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Theoretical and Experimental Research on the Optimal Displacement Ratio of Rotary Two-stage Inverter Compressor with Vapor Injection

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ABSTRACT

Displacement ratio is one of the most important parameters of designing rotary two-stage inverter compressor with vapor injection, which decides the COP (Coefficient of Performance) of the compressor. The optimal displacement ratio can bring about the highest COP. The mathematical model of the optimal displacement ratio of rotary two-stage inverter compressor with vapor injection has been developed and verified with the test data. It can be seen from theoretical and experimental research that the optimal displacement ratio of compressors in different working conditions can be obtained accurately by the mathematical model introduced in this paper.

NOMENCLATURE

COP Coefficient of Performance

Q_0 Objective Refrigerating Output of Compressor (KJ/s)

h_0 Specific Enthalpy of State 0 (KJ/kg)

h_2 Specific Enthalpy of State 2 (KJ/kg)

h_3 Specific Enthalpy of State 3 (KJ/kg)

h_4 Specific Enthalpy of State 4 (KJ/kg)

h_6 Specific Enthalpy of State 6 (KJ/kg)

h_8 Specific Enthalpy of State 8 (KJ/kg)

h_9 Specific Enthalpy of State 9 (KJ/kg)

q_0 Refrigerating Capacity Per Unit Weight in Evaporator (KJ/kg)

q_{md} Mass Flow of Refrigerant Pass Through Low-pressure Compression Cylinder (Kg/s)

q_{mg} Mass Flow of Refrigerant Pass Through High-pressure Compression Cylinder (Kg/s)

q_{vd} Volume Flow of Refrigerant Pass By Low-pressure Compression Cylinder (m^3/s)

V_{hd} Theoretical Volumetric Flow Rate of Low-Pressure Compression Cylinder (m^3/h)

V_{hg} Theoretical Volumetric Flow Rate of High-Pressure Compression Cylinder (m^3/h)

v_1 Specific Capacity of Suction Gas of Low-pressure Compression Cylinder (m^3/kg)

v_3 Specific Capacity of Suction Gas of High-pressure Compression Cylinder (m^3/kg)

λ_d Volumetric Efficiency of Low-pressure Compression Cylinder

λ_g Volumetric Efficiency of High-pressure Compression Cylinder

ξ Displacement Ratio of High-pressure Compression Cylinder and Low-pressure Compression Cylinder

1. INTRODUCTION

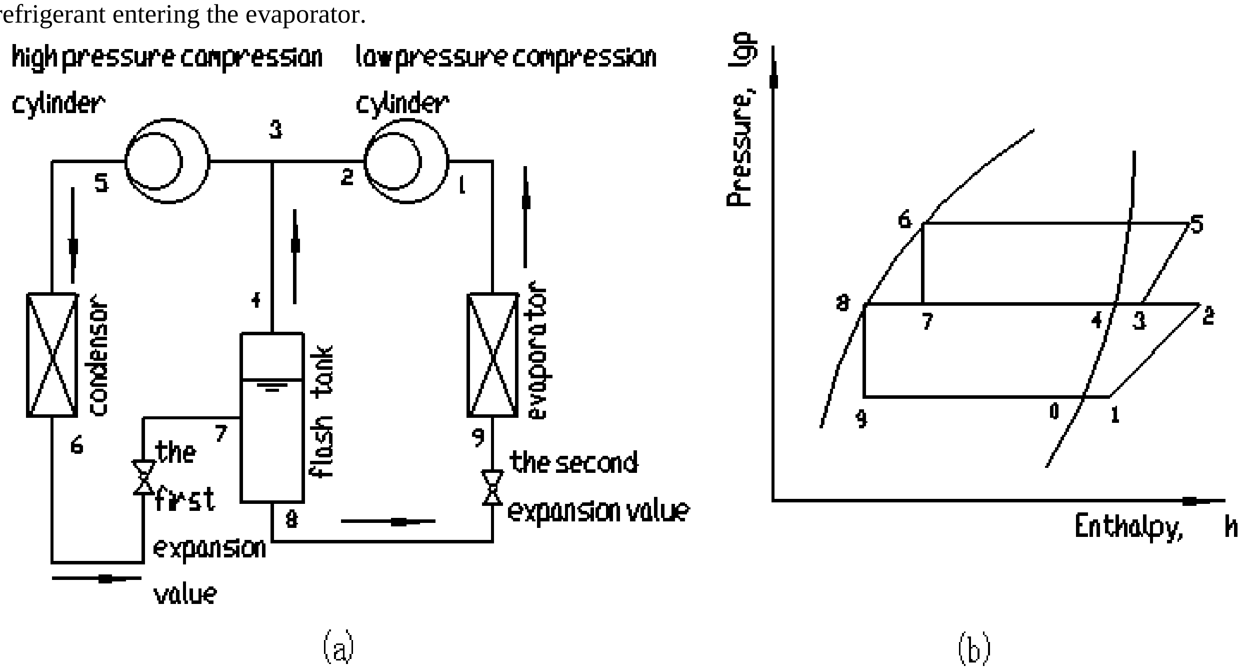
Home air conditioner is the main cooling facilities and heating installation in the building. Recently the development of frequency conversion technology enhance the comfort and energy saving of home air conditioner. However when the temperature lift increase, home air conditioner operating with a single-stage cycle become increasingly inefficient. This is particularly true for conventional air conditioner operating in hotter climates and in colder climates. Hua Zhang et al. (2008) and Nguyen Q. Minh et al. (2006) discussed theoretical and experimental studies of improved vapor compression refrigeration cycles capable of meeting this more flexible agenda. One of the many technologies that appear in order to overcome these disadvantages is two-stage compression with vapour injection.

