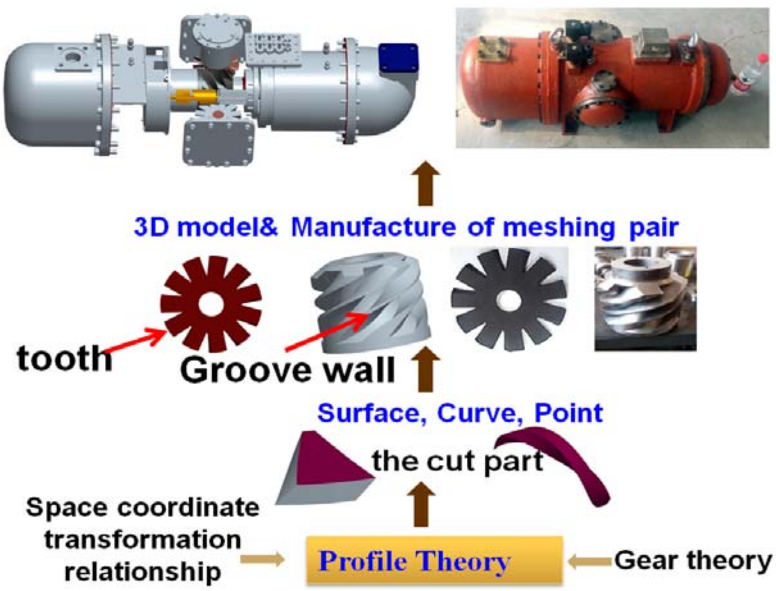
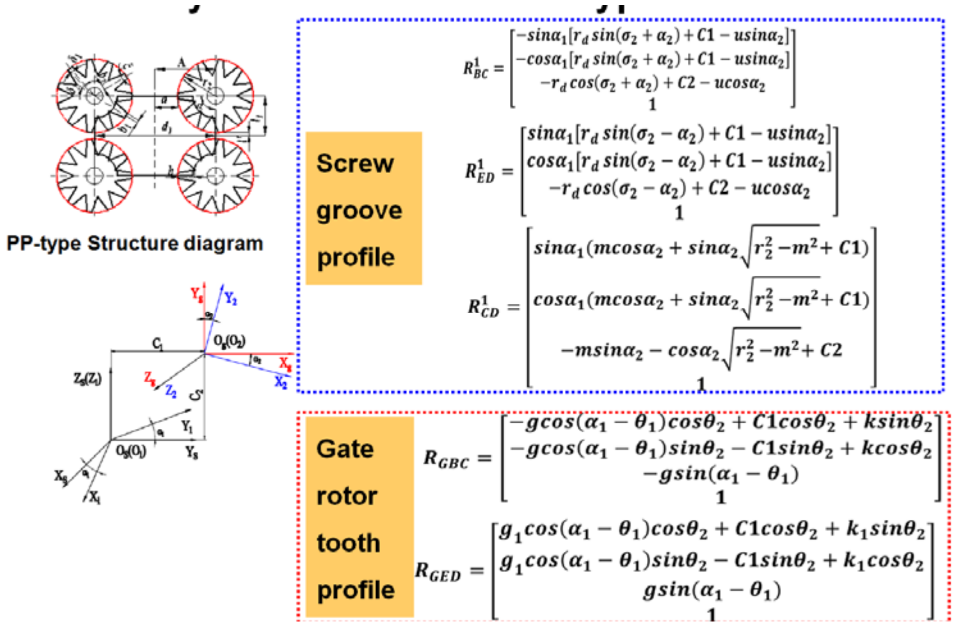


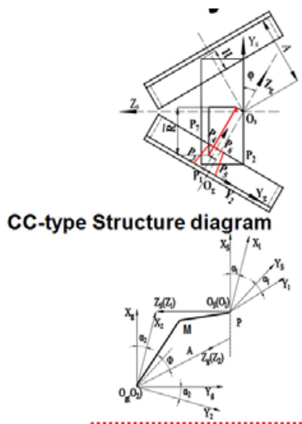
Fig.3: four type of single screw machine



