A Novel Vapor Injection Structure on the Blade for Rotary Compressor

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ABSTRACT

Heat pumps with rotary compressors operating in low temperature ambient will face heavy performance degradation. A novel vapor injection structure on the blade for the rotary compressor has been proposed in this paper to overcome the back-flowing drawback of the traditional cylinder injection structure and enlarge the injection area. Based on a verified numerical model, the performance of a rotary compressor with the blade injection structure has been investigated. The results indicate that: the proposed vapor injection structure can eliminate the back-flowing of the injected refrigerant; compared to the traditional injection structure, the new structure can enhance the volumetric efficiency and injection mass flow-rate by 1.8~2.7% and 26.6~57.2%, respectively; and compared to the traditional injection structure, the new structure can increase the heating capacity and COP by 23.1~48.9% and 3.2~8.0%, respectively.

1. INTRODUCTION

Rotary compressors have been extensively used in room air conditioners and household refrigerators for their advantages, including high efficiency, strong adaptability, and low cost. However, air source heat pumps with rotary compressors will face dramatically degradation as applied in cold regions [1]. Aimed at this problems, considerable research has been carried out and a series of solutions, including economizer technology [2], have been raised. At present, the economizer technology has proved an important technical solution to avoid the rapid performance degradation of heat pump in cold regions [3-4].

In the quasi two-stage compression system with an economizer, the refrigerant gas of the secondary loop is injected into the compression pocket through an injection port, which is also called vapor injection. Because only one compressor is used, the vapor injection technology is relatively cheap. So the vapor injection technology has been widely investigated and applied, especially in scroll compressors and screw compressors [5-9]. For the rotary compressor, most of the investigations of economizer technology focused on the twin-cylinder rotary compressor [10-11]. However, although the cost of a twin-cylinder rotary compressor is lower than two one-cylinder rotary compressors, there still exists an attempt to cut down the cost of the rotary compressor for low ambient temperature heating, which promotes the development of the gas injection technology in the one-cylinder rotary compressor.

Investigations on the gas injection into the one-cylinder rotary compressor is relatively seldom. Yan [12] and Jia [13] studied rotary compressors with vapor injection by experiments. Experimental results indicated that the system heating capacity was enhanced more than 12% by gas injection when outdoor temperatures was lower than -15°C. They also found that, compared to the twin-cylinder rotary compressor with economizer, the heating capacity and COP of the common one-cylinder rotary compressor with gas injection were both higher when ambient temperatures was higher than -15°C, which indicated the one-cylinder rotary compressor with gas injection will have a comparable even better performance than the twin-cylinder rotary compressor under mild working conditions.

In the one-cylinder rotary compressor with gas injection, the compressor injection port is often opened on the cylinder wall. In order to extend the injection time for injecting more refrigerant, the injection port is settled as close as possible to the discharge port. However, the limited area of the injection port and the unavoidable back-flowing of the injection refrigerant into the suction tube diminish the merits of gas injection on the one-cylinder rotary compressor. In this study, a new injection structure was put forward and the performance of the one-cylinder rotary compressor with the new injection structure was investigated.