This paper establish a mathematical model of the optimal displacement ratio of rotary two-stage inverter compressor with vapor injection based on theory of thermodynamics. Next, the experimental research that the optimal displacement ratio of compressors in different working conditions also presents in this paper.

2. MODEL OF TWO-STAGE COMPRESSION REFRIGERATION CYCLE

Two-stage compressor in this paper is a integral two stage rotary inverter compressor which low-pressure stage compression cylinder and high-pressure stage compression cylinder woke synchronously by the same electric motor. The discharge gas of low-pressure stage compression cylinder passes through interior channels arrive the gas suction of the high-pressure stage compression cylinder, which form two stage compression.

Figure 1 shows a two-stage cycle utilizing a flash tank economizer. The flash tank has three functions: to separate the liquid and vapor phases refrigerant, to desuperheat the discharge gas from the low pressure stage compression cylinder and to cool the liquid from the first expansion value to the saturated temperature corresponding to the intermediate pressure. The cycle therefore has less power consumption and higher capacity due to the compression of flash gas only from the intermediate pressure which is higher than evaporating pressure and a lower quality of refrigerant entering the evaporator.



(a).Refrigerant flow diagram (b). Pressure-enthalpy diagram

Fig 1: Two-stage cycle with flash tank

3. THERMODYNAMIC ANALYSIS

For system shown in Figure 1, mathematical is presented as below:

i. The refrigerating capacity per unit weight in evaporator is

$$q_0 = h_0 - h_9 \qquad (1)$$

ii. The mass flow of refrigerant pass through low-pressure compression cylinder is

$$q_{md} = \frac{Q_0}{q_0} = \frac{Q_0}{h_0 - h_9} \qquad (2)$$

Q_0 is the objective refrigerating output of compressor.

iii. The volume flow of refrigerant pass by low-pressure compression cylinder is

$$q_{vd} = q_{md} v_1 \quad (3)$$

v_1 is the specific capacity of suction gas of low-pressure compression cylinder.

iv. The theoretical volumetric flow rate of low-pressure compression cylinder is

$$V_{hd} = 3600 \frac{q_{Vd}}{\lambda} = 3600 \frac{Q_0}{h_0 - h_9} \frac{v_1}{\lambda_d} \quad (4)$$

λ_d is the volumetric efficiency of low-pressure compression cylinder.

v. According as heat balance in the flash chamber, we get the mass flow of high-pressure compression cylinder.

$$q_{mg} = \frac{h_4 - h_8}{h_4 - h_6} q_{md} = \frac{Q_0}{h_0 - h_9} \frac{h_4 - h_8}{h_4 - h_6} \quad (5)$$

vi. The refrigerant enters the high-pressure compression cylinder at state 3, which is mixed gas of discharge gas from the low-pressure compression cylinder and saturated gas from flash tank economizer. Thermodynamic equilibrium equation is

$$(q_{mg} - q_{md}) h_4 + q_{md} h_2 = q_{mg} h_3 \quad (6)$$

vii. The specific enthalpy of state 3 is

$$h_3 = h_4 + \frac{(h_4 - h_6)(h_2 - h_4)}{h_4 - h_8} \quad (7)$$

viii. The theoretical volumetric flow rate of high-pressure compression cylinder is

$$V_{hg} = 3600 \frac{q_{Vg}}{\lambda_g} = 3600 \frac{q_{mg} v_3}{\lambda_g} = 3600 \frac{Q_0}{h_0 - h_9} \frac{h_4 - h_8}{h_4 - h_6} \frac{v_3}{\lambda_g} \quad (8)$$

