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# Evaluation of Methods to Decrease the Discharge Temperature of R32 Scroll Compressor

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## ABSTRACT

Recently, R32 has been considered as an important alternative in application of small to middle capacity air conditioner by many countries due to its advantages such as low global warming potential (GWP), favorable thermal properties, less refrigerant charge and low cost. However, the much increased discharge temperature of R32 compressor, as compared with the R22, becomes the main barrier affecting the wide and quick adoption. Refrigerant injection has proven to be effective in decreasing discharge temperature. In this work, three kinds of refrigerant injection technology used to decrease the discharge temperature of R32 scroll compressor are discussed, namely, two-phase suction, liquid injection and two-phase/gas injection. The detailed scroll compressor model proposed in previous work is modified and validated by experimental data of R32 scroll compressor. The potentials in decreasing discharge temperature of the three methods are investigated. The detailed performance comparisons are presented. The results indicate that the two-phase/gas injection achieves the best performance with the enhancement of cooling capacity by 14.2% and increase in COP by 8.1%.

## 1. INTRODUCTION

### 1.1 R32 as an Alternative Refrigerant

Hydrochlorofluorocarbons (HCFCs), such as R22, are widely used in the vapor compression refrigeration and air conditioning system attributed to its good energy performance. However, the transition from HCFCs is underway for environmental protection pursuant to the Montreal protocol, and the increasingly stringent global restriction of greenhouse gases emission accelerates the schedule. Hydrofluorocarbons (HFCs) have been found as the leading replacement for HCFCs in refrigeration and air-conditioning systems (Bolaji and Huan, 2013). Mixtures of HFCs, such as R410A (50%R32+50%R125) and R407C (23%R32+25%R125+52%R134a), are being used in some countries to replace R22 (Calm and Domanski, 2004), while the global warming potential (GWP) of R410A (GWP=2000) and R407C (GWP=1700) are still relatively high.

Recently, R32 has been considered as an important alternative in application of small to middle capacity air conditioners by many countries due to its advantages such as low GWP (670), favorable thermal properties, less refrigerant charge and low cost (Pham and Rajendran, 2012). Nevertheless, the much increased discharge temperature of R32 compressor, as compared with the R22, becomes the main barrier affecting the wide and quick adoption.

### 1.2 Refrigerant Injection Technology

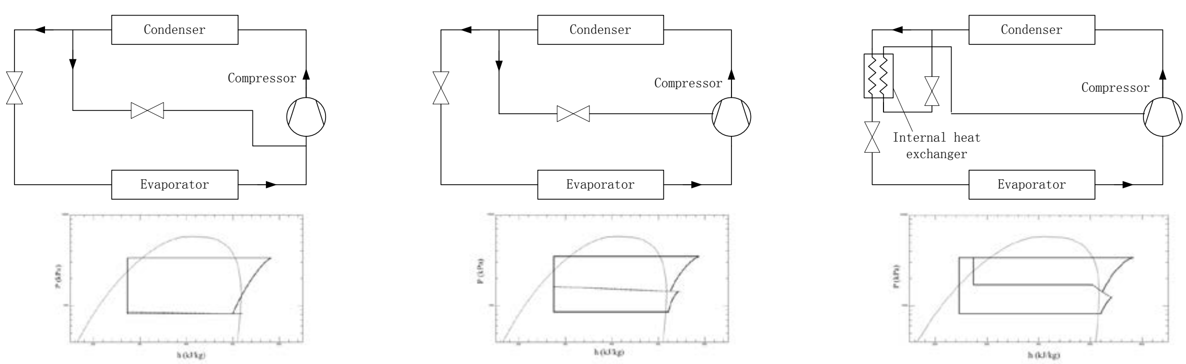
Refrigerant injection is a technique that involves injecting the refrigerant from the condenser outlet to the suction line, or the sealed compression pocket, or the condenser inlet in a vapor compression system (Xu *et al*., 2011), and it has proven to be effective in decreasing discharge temperature (Dutta *et al*., 2001; Park *et al*., 2002). The decrease in discharge temperature by refrigerant injection is mainly caused by the cooling effect of injected refrigerant, and sometimes accompanied with wet compression.