(a) manufacture of single screw machine



(b) analytic solutions of PP-type profile



Screw groove profile

$$R_{1S}=M_{12}R_1=\begin{bmatrix}-T_1\cos\alpha_1+(T_2\sin\phi+T_3\cos\phi)\sin\alpha_1\\ T_1\sin\alpha_1+(T_2\sin\phi+T_3\cos\phi)\cos\alpha_1\\ T_2\cos\phi-T_3\sin\phi\\ 1\end{bmatrix}$$

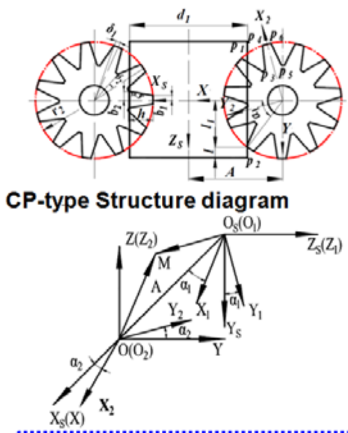
$$R_{2S}=M_{12}R_1=\begin{bmatrix}-T_4\cos\alpha_1+(T_5\sin\phi+T_3\cos\phi)\sin\alpha_1\\ T_4\sin\alpha_1+(T_5\sin\phi+T_3\cos\phi)\cos\alpha_1\\ T_5\cos\phi-T_3\sin\phi\\ 1\end{bmatrix}$$

$$R_{3S}=M_{12}R_2=\begin{bmatrix}-T_6\cos\alpha_1+(T_7\sin\phi+T_8\cos\phi)\sin\alpha_1\\ T_6\sin\alpha_1+(T_7\sin\phi+T_8\cos\phi)\cos\alpha_1\\ T_7\cos\phi-T_8\sin\phi\\ 1\end{bmatrix}$$

Gate rotor tooth profile

$$R_{2OL}=\begin{bmatrix}(-T_1\cos\theta_{2L}-k_{16}\sin\theta_{2L}+P)\cos\theta_2-(T_1\sin\theta_{2L}+k_{16}\cos\theta_{2L})\sin\phi\sin\theta_2\\ -k_{12}\cos\phi\sin\theta_2\\ (T_1\cos\theta_{2L}+k_{16}\sin\theta_{2L}-P)\sin\theta_2-(T_1\sin\theta_{2L}+k_{16}\cos\theta_{2L})\sin\phi\cos\theta_2\\ -k_{12}\cos\phi\cos\theta_2\\ (T_1\sin\theta_{2L}+k_{16}\cos\theta_{2L})\cos\phi-k_{12}\sin\phi+A\\ 1\end{bmatrix}$$

(c) analytic solutions of CP-type profile



screw groove Profile

$$R_{1S}=\begin{bmatrix}(u\cos\alpha_2-b_0\sin\alpha_2+A)\cos\alpha_1\\ -(u\cos\alpha_2-b_0\sin\alpha_2+A)\sin\alpha_1\\ u\sin\alpha_2+b_0\cos\alpha_2\\ 1\end{bmatrix}=\begin{bmatrix}T_1\cos\alpha_1\\ -T_1\sin\alpha_1\\ S_1\\ 1\end{bmatrix}$$

$$R_{3S}=\begin{bmatrix}(u\cos\alpha_2+b_0\sin\alpha_2+A)\cos\alpha_1\\ -(u\cos\alpha_2+b_0\sin\alpha_2+A)\sin\alpha_1\\ u\sin\alpha_2-b_0\cos\alpha_2\\ 1\end{bmatrix}=\begin{bmatrix}T_3\cos\alpha_1\\ -T_3\sin\alpha_1\\ S_3\\ 1\end{bmatrix}$$

