Research on Oil Circulation Rate of CO2 Inverter Rotary Compressors

Li Li
Xi'an Qing'an Refrigeration Equipment Co.ltd, People's Republic of China, lili070905@163.com

Min Sun

Research on Oil Circulation Rate of CO_2 Inverter Rotary Compressor

Li LI[1], Min SUN[2]*

[1]Xi'an Qing'an Refrigeration Equipment Co., Ltd,
Gaoxin 2nd Road, Xi'an, China
E-mail: lili070905@163.com

[2]Xi'an Qing'an Refrigeration Equipment Co., Ltd,
Gaoxin 2nd Road, Xi'an, China
E-mail: sunmin0929@126.com

* Corresponding Author

Abstract

The oil circulation rate(OCR) of a CO_2 inverter rotary compressor is higher than expected. The computational fluid dynamics(CFD) method is used to build a flow field simulation model of the compressor. Boundary conditions are determined according to the real running conditions of the compressor, involving the pressure, the temperature, the mass flow rate and other necessary parameters. There are four paths for refrigeration gas and oil flowing across: the motor rotor channel, the air gap between the motor rotor and the motor stator, the winding gap and the motor stator core cut. The CO_2 mass flow rates of these four paths are obtained and compared. The pressure field in the compressor is obtained and analyzed, which determines the gas and oil flow pattern and path. The velocity is also investigated. The research shows: the CO_2 mass flow rate through motor rotor channel and winding gap have a great influence on the OCR of CO_2 inverter rotary compressors. The simulation result agrees well with the test result.

1. INTRODUCTION

CO_2 is an environmental-friendly refrigerant. However, the OCR of typical CO_2 compressors, a critical parameter for deciding compressor's efficiency, is still high compared to conventional compressors. Analysis of OCR by the flow field simulation method is convenient, visualized and time-saving than the traditional test method.
Guomang YANG et al.(2015) analyze the gas-oil flow field in a rotary compressor by numerical simulation. Some structural changes making the oil returning channel obvious in the compressor are made, so OCR during the whole frequency range is controlled within 0.5%. Lichang XIE et al.(2017) use the CFD method to simulate the circulation of oil and gas in one rolling piston-type compressor, and propose the optimal scheme that effectively reduces the oil rate of the compressor. Tetsuhide Yokoyama et al.(2012) explored an improvement in the oil separation by using CFD analysis, identified two effective measures, and experiments with an actual compressor to verify that oil separation is improved to the target value. But which parameter has the biggest influence on the OCR of CO_2 compressors, the papers did not concerned.
In this paper, a flow field simulation model is built. Also, the flow field of different structures of the compressor is calculated. The relationship between the mass flow rate of CO_2 gas through the four paths were analyzed in detail, which has the biggest influence on the OCR of the compressor according to results.

2. CALCULATION MODEL AND CFD METHODS

2.1 Governing Equations

In this paper, the basic equation of fluid and the multiphase flow model are applied.
The mass conservation equation of incompressible fluid is:

$$\frac{\partial \rho}{\partial t}+u\frac{\partial(\rho u)}{\partial x}+v\frac{\partial(\rho v)}{\partial y}+w\frac{\partial(\rho w)}{\partial z}=0 \tag{1}$$

The momentum conservation equation of incompressible fluid is:

$$\frac{\partial}{\partial t}(\rho\vec{v})+\nabla\cdot(\rho\vec{v}\vec{v})=-\nabla p+\nabla\cdot\left[\mu\left(\nabla\vec{v}+\nabla\vec{v}^{T}\right)\right]+\rho\vec{g}+\vec{F} \tag{2}$$

The volume fraction equation of the multiphase flow model is as follows:
The main phase:

$$\sum_{q=1}^{n}\alpha_q=1 \tag{3}$$

The q phase:

$$\frac{\partial\alpha_q}{\partial t}+v_q\cdot\nabla\alpha_q=\frac{S_{\alpha_q}}{\rho_q}+\frac{1}{\rho_q}\sum_{p=1}^{n}\left(\dot{m}_{pq}-\dot{m}_{qp}\right) \tag{4}$$

$\vec{v}$ ——absolute speed;
u, v, w—— the component of the velocity in the x, y, and z directions;
$\dot{m}_{pq}$—— mass transport from p phase to q phase;
$\dot{m}_{qp}$ —— mass transport from q phase to p phase.

2.2 Assumptions

(1) The mass flow rate of CO_2 discharged from the compression chamber does not change with time;
(2) The mass flow rates of oil discharged from the compression chamber and eccentric shaft oil hole do not change with time.
(3) The exhaust temperature and the exhaust pressure are constant in the compressor.