The injected refrigerant can be liquid, two-phase or gas. In liquid refrigerant injection, the subcooled refrigerant from condenser outlet is directly injected into the injection port. Dutta *et al*. (2001) theoretically and experimentally investigated the influence of liquid refrigerant on performance, and found that the oil temperature decreased with increasing injection ratio and leaded to slight improvement in performance. To achieve two-phase injection or gas injection, an internal heat exchanger is settled in the outlet of condenser, providing heat transfer between the injected mass flow after upper-stage expansion valve and the mass flow to lower-stage expansion valve. Wang *et al*. (2007) compared the influences of gas injection and liquid injection on system performance. It was revealed that gas injection increased the system performance greatly while liquid injection had limited influence. Wang *et al*. (2009b) also analyzed the effects of injection enthalpy. It was found that the indicated efficiency increased with the decrease of injection enthalpy, which was attributed to decrease of the inner leakage and effects on the under-or over-compression loss.

### 1.3 Objective of this Work

The objective of this study is to investigate the possibility of using refrigerant injection to decrease the discharge temperature of R32 scroll compressor, and compare the performance of different refrigerant injection methods.

This work involves three kinds of refrigerant injection technology to decrease discharge temperature: (1) two-phase suction, by injecting liquid refrigerant into the suction line to achieve wet compression; (2) liquid injection, by injecting liquid refrigerant into the compression pocket; (3) two-phase/gas injection, by injecting two-phase refrigerant or gas refrigerant into the compression pocket, an internal heat exchanger is needed in this method. Figure 1 (a~c) shows the schematics and P-h diagrams of the injection cycles of three methods.




a) Two-phase suction    b) Liquid injection    c) Two-phase/gas injection

**Figure 1:** Schematics and P-h diagrams of the injection cycles

## 2 MODEL DEVELOPMENT AND VALIDATION

Scroll compressor offers low vibration and noise level, high efficiency and high reliability, and has become more and more popular in the fields of refrigeration and air-conditioning. Scroll compressor has been found quite suitable for application of refrigerant injection technology, as it is less sensitive to slugging problem (Liu and Soedel, 1994) and more convenient to equip injection and control injection pressure.

### 2.1 Model Development

The refrigerant injection process is a continual parameter-varying and time-varying "adiabatic throttling + isobaric mixing" process (Wang *et al*., 2008). To investigate the effects of refrigerant injection on the whole process of the compressor, a distributed parameter model of scroll compressor is applied. This model involves the suction, compression and discharge process. The refrigerant leakage, both in radial direction and flank direction, and the refrigerant injection have been considered. Besides, the heat transfer of refrigerant with suction tube, the scroll wall, motor, mechanical components and shell have been calculated. The detailed information of proposed model can be found in author's published work (Wang *et al*., 2008; Wang *et al*., 2005).

## 2.2 Model Modification

In the original model, the effects of oil are neglected. In the simulation, the scroll compressor is a high-side piston compressor, which means the oil temperature is mainly affected by the discharge temperature. As the simulated condition varies in a large extent, the oil temperature differs greatly. With the increase of oil temperature, the viscosity of oil decreases and thus leads to the degradation of lubricating performance and higher leakage in the compression process. To include the effects of oil temperature in this model, the leakage coefficient is as a function of compression ratio. The curve is fitted with a set of experimental data, as shown in Figure 2.

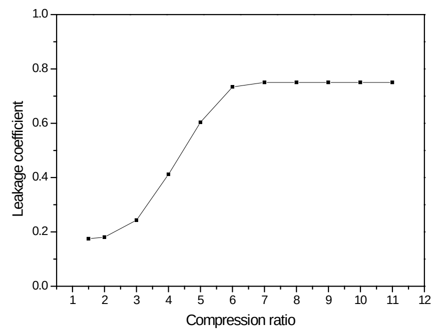



**Figure 2:** Variation of leakage coefficient as a function of compression ratio

## 2.3 Model Validation

The model has to be validated by a variety of conditions before it is employed in performance prediction of R32 scroll compressor. Table 1 presents the parameters of compressor. For conditions with refrigerant injection into compression pocket, the injection port is set at the position after where suction pocket closes.

