Analysis of Flow State of Inflatable Support Area in Aerostatic Guide Way under Condition of Rarefied Gas

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Abstract: Based on the molecular motion and collision law of the gas in the aerostatic guide way of inflatable support area, proposed the stratification theory of the gas film, the gas in inflatable support area was divided into near wall layer, thin layer, continuous flow layer along its height direction, proposed basis for dividing the thin layer and continuous flow layer, proposed physical model and the corresponding equation. Based on air film pressure decreasing in the aerostatic guide way and rate variation of gas flow, the gas in the longitudinal direction was divided into pressure-driven area and Newton friction area. Simulating flow patterns and calculating its velocity and pressure in gas film by LAMMPS and fluent, drew the relevant conclusions: the gas film in the longitudinal direction was divided into pressure-driven area and Newton friction area; and it also was divided into near wall layer, thin layer, continuous flow layer along its height direction; gas stratification present in the pressure-driven and Newton friction areas; the phenomenon of film layered became weaker with slower gas flow in pressure-driven area; Newton friction area remained stable stratification.

Introduction

In aerostatic guide way，the gas film is formed by supporting table and bearing plate which has an important influence on the precision and ultra-precision facilities of the aerostatic guide way.

Due to the thin gas in the film, velocity slip will be happened at the interface, which leads to the gas flow pattern changed in the lubricating film[1]. Velocity boundary slip experienced the development of the without-slippage-velocity boundary condition[2], linear slip condition hypothesis[3] and the approximate constitutive equations for slip[4]. No slip boundary conditions are no longer used in the micro scale flow analysis. When Kn=0.1(the ratio of the average free path of gas to the flow field characteristic length),it is the upper limit of the Navier-Stokes equation and the boundary conditions in the first order velocity slip boundary[5-8]. When Knudsen number increases to 1, the two order model of Cercignani and Deissler is failed[9,10]. Velocity distribution data obtained by fitting the DSMC slip factor to establish new slip model[11], which requires higher performance of the computer. The literature above to established the pressure gradient in the micro channel, and researched the flow pattern of the gas. However, the experimental study found that the gas flow velocity in the air film is complicated[12]. Not only the pressure flow field in the gas film existed in the air film, but also the flow field of the gas. The velocity slip in different field is not known, and this is also the problem to be faced in the study the pattern of gas film in air pressure guide rail.

In this paper, according to the gas flow and the changes of flow velocity in the gas film, the theory of film zoning and film Stratification are put forward, Relevant physical model and corresponding control equation are established. The theory of film zoning and film Stratification not only make up the deficiency of the traditional velocity slip theory, but also enrich the relevant theory of the air film flow, and provide theoretical guidance for the precision, stiffness, stability of aerostatic guide way.

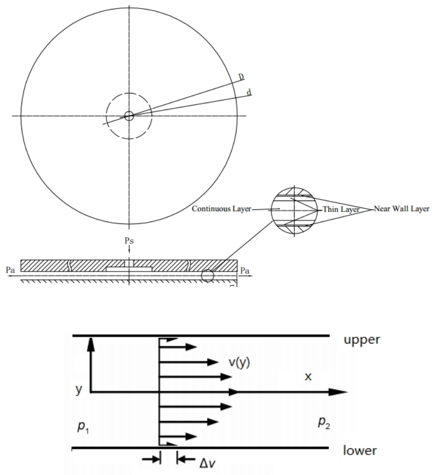


Fig. 1 Schematic diagram of supporting gas film layer

Theoretical Analysis

Air Film Zoning

As shown in Figure 1, it is assumed that the work table and the bearing plate are all smooth enough. According to the Aerostatic lubrication principle, the high pressure gas supplied from the air supply hole into the gas chamber, and reflected by the bearing plate and entered into the gas film gap which is composed by working table and bearing plate. Gas flowed along radial of the bearing, and ultimately connected with the atmosphere. In this process, the gas pressure was throttled, so the pressure gradually reduced to the environment pressure, and accompanied by a series of changes of gas flow pattern in the gas film.

