Study on Heat Transfer Problems of Gas Pendulum Inclination Sensor

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Abstract. According to different mechanisms of thermal conduction, natural convection and heat radiation, relevant physical models are established for the heat transfer of the sensing organ. Based on these models, the heat transfers of conduction, convection and radiation of the sensing organ in the hermetic chamber are calculated. The results indicated that radiation of the sensing organ is very small and can be neglected for the analysis of heat transfer. Heat transfer of conduction is equal to convection in the hermetic chamber; so simplified heat transfer analysis can be made by analysis of conduction in the hermetic chamber.

Keywords: gas pendulum; thermal conduction; natural convection; heat radiation.

1. Introduction

Gas pendulum inclination sensor was researched and developed due to the “pendulum” characteristic of natural convection in a hermetic chamber. Because the mass of gas is small and no swinging mass block, the gas pendulum inclination sensor has large-scale applications for its characteristic of resisting oscillation and shock.At present, gas pendulum inclination sensor has been widely used in missile, ship, tank fire control system and attitude control system of robot [1].

Due to the high temperature of the heat source in the gas pendulum inclination sensor, whether the heat radiation of the closed cavity has a great influence on the performance of the sensor has always been a matter of concern. Thus the heat transfer problem of closed cavity is studied.

2. Model building

According to the physical nature of the heat transfer process, there are three basic heat transfer methods. That is thermal conduction, convection and heat radiation. Thermal conduction is also called heat conduction, which is direct contact heat transfer between parts of an object at different temperatures or between objects at different temperatures. Microscopically speaking heat conduction is caused by the thermal motion of the molecules and atoms that make up the material and the diffusion of free electrons.

Convection or convective heat transfer refers to the heat transfer phenomenon that occurs when there is relative motion between the fluid and the solid wall surface and there is a temperature difference between the fluid and the wall surface. This type of heat transfer is characterized by the existence of macroscopic relative motion between the fluid and the solid wall surface. As far as the cause of the relative motion of the fluid is concerned, convective heat transfer can be divided into: forced convection by external forces that causes the fluid to undergo forced motion, and natural convection in which the fluid is freely moved by inertial force due to its mass.

Solids or liquids emit electromagnetic waves of various wavelengths at any temperature. We call this thermal radiation, that electromagnetic waves are emitted due to the thermal excitation of molecules and atoms in matter. Both conduction and convection require media materials to achieve. However, heat radiation may be transmitted in a vacuum environment without intermediate media, and the higher the vacuum, the better the heat radiation transmission.

As far gas pendulum inclination sensor for horizontal cylindrical closed cavity with heat source, heat transfer problems in the cavity need discussed. In order to calculate thermal radiation, natural convection and thermal conductivity, a reasonable mathematical model must be established.

Fig. 1 is a coaxial cylindrical cavity, reduce the inner radius of the cavity to the diameter of the heat source and turn it into a model of the gas pendulum inclination sensor closed cavity as shown in Fig. 2. The temperature of the inner wall is the temperature of the heat source and outer wall temperature is the ambient temperature.

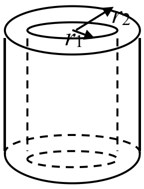

Fig. 1 Coaxial cylindrical cavity

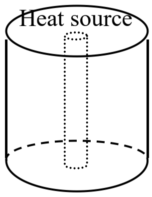

Fig. 2 Model of closed cavity

3. Heat transfer calculation

3.1 Thermal radiation

A closed system consisting of two surfaces is the simplest and most common radiation system. The net energy emitted from the surface of A_1 at this time is equal to the net energy received from the surface of A_2, and is also equal to the energy Q_{12} exchanged between the two surfaces.

$$Q_1 = -Q_2 = Q_{12}$$

Fig. 3 is general graphical representation for this system, applying general computational relations heat quantity expression can be obtained [2]:

$$Q_1 = \frac{E_{b1} - J_1}{\frac{1-\varepsilon_1}{A_1\varepsilon_1}} \qquad Q_{12} = \frac{J_1 - J_2}{\frac{1}{A_1 F_{12}}} \qquad -Q_2 = \frac{J_2 - E_{b2}}{\frac{1-\varepsilon_2}{A_2\varepsilon_2}}$$

In expression E_b represents the black-body radiation force， J represents effective radiation， ε represents blackness，A is the surface area. The bottom corner mark 1 represents the surface of 1, the bottom corner mark 2 represents the surface of 2, F_{12} is called angle coefficient.

