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Optimization analysis of the motor cooling method in semi-closed single screw refrigeration compressor

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Abstract. Semi-closed single screw refrigeration compressors (SSRC) are widely used in refrigeration and air conditioning systems owing to the advantages of simple structure, balanced forces on the rotor, high volumetric efficiency and so on. In semi-closed SSRCs, motor is often cooled by suction gas or injected refrigerant liquid. Motor cooling method will changes the suction gas temperature, this to a certain extent, is an important factor influencing the thermal dynamic performance of a compressor. Thus the effects of motor cooling method on the performance of the compressor must be studied. In this paper mathematical models of motor cooling process by using these two methods were established. Influences of motor cooling parameters such as suction gas temperature, suction gas quantity, temperature of the injected refrigerant liquid and quantity of the injected refrigerant liquid on the thermal dynamic performance of the compressor were analyzed. The performances of the compressor using these two kinds of motor cooling methods were compared. The motor cooling capacity of the injected refrigerant liquid is proved to be better than the suction gas. All analysis results obtained can be useful for optimum design of the motor cooling process to improve the efficiency and the energy efficiency of the compressor.

1. Introduction

As a rotary type compressor, the single screw compressor is firstly invented by Zimmen B in 1960s [1]. Due to the advantages of simple structure, small vibration, good dynamic balance, low noise and high reliability, the single screw compressor has always been regarded as a good theoretical performance compressor. It was first used in air compression field, and then was introduced to the field of refrigeration soon in the mid of 1970s [2,3]. The first opened single screw refrigeration compressor was manufactured in 1975 [4], and the semi-closed single screw refrigeration compressor (SSRC) was researched and developed in 1982 [5]. Now semi-closed SSRCs are widely used in refrigeration and air conditioning systems. The semi-closed SSRC mainly consists of one screw rotor and two star-wheels which symmetrically located with the screw rotor as shown in figure 1. The motor is connected with the screw rotor directly. During the compressor operating process, the copper loss, iron loss, excitation loss, ventilation, friction loss and so on will be generated by the motor and be converted into heat energy which will cause the motor heating. In order to cool the motor, motor cooling methods using suction gas, injected refrigerant gas/liquid or exhaust gas were put forward [6]. In semi-closed SSRCs, motor cooling method will changes the suction gas temperature, this to a certain extent, is an important factor influencing the thermal dynamic performance of the compressor.

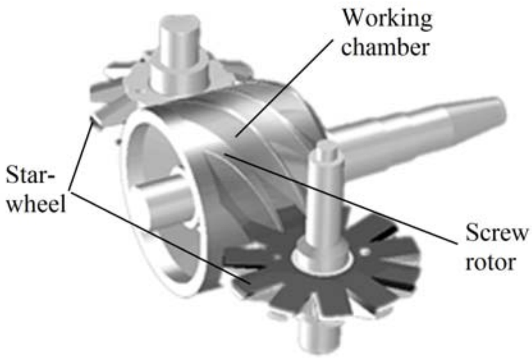

Figure 1. The core working parts of a single screw compressor

Over the years, a series of studies have been carried out for the motor heat dissipation, the motor cooling method and the influence of the motor cooling process on the compressor. Chen et al. built a mathematical model describing flow and heat transfer characteristics of the motor in semi-hermetic twin screw refrigeration compressor under part-load conditions based on fluid network and thermal equivalent circuit theories [7,8]. In their study, the temperature and pressure distribution inside the motor and their influences on performance of the compressor were analyzed. Wen et al. investigated the coil temperature field of electromotor in screw refrigeration compressor. On basis of this, the effects of working condition, velocity of refrigerant flow and electromotor power upon coil temperature were analyzed [9]. He et al. developed a comprehensive model to study the flow and thermal behavior of the motor cooling process through suction refrigerant in semi-hermetic twin screw refrigeration compressors. By using this model, the temperature distribution inside the motor was accurately predicted [10]. He et al. analyzed the temperature distribution of motor in the semi-hermetic screw refrigerant compressor which was applied in high temperature heat pump system [11]. Liang et al researched the influence of the motor cooling process on the enclosed type compressor and the semi-closed compressor with motor cooling methods using suction gas and injected refrigerant gas/liquid [12]. Dutra et al. presented a simulation approach for hermetic reciprocating compressors including electrical motor modeling, and studied the effect of the motor on the performance of the compressor [13]. For the semi-closed SSRC, Wang et al. established the mathematical model to analysis the thermodynamic performance of the semi-closed SSRC with the consideration of motor cooling process using suction gas [14]. Although many scholars have done a lot of work, so far no work has been done about the contrastive analysis of different motor cooling method in semi-closed SSRCs. In semi-closed SSRCs, motor cooling method is an important factor influencing the thermal dynamic performance of the compressor. Thus the effects of motor cooling method on the dynamic performance of semi-closed SSRCs must be studied.