λ_g is the volumetric efficiency of high-pressure compression cylinder, v_3 is the specific capacity of suction gas of high-pressure compression cylinder.

ix. Displacement ratio of high-pressure compression cylinder and low-pressure compression cylinder when flash tank economizer is used in two-stage refrigeration cycle is

$$\xi = \frac{V_{hg}}{V_{hd}} = \frac{h_4 - h_8}{h_4 - h_6} \frac{v_3}{v_1} \frac{\lambda_d}{\lambda_g} \quad (9)$$

x. Displacement ratio of high-pressure compression cylinder and low-pressure compression cylinder when flash tank economizer is turned off in two-stage refrigeration cycle is

$$\xi = \frac{V_{hg}}{V_{hd}} = \frac{v_3}{v_1} \quad (10)$$

The following assumptions have been made to simplify the analyses:

(1) System operates in steady state.

(2) The compression processes in high-pressure compression cylinder and low-pressure compression cylinder both are isentropic compression processes.

(3) Heat transfer with the surroundings is negligible.

(4) No pressure drop occurs in evaporator, condenser, flash tank economizer, and their connecting pipelines.

4. RESULTS OF THEORETICAL ANALYSIS

Based on the above formulas and assumptions, numerical simulation for two-stage R410A compression refrigeration cycle with flash tank economizers is processed. CoolPack version 1.46 is used to calculate the thermodynamic parameter of R410A.

The displacement ratio of high-pressure compression cylinder and low-pressure compression cylinder which makes the two-stage compressor has the highest COP is called the optimal displacement ratio. Table 1 shows the optimal displacement ratio of high-pressure compression cylinder and low-pressure compression cylinder in three different refrigeration operating conditions.

Table 1 The optimal displacement ratio in three different refrigeration operating conditions

operating condition		the first	the second	the third
Condensing temperature(℃)		54.4	42	49
Evaporating temperature(℃)		7.2	18	10.5
Superheat(℃)		27.8	8	13.5
Subcooling(℃)		8.3	5	8
Ambient temperature(℃)		35	35	35
The optimal displacement ratio	flash tank economizer is turned off	0.4476	0.6524	0.5329
	flash tank economizer is turned on	0.6885	0.8628	0.6826

5. RESULTS OF EXPERIMENTAL RESEARCH

Based on theoretical analysis, the experimental project of compression-refrigeration system with flash-tank economizer coupled with a series of different displacement ratio two-stage rotary compressors. The different displacement ratio is 0.4, 0.45, 0.5, 0.55, 0.6, 0.65, 0.7, 0.75 and 0.8. These nine different prototypes have the same design parameters except the excentricity of high-pressure cylinder. All the tests are carried on the same compressor performance test board.

Figure 2 shows the optimal displacement ratio in the first operating condition when flash tank economizer is turned off is 0.45, which is very near the theoretical calculation result 0.4476 in Table 1. Figure 2 also shows that the COP is increasing at first then is degressive when the displacement ratio is increasing, and there is the optimal displacement ratio which make the COP arrive the peak value.

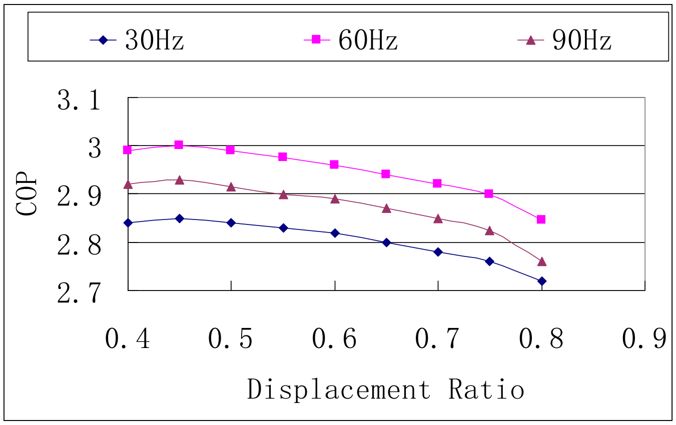


Fig 2: schematic explanation of the relation between COP and displacement ratio in the first operating condition when flash tank economizer is turned off

Figure 3 shows the optimal displacement ratio in the second operating condition when flash tank economizer is turned off is 0.65, which is very near the theoretical calculation result 0.6524 in Table 1. Figure 2 also shows that the COP is increasing at first then is degressive when the displacement ratio is increasing, and there is the optimal displacement ratio which make the COP arrive the peak value.