$$R_{2S}=\begin{bmatrix}(-\sqrt{r_2^2-b^2}\cos\alpha_2-b\sin\alpha_2+A)\cos\alpha_1\\ -(-\sqrt{r_2^2-b^2}\cos\alpha_2-b\sin\alpha_2+A)\sin\alpha_1\\ -\sqrt{r_2^2-b^2}\sin\alpha_2+b\cos\alpha_2\\ 1\end{bmatrix}=\begin{bmatrix}-T_2\cos\alpha_1\\ T_2\sin\alpha_1\\ S_2\\ 1\end{bmatrix}$$

gate rotor tooth Profile

$$R_{2gL}=\begin{bmatrix}T_1\cos\theta_2+S_1\sin\theta_2-A\cos\theta_2\\ -T_1\sin\theta_2+S_1\cos\theta_2+A\sin\theta_2\\ 0\end{bmatrix}\qquad R_{2gL}=\begin{bmatrix}T_1\cos\theta_2\cos\alpha_0+S_1\sin\theta_2-A\cos\theta_2\\ -T_1\sin\theta_2\cos\alpha_0+S_1\cos\theta_2+A\sin\theta_2\\ -T_1\sin\alpha_0\end{bmatrix}$$

$$R_{2gR}=\begin{bmatrix}T_3\cos\theta_2+S_3\sin\theta_2-A\cos\theta_2\\ -T_3\sin\theta_2+S_3\cos\theta_2+A\sin\theta_2\\ 0\end{bmatrix}\qquad R_{2gR}=\begin{bmatrix}T_3\cos\theta_2\cos\alpha_0+S_3\sin\theta_2-A\cos\theta_2\\ -T_3\sin\theta_2\cos\alpha_0+S_3\cos\theta_2+A\sin\theta_2\\ -T_3\sin\alpha_0\end{bmatrix}$$

(d) analytic solutions of CP-type profile

Fig.4: manufacture theory of four type single screw structure

Under the guide of mathematical model of profile of CP-type single screw structure, a generating processing technology and 2 sets of special machine tools were developed to massive manufacture screw rotors from Φ20 to Φ450mm at high precision and low cost. The cutting tool and moulds for machining the gate rotor have been successfully designed and machined. Based on the mathematical model of profile of PP-type single screw structure, PP-type screw rotor with symmetrical arrangement of left and right handed helix has also been successfully manufactured first time in world.