In this paper, mathematical models of the motor cooling process by using suction gas or injected refrigerant liquid were established. On the basis of these models, the influences of the motor cooling parameters such as suction gas temperature, suction gas quantity, temperature of the injected refrigerant liquid and quantity of the injected refrigerant liquid on the thermal dynamic performance of the compressor were analyzed. The performances of the compressor using these two kinds of the motor cooling methods were compared. All analysis results obtained in this paper can be useful for optimum design of the motor cooling process in the semi-closed SSRC to improve the efficiency and the energy efficiency of the compressor.

2. Motor cooling principle in the SEMI-CLOSED SSRC

At present, the common methods used in semi-closed SSRC for cooling the built-in motor are the suction gas cooling method, the injection gas cooling method and the exhaust gas cooling method. In this study, the motor cooling method using the suction gas and the injected refrigerant liquid were investigated. The motor cooling principles of these two methods are shown as follows.

2.1. Motor cooling method using the suction gas

Figure 2 shows the structure of the semi-closed SSRC with the motor cooling method using suction gas (case 1). As shown in figure 2, the semi-closed SSRC is composed by three parts: motor, working component and the oil-gas separator. The screw rotor of the work component is driven by motor directly. When the semi-closed SSRC begins to run, the refrigerant gas with lower temperature and pressure will flows into the suction chamber through the motor after filtering. After this process, the motor windings will be cooled, and the refrigerant gas will be overheated. Then the overheating refrigerant gas will enters into the compression chamber of the working component and be compressed to a high pressure.

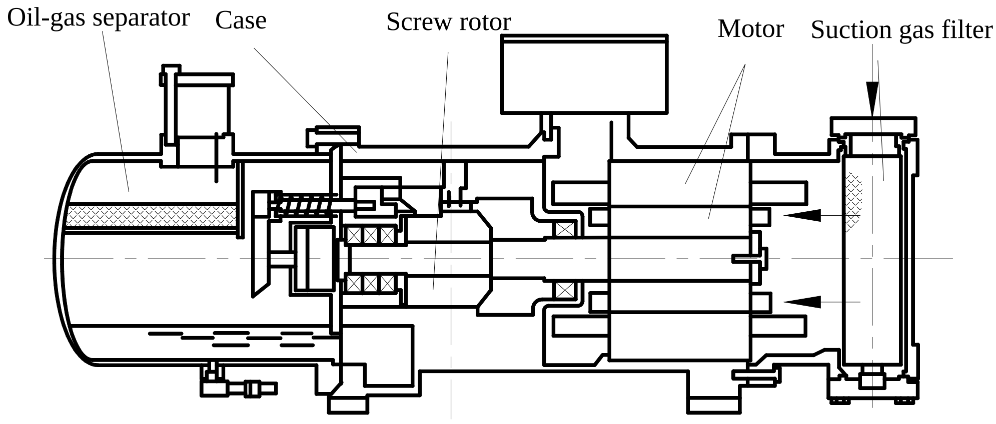

Figure 2. Semi-closed SSRC with the motor cooling method using suction gas

As shown in figure 3, the refrigerant gas with lower temperature and pressure at the state point 1’ will be overheated to the state point 1 after cooling the motor. The larger suction superheat will increases, the specific volume of the suction refrigerant gas which will cause the decrease of the compressor volume flow per unit time, and will eventually reduce the compressor working performance. So in this study, the influence of the refrigerant gas overheating caused by the motor cooling process has been analyzed.