2. THE NEW VAPOR INJECTION STRUCTURE

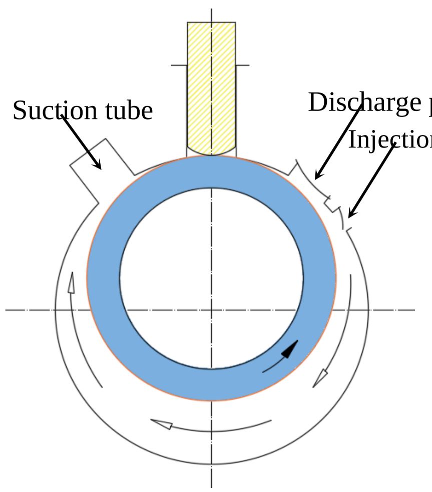


Fig. 1. Traditional injection structure

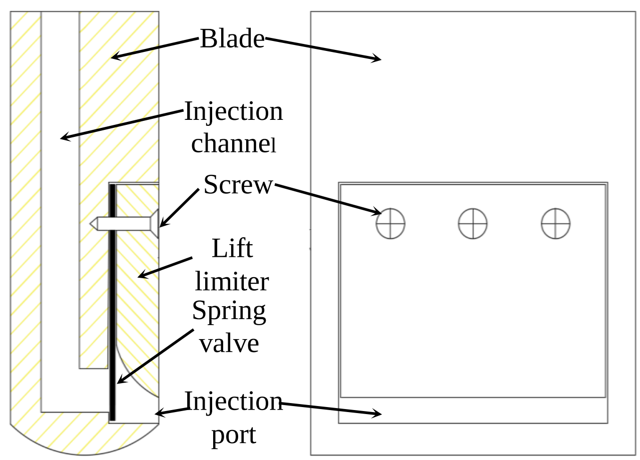


Fig. 2. Schematic of the blade with gas injection structure

Figure 1 shows a rotary compressor with traditional injection structure. The injection port is opened on the cylinder wall. In the beginning period of gas injection (just like the position in the Figure 1), the suction tube is still connected with the compression pocket. So the part of injected refrigerant will flow back to the suction tube, which will result in a decline of effective suction mass flow and compressor volumetric efficiency. At the same time, the area of the traditional injection port must be small in order to reduce the time of the back-flowing of the gas injection refrigerant.

In order to avoid the injected refrigeration gas flowing back into the suction tube and enlarge the area of injection port, a novel injection structure is proposed in Figure 2, in which the injection passage is screwed in the middle of the blade and the injection port is opened oriented to the discharge port. The new injection structure also need to mill a platform on the blade where the spring valve plate and the lift limiter are installed.

Figure 3 details the working process of the rotary compressor with the new injection structure. Before the suction pocket is isolated from the suction tube (Figure 3(a)), the blade don't protrude enough and the injection port is still sealed by the wall of the blade house. Under the press of the spring valve, the injection port is closed, and the injection process does not start. When the suction pocket is isolated from the suction tube, the suction process finishes (Figure 3(b)). At the same time, the blade moves down where the lower edge of the injection port exactly reveals, the injection port connects to the compression pocket and then the spring valve plate opens as the injection pressure is greater than the compression pocket pressure, starting injection. With increase of the rotation angle and increase of the compression pocket pressure, as the compression pocket pressure equals the injection pressure, the spring valve plate closes and the injection process ends, as shown Figure 3(c). Hereafter, the rolling piston rotates to the bottom center (Figure 3(d)), the initial discharge (Figure 3(e)) and the end of discharge (Figure 3(f)), respectively. The injection spring valve plate keeps close.