2.3 Calculation Model

Figure 1 shows three geometric models of the compressor. The distance between the rotating cap and the motor rotor of Model 1 is 0.022m. The distance between the rotating cap and the motor rotor of Model 2 is 0.0095m. The distance between the rotating cap and the motor rotor of Model 3 is 0.0095m, and there is an additional lower balance weight shell in model 3.

Figure 2 shows the mesh model of model 1. Tetrahedron grids are used to mesh the fluid volume. The grid number is approximately 4,300,000. The mesh method used in Model 2 and Model 3 is the same as in Model 1.

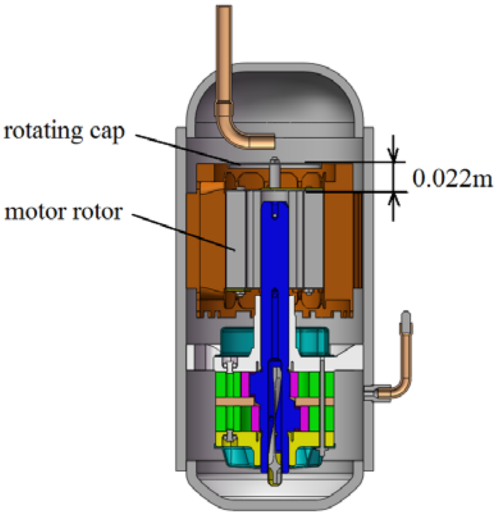
The calculation rotating speed is 60r/s. The boundary conditions are listed in Table 1.

Table 1: Boundary conditions

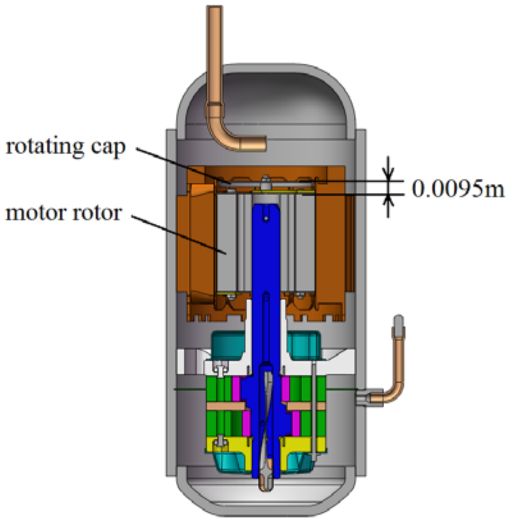
Boundary conditions	Position
Mass flow inlet	Muffler discharge hole
Pressure outlet	Compressor discharge pipe
Rotary body	Motor rotor and shaft
Static body	Bodies except for rotary body
Interface	Faces on which rotary body and static body coincide

2.4 CFD method

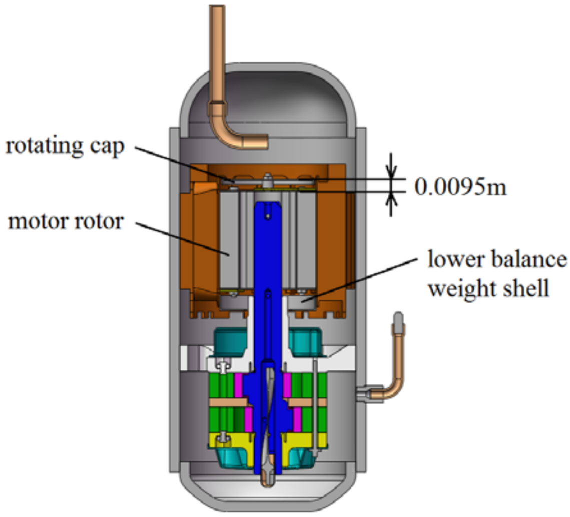
The two-phase model is used to include the mutual interaction of CO_2 gas and oil droplets. CO_2 gas is the continuous phase, and oil droplets are the discrete phase. Four effects are considered when oil droplets colliding on the wall: escaped, wall-jet, reflect and trap. The escaped effect is utilized to the inlet and outlet boundary. The wall-jet effect is utilized to the static wall boundary. The reflect effect is utilized to the rotary wall boundary. The trap effect is utilized to the wall boundary near the oil level. The reference frame model is used to represent the rotation. The rotary body mesh is rotating all the time totally, so it is not needed to mesh again when calculating. The geometric faces are rotating with the rotary body meshes also.