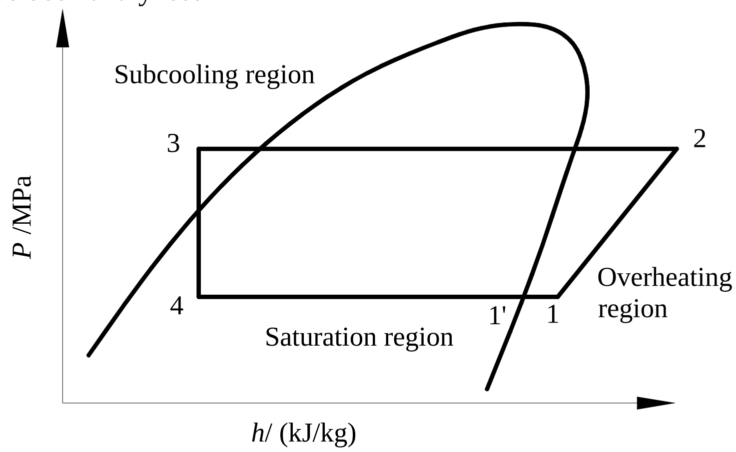

Figure 3. Semi-closed SSRC work cycle with the motor cooling method using suction gas

2.2. Motor cooling method using injected refrigerant liquid

Figure 4 shows the structure of the semi-closed SSRC with the motor cooling method using injected refrigerant liquid (case 2). In this method, the liquid refrigerant from the condenser is divided into two parts. One part of the liquid refrigerant with high pressure and low temperature enters into the evaporator after flowing through the expansion valve to participate in the refrigeration cycle process, the other part of the liquid refrigerant with high pressure and low temperature is directly injected into the motor chamber after flowing through the throttling capillary to realize the cooling of the motor windings. Then this part of the refrigerant used for cooling the motor will be mixed with the rest of the refrigerant and entered into the working chamber to participate in the refrigeration cycle process. By using this method, the temperature of the suction refrigerant gas will be decreased than that of the case 1. The influence of cooling process using injected refrigerant liquid also has been analyzed as follows.

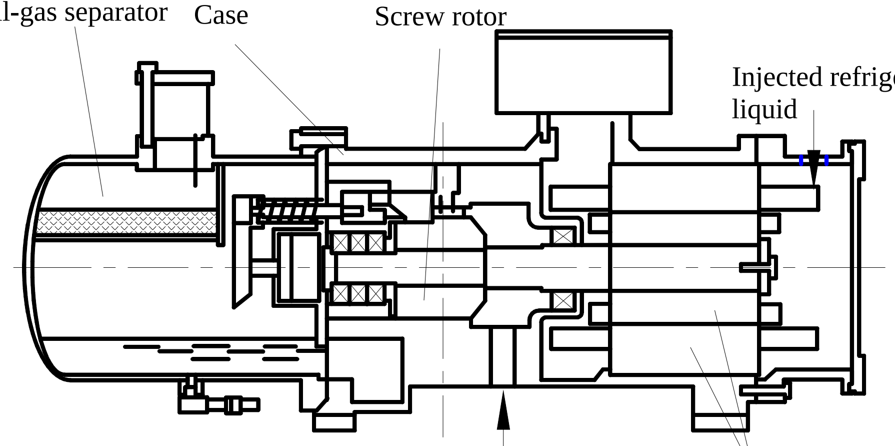

Figure 4. Semi-closed SSRC with the motor cooling method using injected refrigerant liquid

3. Mathematical model of the motor cooling process

3.1. Energy loss calculation model for the motor

According to the motor cooling principle in the semi-closed SSRC, the dissipation heat generated by the motor must be carried off by the refrigerant. So in order to analyze the motor cooling process, the dissipation heat generated by the motor under the steady state must be gained. By the motor design theory, dissipation heat generated by the motor due to the energy loss in the process of electrical energy converted into mechanical energy mainly include the basic iron loss, the electric loss and the stray loss [15]. The energy loss calculation model for the fixed frequency motor is shown as follows.

Basic iron loss of the fixed frequency motor contains the hysteresis loss and eddy current loss caused by the main magnetic field changes in the core, the calculation formula of these basic iron losses is:

$$P_{Fe} = K_a P_{he} G \sum_i P_{hei} G_i \tag{1}$$

Where K_a is the experience factor which is used to represent the basic iron losses increase caused by the processing and of the steel, the magnetic flux density distribution and change, P_{hei} is the loss coefficient, G_i is the quantity which is suffered by the magnetizing effect.

The electric loss of the fixed frequency motor includes the copper (aluminum) consumption loss of each winding and the contact consumption loss between the brush, collector ring and the commutator, the calculation formula of these basic iron losses is:

$$P_{\mathrm{Cu(Al)1}} = m I_x^2 R_x \tag{2}$$

$$P_{\mathrm{cb}} = \Delta U_b I_b \tag{3}$$

Where m is the phase number, I_x is the electric current in the winding, R_x is the resistance of the winding, ΔU_b is the contact voltage drop of the brush, I_b is the electric current flow through the brush.

