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Study on Lubrication Theory of Orificed Throttle Based on Molecule Collision

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Abstract: Orifice restriction is a traditional form of throttle used in aerostatic guide way. Practically, self-excited vibration or even air hammer phenomenon will appear in gas film interior when supply gas enlarges or the film thickness decreases to micron scale. In order to analyze the process from the pressure inlet to the entrance of completely developed laminar flow, Reynolds Equation coupled with the first order velocity slip is used. Since it has rarefied property, turbulence model and molecular dynamics theory are adopted based on molecular collision theory. This paper reveals the internal cyclone law in gas chamber and the relationship between essence of the shock formation and the gas molecule velocity excitation. Further study shows that, supply pressure, film parameters and chamber parameters have important influences on cyclone phenomenon and shock wave.

Key words: orifice throttling; molecular collision; shock wave; cyclone phenomenon

1 Introduction：

Orifice restriction is a traditional type of throttle in aerostatic guide way. Lots of research reports on orifice compensated air bearing at home and abroad are available. R.R.Willis published an articles on gas pressure in orifice plate in 1828, which is the earliest literature of gas lubrication[1]. G.Belfforte derived gas flow coefficient of orifice compensated thrust bearing by experiments. And he also derived empirical formula for calculation of gas consumption and pressure distribution with a view to Reynolds number analysis and the two throttling action in 2006[2].One important phenomenon that orifice throttling is different from the inherent throttling is that the gas chamber structure will form a cyclone. In that case, there may be a shock phenomenon near gas supply hole. Carfagno S P found that through experiment: in area between the gas supply hole and the pressure gas film, the radial pressure distribution curve had a sudden drop according to laminar assumption[3].The phenomenon of gas film fluctuation in the air static pressure guide rail was studied by AOYAMA. In order to restrain the fluctuation of gas film [4-5], the structure of the throttle was reformed. Through numerical simulation; CHEN proposed that orifice gas bearing had a large vortex in the groove, so the bearing is not stable enough [6]. According to Reynolds equation, Giving appropriate initial values and boundary conditions, Meng Xian and Liu Fan used turbulence model under isothermal conditions coming to the conclusion that the gas has spiral movement along the circumferential direction of gas chamber before the gas is discharged from the gas chamber[7]. In the view of the problem of air film fluctuation in air static pressure guide, Chen Dongju found that there was a close connection between the cyclone phenomenon and the film vibration [8]. The traditional explanation of the shock in the throttle is due to the improper parameter selection, and then it produces supersonic zone near the throttle hole. Gas velocity is changed to subsonic after shock wave. These documents had no complete description of the orifice throttling process. In this paper, Reynolds Equation coupled with the first order velocity slip was used to describe the internal cyclone law in gas chamber and the relationship between essence of the shock formation and the gas molecule velocity excitation based on molecular collision theory. A more detailed description of the orifice throttling process and flow mechanism was deduced.

2 Mathematical model and theoretical research

2.1 Modeling

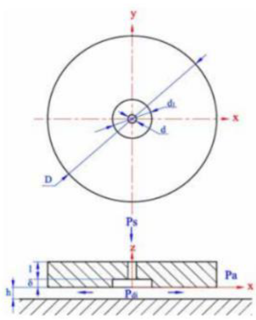


Fig 1 Diagram of orifice throttling in Descartes coordinate system

As shown in Fig.1, a single orifice compensated throttle was located in the center of a disc aerostatic thrust bearing.

Definition of effective flow sections:

$$A_{11}=\pi d^2/4, A_{12}=\pi d\left(h+\delta\right), A_{21}=\pi d_1^{\,2}/4, A_{22}=\pi d_1 h$$

Given fundamental equations of gas flow (momentum equation, continuity equation and state equation in Cartesian coordinate system), velocity slip boundary condition was taken into account:

$$\text{z=0}, u=U+l'\frac{\partial u}{\partial z}, v=l'\frac{\partial \omega}{\partial z}, \omega=0 \qquad (1)$$

$$\text{z=h}, u=-l'\frac{\partial u}{\partial z}, v=-l'\frac{\partial w}{\partial z}, \omega=u\frac{\partial h}{\partial x}+v\frac{\partial h}{\partial y} \qquad (2)$$

