Research Paper
International Journal of Aerospace System Engineering
Vol.2, No.2, pp.50-53 (2015)

ISSN 2383-4986

Hypersonic Aero-Heating Ground-Test Simulation Technique

Ruiqu Li[1,†], Dapeng Yao[1], Xinguo Sha[1], Jian Gong[1]
[1] *China Academy of Aerospace Aerodynamics*

Abstract: It would encounter some complicated flow fields, such as transition, separation, reattachment and disturbances, in the hypersonic flight. Thus, it is difficult to theoretically analyze the hypersonic aerothermodynamics effects, so that the ground-test simulation is thought of as one of the most important methods to improve the understanding level of the hypersonic aerothermodynamics. However, the aero-heating tests could not simulate all aerodynamics and geometry parameters in the real flight due to the differences between the experimental environments supplied by the ground facilities and the flight, so that the feasible technique for the ground-test simulation of the hypersonic aerothermodynamics effects is required to be advanced. The key parameters that are especially required to simulate for aero-heating tests are analyzed and one detailed approach is suggested to perform the experimental investigation on the hypersonic aero-heating effects in the ground facilities in this paper, and the tests are performed in the FD-20 gun tunnel of CAAA (China Academy of Aerospace Aerodynamics) to give out the data which could be used to confirm the equation from the theoretical analysis.

Key Words : Ground-test simulation; Hypersonic; Aerothermodynamics, Dimensionless heat transfer

1. Introduction

The flow fields on or in the aircrafts with the shock wave, transition, separation, turbulence, reattachment and disturbances in the hypersonic flight could be very complicated for researchers to give out a deep theoretical analysis. Thus, three methods including ground test, numerical analysis and flight test are developed to estimate the aerothermodynamics effects of the hypersonic vehicle. Due to the high cost of the flight test and the faultiness of the numerical analysis, the wind tunnel test on the ground is always an indispensable method to increase or improve the understanding of the hypersonic thermodynamics effects. However, the aerodynamics and geometry parameters in the real hypersonic flight could not be entirely duplicated in the aero-heating tests on the ground because of the limitation for the simulation ability of the ground facilities. The aero-heating experiments conducted in the hypersonic wind tunnels are usually based on the hypothesis of viscous, compressible and steady flow, so that those measurements could not be directly used in the estimation of aerothermodynamics data in the real flight.

Based on the hypothesis in the similarity theory, the aerodynamics equations could be derived to analyze the characteristics and functions of those dimensionless parameters with the relatively large influence to the aero-heating measurements. Gusev [1] discussed the factors that affect the heat transfer in details and the results show that the heat

Received: June 05, 2015 Revised: Aug. 01, 2015
Accepted: Sep. 21, 2015
†Corresponding Author
Tel:+ 86-010-6874-3513,
E-mail: lirq995688@126.com

transfer on the surface of the hypersonic vehicles are principally affected by Reynolds number, Mach number, the ratio of wall temperature and the direction angle of the model, such as the angle of attack, yaw and roll, and so on, that is, the heat transfer on the surface is function of those dimensionless parameters, and the hypersonic aero-heating ground-test simulation technique could be considered as the method to experimentally confirm this function. Goodrich et al. showed a comparison of flight and wind tunnel data of the shuttle orbiter boundary-layer transition [2]. Boman et al. analyzed the application of the STAPAT II code to the hypersonic vehicle aerothermodynamics [3].

Based on the data base, those past studies reveal the complexity of the investigations on the correlation between the flight data and the ground test results, but nobody could give out the detailed equations, so that many repeated experimental works have to be performed for the subsequent researchers. It is an attempt to obtain some useful equations due to the similarity analysis and measurements in wind tunnel to preliminarily explore the hypersonic aero-heating ground-test simulation technique in this paper.