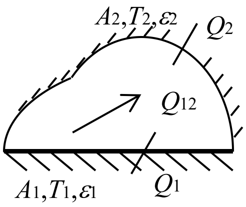

Fig. 3 Two surface containment radiation systems

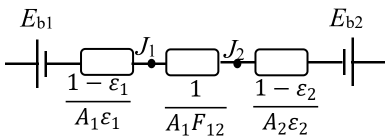

Fig. 4 Radiation heat transfer network diagram

Similar to the series circuit as shown in Fig. 4 can be concluded：

$$Q_{12} = Q_1 = -Q_2 = \frac{\sigma\left(T_1^4 - T_2^4\right)}{\frac{1-\varepsilon_1}{A_1\varepsilon_1} + \frac{1}{A_1F_{12}} + \frac{1-\varepsilon_2}{A_2\varepsilon_2}}$$

σ is black body radiation constant. T is thermodynamic temperature of surface. For an infinitely long coaxial cylindrical cavity

$$A_1 / A_2 = r_1 / r_2, \quad F_{12} = 1,$$

$$Q_{12} = \frac{\sigma A_1\left(T_1^4 - T_2^4\right)}{\frac{1}{\varepsilon_1} + \frac{1-\varepsilon_2}{\varepsilon_2}\left(\frac{r_1}{r_2}\right)^2} \tag{1}$$

Assuming that the closed cavity is a closed system, for the closed cavity, the diameter of the cavity is much larger than the diameter of the heat source, and the radiation and absorption radiation energy of the air in the cavity is negligible. The analysis using formula (1) is as follows: the diameter of the heat source is 10 mm and the length of the cavity is 20 mm. ε can be obtained by looking up the table. T_1 is 343K and T_2 is293K, Q_{12} calculated as 2.25×10^{-11} W , order of magnitude is 10^{-11} . It can be seen that for heat sources with small surface areas, the thermal radiation generated in the cavity is completely negligible. For the actual closed cavity, the thermal radiation is smaller than the thermal radiation of the closed cavity, so the thermal radiation of gas pendulum in cavity is negligible.

3.2 Thermal conduction

The thermal conduction without flow of media in cavity is discussed below. The pure thermal conduction in the cavity belongs to the stable thermal conduction. In the physical sense, the heat transmitted is equal to the heat emitted at any time in the cavity. However, the interior of the cavity does not mean there is no temperature difference, but on the contrary, the temperature gradient always exists.

For coaxial cylinder walls, if the heat conduction in the direction of the cylinder axis is ignored, the radial heat conduction of the cylinder is a one-dimensional radial guide heat. In a stable situation

$$\frac{1}{r}\frac{\mathrm{d}}{\mathrm{d}r}(kr\frac{\mathrm{d}T}{\mathrm{d}r})=0$$

Where k is coefficient of thermal conductivity. Border conditions are

$$r=r_1,\quad T=T_1$$

$$r=r_2,\quad T=T_2$$

T_1 、 T_2 is the temperature of the inner and outer wall of the cylinder respectively. Solved temperature distribution in the cylinder as

$$T=T_1-\frac{T_1-T_2}{\ln\frac{r_2}{r_1}}\ln\frac{r}{r_1}$$

In the case of tube length L, the radial guide heat quantity [3]:

$$Q_L=-k2\pi rL\frac{\mathrm{d}T}{\mathrm{d}r}=\frac{2\pi kL}{\ln\frac{r_2}{r_1}}(T_1-T_2) \tag{2}$$

For a closed chamber of a gas pendulum tilt sensor, there is air in the cavity, k is thermal conductivity of air, check list and got 0.026W/(m・℃). Temperature difference between inner wall and outer wall is 50℃. The ratio of the outer wall to the inner wall radius is 10^3 . The result of the calculation is

$$Q_L=0.0237\mathrm{W}$$

3.3 Natural convection

Natural convection is caused by the mass force acting on a fluid with a density gradient. The net effect is that the lift causes convection. It is due to the temperature gradient and the mass force generated by the gravitational field, which caused convection in the closed cavity [4]. Therefore, what actually occurs in the closed cavity is natural convection.