The leakage magnetic field (including harmonic magnetic field) which is generated by the working current in the stator and rotor will cause the loss in the winding and iron core and structures. These losses compose the stray loss and make the stray loss very complex. In view of this, the stray loss of the fixed frequency motor is difficult to calculate accurately. At present, motor design scholars at home and abroad tested the stray loss of different types and specifications induction motor under load condition. Through summarizes the result of the test, the relationship between the load stray loss and the motor rated power was obtained. For the cast aluminum rotor, the load stray loss in proportion to the rated power of motor is shown in table 1. So the stray loss can be calculated by the rated power of motor.

Table 1. The load stray loss in proportion to the rated power

Motor series	2	4	6	8/10
P_{s1} / P_N	0.025	0.02	0.015	0.01

In addition, the friction loss and ventilation loss also vary with the change of the variable frequency motor rotation speed. Generally speaking, the friction loss of rolling bearing is proportional to the speed, and the ventilation loss is proportional to the three times of the speed. By solving the losses mentioned above, the heat generated by the motor used in the semi-closed SSRC can be obtained.

3.2. The heat exchange process calculation model

In the case 1, the suction refrigerant gas with lower temperature and pressure will flows into the suction chamber through the motor. Then the heat exchange between the suction refrigerant gas and the motor will occurs which will cause the heat of the refrigerant gas. This inspiratory preheating phenomenon will changes the thermodynamic properties of the suction refrigerant gas, and eventually result in the decrease of capacity and efficiency of the semi-closed SSRC. As a consequence, in semi-hermetic SSRCs, the dissipation heat generated by the motor has bigger influence on the suction refrigerant gas. According to the principle of conservation of energy, the dissipation heat generated by the motor can be divided into two parts. One part of it makes the motor temperature rise, and the other part of it will be distributed to the refrigerant gas flows through the motor. So the distribution of the heat generated by the motor can be obtained:

$$\dot{Q}\mathrm{d}t = C\mathrm{d}T + \alpha_{\mathrm{m}} ST\mathrm{d}t \tag{4}$$

Where $\dot{Q}$ is heat generated by the fixed frequency motor per unit time, C is the heat capacity of the motor, α_{m} is the heat transfer coefficient of the motor, S is the heat transfer area of the motor, T is the temperature rise of the motor.

When the motor running to steady state, the dissipation heat generated by the motor will all is passed to the suction refrigerant gas which will cause the overheating of the gas. And then a steady state temperature rise will be achieved. The temperature rise of the suction refrigerant gas caused by the motor is:

$$\dot{Q}\mathrm{d}t = c_{\mathrm{g}} m_{\mathrm{g}} \left(T_{\mathrm{sd}} - T_{\mathrm{s}}\right) \tag{5}$$

Where c_{g} is the specific heat of refrigerant, m_{g} is the mass of refrigerant, T_{s} is the suction temperature of refrigerant.

In the case 2, the part of the liquid refrigerant with high pressure and low temperature is directly injected into the motor to take away the dissipation loss of the motor. After the heat transfer process, the liquid refrigerant absorbs heat and becomes superheated steam. Then the superheated refrigerant gas will enters into the suction chamber and be mixed with the rest of the refrigerant. The mixed refrigerant gas finally enters into the working chamber to participate in the refrigeration cycle process. In this method, there are two times of heat exchange process: the first process is the heat exchange between the liquid refrigerant and the motor, the second process is the heat exchange between the superheated refrigerant and the refrigerant comes from the evaporator.

According to the energy conservation equation, the heat exchange process between the liquid refrigerant and the motor can be expressed as follows:

$$\dot{Q}\mathrm{d}t + m_1 h_1^{'} = m_1 h_1 \tag{6}$$

The heat exchange process between the superheated refrigerant and the refrigerant comes from the evaporator can be expressed as:

$$m_1 h_1 + m_2 h_2 = (m_1 + m_2) h_s \tag{7}$$

Where m_1 is the mass of the injected liquid refrigerant, $h_1^{'}$ is the enthalpy of the injected liquid refrigerant, h_1 is the enthalpy of superheated steam, m_2 is the mass of the refrigerant comes from the evaporator, h_2 is the enthalpy of the refrigerant comes from the evaporator, h_s is the enthalpy of the suction refrigerant gas.