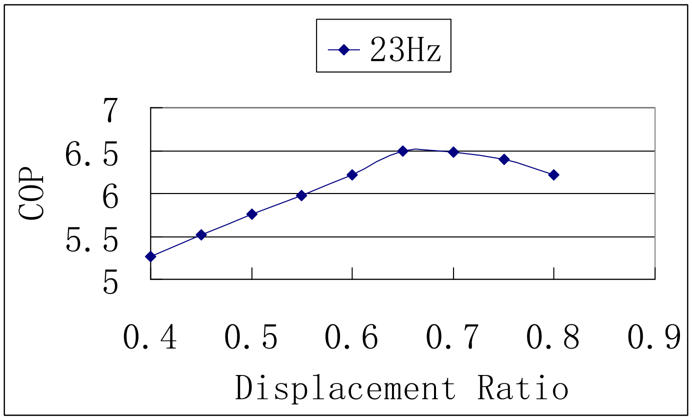


Fig 3: schematic explanation of the relation between COP and displacement ratio in the second operating condition when flash tank economizer is turned off

Figure 4 shows the optimal displacement ratio in the third operating condition when flash tank economizer is turned off is 0.55, which is very near the theoretical calculation result 0.5329 in Table 1. Figure 2 also shows that the COP is increasing at first then is degressive when the displacement ratio is increasing, and there is the optimal displacement ratio which make the COP arrive the peak value.

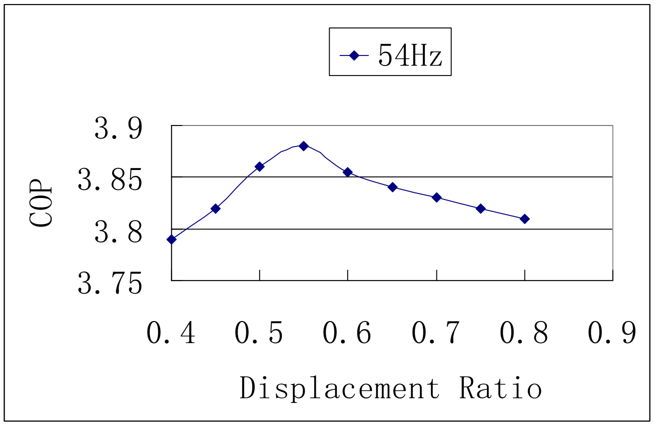


Fig 4: schematic explanation of the relation between COP and displacement ratio in the third operating condition when flash tank economizer is turned off

Figure 5 shows the optimal displacement ratio in the third operating condition when flash tank economizer is turned on is 0.7, which is very near the theoretical calculation result 0.6862 in Table 1. Figure 2 also shows that the COP is increasing at first then is degressive when the displacement ratio is increasing, and there is the optimal displacement ratio which make the COP arrive the peak value.

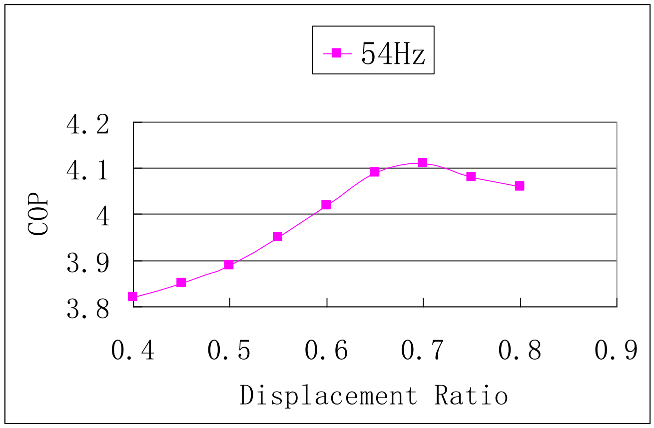


Fig 5: schematic explanation of the relation between COP and displacement ratio in the third operating condition when flash tank economizer is turned on

6. CONCLUSIONS

The mathematical model of the optimal displacement ratio of rotary two-stage inverter compressor with vapor injection has been developed and verified with the test data in this paper, the calculation only take account of R410A in three common compressor operating conditions. The following conclusions are made on the rotary two-stage inverter compressor:

(1) The optimal displacement ratio of high-pressure compression cylinder and low-pressure compression cylinder of rotary two-stage compressor is decided by operating condition. Once the operating condition is fixed on, the optimal displacement ratio is also fixed on.

(2). The mathematical model of the optimal displacement ratio of rotary two-stage inverter compressor with vapor injection is verified and the method of theoretical analysis is correct. Comparing with experimental research, theoretical analysis is more convenient and cost less. The optimal displacement ratio of compressors in different working conditions can be obtained accurately by the mathematical model introduced in this paper.

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