For a closed cavity consisting of two coaxial cylinders, the heat transfer of natural convection formula is used to calculate

$$Q_C=\frac{2\pi k_{eff}L}{\ln\frac{r_2}{r_1}}(T_1-T_2) \tag{3}$$

Where k_{eff} is effective thermal conductivity, meaning that the heat transfer of a moving fluid is replaced by the heat transfer of a stationary fluid. The thermal conductivity of a stationary fluid k_{eff} can be calculated by:

$$\overline{Nu} = \frac{k_{eff}}{k} \tag{4}$$

$\overline{Nu}$ is average *Nussel* coefficient. By literature [5] average *Nussel* coefficient of the cavity was expressed

$$\overline{Nu} = \frac{Nu}{S^*}$$

Nu is *Nussel* coefficient. Here S^* is heat conduction shape factor

$$S^* = \frac{2\pi}{\ln\frac{r_2}{r_1}}$$

$Nu \approx 1$, which has been discussed in[6]. The ratio of the outer wall to the inner wall radius is 10^3. Substituting known conditions into the above formula to calculate the results is

$$\overline{Nu} = \frac{k_{eff}}{k} = 1.098$$

By (3) and (4), the heat transfer of natural convection is

$$Q_C = 0.026\text{W}$$

That means

$$Q_C \approx Q_L$$

It can be seen that the heat transfer of natural convection in the closed cavity is equivalent to the heat conduction .The current of the heat source is about 50mA, and the resistance is about 10.6Ω in the experiment. Therefore, the energy provided by the heat source per unit time was

$$Q = I^2R = 0.0265\text{W} \approx Q_C$$

Utilizing ANSYS-FLOTRAN CFD, can calculate the distribution of convection and temperature fields can be calculated caused by point heat sources in a two-dimensional closed cavity.The temperature of the heat source is 70 ℃ and the ambient temperature is 20 ℃, and the calculation results are as follows

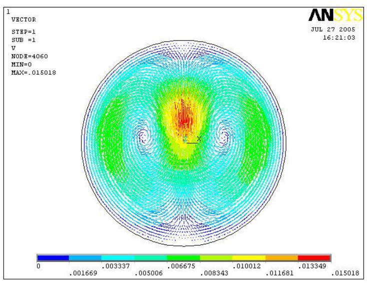

Fig. 5 Velocity field vector diagram

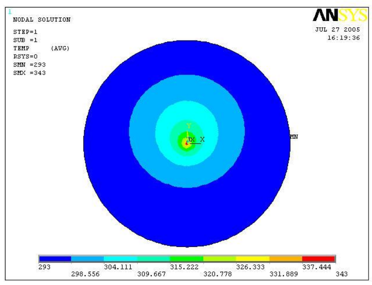

Fig. 6 Temperature field cloud map

From the velocity field vector diagram in Fig. 5, it can be seen that the effect of the internal heat source causes a temperature difference between the hot wire and the cavity, resulting in a change in air density in the air cavity which leaded to significant natural convection in the cavity. However, due to the low temperature of the heat source and the low flow velocity in the cavity, the heat transfer through natural convection is equivalent to that through heat conduction. For the obvious natural convection generated in the cavity, the principle of fluid similarity can be applied to eliminate the influence of environmental temperature on sensor performance, about this issue have been discussed in reference [6].

4. Summary

From the above calculation, we can draw the following conclusions:

- Compared with other heat transfer methods, the thermal radiation in the closed cavity is very small and can be ignored. When analyzing the sensitivity mechanism of the gas pendulum inclination sensor, the influence of thermal radiation is not considered.
- In a closed chamber the heat transfer of convection is basically the same as of conduction without flow of media.
- The heat transfer problem in closed cavity is mainly convective heat transfer. If heat transfer problems need to be analyzed, which can be simplified by means of thermal conduction analysis.
- There is obvious natural convection in the cavity, and the performance of the sensor can be improved based on the principle of flow similarity.

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