Simulation Research on Hot Bulb Anemometer Under Low Pressure

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Abstract: In the Mars exploration, the atmosphere and wind speed on the surface of Mars result in the difference in heat transfer between Mars rover and general earth orbit spacecraft. In addition to solar radiation and infrared radiation, surface heat conduction and convection heat transfer of the atmosphere are the primary heat transfer forms on the surface of Mars. In order to correct the thermal model of Mars rover and verify the ability of thermal control system to maintain the system at working temperature under extreme thermal environment, the low pressure and wind speed environment of Mars surface should be simulated in the Mars rover test. Therefore, the wind speed should be measured on multiple positions in the thermal test under low pressure. The dynamic, thermal and ultrasonic anemometers have the problems such as small signal, low precision and need to be recalibrated under low pressure. A numerical simulation model for constant heat flow hot bulb anemometer under low pressure has been established by CFD method. The response characteristics at low pressure are analyzed by the model. A test system was built in space environment simulation chamber to verify the simulation. Test and CFD method reach a similar result, which proves the validity of the analysis.

1 INTRODUCTION

The atmospheric pressure on the surface of Mars is about 700Pa, and the gas is dominated by carbon dioxide, with a surface temperature of about -120~20 ℃ . At the same time, there is a 0-15m/s wind speed on the surface of Mars, which causes the heat exchange environment on the surface of Mars being different from that of the earth orbit environment. To achieve the purpose of thermal model correction, early fault screening, and performance testing in extreme environment, hardware developer usually prefers to test the rover in a more realistic simulation environment The pressure, thermal boundary and wind speed is required to be simulated in thermal test(Ransome et al., 2001, Johnson). The simulation of low pressure and thermal boundary can be achieved by the space environment simulation chamber and its inner heat sink. Meanwhile, the wind speed should be simulated and measured under low pressure. The commonly used methods of wind speed measurement in the industry include dynamic pressure measurement, thermal measurement, and ultrasonic measurement.

The dynamic pressure measurement calculates the dynamic pressure via the difference between the total pressure and the static pressure of the fluid. The dynamic pressure is only related to the density of the gas and the fluid velocity. The advantage of dynamic pressure wind speed measurement is that the velocity conversion formula is explicit. However, its limitation is also very obvious. With the decrease of gas density, the dynamic pressure will decrease rapidly correspondingly. When measuring the 0-15m/s wind speed in the 700Pa environment, the resolution of pressure measurement should reach at least 0.1Pa. Although the laboratory micro pressure sensor can meet the requirements of its measurement accuracy, its volume and weight are often challenging to achieve the requirement of measuring the multipoint wind speed in the limited space of the space environment simulation chamber(Wilson, 2003). The principle of the thermal anemometer is that the convection heat transfer coefficient increases gradually with the rise of the wind speed (Bruun,

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1995). Thermal anemometer has serval advantages including simple structure and lightweight(Numata et al., 2011, Chamberlain et al., 1976). Its disadvantage, however, is that the exact analytical solution of convection heat transfer characteristics can hardly be obtained. Thus, the thermal anemometer can be measured accurately only when it has been fully recalibrated under the operating environment. Thermal anemometer has been carried on a variety of Mars lander and rover while all of them are customized products (Seiff et al., 1997). The central principle of ultrasonic wind speed measurement is that the sound velocity is only related to the local gas composition and temperature. However, the ultrasonic signal highly attenuates at low pressure(Kapartis, 1999). As a result, industrial products cannot be directly used for wind speed measurement under low pressure. It is often essential to optimize the ultrasonic anemometer from software and hardware(Banfield et al., 2012) .

To sum up, in the field of Mars and stratospheric wind speed measurement, the sensors used are all customized products. This paper aims to use industrial products in wind speed measurement under low pressure. A constant heat flow hot bulb heat transfer model has been established by CFD method, which was used to analyses probe response under different pressure. The result has been verified by a test system which was built in space environment simulation chamber. The simulation analysis and test have obtained a similar result, which demonstrates the correctness of the analysis and provides a reference for future related test.

2 HEAT TRANSFER MODEL

2.1 CFD model

The hot bulb probe used in this paper is a ceramic encapsulated sphere with a diameter of 0.6mm. It has internal heating wire and thermocouple hot junction, and the cold junction of the thermocouple is located outside the hot bulb.