These calculation models were integrated into the mathematical model describing the working process of the SSRC as a subroutine in the form of the preheating of the suction refrigerant gas caused by the motor cooling process [14]. a step-by-step calculation procedure as shown in ref [14]with the fourth order Runge-Kutta method was compiled to solve the presented theoretical calculation model. Then influences of motor cooling parameters on the thermal dynamic performance of the compressor can be analyzed. In order to compare accurately, lubricating oil heat exchange effect was ignored in this study.

4. Results and discussion

In this paper, a typical semi-closed SSRC used in refrigeration and air conditioning field with the structure and operation parameters as shown in table 2 was chosen for the calculate example. By using this semi-closed SSRC, the influence of the motor cooling parameters such as suction gas temperature, suction gas quantity, temperature of the injected refrigerant liquid and quantity of the injected refrigerant liquid on the thermal dynamic performance of the compressor were analyzed. The performances of the compressor using these two kinds of the motor cooling methods were compared. The analysis results are shown as follows.

Table 2. The main parameters

Parameters(and unit)	Symbols	Value	Parameters(and unit)	Symbols	Value
Gear ratio	ε	11/6	Length of the screw (mm)	L	155.7
Radius of the screw (mm)	R_1	181	Star wheel thickness (mm)	t	7.25
Star wheel radius (mm)	R_2	181	Refrigerant/Lubricating oil	Re/ oil	R22/S uniso 4GS
Center distance (mm)	A	144.8	Evaporation temperature (K)	T_e	278.15
Breadth of the star wheel (mm)	b	26.5	Condensation temperature (K)	T_c	313.15
Rotate speed (r.min^{-1})	n	2880	Superheat temperature (K)	ΔT	5

For the case 1, the influence of the suction gas quantity on the thermal dynamic performance of the compressor is analyzed by changing the rotate speed of the compressor and is shown in figure 5. The variation tendency of the curves in figure 5 shows that the suction gas temperature of the compressor will rises due to the dissipation heat generated by the motor. That will cause the increase of the specific volume and the decrease of the displacement of the compressor. The temperature rise of the suction gas and the specific volume increment will decrease with the increase of the compressor rotate speed. But the lower degree of displacement will increases with the increase of the rotate speed.

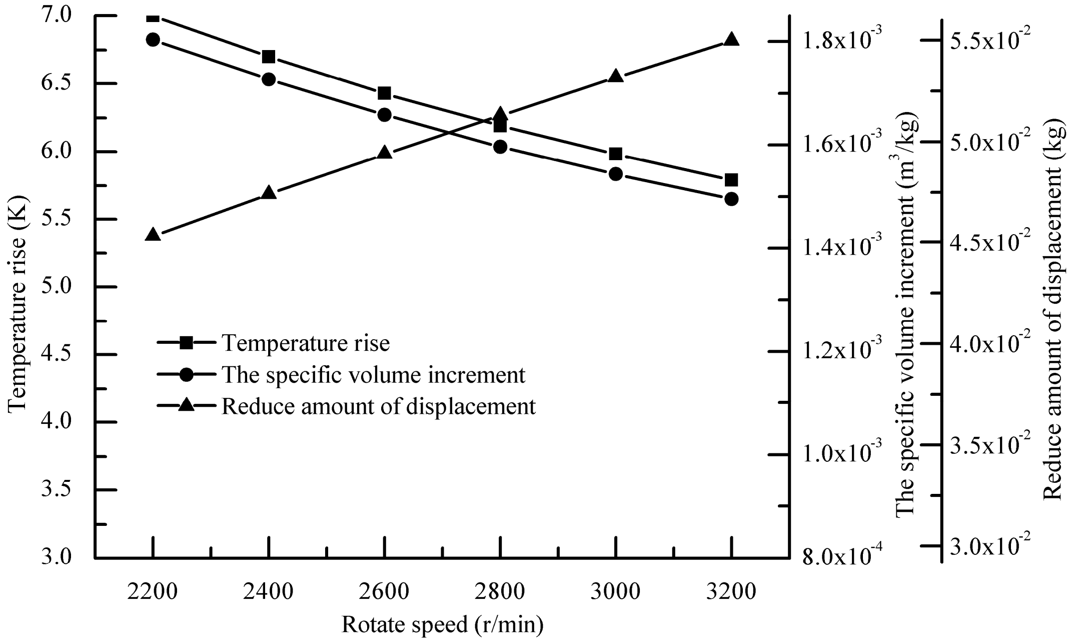

Figure 5. The influence of the suction gas quantity in the suction gas cooling method