where: l' is the fluid slip length, $l'=\lambda\left(2-\sigma_v\right)/\sigma_v$. σ_v is a molecular tangential momentum regulation coefficient, which indicates the proportion of molecules that diffuse reflection at the surface of the object. λ is the average free path of gas molecules. U is the relative velocity of the slide plate and the guide rail. u , v , ω is the velocity component of x, y, z direction. u , v , ω is calculated by the momentum equation of x, y, z direction and formula (1),formula (2). ρ is eliminated through gas state equation under isothermal condition. At last get the Reynolds equation of micro scale effect by the gas continuity equation:

$$\frac{\partial}{\partial x}(ph^3\frac{\partial p}{\partial x})+\frac{\partial}{\partial y}(ph^3\frac{\partial p}{\partial y})=\frac{6\eta U}{1+6k'_n}+\frac{12\eta}{1+6k'_n}\frac{\partial(ph)}{\partial t} \qquad (3)$$

where: $k'_n=\left(2-\sigma_v\right)k_n/\sigma_v$, k_n is Knudsen number. Dimensionless mathematical model was shown as Formula (3), and the Reynolds equation was obtained under micro scale:

$$\frac{\partial}{\partial \bar{x}}(\bar{h}^3\frac{\partial \bar{p}^2}{\partial \bar{x}})+\frac{\partial}{\partial \bar{y}}(\bar{h}^3\frac{\partial \bar{p}^2}{\partial \bar{y}})=\forall_x\frac{\partial(\overline{p}\overline{h})}{\partial x}+\sigma\frac{\partial(\overline{p}\overline{h})}{\partial \bar{t}} \qquad (4)$$

where:

$$\forall_x=\frac{12\eta lU}{(1+6k')p_0h_m^2}, \sigma=\frac{24\eta lv}{(1+6k'_n)p_0h_m^2}$$

When U=0:

$$\frac{\partial}{\partial \bar{x}}(\bar{h}^3\frac{\partial \bar{p}^2}{\partial \bar{x}})+\frac{\partial}{\partial \bar{y}}(\bar{h}^3\frac{\partial \bar{p}^2}{\partial \bar{y}})=\sigma\frac{\partial(\overline{p}\overline{h})}{\partial \bar{t}} \qquad (5)$$

2.2 Theoretical research

The external high pressure gas flows through the gas supply hole. Partial gas velocity vector is not change, but the others enter the gas chamber directly in form of diffusion. The molecular without speed vector changes has an impact on the bottom of the gas chamber. Molecular kinetic energy is converted into gas pressure energy, elastic deformation energy of support surface and Heat energy, etc. Hypothesis from the beginning of impact, all kinetic energy converted into pressure energy. The speed of the molecules that impact the bottom of the gas chamber is reduced. Temperature at the bottom of the gas chamber can be reduced, which makes the Heat flux in this part has instantaneous maximum. This induces fluctuation of gas film.

Assuming that the σ_v portion of the flow molecule is completely diffuse reflection, the rest $(1-\sigma_v)$ is completely specular reflection. In the case of specular reflection, normal velocity component is changed only at the impact surface. In the case of diffuse reflection, the velocity is in line with Maxwell distribution. Both specular reflection and diffuse reflection can change the movement direction of the gas molecules, which makes the angle between the two sides of the gas molecules that reflected less than 180 degrees. Through the molecular interaction and the collapse of the surface of the gas film, a small fraction of molecules get into gas film directly. Given the thickness of gas film is h, most of the molecules collide with each other and collide with the surface of the gas chamber. The molecules rise to the upper surface of gas chamber with spiral movement. Then molecules form vortex.

When h is taken from the micron level, the area of A_{22} must be less than the area of A_{21}, the area of A_{22} less than the area of A_{12}. It is clear that at least two cross section flow occurs when the external high pressure gas flows from the inlet to the gas chamber and then to the rail gap. According to the flow continuity equation, the inlet cross section area is 10 times of the area of the outlet cross section. Therefore, the external molecular velocity v_{out} of the gas chamber is 10 times of the molecular velocity v_{in} in the gas chamber. The presence of a high pressure gas chamber makes a large number of high-speed molecules near the exit of the gas chamber.