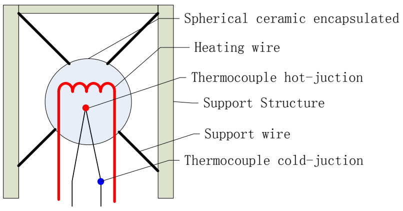

Figure 1: hot ball probe model.

When the hot bulb anemometer works, a constant heat flow is produced on the ceramic bulb. With different wind speed, the surface of the sphere also has a different convective heat transfer coefficient. When radiation and conduction heat transfer are tiny, the heat lost through the surface of the sphere approximately equals to the heat flow of the electric heating wire

$$Q_{Power}=I^2R=Sh(T_s-T_e)=S\frac{Nu\lambda}{l}(T_s-T_e)$$

Where Q_{Power} is heat generate by the heating wire(W), can be calculated by the current (A) and resistance (Ω), S is bulb surface area(m^2), T_s is the sphere temperature (K), T_e is the ambient temperature (K), h is convection heat transfer coefficient (W/m^2 • C), can be expressed by Nusselt number, Thermal conductivity λ (W/m • ℃), and characteristic length l (m). The Nusselt number can be expressed by a function of Reynolds number (f_{Nu}), the temperature difference between the hot bulb and environment can be calculated by a function of the thermoelectric potential (f_t), the equation can be simplified to:

$$I^2R=\frac{S\lambda}{l}f_{Nu}(\frac{vl}{\upsilon})f_t(\Delta V)$$

As shown above, the hot bulb output signal and the wind speed V can be one-to-one correspondences when the environment parameters are known precisely. Through experiments, Kramers, Whitaker, Yuge, Vilet, Raithby and other scholars have given various Nu-Re empirical formula for spheres. However, almost most of the formula has more than 50% of the error in the low Reynolds number range (0.1-100) (Dennis et al., 2006). Therefore, it is difficult to predict the response of the hot bulb wind probe at low pressure by dimensionless number analysis method.

In this paper, a 2-dimensional model of constant heat flow hot bulb anemometer under low pressure has been established by CFD simulation. The axisymmetric swirl model was selected to simulate the axisymmetric flow field. The flow field grid is shown in Figure 2.

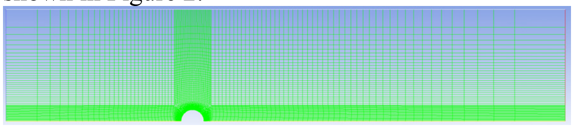

Figure 2: CFD simulation mode.

Because the whole flow field is low-speed flow, the Incompressible ideal gas model has been chosen to calculate the density. The k-omega model and surface to surface model were selected to simulate the turbulence flow and radiation heat transfer. The boundary conditions are shown below:

Table 1: Boundary conditions.

Position	Boundary condition
Symmetric axis	Axis
Sphere surface	Wall，constant heat flux
Inlet	Velocity Inlet
Outlet	Outflow
Outer boundary	Moving Wall Velocity= Inlet Velocity

2.2 Grid independence analysis

In order to minimize the errors caused by the grid in the analysis, the multiple cases with different grid numbers have been calculated in this paper. The convection heat transfer coefficient and the surface average Nusselt number are analyzed to evaluate the grid. The result is shown below:

Table 2 Grid independence analysis.

Cells	Convective heat transfer coefficient(W/m^2·℃)	Average Nusselt number
1656	98.12764	4054.861
3256	98.64166	4076.101
6346	98.85119	4084.76
12534	98.81493	4083.262
24592	98.86643	4085.39

As shown in the table, when the number of cells is over 6000, the change of heat transfer results is very little. In the model with 6000 cells, the errors caused by mesh can be ignored in the CFD simulation. The velocity and temperature distribution around the hot bulb probe are shown below.

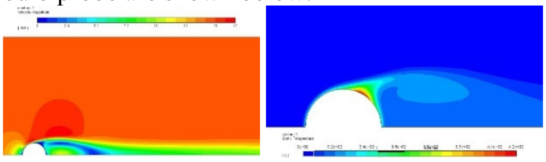

Figure 3: the velocity and temperature distribution.

2.3 Test verification

In order to verify the CFD model of the hot bulb anemometer, a wind speed calibration system based on rotation has been built in this paper. The rotating platform and cantilever were installed inside a medium-size space environment simulation chamber. The rotating platform drives the cantilever to rotate at a set speed to simulate the different wind speed around the probe, and the medium-size space environment simulation chamber provides the different pressure environment for the test.