**Table 1:** Parameters of the scroll compressor

| Item | Value |
|---|---|
| Basic circle radius (mm) | 3.36 |
| Thickness of the scroll (mm) | 5.49 |
| Height of the scroll (mm) | 40.60 |
| Number of the circle (mm) | 3.00 |

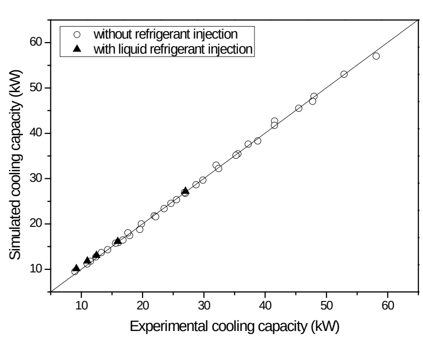



**Figure 3:** Comparison of experimental and simulated cooling capacity

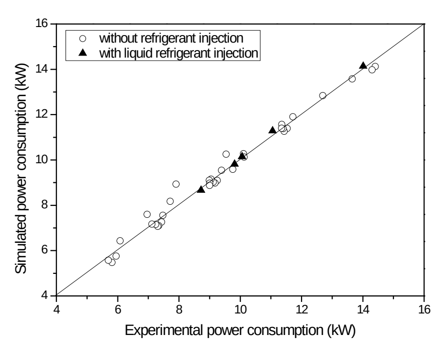



**Figure 4:** Comparison of experimental and simulated power consumption

Both conditions without refrigerant injection and those with liquid refrigerant injection are validated, as shown in Figure 3 and Figure 4. It can be concluded that the predicted results agree well with experimental results, with the relative errors of cooling capacity and power consumption within 6% and 10%, respectively. The results indicate that the model is capable of predicting performance of R32 scroll compressor.

## 3. RESULTS AND DISCUSSION

In a R32 scroll compressor without refrigerant injection, the operating envelope is limited to a smaller one than those of compressors using other kinds of refrigerants essentially due to the high discharge temperature especially in sever conditions such as high temperature cooling and low temperature heating. As mentioned previously, three kinds of refrigerant injection method are applied to decrease the discharge temperature with the purpose to cover a wider operating envelope. During the investigation, the conditions with discharge temperature higher than 135°C are considered to be unacceptable and hence beyond the operating envelope. The subcooling of condenser and superheating of evaporator are respectively kept at 7°C and 5°C during the simulation.

### 3.1 Two-phase Suction

In two-phase suction, the liquid refrigerant from condenser out is directly injected to the suction line to adjust the enthalpy of the suction refrigerant. By lowering the suction quality to a certain degree, within scroll compressors' ability to handle liquid slugging, it is possible to reduce the discharge temperature of R32 compressor.

Figure 5 shows the comparison of operating envelopes of R32 scroll compressor with different suction quality. The envelope of suction refrigerant with superheating of 5°C refers to the envelope of R32 scroll compressor without injection. In general, with more liquid refrigerant injected into suction, R32 compressor achieves a lower suction quality and a wider operating envelope, which also increases the risk of liquid slugging. For compressors with suction quality keep at 0.95 and 0.9, the envelopes expand about 8°C and 19°C in condensing temperature over that without injection, while envelope for compressors with saturated suction expands slightly.

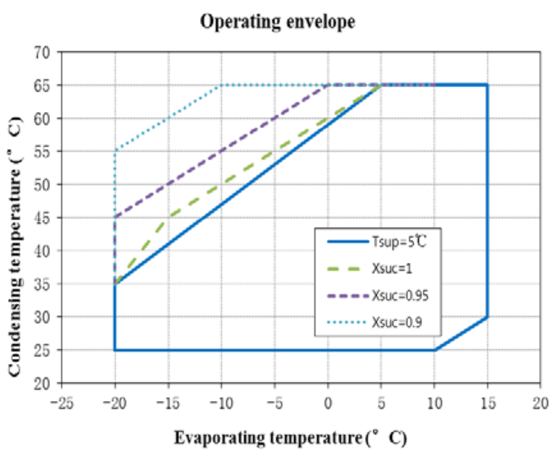
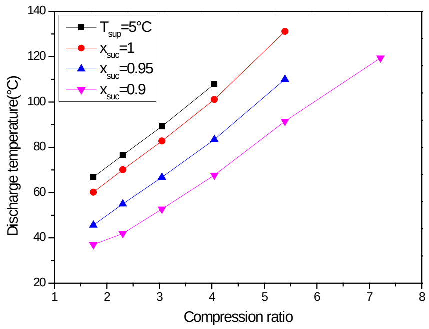