Assuming：

$$M = \frac{\partial u}{\partial x} \quad (1)$$

When $M > 0$, the local gas is in pressure-driven area, when $M = 0$,the ground gas is the Newton friction zone.

pressure-driving area

P_1 and P_2 are respectively the inlet and outlet pressure, y and x are respectively radial and axial coordinates, $v(y)$ for the gas velocity distribution equation.

Assuming that the air flow is Newton fluid, according to Newton's law of shear, $v(y)$ can be expressed as

$$v(y) = -\frac{\Delta p}{L}\frac{y^2}{4m} + \frac{C_1}{m}\ln y + C_2$$

(2)

Where $\Delta p = p_1 - p_2$, m is the dynamic viscosity of the fluid, and L is the length of the film. C_1 and C_2 are the undetermined constants, which can be solved by boundary conditions, that is, when $y = 0$, the shear stress is 0, and on the wall of the boundary, $v(h/2) = \Delta v$. So $v(y)$ can be expressed as

$$v(y) = \frac{\Delta p}{4mL}\left(-y^2 + \left(\frac{h}{2}\right)^2\right) + \Delta v$$

(3)

By formula (3) can be obtained, in different pressure, the different position of the velocity distribution is different, the gas film flow velocity slip is not the same.

Newton friction area

In this region, the interaction force between gas molecules in the moving process is mainly based on the Newton internal friction, and the velocity and the law of the velocity are basically followed the boundary layer theory in the process of gas viscosity. When the inlet pressure and the outlet pressure of the air film is equal, that is, $\Delta p = p_1 - p_2 = 0$, the formula (3) is

$$v(y) = \Delta v$$

(4)

Obviously, $v(y)$ is a constant, that is, the gas flows at a constant speed.

Film Stratification

As shown in Figure 1, the laminar flow in the gas film, according to the flow state there, the air flow should be divided into three layers. The first layer, named as the near wall layer, which is near the counter top and the bearing plate; The third layer, named as the continuous layer, acrossed the center line of the film in the middle area. The second layer, named as the thin layer, which is between the near wall layer and the continuous layer.

In the thin layer, flow of rarefied gas, the thickness of gas film is sub micron, by estimating the available local $0.01<Kn^*<0.1$, namely the gas in the slipstream field [13]. Fluid at low Reynolds number, i.e., $1<Re^*<10$, can be considered as a layer of complete development of gas flow in the gas film.

Definition :

$$N_{fw} = \frac{K_n / K_n^*}{R_e / R_e^*} = \frac{vdL}{l\,u} \tag{5}$$

where: R_e is the Reynolds number; l is the average free path of the molecule; L is the length of the fluid characteristic.

When $N_{fw} > 1$, local gas belongs to the continuous layer. while $N_{fw} < 1$, the local gas belongs to the thin layer.

Near Wall Layer

The thickness of the near wall layer is assumed as the width of average free path of the molecule (under the working conditions, a gas molecule in the average distance for two times by the collision). Molecular motion in the layer is in accordance with the boundary conditions of fully diffuse reflection[14]. The relationship of quality and normal momentum between molecular and solid surface are established.

$$\begin{aligned}&\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\left(V^0+V^i\right)_i m_i f_s^i(V)\,d^3c = \\ &\int_{-\infty}^{\infty}\int_{-\infty}^{0}\int_{-\infty}^{\infty}\left(V^0+V^i\right)_{iR} m_{iR} f_s^i(V)\,d^3c + \\ &\int_{-\infty}^{\infty}\int_{0}^{\infty}\int_{-\infty}^{\infty}\left(V^0+V^i\right)_w m_w f_w^i(V)\,d^3c\end{aligned} \tag{6}$$

$$\begin{aligned}&\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\left(V^0+V^i\right)_i^2 m_i f_s^i(V)\,d^3c = \\ &\int_{-\infty}^{\infty}\int_{-\infty}^{0}\int_{-\infty}^{\infty}\left(V^0+V^i\right)_{iR}^2 m_{iR} f_s^i(V)\,d^3c + \\ &\int_{-\infty}^{\infty}\int_{0}^{\infty}\int_{-\infty}^{\infty}\left(V^0+V^i\right)_w^2 m_w f_w^i(V)\,d^3c\end{aligned} \tag{7}$$