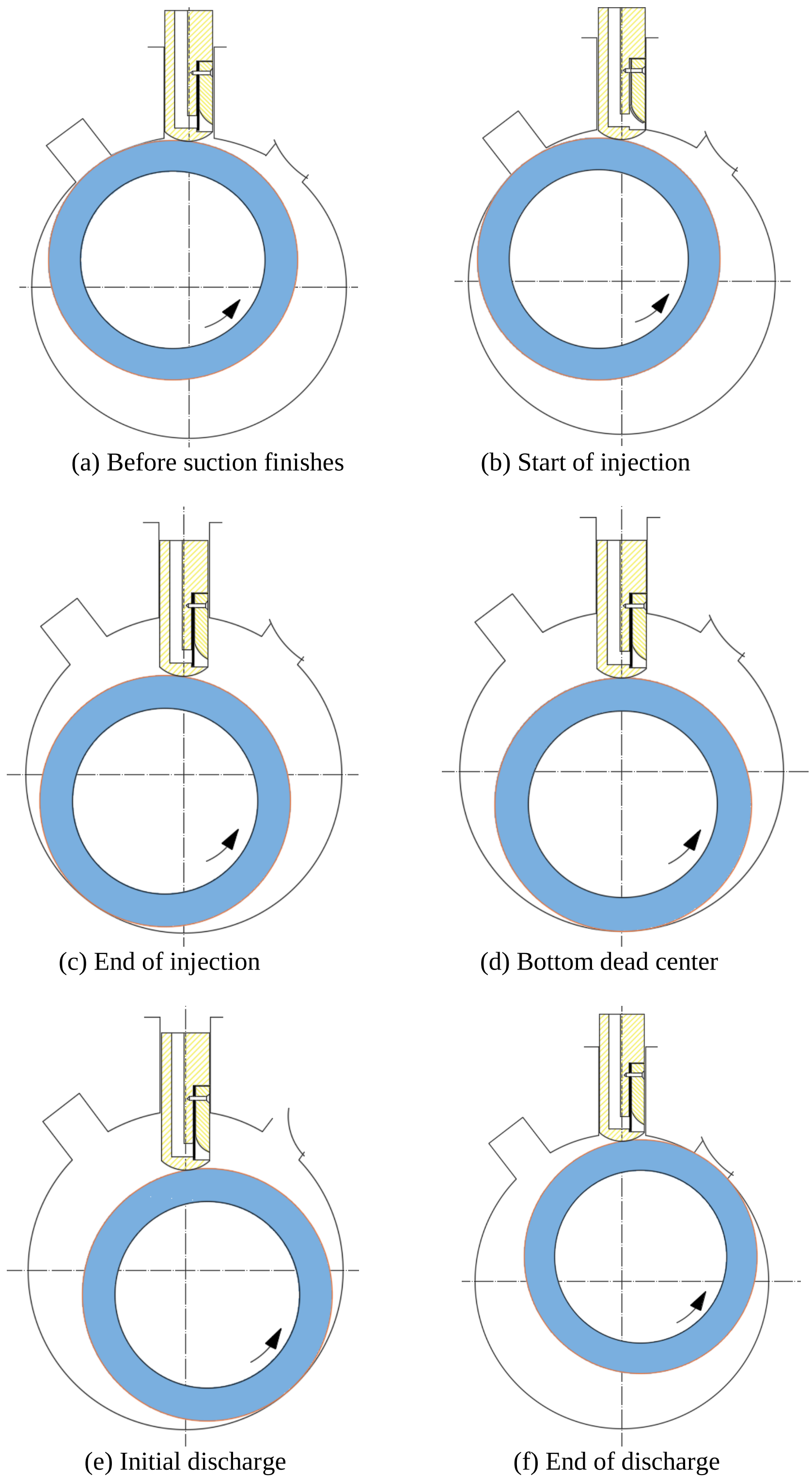


Fig. 3. Working process of the rotary compressor with injection channel on blade

Therefore, the rotary compressor with the blade injection structure can totally avoid the back-flowing of the injection refrigerant into the suction tube. At the same time, it can achieve injection at the first time when the suction process finishes, and so it can achieve the maximum of injection mass flow. Moreover, the volume between the injection port and the spring valve plate at the injection structure has no influence upon the volumetric efficiency.

Because the volume does not connect to the suction tube, it has no influence on the compressor suction mass flow-rate from the suction tube.
The effects of setting gas injection structure in the blade on the pressure balance of the blade, lubrication and leakage also have been considered. Because the new injection port was designed to be narrow (1.0~2.0 mm in width) and long, and injection port is with a large area. After injection starts, the new injection structure can inject a lot of refrigerant rapidly at a short time and result in the injection process time being very short. The injection structure influence on the blade movement characteristic does not display a large difference compared to the traditional injection structure compressor, and the pressure balance can be achieved. Actually, the existence of the injection port and lift limiter can achieve better lubrication and leakage decrease. Besides, in order to ensure structural strength, the vertical injection channel could use multiple parallel round holes instead of a narrow and long injection channel.

3. METHODOLOGY

In order to investigate the performance of the proposed rotary compressor, a detailed distributed-parameter model of the rotary compressor with the new injection structure is built.

3.1 Modelling

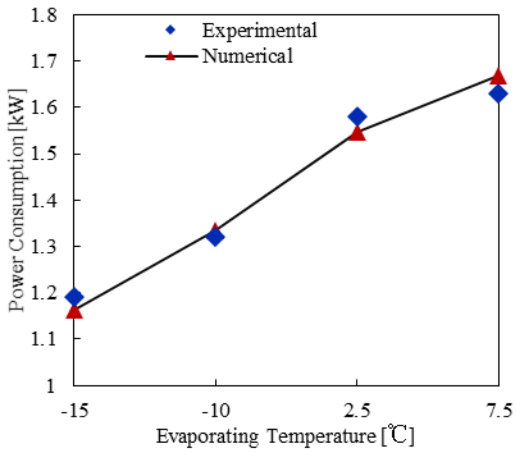
The suction, compression and discharge process of the rotary compressor with gas injection is a typical thermodynamic process of the open system. The thermodynamic model of the rotary compressor could be deduced according to the energy-balance and mass-balance equations [14].
The geometric models include dynamic characteristics of the suction pocket, compression pocket and blade with the rotation angle change [14]. Before the rolling piston rotates from top dead center to the end of suction, the injection area of the blade injection structure equals 0. After the suction process finishes, the injection port opens and the injection area rapidly increases and reaches maximum at a short time. Afterward, the injection area remains unchanged until rotating to bottom dead center. The change rule of injection area with rolling piston rotating from bottom dead center to top dead center is symmetrical with the rolling piston rotating from top dead center to bottom dead center. The traditional injection structure (opening the injection port in cylinder wall close to the discharge port) needs to consider the throttling characteristic of the injection process. When the rolling piston is rotated to the injection port, the injection area is equal to the minimum value between the injection port area and three-dimensional surface area under the injection port and rolling piston.
A modified one-dimensional throttle nozzle model is used to calculate leakage process through radial clearance, blade clearance and clearance between the rolling piston and blade [15]. The researched compressor is with a high-pressure shell, which means the high-pressure gas discharged by compression pocket entries into the compressor shell, where the high-pressure gas exchanges heat with the motor, the outdoor environment and the suction tubes. The heat balance equation was applied to describe the heating exchange process in the compressor shell. The heat exchange between refrigerant gas and compression pocket in the compression process is also considered. The Dittus-Beolter equation is used to describe it under the assumption that the temperature change of the cylinder wall from the suction port to the discharge port is linear with rotation angle [16]. The Nusselt number in suction preheated process is assumed constant (Nu=3.66) as the suction tube is very short [17].