**Figure 5:** Comparison of operating envelopes of R32 scroll compressor with different suction quality

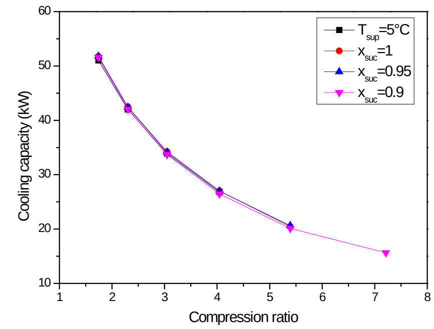
**Table 2:** Six typical conditions selected for performance comparison of different suction quality

| Conditions | Evaporating temperature (°C) | Condensing temperature (°C) | compression ratio |
|---|---|---|---|
| 1 | 10 | 30 | 1.74 |
| 2 | 5 | 35 | 2.30 |
| 3 | 0 | 40 | 3.05 |
| 4 | -5 | 45 | 4.05 |
| 5 | -10 | 50 | 5.39 |
| 6 | -15 | 55 | 7.21 |

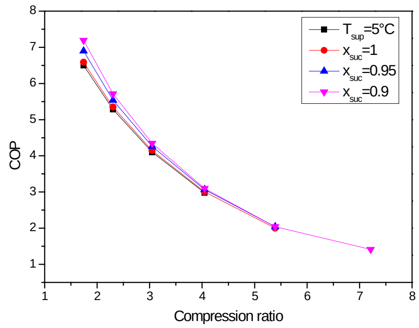
To conduct a detailed performance comparison of R32 scroll compressors with different suction quality, six typical conditions with different compression ratio in the envelope are selected, as presented in Table 2.



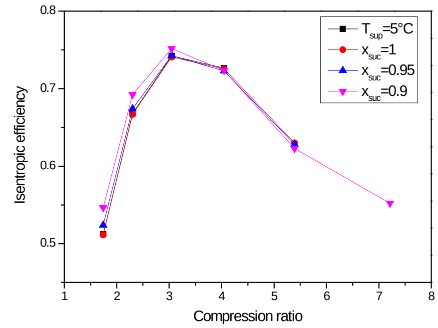

a) Discharge temperature




b) Cooling capacity




c) COP




d) Isentropic efficiency

**Figure 6:** Detailed performance comparison of R32 scroll compressors with different suction quality

Figure 6 (a~d) illustrates the detailed comparison of discharge temperature, cooling capacity, COP and isentropic efficiency. In average, discharge temperature decreases about 6°C, 22°C and 34°C by lowering suction quality to 1, 0.95 and 0.9, respectively. With the suction quality going down, the two-phase suction obtains greater potential in decreasing discharge temperature, while shows barely difference on cooling capacity. Moreover, two-phase suction shows a slight improvement in COP in low compression ratio, this is mainly caused by the much decreased oil temperature which leads to better lubricating performance and a higher isentropic efficiency. The two-phase suction has good feasibility in control strategy. However, the lowering suction quality also reduces the reliability of compressor, especially for low-side piston compressors, in which two-phase suction could result in oil dilution and performance deterioration.

## 3.2 Liquid Injection

In liquid injection, the liquid refrigerant is injected into compression pocket in severe conditions to control the discharge temperature within 135°C, and injection is not adopted in mild conditions.