Formula (6) and formula (7) expresses the mass flux and the flux of this layer respectively. Where: m_i and m_{iR} indicate the group of the quality of the net flux and the incident mass flux; m_{iR} is the diffuse reflection and the diffuse emission mass flux. V^0 and V^i respectively for gas macro velocity and the movement speed of i groups. y is the surface normal to coordinate; f_s^i for distribution function of the near wall layer edge speed, f_w^i for the wall Maxwell velocity distribution function, s and w respectively, expresses corner near the wall and the wall of the outer layer.

Thin Layer

VHS model (variable hard sphere) was used as typical collision member, its physical principle that can be expressed as Boltzmann equation.

$$\frac{\partial f}{\partial t}+v\frac{\partial f}{\partial r}+F\frac{\partial f}{\partial t}=\int_{-\infty}^{+\infty}\int_{0}^{4p}(f'f_1'-ff_1)gs(g,r)\,d\Omega dv_1 \tag{8}$$

$$f=f(r,v,t)\quad f_1=f(r,v,t),\quad f'=f(r,v,t)\quad f_1'=f(r,v_1',t)$$

Where: f is the times of t range of r to $r+dr$ micro volume element of gas molecule number in velocity range of v to $v+dv$; v and v_1 respectively for the speed of the two molecules before the collision; v' and v_1' respectively for the speed of the two molecules after the collision; Ω in post collision relative velocity in the direction of g'; s is differential collision cross section; F is the force of the unit mass molecule.

Based on the characteristics of the gas molecule collision relaxation,the BGK model is used in this paper. The collision term of the Boltzmann equation is replaced by a simple operator, and its expression (without considering the external force) can be written as

$$\frac{\partial \mathrm{f}}{\partial t}+\bar{V}\frac{\partial f}{\partial \bar{r}}=v(f_m-f) \tag{9}$$

Where: v is the collision frequency; the $\bar{V}$ is the constant, which is independent of the speed f of the gas molecule, f_m is the local Maxwell equilibrium state velocity distribution function, the value is

$$f_m=\frac{n}{(2pRT)^{3/2}}\exp\left(-\frac{C^2}{2RT}\right) \tag{10}$$

Continuous Layer

Air flow in this layer is considered as a two dimensional flow. In the coordinate system as shown in Figure 1, the mass force is neglected, and the Stokes hypothesis is applied, and the corresponding two-dimensional steady incompressible Navier-Stokes equation is obtained(*x* is the direction of the air flow).

$$r\left(u\frac{\partial u}{\partial x}+v\frac{\partial v}{\partial y}\right)=-\frac{\partial p}{\partial x}+m\left(\frac{\partial^2 u}{\partial^2 x^2}+\frac{\partial^2 u}{\partial^2 y^2}\right) \tag{11}$$

$$r\left(u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}\right)=-\frac{\partial p}{\partial y}+m\left(\frac{\partial^2 u}{\partial^2 x^2}+\frac{\partial^2 v}{\partial^2 y^2}\right) \tag{12}$$

The two order velocity slip condition is

$$u|_w = 1.1466\,l\,\frac{\partial u}{\partial y}\bigg|_w - 0.9757\,l^2\,\frac{\partial^2 u}{\partial^2 y}\bigg|_w \tag{13}$$

Where: p is the pressure, ρ as the gas density, m for gas dynamic viscosity coefficient, u for fluid particle velocity along the direction of the x component, and v is along the y direction of the component.

Simulation Analysis

Air film zoning

Simulating Aerostatic Guide Way working conditions, supply pressure Ps is 0.6MPa,0.8MPa,1.0MPa, Outlet is communicating with the atmosphere, which Pa is 0.1MPa, gas membrane height is 1μm, there is room temperature.