3.2 Solving procedure

The Visual Studio was used to solve equations because the solution procedure includes many submodules, and the method of variable step size was applied during calculating to reduce the calculation time. The method of 4th Order Runge-Kutta was used to improve calculation accuracy and accelerate the convergence process.

3.3 Model verification

In order to verify the accuracy of the model, the experimental data from two public papers [12] are collected for comparing. Figure 4(a) and (b) show the simulation results of a single-cylinder rotary compressor compared to experimental results [22], which indicates that the errors of the heating capacity and the power consumption are within 3%. Generally speaking, the developed models have relative high accuracy and can be used in the further research.



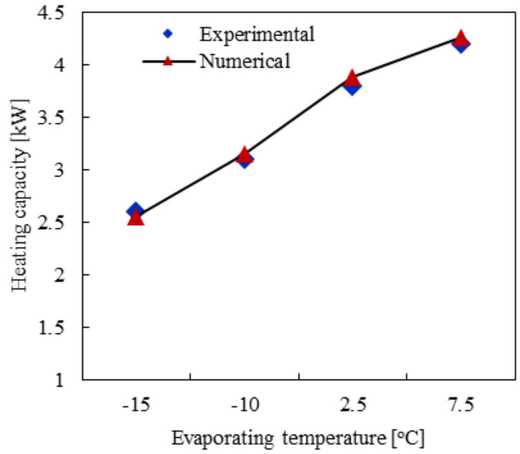


Fig. 4. Experimental verification for single rotary compressor

4. RESULTS AND DISGUSSION

4.1 Effect on inner compression process

The variations of the injection port areas of the traditional cylinder injection and the proposed blade injection with the change of the rotation angle are shown in Figure 5. According to Figure 5, the injection area of the traditional injection structure almost does not change when the rolling piston rotation angle is less than 300 degrees. With the rotation angle increase later, the rolling piston would be near to the injection port where the throttling effect appears, so the injection area decreased first, and then increased. When the rolling piston rotates from the position where the discharge process ends to the position where the suction process ends, the injection area of the traditional injection structure is not equal to 0, and the injection pressure is greater than the pressure of the suction pocket. Therefore, the process of the injection refrigerants back-flowing into the suction pocket is inevitable for rotary compressors with the traditional injection structure. However, the proposed injection structure opening injection port in the blade can totally avoid the back-flowing process, because its injection area equals 0 before the suction process finishes, and after the discharge process ends.

The non-back-flowing characteristic of the proposed compressor also can be observed by the instantaneous injection mass flow-rate through the injection port. Figure 6 shows the instantaneous injection mass flow-rate of different injection structures. Before the rolling piston rotates to the suction port, the injection mass flow-rate through the injection port of the traditional cylinder injection does not equal 0, then the injection refrigerant would flow back into the suction tube. However, when the injection port is opened in the blade, before the suction process is finished, the injection mass flow-rate keeps 0. After the rolling piston rotates over the suction port, the instantaneous injection mass flow-rate increases with the injection area increase rapidly, which means the blade injection structure can successfully avoid the injection refrigerant back-flowing into the suction tube.