Figure 7 presents the distribution of discharge temperature in the envelope of R32 scroll compressor with injection. It can be seen that the envelope covers all the condition in the left upper zone by liquid injection, which indicates the high effectiveness of liquid injection in decreasing discharging temperature. The distributions of cooling capacity and COP are shown in Figure 8. Liquid injection reduces the risk of oil dilution as compared with the two-phase suction, and it is also very convenient to realize the control strategy. It can be concluded that liquid injection is able to guarantee the steady operation in severe conditions.

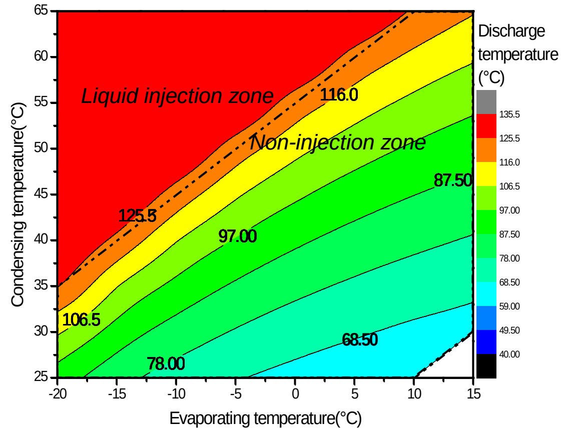
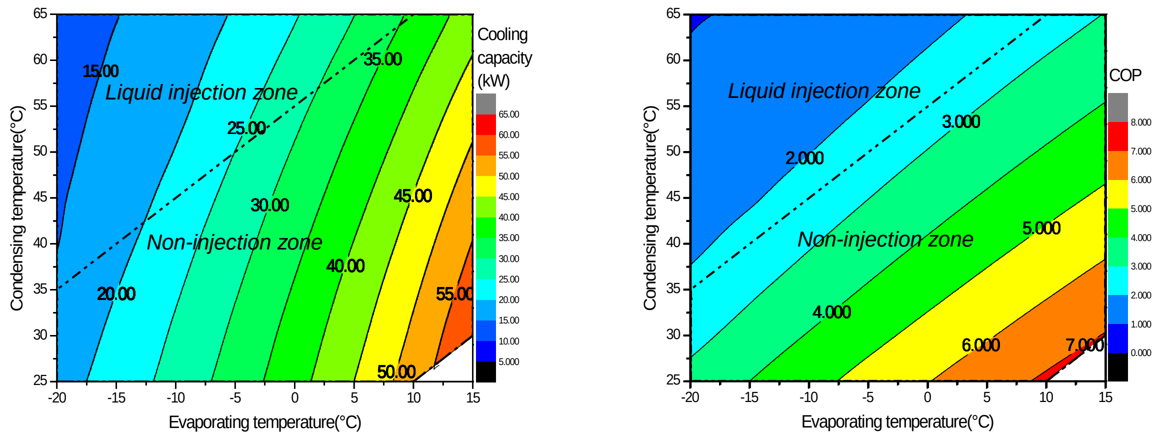