Figure 2 is velocity vector of gas which is from the supply holes into the gas chamber and then into air film support area

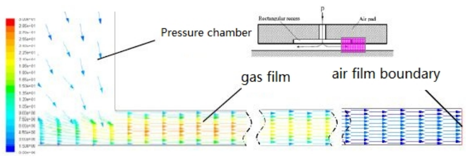
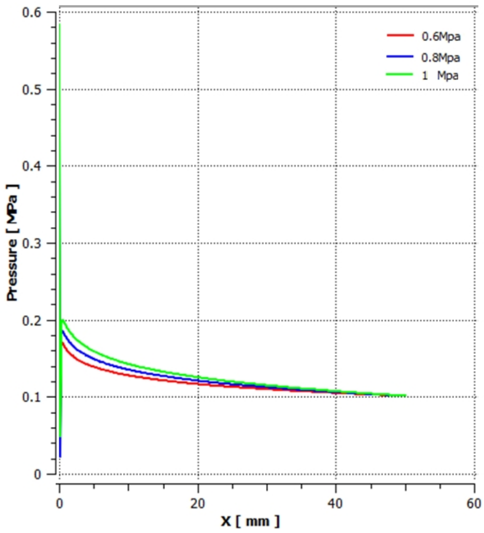


Fig. 2 velocity vector of gas in gas film

As shown in figure 2, according to the changes of gas flow rate, it can be drawn that air film is divided into two different areas ,there are larger flow rate changes in the height and length direction of gas film; On the contrary, there are smaller flow rate changes in the height and length direction of gas film.



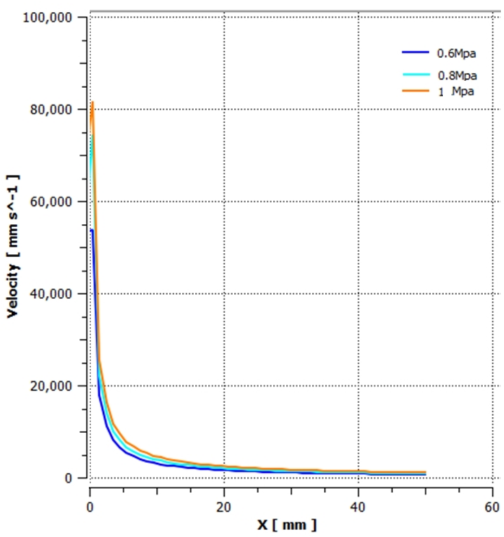


Fig. 3 pressure in the radial direction of gas film Fig. 4 velocity in the radial direction of gas film

Further analysis and calculating in gas flow rate in the gas film, as shown in Figure 3 and Figure 4. the gas from the stomata to the gas chamber whose speed is rapid changed, when the supply pressure is 0.8MPa, which can be obtained in Figure 4. Gas flow rate from 4.2m/s was reduced to

1.5m/s, that is pressure-driven area; near the exit area, gas flow rate to maintain 1.5m/s unchanged, that is Newton friction area.

Verified LAMMPS Simulation Method

When the film's long high ratio is 100, *Kn*=1.5, gas flow velocity Ma=1, the calculation of the y/H=0 at the bottom of the wall, y/H=1 for the upper wall position. LAMMPS and DSMC were used to calculate the pressure along the height of the film, as shown in Figure 5. From the results of LAMMPS and DSMC, the closer to the upper and lower wall, the smaller the pressure. Also, the obvious change of the pressure gradient near the wall, and the pressure change is not obvious in the middle of the supporting gas film. Compared with the results of DSMC, the numerical error is small, which can be seen from the results of LAMMPS, and it is also more advanced than DSMC.