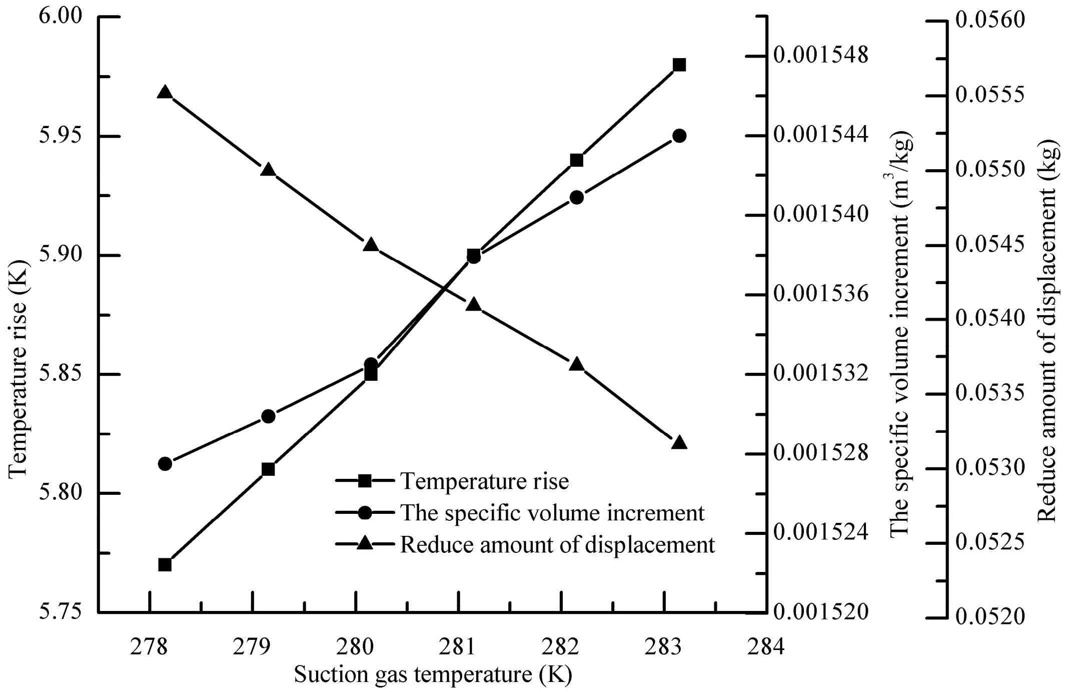

Figure 6. The influence of the suction gas temperature in the suction gas cooling method

Figure 6 shows the influence of the suction gas temperature on the thermal dynamic performance of the case 1. As the variation tendency of the curves shown in figure 6, the temperature rise of the suction gas, the specific volume and the displacement of the compressor are all affected by the suction gas temperature. The temperature rise of the suction gas and the specific volume increment will increases with the increase of the suction gas temperature. But the lower degree of displacement will decreases with the increase of the suction gas temperature.

After researching the influence of the motor cooling parameters on the thermal dynamic performance of the case 1, the influence of the motor cooling parameters for the case 2 were also analyzed. The analysis results are shown as follows.