(a) Model 1



(b) Model 2



(c) Model 3

Figure 1: Geometric models

2.5 CO_2 gas flow path

There are four paths for CO_2 gas and oil droplets flowing through, either from the space below the motor to the space above the motor, or from the space above the motor to the space below the motor. They are the motor rotor channel, the air gap between the motor rotor and the motor stator, the winding gap and the motor stator core cut respectively, and listed in Table 2. Figure 3 shows the location of the four paths. There are six channels for Path 1, nine channels for Path 3, and nine channels for Path 4.

Table 2: The relationship between path number and location

Path number	Location
Path 1	Motor rotor channel
Path 2	Air gap between the motor rotor and the motor stator
Path 3	Winding gap
Path 4	Motor stator core cut

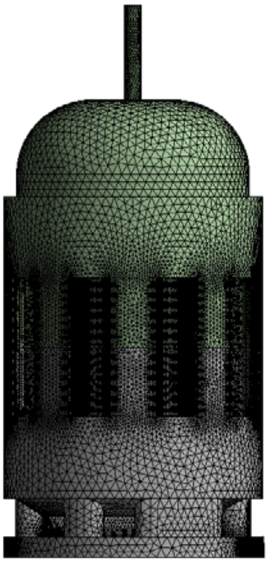


Figure 2: Mesh model of Model 1

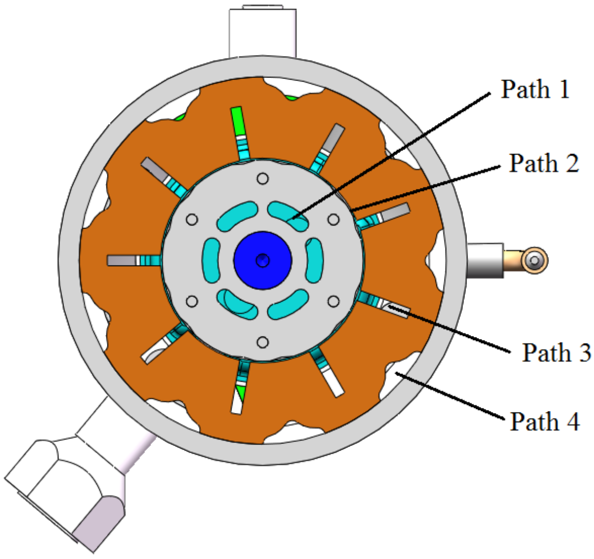


Figure 3: Location of flow paths

3. EXPERIMENT

The experiment was finished in a CO_2 compressor calorimeter. The experimental conditions are listed in Table 3.

Table 3: The experimental conditions

Item	Suction pressure(Pa)	Discharge pressure(Pa)	Rotation speed(r/s)
Data	8e6	2.4e6	45/60

The OCR of 45r/s and 60r/s are tested by oil separation method. Oil in the discharge gas mixture was separated and stored in a transparent graduated container. The mass flow rate of oil was calculated, and the mass flow rate of CO_2 gas was displayed, so the OCR could be calculated.

4. CFD RESULTS AND ANALYSIS

4.1 CO_2 Gas Flow Rate Analysis

CO_2 gas flow rate in the four paths are listed in Table 4. A positive number means that the gas is flowing from the bottom up, and a negative number means that the gas is flowing from the top down.

Table 4: CO_2 gas flow rate in the four paths

Model	**Path 1(kg/s)**	**Path 2(kg/s)**	**Path 3(kg/s)**	**Path 4(kg/s)**
Model 1	0.392	-0.005	-0.080	-0.206
Model 2	0.259	-0.005	-0.006	-0.147
Model 3	0.092	-0.002	0.054	-0.043

Because CO_2 mass flow rate of muffler discharge hole is 0.101kg/s, so

$$m_1 + m_2 + m_3 + m_4 = 0.101 \tag{5}$$

m_1, m_2, m_3, m_4 —— CO_2 mass flow rate in Path 1, Path 2, Path 3 and Path 4.

According to the data listed in Table 4, Model 1, Model 2 and Model 3 all satisfy Equation (5), consistent with hydrodynamics theory. For Model 3, despite the CO_2 gas flow rate through the motor rotor channel is very low, the CO_2 gas flow direction through the winding gap is from the bottom up, different from model 1 and model 2.
CO_2 gas flow rate from the bottom up and from the top down are calculated, and listed in Table 5. CO_2 gas flow rate from the bottom up of these three models have following relation:

$$m_{model3\_up} < m_{model2\_up} < m_{model1\_up} \tag{6}$$

$m_{model1\_up}, m_{model2\_up}, m_{model3\_up}$ —— CO_2 mass flow rate from the bottom up of Model 1, Model 2 and Model 3.