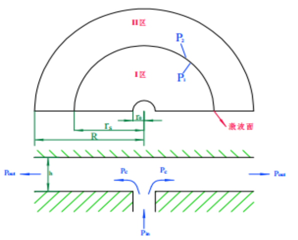


Fig 2 Diagram of supersonic zone around throttle

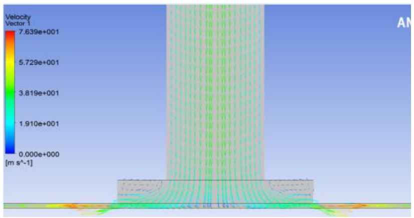
As shown in Figure 2: Gas flow along the radius direction, which is equivalent to the one dimensional flow of the tube whose cross-section area continues to become large. The speed of molecules in the place $r = r_0$ reaches sound speed. Obviously, it is a critical state. With speed increasing, the molecule is rapidly compressed when velocity reached supersonic. Meanwhile, shock wave generates at $r = r_s$. With the collision between each other of high speed movement, molecules become more intense, the energy consumption increases, the pressure drops, and negative pressure zone even occurs. The large pressure loss means that the bearing capacity and the static stiffness of the static pressure guide rail are decreased.

3 Simulation and analysis

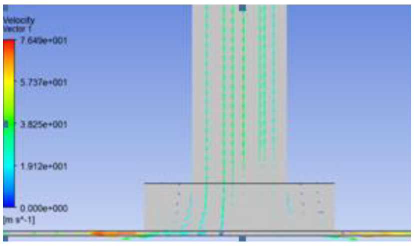
Simulation of orifice compensated aero static thrust bearing with one inlet hole located in the center by ANSYS. Initial values and boundary conditions:(1)Temperature is239K.(2)Reference pressure is Pa=0.1MPa.(3) the Pressure inlet is 0.6Mpa .(4) the gas density is $1.205\,\mathrm{kg/m^3}$ .Gas kinetic viscosity is $1.789\times10^{-5}\,\mathrm{Ns/m^2}$.(5) The other boundaries beside inlet and oulet are all solid wall.(6) There is no heat transfer and chemical change in the whole process.

3.1 Analysis of different sizes of gas chamber cyclone

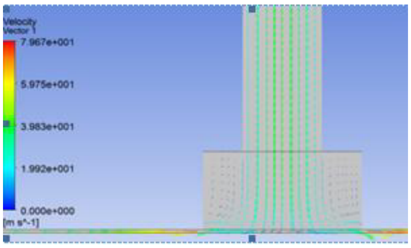
As shown in Figure 3,the results of the simulation are well matched to the lubrication theory of orifice throttle based on molecule collision. The phenomenon of cyclone is an important phenomenon of orifice throttle air static pressure guide. The presence of the cyclone can cause the fluctuation of the gas film affecting the motion accuracy of the air static pressure guide. A large number of high speed vertical movement of gas molecules have collision with gas cavity bottom. Then the speed directions of molecules change. Through the interaction between the gas molecules and the interaction between molecules and the wall surface, cyclone generates. Because of the existence of the cyclone, molecular velocity has component perpendicular to the surface of the gas chamber, which can cause the fluctuation of the gas film. As shown in Figure 3 a), b),c),gas chamber height are δ=25μm, δ=50μm, δ=80μm .With the increase of the height of the gas chamber, cyclone has a different degree of increase. This is related to the area of A and B. When A is larger, gas tends to flow in the direction of small gas resistance. A large number of molecules enter into the gas chamber after the collision with the gas film and the degree of the cyclone will become large.



a） δ=0.025mm



b) δ=0.05mm



c) δ=0.1mm

Fig 3 Simulation of gas flow in feed chamber of different heights

3.2 Shock phenomenon

The system working pressure is about (0.5~0.6) MPa , generally no more than 1 MPa . The thickness of gas film is generally a few microns to a dozen microns. As shown in Figure4,Figure 5, Pressure of gas film in radial direction and radial velocity with different supply pressures that are 0.2 MPa ,0.5 MPa ,0.6 MPa ,0.7 MPa ,0.8 MPa ,1 MPa respectively and the gas film thickness is 10μm .When supply pressure suddenly increases to more than 0.8 MPa , molecular velocity in the gas chamber increase suddenly. Molecules through the gas film gap get out of the gas chamber. Velocity increases rapidly until the supersonic. The volume of a large number of high speed movement molecules is rapidly compressed and the collisions between molecules are intense. Then shock wave phenomenon occurs. The molecular kinetic energy is converted into internal energy after the impact of the collision and gas flow along the radius direction, which is equivalent to the one dimensional flow of the tube whose cross-section area continues to become large. Molecular motion velocity decreases rapidly to the subsonic speed.