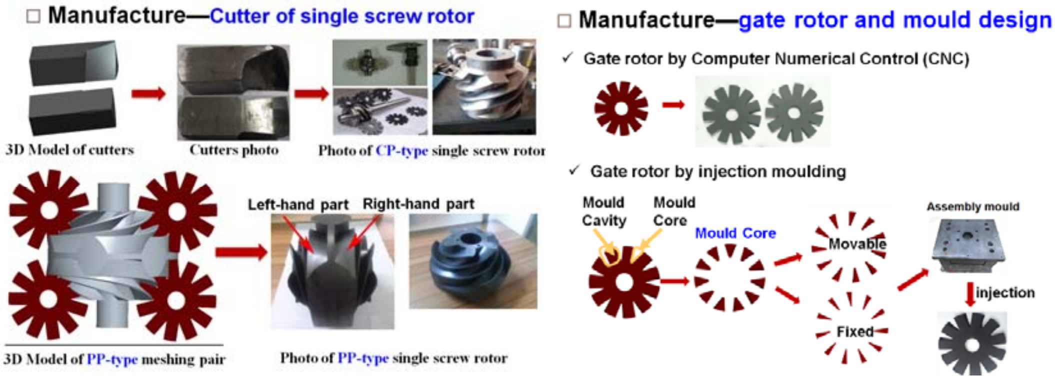


Fig.5: Manufacture of single screw rotor and gaterotor

Fig.6: single screw rotor and gaterotor prototypes with different sizes

4. DEVELOPMENT OF SINGLE SCREW EXPANDER

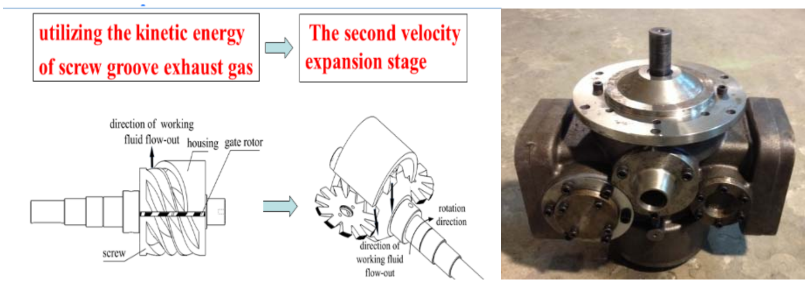
On the basis of spatial relationship between single screw rotor and gate rotor, also under the guide of principle that the groove volume element is equal to the product of meshing area of gate rotor and centroid distance, the main geometric relationship of CP-type, PP-type, CC-type and PC-type structure has been studied. The groove volume of CP-type, PP-type, CC-type and PC-type structure are derived. And the unwrapped helix of single screw rotor deciding the suction size and discharge position are obtained. Moreover, the changing rules of groove volume and volume ratio are quantitatively analyzed with changing structural parameters such as tooth width and length of gate rotor, meshing center distance and side angle of gate rotor tooth. Mathematical and physical model of single screw expander were made, performance test system with compressed air and organic working fluid were also set up. By numerical simulations and experimental tests, Influence mechanism of clearance, rotating speed, temperature and lubricate oil on single screw expander were obtained.

Six single screw expander prototypes in wide power range from 5kW to 172 kW were developed, including a single screw expander working at high pressure as 6.5 MPa[12]. Experimental results indicated that all the six single screw expander prototypes can be operated stable at long periods and the shaft efficiencies were in the range of 52% to 73%.

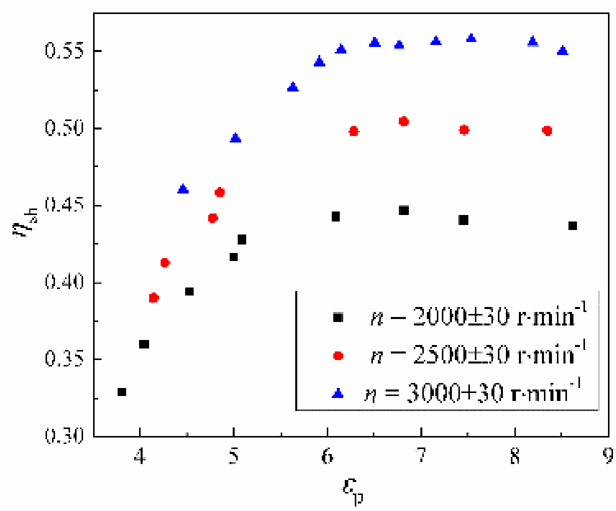
Module	Outpower(kW)	Max. Shaft Efficiency(%)	Max. Temp. difference(℃)
Φ117(1.5MPa)	8.5	66%	63
Φ117(6.5MPa)	56.55	52%	
Φ147	10	73%	64
Φ175	22.4	70%	70
Φ195	51.8	63%	88
Φ350	172	65%	78

Fig.7: single screw expander prototypes[13-16]

A double-stage single screw expander by utilizing the discharge velocity of screw grooves was developed. Experimental result indicates that the developed single screw expander performed well under different expansion ratio conditions. The coefficient of discharge velocity utilization achieved 0.42[17].



(a) operating principle (b) prototype picture



(c) experimental results

Fig. 8: Double-stage Single screw expander by utilizing the discharge velocity of screw grooves

5. RESEARCH AND DEVELOPMENT OF ORC SYSTEM

A formula was obtained to describe the impacts of the three categories of pressure losses on ORC efficiency. The expander efficiency, Work Loss Factor of lubricant oil Supply (WLFS), pumping work factor and condensing work factor was used to indicate the impacts of corresponding elements of ORC systems. An optimized ORC system working with R123 was developed, the maximum efficiency achieved 9.3%[17]. Three demonstration projects were established respectively with solar and internal combustion engine waste heat.