Table 5: CO_2 gas flow rate from the bottom up and from the top down

Model	From the bottom up (kg/s)	From the top down (kg/s)
Model 1	0.392	-0.291
Model 2	0.259	-0.158
Model 3	0.146	-0.045

Because the motor rotor channels are rotating all the time when the compressor is running, the path lines of gas and oil mixture through Path 1 are upward spirals. In the motor rotor channel, the lower the mass flow rate of the gas, the lower the velocity of the gas, the more turns the gas rotates when it rises to a certain height, and the easier it is for oil droplets to be separated by centrifugal force. So oil discharging from the outlet is less, OCR of the compressor should be lower as well.
Table 6 shows the OCR tested in the experiment. The OCR of Model 2 is lower significantly than Model 1, which is consistent with the analysis above. Model 1 compared to Model 2, the reduction ratio of OCR at 60r/s is greater than the reduction ratio of OCR at 45r/s.

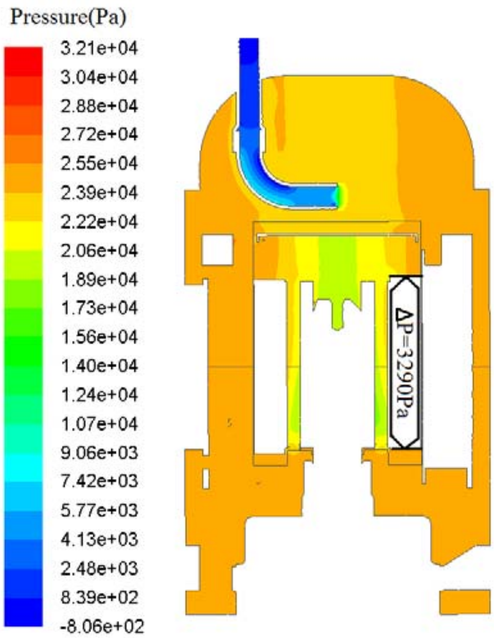
Table 6: OCR tested in the experiment

Model	OCR(%)	
	45(r/s)	60 (r/s)
Model 1	0.30	0.94
Model 2	0.14	0.22
Model 3	0.18	0.61

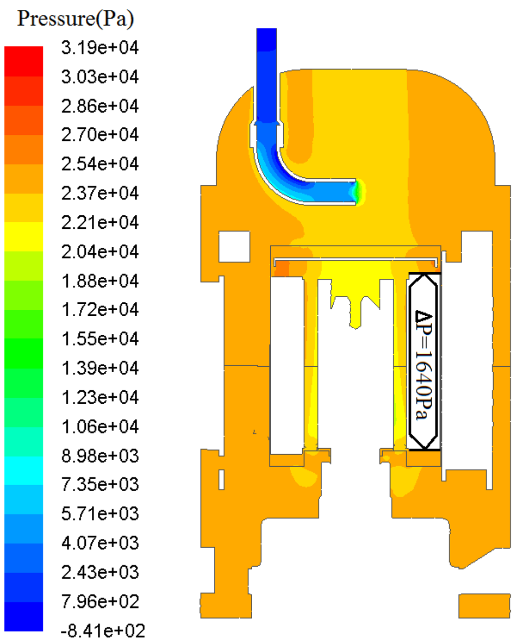
The OCR of Mode 3 is also lower than Model 1, but higher than Model 2. That seems not consistent with the analysis above. But it is clear that the direction of gas flowing in Path 3 of Model 2 and Model 3 is different. The flow direction in Path 3 of Model 3 is from the bottom up, so the gas and oil mixture has not been subjected to centrifugal force compared to the gas and oil mixture that flows through the motor rotor channels . As a result, the oil droplets in the mixture that flows through Path 3 of Model 3are barely separated, resulting in an increase of OCR.