At the same time, the millivolt signal transmitter installed on the turntable can measure the signal of the probe and transmit it to the computer outside the chamber by RS-485. The schematic diagram of the calibration system is shown below.

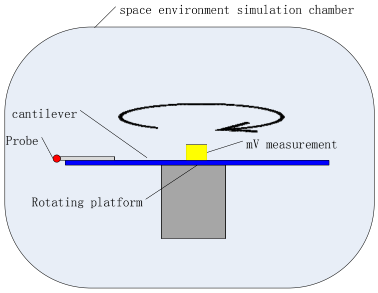

Figure 4: Calibration system.

The total power of the hot bulb probe used in this paper is 0.08W, which contains the heat lost on the bulb and the cables or wires. The relationship between total power and probe output voltage can be simplified to:

$$C_1 Q_{Power} = Sh(T_s - T_e) = Sh\frac{\Delta V}{C_2}$$

Where C_1 is the ratio of the hot bulb power to the total power. Because the resistance changes little, it can be considered as a constant. C_2 is the sensitivity of the thermocouple (mV/ C), S is the surface area(m^2), Q_{Power} is the total power(W). When the sensitivity of the thermocouple varies little within the range of use, the convection heat transfer coefficient should be inversely proportional to the output thermoelectric potential.

Through the experiments under different pressures, the output thermal potential of the hot bulb probe at 1-15m/s has been recorded. The convection heat transfer coefficient calculated by the CFD method is multiplied by thermal potential respectively. The result is shown in Figure 5.

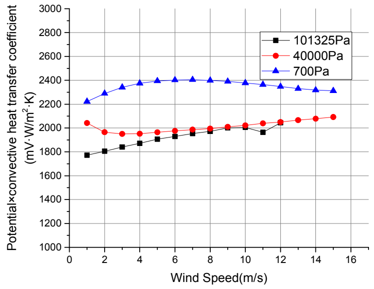

Figure 5: thermal potential·heat transfer coefficient.

As shown in Figure 5, the experimental thermal potential • CFD calculated heat transfer coefficient is approximately constant. The fluctuation is less than 10%, and the value in ambient pressure is very close to the 40000Pa result. However, in the case of 700Pa, the error is about 20%, which is similar to the result of literature(Numata et al., 2011), it is mainly because the Nu-Re empirical correlation will also change under very low pressure.So that, there is a non-ignorable error in calculating the output of a thermal anemometer by simulation, and the result should be corrected with experimental methods.

After solving the coefficient, the probe signal can be predicted by the CFD simulation, the predicted output and test result have been compared, as shown in Figure 6.

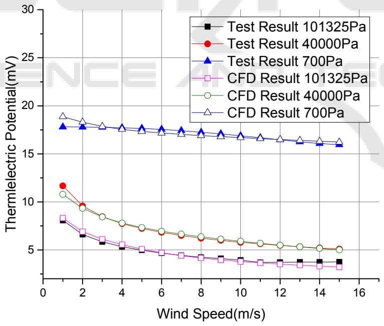

Figure 6: Test result and CFD calculation.

As shown in Figure 6, the response of the constant heat flow hot bulb anemometer in the environment above 40000Pa can be efficiently estimated by CFD simulation. However, for the incredibly low-pressure environment, especially for the low wind speed environment, the model should be corrected by the experimental data. The main reason of the deviation includes the deviation of the heat transfer calculation, the larger error of the pressure measurement under low pressure, the more significant error of the turntable at low speed, and the more massive natural convection caused by the higher temperature. Meanwhile, the sensitivity of the hot bulb probe is about 0.01~0.2mv/(m/s). When the test is carried out at low pressure, the Voltage signal data acquisition hardware should also meet the accuracy requirement.

3 CONCLUSIONS

This paper aims at the problem of wind speed measurement under low pressure. A heat transfer model for constant heat flow hot bulb probe has been established by CFD simulation method. A test system has been built in space environment simulation chamber to verify the probe output model. The simulation model and the experiment have obtained the similar result under ambient pressure and 40000Pa. The heat transfer model builds in this paper can be directly applied to constant heat flow hot bulb under 40000Pa or higher pressure, and can be used to 700Pa environment through experimental data correction. The model can be used to evaluate the output of hot bulb sensors in different environments, and provide a reference for future related test.

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