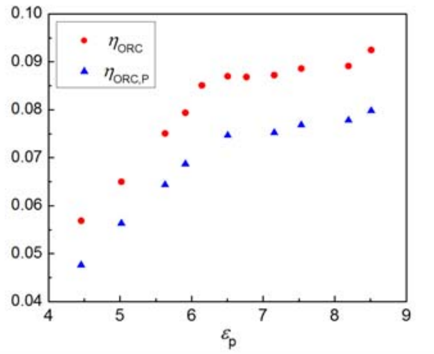


Fig.9: Optimized ORC system and test results

Fig.10: ORC demonstration projects from Coalbed gas Engine waste heat

Fig.11: ORC demonstration projects from diesel Engine waste heat[18]

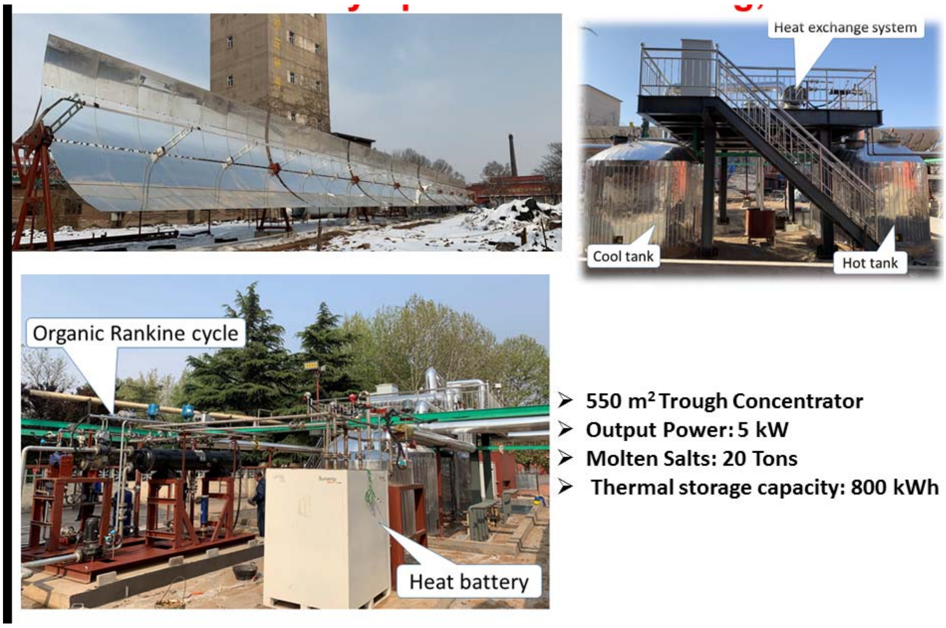


Fig. 12: 5 kW CSP demonstration project have been finished and successfully operated in Lincheng, Hebei

6. CONCLUSION

(1) Single screw expander is a machine which can realize volume change by means of a screw and two gaterotors. Single screw expander was recognized as the best volumetric expander for the advantages of ideal force balance, low leakage, low noise, low vibration, long life, low maintenance cost, high pressure ratio, etc.
(2) Mathematical models on the profile of CP-type, PP-type, CC-type and PC-type structure are established. The groove volumes of the four types of structure are derived. And the unwrapped helix of single screw rotor deciding the suction size and discharge position are obtained.
(3) Developed a generating processing technology and 2 sets of special machine tools to massive manufacture screw rotors from Φ20 to Φ450mm at high precision and low cost. The cutting tool and moulds for machining the gate rotor have been successfully designed and machined.
(4) Thermo- fluid dynamic models and performance testing system of single screw expander were established. Influences of clearance height, lubrication oil, rotating speed, pressure and temperature on single screw expander were investigation by experiments and numerical simulations.
(5) Developed six module single screw expander prototypes in wide power range from 5kW to 172 kW. A double-stage single screw expander by utilizing the discharge velocity of screw grooves was developed. Experimental result indicates that the developed single screw expander performed well under different expansion ratio conditions. The coefficient of discharge velocity utilization achieved 0.42.
(6) An optimized single screw expander ORC system working with R123 was developed, the maximum efficiency achieved 9.3%. Three demonstration projects were established respectively with solar and internal combustion engine waste heat.