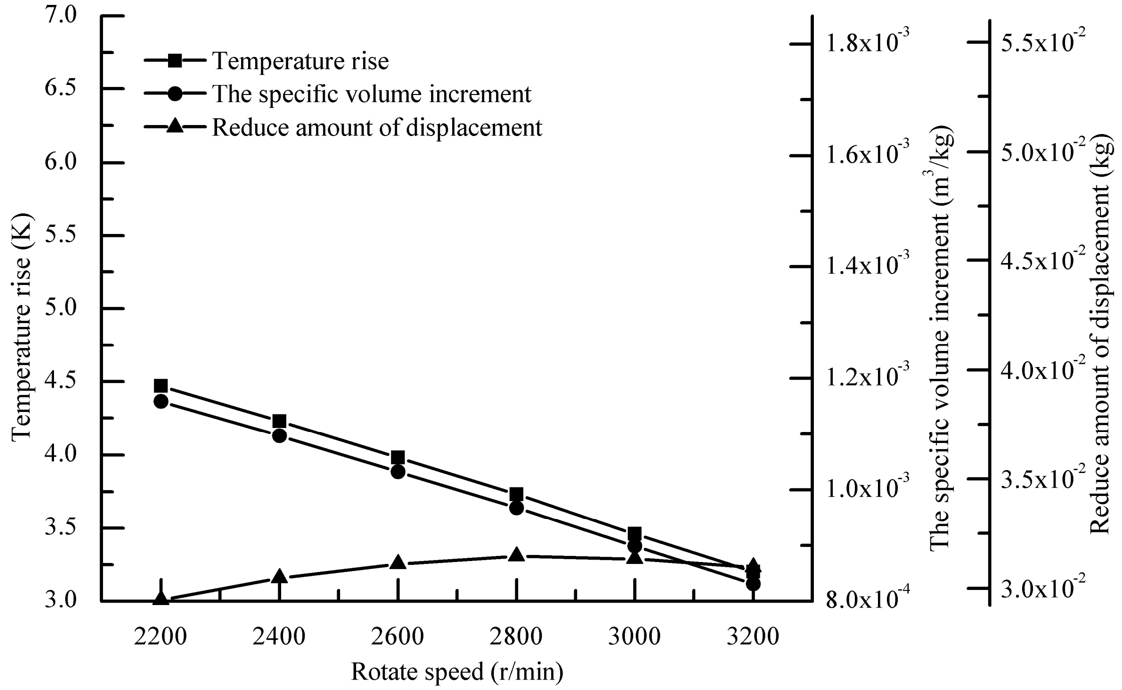

Figure 7. The influence of the suction gas quantity in the refrigerant liquid cooling method

The influence of the rotate speed on the thermal dynamic performance of the compressor is analyzed and shown in figure 7. The contrast of the curves in figure 5 and figure 7 shows that the temperature rise of the suction gas caused by the motor cooling process in case 2 is lower than that in the case 1. The lower temperature of the suction gas will cause the lower specific volume increment and the lower reduce amount of displacement. That means the motor cooling capacity of the injected refrigerant liquid is better than the suction gas. The variation tendency of the curves in figure 7 shows that the temperature rise of the suction gas will decreases with the increase of the compressor rotate speed. The specific volume increment will increases with the increase of the rotate speed. But the lower degree of displacement will increases firstly and then decreases with the increase of the rotate speed.

The influences of the liquid refrigerant temperature and the liquid refrigerant quantity on the thermal dynamic performance of the case 2 are shown in figure 8 and figure 9 respectively. Through the variation tendency of the curves in figure 8, the temperature rise of the suction gas, the specific volume increment and the lower degree of displacement will all increase with the increase of the liquid refrigerant temperature. But the curves in figure 9 show that the temperature rise of the suction gas, the specific volume increment and the lower degree of displacement will all increase firstly and then decrease with the increase of the liquid refrigerant quantity.