2. Similarity Analysis

For the hypersonic flow with the heat exchange, the parameters in the flow field could be described by the following equations [4]:

$$\frac{\partial(\rho v_i)}{\partial x_i} = 0 \tag{1}$$

$$v_j\frac{\partial v_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \nu\frac{\partial^2 v_i}{\partial x_j^2} + \frac{1}{3}\nu\frac{\partial}{\partial x_i}\left(\frac{\partial v_k}{\partial x_k}\right) \tag{2}$$

$$v_i\frac{\partial T}{\partial x_i} = -\frac{v_i}{\rho c_{p_f}}\frac{\partial p}{\partial x_i} + a\frac{\partial^2 T}{\partial x_i^2} + \frac{\nu}{2c_{p_f}}\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i}\right)^2 \tag{3}$$

$$p = \rho RT \tag{4}$$

$$q_w = h(T_w - T_\infty) \tag{5}$$

where p, ρ, v, T_w, T_∞, q_w,ν, R, h, are respectively the pressure, density, velocity, wall temperature, free stream temperature, wall heat transfer, viscosity coefficient, gas state constant and heat exchange coefficient. Of course, those equations are built up due to the hypothesis of viscous, compressible and steady flow in a continuum gas media (Kn<<1). If a free-molecular (Kn >>1) and a transitional (Kn ~ 1) flow conditions were considered, it will be more complicated and difficult to solve that problem.

From those equations, any aerodynamic characteristic C could be derived as [1, 4, 5]:

$$C = f\left(Re, Pr, \gamma, Ma, \frac{T_w}{T_\infty}, \frac{x_i}{L}\right) \tag{6}$$

Where Re is Reynolds number, Pr is Prandtl number, γ is the specific heat ratio, Ma is Mach number, L is the characteristic size.

In the FD-20 gun tunnel, the test gas is air, so that the specific heat ratio could be thought of as a constant during the tests. Otherwise, the running time of that tunnel is short as about 20 ~ 40 milliseconds, so that the influence of the temperature to the heat conduction coefficient could be neglected and the Prandtl number could also be considered as a constant. For the dimensionless length x_i/L, the angle of attack and the scale of the model are two factors that should be regarded. Finally, the aerodynamic characteristic C in aerothermodynamics simulation is represented by the dimensionless heat transfer. Thus, the equation (6) could be rewrote as:

$$q = f\left(Re, Ma, \frac{T_w}{T_\infty}, Sca, \alpha\right) \tag{7}$$

Where $q = q_w/q_s$, in which q_w is the heat transfer on the wall and q_s is the heat transfer at the stagnation point, α is the angle of attack, Sca is the scale of the model.

Due to the engineering experiences and the measurements, one type of function 'f' could be assumed as:

$$q = e^{C_1\alpha + C_2 Sca + C_3} Re^{C_4} Ma^{C_5} \left(\frac{T_w}{T_\infty}\right)^{C_6} \tag{8}$$

Where $C_1 \sim C_6$ are the coefficients.

3. Experimental Results

The heat transfer distribution along the center line of the cone-like model, which is shown in Fig.1, is measured by the thin film resistance technique in the FD-20 gun tunnel in CAAA. Many groups of experimental data are obtained by variation of the dimensionless parameters with Mach number of 8, 10, 12, unit Reynolds number of 2×10^6 (1/m), 4.1×10^6 (1/m), 4.8×10^6 (1/m), 1.3×10^7 (1/m), 2.2×10^7 (1/m), model scale of 1/2, 1/3, 1/4, angle of attack of 0 and 10 degree, the wall temperature ratio of 0.19~0.29. Those data are statistically solved and the formula of heat transfer along the center line of the cone-like model under the laminar flow condition is derived as equations (9) and (10), which are respectively represented as the data on the 0°and 180°center line.

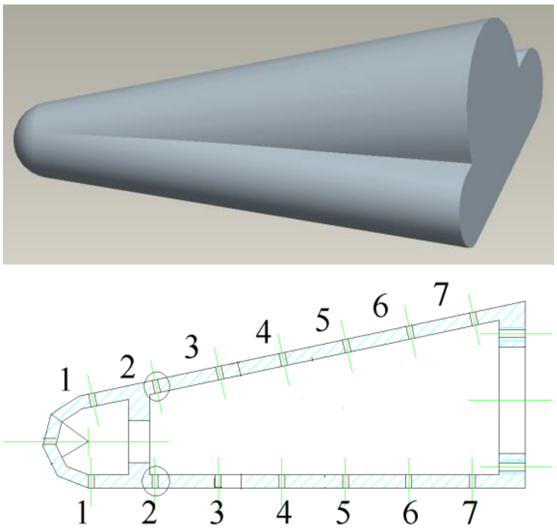

Fig. 1 Schematic of the combination configuration

$$q_{w0} = e^{0.0906\alpha+0.5462Sca+5.7380}\mathrm{Re}^{-0.7468}\mathrm{Ma}^{-2.3899}\left(\frac{T_w}{T_\infty}\right)^{-3.1043} \quad (9)$$