**Figure 7:** Distribution of discharge temperature of R32 scroll compressor with liquid injection in the envelope




a) Cooling capacity

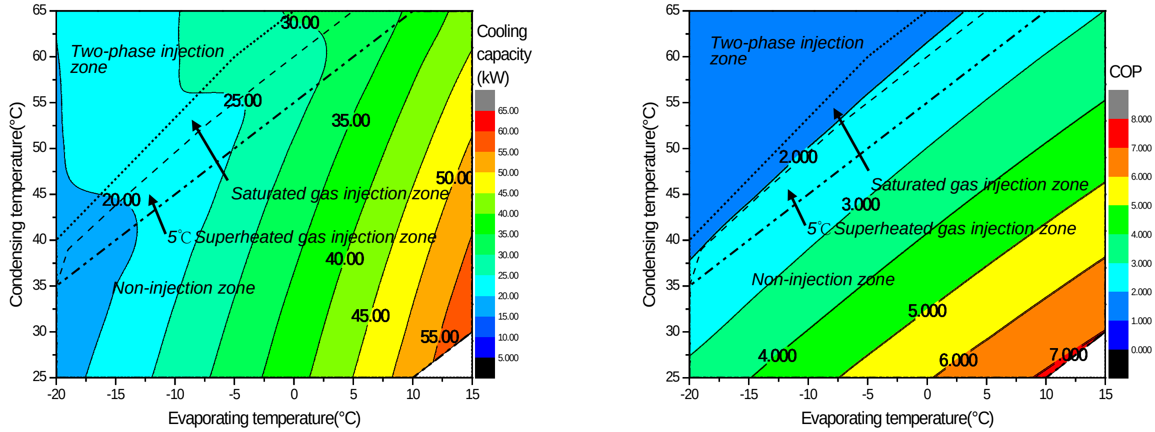
b) COP

**Figure 8:** Performance of R32 scroll compressor with liquid injection in the envelope

### 3.3 Two-phase/Gas Injection

In the two-phase/gas injection, the refrigerant is injected into compression pocket after heat transfer in internal heat exchanger. In slightly severe conditions, the injected refrigerant is controlled at superheated or saturated state, as gas injection has been proven to have a positive effect on system performance (Wang *et al.*, 2009a). A certain degree of superheating brings convenience in control of gas injection, as it provides a control signal. In more severe conditions, where gas injection is not able to control the discharge temperature within 135°C, two-phase injection is adopted.

The performance in operating envelope of R32 scroll compressor with two-phase/gas injection is given in Figure 9 (a~b). The gas injection with a superheating of 5°C has a narrow operating range and is not able to effectively decrease discharge temperature in more severe conditions. However, the combination of two-phase injection and gas injection is able to cover all the conditions in the left upper zone. In addition, an enhancement in cooling capacity and an increase in COP can be observed in the injection zone as compared with liquid injection. The enhancement of cooling capacity can be attributed to the further subcooling of refrigerant in internal heat exchanger, while the increase in COP is mainly due to reduction in under-compression loss. It should also be mentioned that the control strategy for two-phase injection is relatively complex and that careful consideration is needed in optimization of injection pressure.




a) Cooling capacity b) COP

**Figure 9:** Distribution of COP of R32 scroll compressor with two-phase/gas injection in the envelope

### 3.4 Performance Comparison of Three Injection Methods

All the three proposed injection methods show promising capability to decrease discharge temperature in severe conditions. To give a comprehensive performance comparison of the three methods, six typical conditions in the upper left zone with high compression ratios are selected, as presented in Table 3. To set a fairly baseline, the discharge temperature of R32 scroll compressor is controlled at the 135°C by various methods.

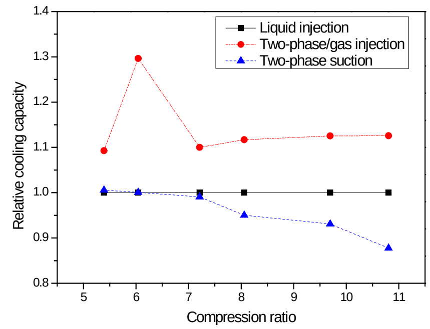
**Table 3:** Six typical conditions selected for performance comparison of the three methods

| Conditions | Evaporating temperature (°C) | Condensing temperature (°C) | compression ratio |
|---|---|---|---|
| 1 | -10 | 50 | 5.39 |
| 2 | -10 | 55 | 6.04 |
| 3 | -15 | 55 | 7.21 |
| 4 | -15 | 60 | 8.06 |
| 5 | -20 | 60 | 9.70 |
| 6 | -20 | 65 | 10.81 |

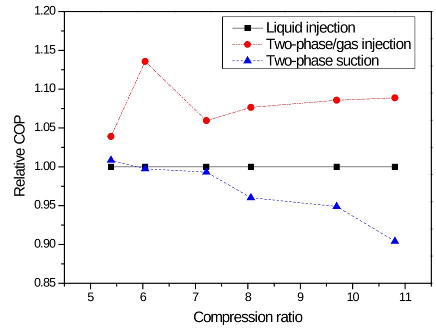
Figure 10 illustrates the performance comparison of R32 scroll compressor with different injection method. The relative values of compressors with liquid injection are treated as 1, as liquid injection has relatively limited effect on cooling capacity and COP (Dutta *et al.*, 2001). The two-phase/gas injection shows significant enhancement in cooling capacity and COP by 14.2% and 8.1% in average over liquid injection. The enhancement is caused by two reasons. On one hand, the heat transfer in internal heat exchanger leads to large enthalpy difference between the inlet and outlet of evaporator. On the other hand, the two-phase/gas injection reduces the under-compression loss and therefore obtains a higher isentropic efficiency. For the two conditions with lower compression ratios, the gas injection is adopted, and more obvious enhancement is observed in performance of condition 2 due to more injected refrigerant into compressor. In general, more injected refrigerant is needed to decrease discharge temperature for conditions with extremely high compression ratio. The two-phase/gas injection also increases the pressure in the injected compression pocket, resulting in a slight increase in leakage and decrease in suction mass flow rate.

