Transient flow analysis for multi-state automotive scroll compressors

Yao Yu1, Xiumei Wang1

1Shanghai University,99 Shangda Road BaoShan District, Shanghai 20444 P.R. China
Yuyao_28@163.com

Abstract. Due to the merit of high efficiency, low noise and vibration, scroll compressor has been rapidly developed in recent years. The working process of a scroll compressor is a three-dimensional non-constant compressible viscous flow process. In order to optimize the compressor design for better performance, it is necessary to understand and reveal the detailed mechanism of the unsteady flow inside a scroll compressor. In this paper, a three-dimensional flow-field model of scroll compressor is established. Non-stationary transient simulation of the flow field is carried out by using a combination of dynamic grid and User-Defined-Files. The distribution of temperature, pressure and velocity within the flow field of the work gas under different operating conditions were obtained. In this paper, the flow phenomenon of gas reflux at the suction and discharge ports and its effect on the performance of the scroll compressor was analysed.

1. Introduction

The development of scroll compressor has become a research hotspot recently for the purpose of environment protection and energy conservation. Scroll compressor is widely employed in air conditioning, vehicle refrigeration system. In recent years, Computational Fluid Dynamics (CFD) develops very quickly, and has been widely used in the study of flow field in fluid machinery. Many researchers use CFD to investigate the inner mechanism of scroll compressor. Wang B et al. [1, 2] mainly focus on the overall steady-state scroll model, due to the challenges in obtaining transient flow parameters. Evandro et al.[3] built 2D transfer model to predict fluid flow and heat transfer inside the suction and compression chambers of scroll compressors, an algorithm was applied to adapt the computational mesh automatically for each orbiting angle. In these cases, a simplified two-dimensional model allows the comprehension of the fluid dynamic of scroll compressor. However, 3D approach is essential to explore the detailed fluid dynamic features inside the working chamber. Three dimensional application with Dynamic mesh strategy was adapted by Zhen Liu et al. [4], which temperature and deformation distributions of the scroll wraps were obtained through fluid-thermal-solid numerical coupling simulation.

In this paper, FLUENT dynamic grid method is used to perform transient calculations on the three-dimensional flow field inside the scroll compressor. The distribution of pressure and temperature within the compression chamber was obtained under different working conditions. Severe reflux is observed at both the suction and discharge ports.
2. Mathematical Model

2.1. Geometric Model

The brief structure of a scroll compressor is shown in the sketch of Figure 1. A scroll compressor consists of discharge port, fixed scroll, orbiting scroll, anti-rotation mechanism and frame [5], etc. The fixed scroll and orbiting scroll are assembled at a relative angle of 180° and offset by a distance equals to the radius of the crankshaft, thus they mesh at several points and form a series of crescent-shaped chambers [6, 7].

The working process of a scroll compressor consists of three processes: suction, compression and discharge process. The volume of compression chamber changes with the relative motion of fixed scroll and orbiting scroll as shown in the sketch of Figure 2, where a dynamic mesh method is needed to establish CFD model. When the orbiting scroll moving, compressing chambers gradually move into the center, gas is then compressed and exhausted through discharge port.

The working process of compression chamber is shown in Figure 2. There are 4 positions in the picture, corresponding to the operating status while crankshaft rotation angles θ increases from 90 to 360 degree. With the rotation of crankshaft, suction chamber is formed between orbiting scroll and fixed scroll. The volume of chamber increased gradually with rotation, and gas flows into the suction chamber continuously. While θ reaches at 360° (0°), suction process ends as the suction chamber is closed.

The compression process begins while the angle of crankshaft is 360°. The volume of compression chamber decreases as θ increases, thus the pressure of gas increases. At the same time, the discharge port opens, high pressure medium can exhaust through discharge port. Suction process is carried out simultaneously during the compression process. Actually, the refrigerant is continuously compressed, for several cycles instead of only one, to complete compression process.
2.2. Media Model
A standard commercial software ANSYS-FLUENT is used to conduct numerical simulation. Based on the method of dynamic mesh technique and numerical simulation, the whole flow domain is divided into two parts: discharge pipe and the deforming subdomain, as shown in Figure 3.

![Flow domain diagram](image)

Figure. 3. Flow domain diagram

An interface is built between the bottom end of the discharge pipe and the upper face of the deforming subdomain. Hexahedral structured grids were generated in the deforming subdomain. The mesh regenerated every time step as the orbiting scroll moves according to the dynamic mesh regenerate mechanism.

![Meshes at different crankshaft rotation angle](image)

Figure. 4. Meshes at different crankshaft rotation angle

2.3. Boundary Conditions and mesh regeneration
Since the mass of the gas inside the scroll compressor varies with the rotation of the principal axis, the equation of state and the mass conservation equation can be expressed as the following function:

\[ f(P, V, T, M) = 0 \]  
\[ \delta m_i - \delta m_e = \Delta m_{cv} \]  

Similar to the mass conservation equation, the energy equation can be expressed as:

\[ \delta Q = dE_{cm} + \delta W \]  

Where \( dE_{cm} \) is the energy of controlling mass in \( dt \)'s time:

\[ dE_{cm} = dE_{cv} + (e_e \delta m_e - e_l \delta m_l) \]  

\( \delta W \) represents the work done by controlling the volume:

\[ \delta W = \delta W_{cv} + (pV \delta m)_e - (pV \delta m)_l \]  

\( \delta W_{cv} \) could regard as the boundary work as the volume of compressor chamber is changing constantly.