Phenomenon of shock is more obvious with the increasing of supply pressure, which will bring huge fluctuations affecting the stability and rigidity of the air static pressure guide. We should try our best to avoid this phenomenon. Under the premise of ensuring the bearing capacity, the working pressure should be controlled below 0.8 MPa . As shown in Figure 5, the frontier of the velocity curve is basically coincident under different air supply pressure.

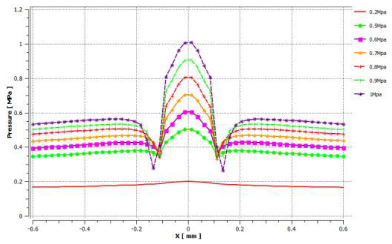


Fig 4 Pressure of gas film in radial direction with different supply pressures

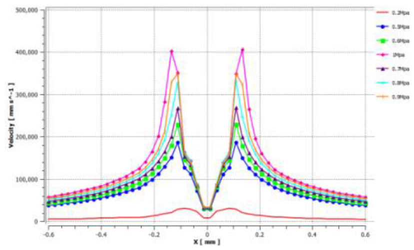


Fig 5 Radial velocity of gas flow in gas film with different supply pressures

As shown in Figure 6 and Figure 7, pressure of gas film in radial direction and radial velocity with film thickness that are 6μm,7μm,8μm,9μm,10μm respectively and the supply pressure is 0.8 MPa . Figure 7 shows that when the gas film thickness is less than 10μm , the variation tendencies of radial velocity are almost the same. When the film thickness is 10μm , the speed change is obvious. Shock wave phenomenon occurs. Figure 6 shows that, when the film thickness is 10μm , pressure in chamber change rapidly. The support ability of the high pressure gas chamber is reduced. Shock wave causes the pressure drop that causes a larger gas film wave fluctuation and the decrease of static stiffness of rail guide. Gas molecules in the gas chamber have the same speed variation trend on the condition that film thickness is not sufficient to cause a shock. There are plenty of molecules to flow out through the gas film at the same time when the film thickness increases appropriately causing shock waves. Reducing gas film thickness appropriately can improve the bearing capacity of high pressure gas chamber.

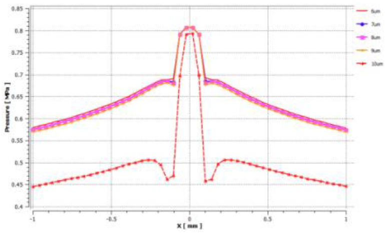


Fig 6 Pressure of gas film in radial direction with different film thickness

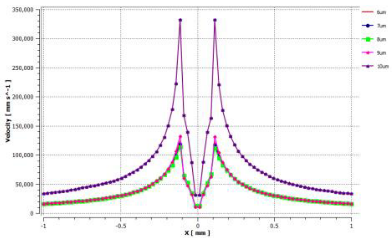


Fig 7 Radial velocity of gas flow in gas film with different film thickness

As shown in Figure 8, pressure of gas film in radial direction with different chamber height: 80μm, 90μm, 100μm, 110μm, 120μm and 200μm . The gas film thickness is h=10μm .The influence of gas chamber height on the pressure change in the gas chamber and the film is little. The position of the shock wave is not changed with the increase of the height of the gas chamber. Pressure before and after shock wave has a litter change.

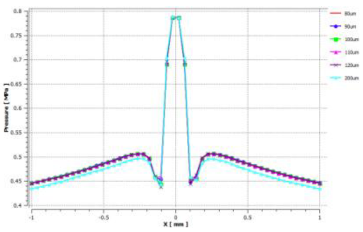


Fig 8 Pressure of gas film in radial direction with different chamber height

4 Conclusions

(1) This paper revealed the flow law from gas supply hole to gas chamber and lubrication theory of orificed throttle based on molecule collision. A new basis for the design of air static pressure guide with more stable and higher bearing capacity is put forward by analyzing the factors which influence the gas molecule collision (gas film thickness, gas chamber height, air inlet pressure).

(2)The factors that influence the stability of air static pressure guide rail are revealed. The direction of collision between the incident gas molecules and the bottom surface of the gas film change, and interaction between the gas molecules and the interaction between molecules and the wall surface causing the phenomenon of cyclone. The shock phenomenon caused by the pressure of the gas supply to the velocity of the excited molecules to the supersonic. The special structure of the orifice throttle caused the existence of the cyclone.

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