References

[1] Rahbar K, Mahmoud S, Al-Dadah R K, et al. Review of organic Rankine cycle for small-scale applications[J]. Energy Conversion and Management, 2017, 134: 135-155.
[2] Ando Junior O H, Maran A L O, Henao N C. A review of the development and applications of thermoelectric microgenerators for energy harvesting[J]. Renewable and Sustainable Energy Reviews, 2018, 91: 376-393.

[3] Mahmoudi A, Fazli M, Morad M R. A recent review of waste heat recovery by Organic Rankine Cycle[J]. Applied Thermal Engineering, 2018, 143: 660-675.
[4] Imran M, Usman M, Park B-S, et al. Volumetric expanders for low grade heat and waste heat recovery applications[J]. Renewable and Sustainable Energy Reviews, 2016, 57: 1090-1109.
[5] Quoilin S, Broek M V D, Declaye S, et al. Techno-economic survey of Organic Rankine Cycle (ORC) systems[J]. Renewable and Sustainable Energy Reviews, 2013, 22: 168-186.
[6] Kang S H. Design and preliminary tests of ORC (organic Rankine cycle) with two-stage radial turbine[J]. Energy, 2016, 96: 142-154.
[7] Zheng N, Zhao L, Wang X D, et al. Experimental verification of a rolling-piston expander that applied for low-temperature Organic Rankine Cycle[J]. Applied Energy, 2013, 112: 1265-1274.
[8] Song P, Wei M, Shi L, et al. A review of scroll expanders for organic Rankine cycle systems[J]. Applied Thermal Engineering, 2015, 75: 54-64.
[9] Ziviani D, A. Groll E, E. Braun J, et al. Review and update on the geometry modeling of single-screw machines with emphasis on expanders[J]. International Journal of Refrigeration, 2018, 92: 10-26.
[10] Ziviani D, Suman A, Lecompte S, et al. Comparison of a Single-screw and a Scroll Expander under Part-load Conditions for Low-grade Heat Recovery ORC Systems[J]. Energy Procedia, 2014, 61: 117-120.
[11] Ziviani D, Van Den Broek M, De Paepe M. Geometry-based Modeling of Single Screw Expander for Organic Rankine Cycle Systems in Low-grade Heat Recovery[J]. Energy Procedia, 2014, 61: 100-103.
[12] Li G, Lei B, Wu Y, et al. Influence of inlet pressure and rotational speed on the performance of high pressure single screw expander prototype[J]. Energy, 2018, 147: 279-285.
[13] He W, Wu Y, Peng Y, et al. Influence of intake pressure on the performance of single screw expander working with compressed air[J]. Applied Thermal Engineering, 2013, 51(1-2): 662-669.
[14] Wang J, Zhang X, Zhang Y, et al. Experimental Study of Single Screw Expander Used in Low-medium Temperature Geothermal Power System[J]. Energy Procedia, 2014, 61: 854-857.
[15] Wang W, Wu Y, Ma C, et al. Preliminary experimental study of single screw expander prototype[J]. Applied Thermal Engineering, 2011, 31(17-18): 3684-3688.
[16] Wang W, Wu Y, Ma C, et al. Experimental study on the performance of single screw expanders by gap adjustment[J]. Energy, 2013, 62: 379-384.
[17] Lei B, Wang W, Wu Y, et al. Development and experimental study on a single screw expander integrated into an Organic Rankine Cycle[J]. Energy, 2016, 116: 43-52.
[18] Zhang Y, Wu Y, Xia G, et al. Development and experimental study on organic Rankine cycle system with single-screw expander for waste heat recovery from exhaust of diesel engine[J]. Energy, 2014, 77: 499-508.