The initial conditions and boundary conditions are set as follows: The calculation option is chosen as unsteady flow. The suction port was set as pressure boundary and the value was 101 kPa, discharge port pressure is 300 kPa, 400 kPa and 500 kPa respectively corresponding to three operating conditions of scroll compressor. 2000 time steps are used in the calculation configuration, and the time step size is 1E-5s, the crankshaft rotation speed is 3000 rpm. When crankshaft rotating 360°, it costs
0.02s. As the rotation speed of the scroll compressor is relatively high, the working process is assumed to be an adiabatic process \[^{[10]}\]. The flow regime in scroll compressor is mainly viscous flow, so the wall boundary was defined as no slip smooth wall. The flow of gas in the working chamber is controlled by conservation equation listed in subsection 2.3, finite volume method is used to discrete differential equations, and SIMPLE algorithm is used to solve the coupled equations of pressure and velocity. Gas is set as ideal gas. Time discretization employ implicit second-order accuracy format. Turbulence model is $k$-$\varepsilon$ model. After trade-off between the computational time versus accuracy of results, the radical clearance was set to be 40 μm while the axial clearance was not considered, because of the application of a sealing strip in the compressor.

Remeshing with the smoothing dynamic mesh option is used for time dependent grid construction. User Defined Files (UDF) is applied to define the movement of orbiting scroll. The motion of scroll can be obtained from the following equations:

$$
\begin{align*}
V_x &= \omega R_{or} \sin (\omega t) \\
V_y &= \omega R_{or} \cos (\omega t)
\end{align*}
$$

(6)

Where $V_x, V_y$ are spatial velocity of orbiting scroll, $R_{or}$ is the orbiting radius. In this model, $R_{or}$ is set to 5.9 mm. During the simulation process, the element nodes of the deforming subdomain change every time step according to the principle of the movement of the orbiting scroll. The general parameters of the compressor are given in Table 1.

| Items                              | Value   |
|------------------------------------|---------|
| Radius of basic circle             | 3.18 mm |
| Initial angle of involute          | 0.62 rad|
| Height of scroll wrap              | 37 mm   |
| Thickness of scroll wrap           | 4 mm    |

3. Results and discussion

3.1. Simulation Reliability Verification

Pressure and temperature field is obtained through numerical simulation of the working process in a scroll compressor. To verify the accuracy of the above-mentioned 3D transient flow field simulation, refer to the experiment given in Wang J \[^{[9]}\] The peak thermodynamic data of the compressor operation were verified. The comparison results are shown in Table 2.

| Angles | Temperature(K) | Pressure(MPa) |
|--------|----------------|---------------|
|        | 0°  | 90°  | 180° | 270° | 0°  | 90°  | 180° | 270° |
| Test   | 468 | 466  | 467  | 469  | 0.378 | 0.304 | 0.303 | 0.304 |
| Simulation | 509 | 448  | 449  | 477  | 0.41  | 0.329 | 0.294 | 0.318 |
| Errors | 8.7% | 3.9% | 3.9% | 1.7% | 8.5%  | 8.2%  | 3.0%  | 4.6%  |

From the comparison results in the Table 2, it can be seen that the simulation value has a good agreement with the test value, with a maximum relative error of 8.7%, which verifies that the reliability and accuracy of the transient three-dimensional flow field simulations in this paper.

3.2. CFD Simulation Results

According to the scroll compressor parameters shown in Table 1, the simulation was carried out under the working condition of 0.3MPa, 0.5MPa and 0.7MPa outlet pressure, when the rotation speed is 3000rpm 4000rpm and 5000rpm. The figure below shows the distribution of pressure and temperature of the internal flow field during operation of the scroll compressor for this operating condition.
As can be seen in figure (a), there is a pressure difference between adjacent compression chamber, and the pressure distribution of the same compression chamber is uniform. In the working process, with the rotation of the crankshaft, the engagement point of the fixed and dynamic scrolls moves inward, the pressure gradually increases as the volume of the chamber decreases. In figure (b), there is an inhomogeneous distribution of the internal temperature of the same chamber, which is due to the fact that the head part of the scrolls will interfere with gas flow, resulting in inhomogeneous temperature distribution. As the crankshaft rotates, the temperature of the chamber gradually increases.

The flow field of the scroll compressor at different rotational speeds under the same discharge pressure is selected for comparative study. The following figure shows the flow field at different speeds of 300rpm, 4000rpm and 5000rpm at an exhaust pressure of 0.3MPa.
The difference in pressure distribution when the scroll compressors operate at different rotation speeds is not obvious, and the peak pressures are also close to each other, values are 0.29MPa, 0.3MPa, 0.29MPa, separately. But there is a clear distinction in the temperature distribution, at high rotation speed conditions, the area of high temperature distribution in the chamber is significantly smaller than at lower rotation speed because of the accelerated thermal convection at higher rotation speeds.

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