However, the two-phase suction shows different characteristics in performance. In the conditions with relatively low compression ratios, two-phase suction acquires almost the same the cooling capacity and COP as liquid injection, while in conditions with higher compression ratios, it shows degradation both in cooling capacity and COP. With a small amount liquid refrigerant injected into suction line, the density of suction refrigerant increases and the suction mass flow from evaporator remains basically unchanged. In the severe conditions, a considerable amount of liquid refrigerant is injected into suction line, as a result, the pressure drop in suction line increases and the suction mass flow from evaporator decrease.

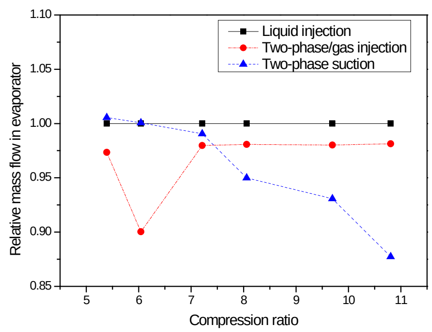
Based on the above performance comparison and analysis, it can be concluded that the two-phase/gas injection achieves the best performance in various conditions. Despite the advantages in performance, two-phase/gas injection is very difficult to control in operation, while the systems of two-phase suction and liquid injection are simpler and the control strategies are easier.



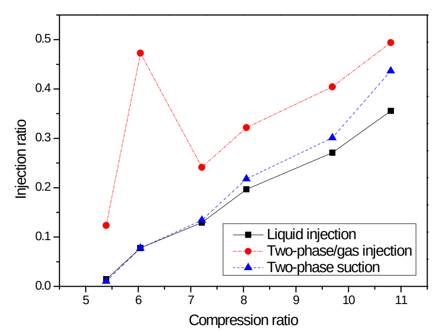

a) Relative cooling capacity




b) Relative COP




c) Relative mass flow in evaporator




d) Injection ratio

**Figure 10:** Performance comparison of R32 scroll compressor with different injection method

## 4. CONCLUSION

R32 is an important alternative refrigerant, and the high discharge temperature has been the main barrier for wide and quick adoption. In this work, three kinds of injection technology are proposed to decrease discharge temperature of R32 scroll compressor, namely, two-phase suction, liquid injection and two-phase/gas injection. Through the comprehensive performance investigation, the conclusions can be drawn as follows:

(1) All the three methods show promising potential in decreasing discharge temperature of R32 scroll compressor, while there is some difference in performance.

(2) By lowering suction quality to 0.95 and 0.9, the envelopes expand in condensing temperature by about 8°C and 19°C, respectively, while envelope expands slightly for compressors with saturated suction. In spite of the good feasibility in control strategy, two-phase suction reduces the reliability of compressor.

(3) Liquid injection and two-phase suction achieve almost the same performance in less severe conditions, while two-phase suction shows performance degradation in more severe conditions. Besides, liquid injection reduces the risk of oil dilution as compared with two-phase suction.

(4) Although gas injection is less effective in decreasing discharge temperature, the combination of two-phase/gas injection is able to cover all the conditions in the upper left zone. Moreover, two-phase/gas injection is effective in reduction of under-compression loss, and achieves the best performance with the enhancement of cooling capacity by 14.2% and increase in COP by 8.1%. Still, control strategy for two-phase injection is difficult and careful consideration is needed in optimization of injection pressure.

## ACKNOWLEDGEMENT

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