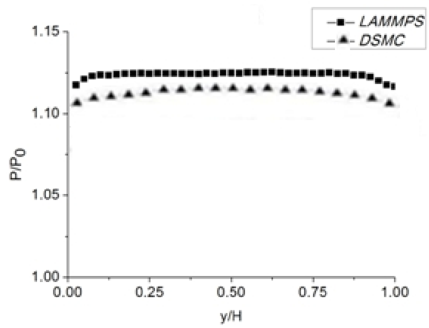


Fig. 5 Comparison of results of DSMC and LAMMPS

Stratification in Newton Friction and Pressure-driven Areas

Stratification in Newton Friction Area

Calculating gas velocity at different locations along the height direction in pressure-driven area, Supply pressure Ps is 0.8MPa, Outlet is communicating with the atmosphere, which Pa is 0.1MPa, gas membrane height is 1μm, there is room temperature. As shown in figure 6, thin layer occurs at ($0<y<4\text{nm}$ and $996\text{nm}<y<1000\text{nm}$) and Continuous Flow Layer occurs at($4\text{nm}<y<996\text{nm}$). With decreasing of gas flow velocity, gas flow rate is stabler, and velocity difference decreases in thin layer, stratification is weaker in pressure-driven area.

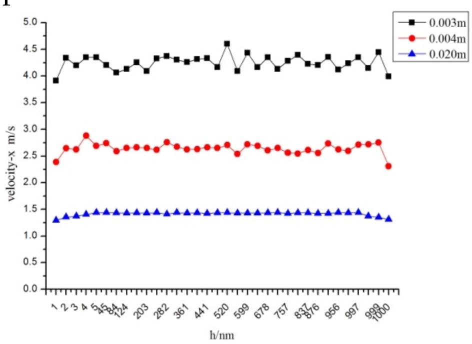


Fig. 6 rate changes at different locations in pressure-driven area

Stratification in Pressure-driven Area

Gas flow rate remains stable in Newton friction area as shown in Figure 7, thin layer occurs at (0<*y*<5nm and 995nm<*y*<1000nm) and Continuous Flow Layer occurs at(5nm<*y*<995nm). the thickness of continuous flow layer and thin layer remain constant, the speed of slippage remains unchanged.

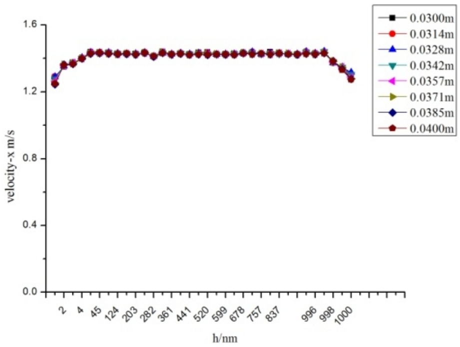


Fig. 7 different locations of gas flow rate variation diagram in Newton friction area

As shown in Figure 8, in the case of speed of these two regions, gas stratification present in the pressure-driven and Newton friction areas, there is significant speed slip in pressure-driven area, because of larger gas flow rate. In Newton friction zone, the gas flow rate is relatively small, the speed of slippage is not obvious.

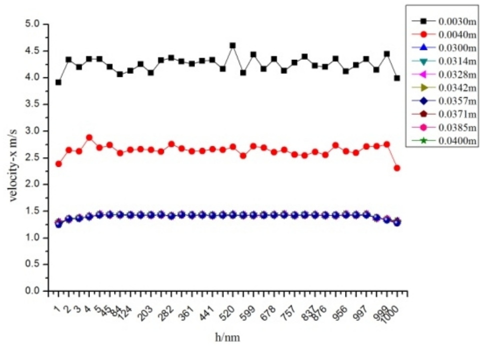


Fig. 8 different locations of gas flow rate variation diagram in Newton friction and pressure-driven areas

Conclusions

(1) Proposed the stratification theory of the gas film, the gas in inflatable support area was divided into the near wall layer, the thin layer, and the continuous flow layer, established corresponding equation. Verified the validity of stratification theory by the calculation of LAMMPS.

(2) Proposed theory of film zoning, Based on rate variation of gas flow, the gas in the longitudinal direction was divided into pressure-driven area and Newton friction area, and established corresponding equation. Concluded that gas stratification present in the pressure-driven and Newton friction areas, the Phenomenon of film Layered became weaker with slower gas flow in pressure-driven area; Newton friction area remained stable stratification.

(3) LAMMPS simulation result is reliable compare with DSMC. Further proof the film area is divided into the near wall layer, the thin layer, and the continuous layer is feasible.

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