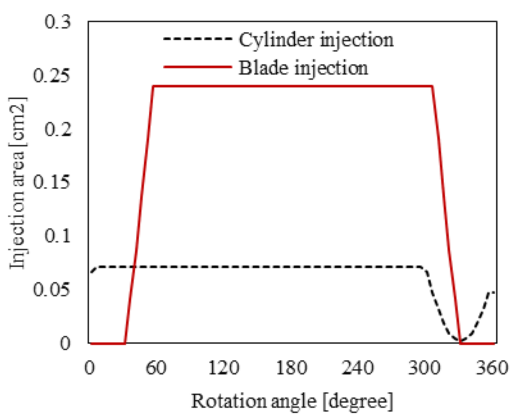


Fig. 5. Injection area

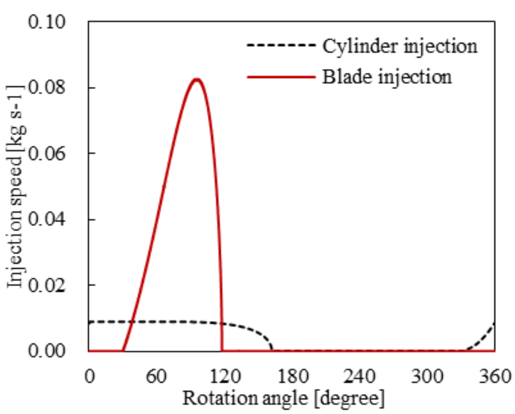


Fig. 6. Instantaneous injected mass flowrate

Moreover, it can found that the instantaneous injection mass flow-rate of the new injection structure is greater than the traditional injection structure, which can be attributed to the 2.5 times injection area of the new injection structure relative to the traditional injection structure. This much larger injection area also leads to the injection process finishes in a short time. After that, the pocket pressure is larger than the injection pressure and the injection spring valve plate closes.
To quantitatively describe the back-flowing, the back-flowing rate is defined, which is the ratio of the mass flow-rate of injection refrigerants directly back-flowing into suction tube divided by the total mass flow-rate of injection refrigerants and the leakage is not included. Figure 7 shows the back-flowing rates of the rotary compressor with different injection structures in condensing temperature 50ºC. The back-flowing rates of the rotary compressor with the traditional injection structure increases from 23.3% to 29.3% with the increase of the evaporating temperature, but the back-flowing rate with the new injection structure remains 0.

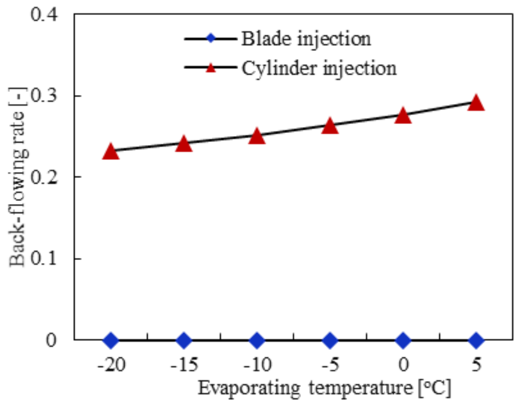


Fig. 7. Back-flowing rate

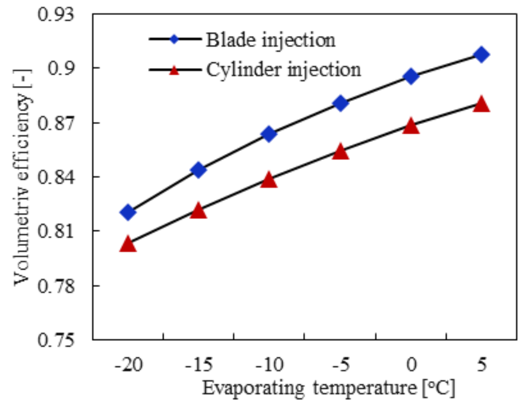


Fig. 8. Volumetric efficiency

Fig. 8 shows volumetric efficiency of the rotary compressor with different injection structures when the condensing temperature keeps 50ºC. Compared to the rotary compressor with the traditional injection structure, the volumetric efficiency of the rotary compressor with the new injection structure can be enhanced by 1.8~2.7%.

4.2 Effect on compressor performance

The injection rate is the key factor affecting the performance of the injected compressor. Figure 9 shows injection rate of the rotary compressor with different injection structures under different working conditions. The injection rate with different injection structures both fall with the evaporating temperature increase. Compared to the traditional injection structure, the new blade structure can inject much larger refrigerant into the compressor.