4.2 Pressure Field Analysis

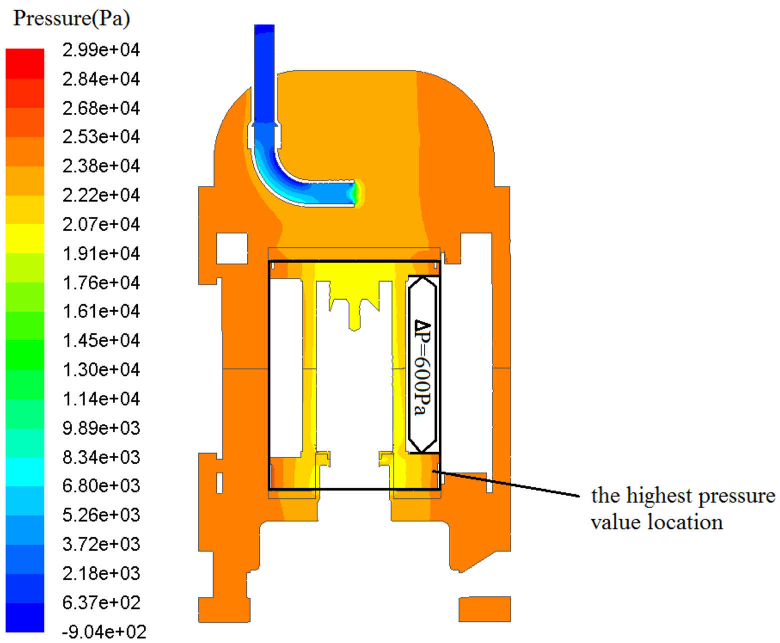
Figure 4 shows the pressure field of three models. In the motor rotor channels, gas flows from the bottom up, so the bottom pressure is higher than the top pressure. The pressure difference between the motor rotor channel inlet and outlet is showed in Figure 4. The pressure difference in Model 1 is about twice the pressure difference in Model 2. The pressure difference in Model 2 is about 2.5 times the pressure difference in Model 3. The smaller the pressure difference, the lower CO_2 gas flow rate in the channels, which is consistent with the result in Section 4.1. The pressure field below the motor rotor of Model 3 is rearranged, so pressure data from the rotating center to the outside area in the space below and above the motor rotor is uniformly distributed, reducing the pressure difference between the motor rotor channel inlet and outlet significantly. For Model 3, the highest pressure value is located in the outermost part of the area within the cover of the lower balance weight shell below the motor rotor, which leads to the outflow of gas from this area and upward flow through the winding gap. In the above flow, the risk of increased OCR is significant because the oil droplets in the gas mixture are not subjected to centrifugal force. So the highest pressure value location of Model 3 is not good for reducing OCR, and the test results confirm this.



(a) Model 1



(b) Model 2



(c) Model 3

Figure 4: Pressure field

To obtain the lower pressure difference between the motor rotor channel inlet and outlet, the pressure field should be designed. The pressure field determines gas flowing mode and direction, which greatly affects the OCR of the compressor. So not only the compressor parts need to be designed, but also the pressure field in the compressor need to be designed.

4.3 Velocity Field Analysis

Table 7 lists the vertical gas velocity in the motor rotor channels. They have the same relationship with the CO_2 gas mass flow rate illustrated in Equation (6). The gas vertical velocity of Model 3 is smaller than Model 2, and the gas vertical velocity of Model 2 is smaller than Model 1. Lower the velocity, and more oil droplets tend to be separated from the gas, so OCR would be smaller.

Table 7: Gas vertical velocity in the motor rotor channels

Model	Gas vertical velocity (m/s)
Model 1	4.9
Model 2	3.2
Model 3	1.2

5. CONCLUSIONS

(1) By simulation and experiment, it is confirmed that the CO_2 mass flow rate through the motor rotor channel and winding gap have a great influence on the OCR of the compressor.
(2) If the gas flows from up down through the winding gap, OCR has the same changing trend with CO_2 gas flow rate in the motor rotor channels, pressure difference between the motor rotor channel inlet and outlet, and vertical gas velocity in the motor rotor channels. Lower CO_2 mass flow rate, pressure difference and gas vertical velocity in the motor rotor channels, smaller OCR, and vice versa.
(3) If the gas flows from the bottom up through the winding gap, OCR is much higher than the estimated value by the CO_2 mass flow rate in the motor rotor channels.
(4) The pressure field should be designed to obtain small OCR data. The OCR can be reduced from 0.94% to 0.22% at 60r/s when the pressure difference between the inlet and the outlet of the motor rotor channels reduces about 1600Pa.

REFERENCES

[1] Liying, D., Shebing, L., Guomang, Y. (2015). Optimization analysis of oil circulation rate in rotary compressor base on CFD. Refrigeration. 34(3), 84-90.
[2] Ke, C., Haofu, L., Lichang, X. (2017). Simulation and optimization of oil rate in rolling piston type compressor. Refrigeration and air-conditioning. 17(2), 83-87.
[3] Keisuke, S., Shin, S., Tetsuhide, Y. (2012). CFD analysis inside a CO_2 rotary compressor shell to improve oil separation and reduce the shell size. International Compressor Engineering Conference at Purdue(1230,1-10). West Lafayette, America.