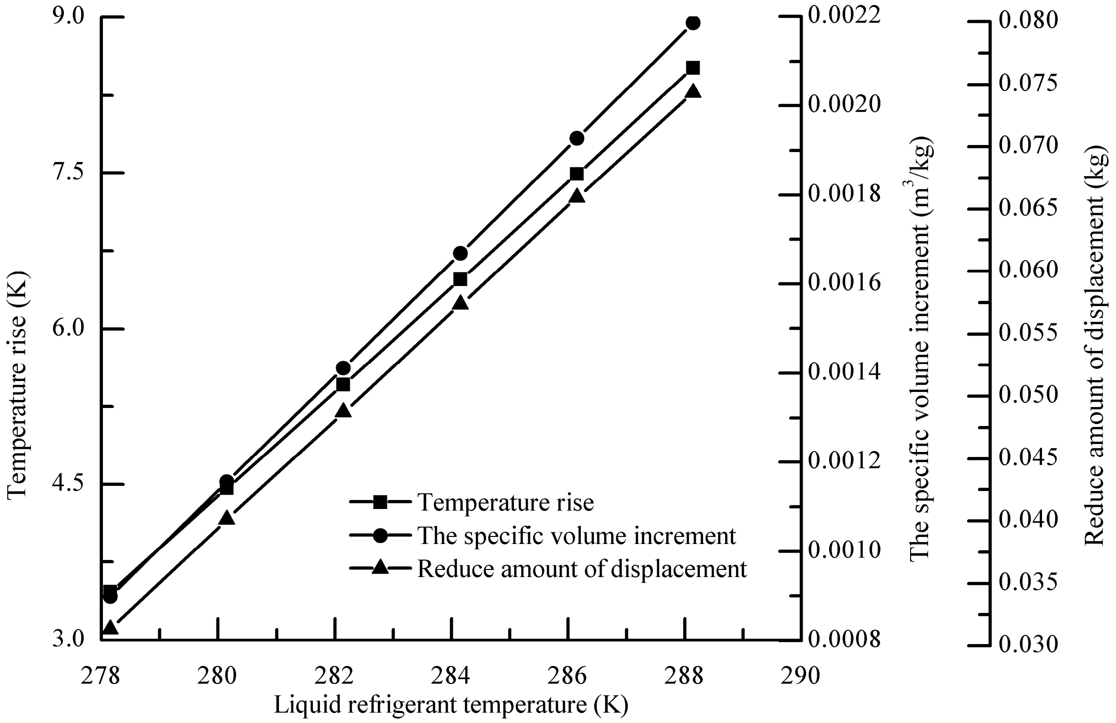

Figure 8. The influence of the liquid refrigerant temperature

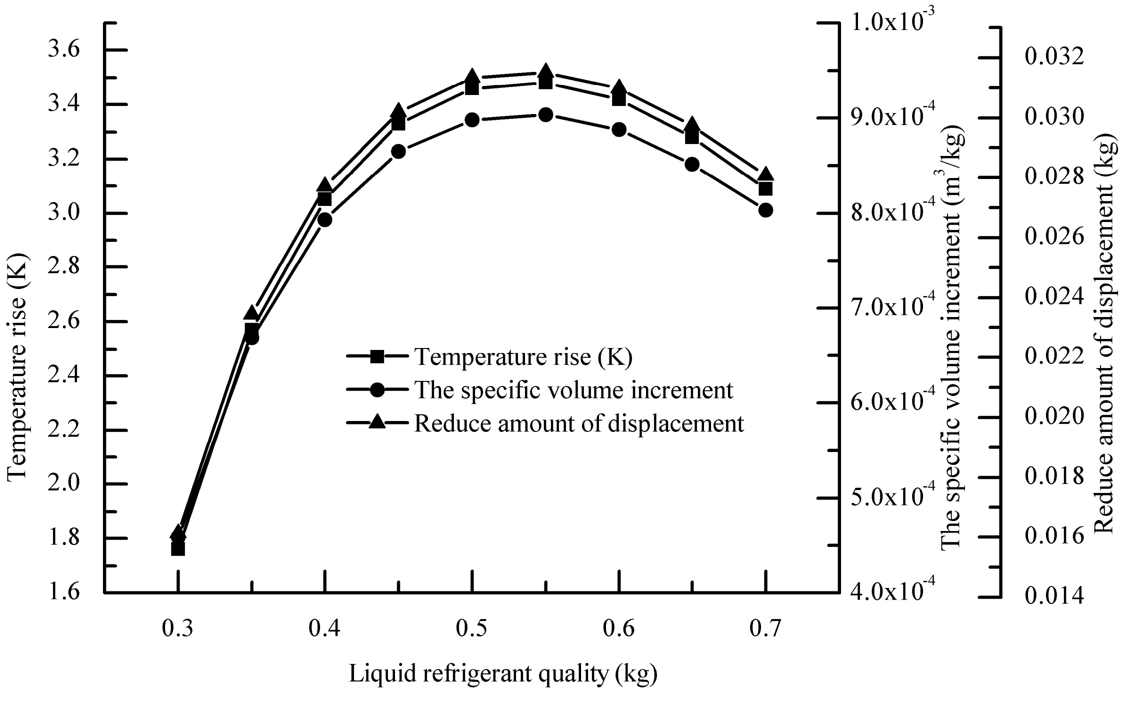

Figure 9. The influence of the liquid refrigerant quantity

5. Conclusion

1) All of motor cooling methods by using suction gas and injected refrigerant liquid will affect the thermal dynamic performance of the semi-closed SSRC. The motor cooling capacity of the injected refrigerant liquid is better than the suction gas.
2) For the semi-closed SSRC with the motor cooling method using suction gas, the increase of the compressor rotate speed will makes the decrease of the suction gas temperature rise and the specific volume increment but the increase of the displacement lower degree. But the influence of suction gas temperature is just the opposite.
3) For the semi-closed SSRC with the motor cooling method using injected refrigerant liquid, the increase of the compressor rotate speed will results in the decrease of the suction gas temperature rise and the increase of the specific volume increment. The lower degree of displacement will increases firstly and then decrease with the increase of the rotate speed.
4) In the semi-closed SSRC with the motor cooling method using injected refrigerant liquid, the temperature rise of the suction gas, the specific volume increment and the lower degree of displacement will all increase with the increase of the liquid refrigerant temperature. But the temperature rise of the suction gas, the specific volume increment and the lower degree of displacement will all increase firstly and then decrease with the increase of the liquid refrigerant quantity.

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