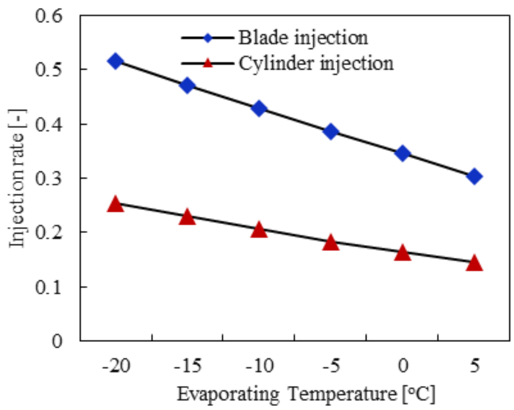


Fig. 9. Injection rate

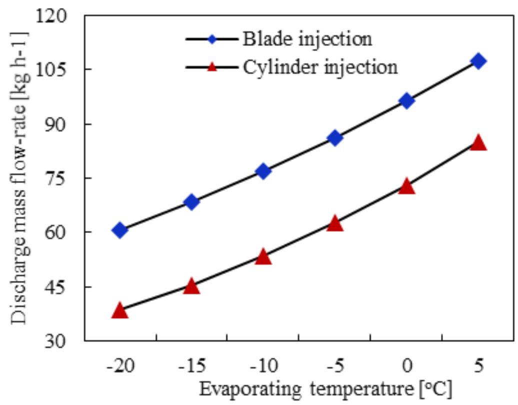


Fig. 10. Discharge mass flowrate

Figure 10 shows discharge mass flow-rate of a rotary compressor with different injection structures under different working conditions. Compared to the rotary compressor with the traditional injection structure, the discharge mass flow-rate of the rotary compressor with the new injection structure increased by 26.6~57.2%.

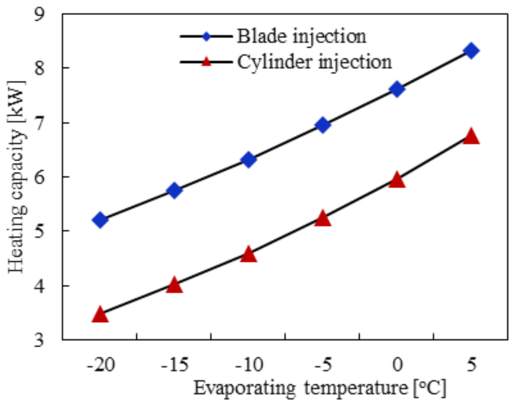


Fig. 11. Heating capacity

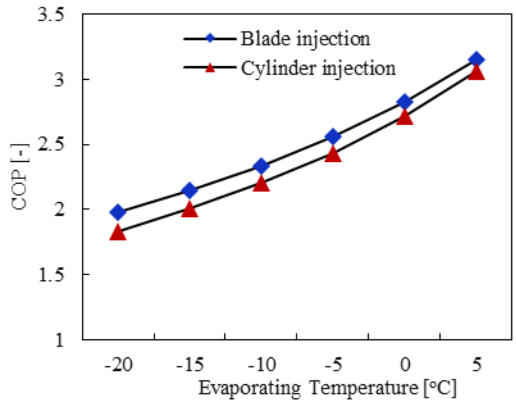


Fig. 12. COP

Figure 11 and Figure 12 show heating capacity and COP of a rotary compressor with different injection structures under different working conditions. Comparing to the rotary compressor with traditional injection structure, the heating capacity and COP of the rotary compressor with the blade injection structure are larger by 23.1~48.9% and 3.2~8.0%, respectively. That means the rotary compressor with the new injection structure can solve the degradation of the heating capacity and COP in low ambient temperature to a large extent.

However, it should be noticed that the performance here, including the injection rate, mass flowrate, heating capacity and COP, is just the performance of the compressor, not the performance of the injected heat pump system. Indeed, the real performance enhancement of injection on the heat pump system is much lower due to the limited gas refrigerant generated in the flash tank, higher condensing temperature, lower evaporating temperature, etc. The injection performance of the new injection structure will be investigated in the future.

5. CONCLUSIONS

Based on a verified numerical model, the performance of the proposed blade rotary compressor is investigated and the results indicate:

1) Compared to the traditional injection structure, the blade injection structure avoids about 23.3~29.3% of the injected refrigerant gas back-flowing into the suction tube;

2) The volumetric efficiency and the discharge mass flow-rate of the rotary compressor with the proposed injection structure is enhanced by 1.8~2.7% and 26.6~57.2%, respectively, relative to the traditional one.

3) Compared to the traditional injection structure, the heating capacity and COP of rotary compressor with the new injection structure is enhanced by 23.1~48.9% and 3.2~8.0%, respectively.

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