$$q_{w180} = e^{-0.1145\alpha+0.6038Sca+3.1298}\mathrm{Re}^{-0.4680}\mathrm{Ma}^{-1.0425}\left(\frac{T_w}{T_\infty}\right)^{-1.3806} \quad (10)$$

For the simulation ability of FD-20, the parameters could be selected in the range with Mach number of 5~15, unit Reynolds number of 1×10^6~7×10^7(1/m). It is obviously not enough to simulate the real hypersonic flight. Equation (9) and (10) could be considered as a start point for us to explore a detailed method of wind tunnel simulation on the ground. For example, if the simulated parameters are Mach number of 25 and unit Reynolds number of 10^5(1/m), for an aircraft with a forebody similar to the model shown in Fig. 1 and for some location of x = 50 mm on its 0°center line and the Scale of 1/3, the angle of attack of zero degree and the wall temperature ratio of 0.2191, Equation (9) could give out the variation of the dimensionless heat transfer ratio with Mach number and unit Reynolds number, which is shown in Fig. 2.

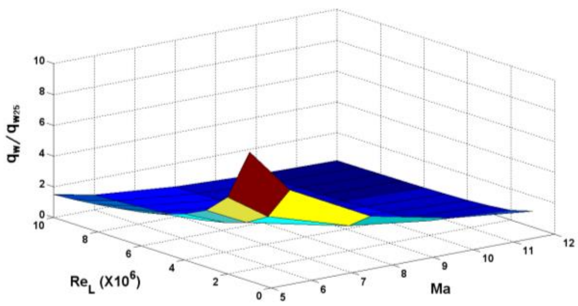

Fig. 2 Dimensionless heat transfer ratio vs. Mach number and unit Reynolds number

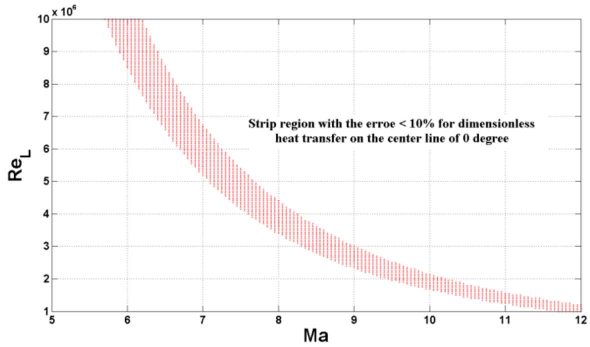

Fig. 3 the strip region with the error < 10% for dimensionless heat transfer on the center line of 0 degree

It is assumed that the error of the simulation in the ground-test wind tunnel is less than 10%, the result shown in Fig. 2 could be projected in the Ma-Re_L plane as the strip region. Fig. 2 shows that when the scale of model, the angle of attack and the wall temperature ratio are given, to simulate the dimensionless heat transfer with the error less than 10% on the centerline of zero degree at the condition of Mach number of 25 and unit Reynolds number of 10^5, the free stream parameters including Mach number and unit Reynolds number could be selected in the red strip region. For instance, the free stream with Mach number of 8 and unit Reynolds number of 4×10^6(1/m) could be selected, and the free stream with Mach number of 10 and unit Reynolds number of 2×10^6(1/m) could also be feasible.

4. Conclusions

It is difficult to simulate those real hypersonic flight environments in the wind tunnel tests on the ground due to the complexity of those flow fields. A method based on the similarity law, dimensional analysis and experimental data in a gun tunnel is advanced to preliminarily solve that problem. The equations could be used to select the free stream parameters simulated in the wind tunnel tests.

However, the technique is only a preliminary work. In the future, the measurements should be extended, the equations should be validated by the numerical results and even the data in the flight tests. And another problem is that the nonequilibrium effects with higher Mach number of more than 20, the variation of the gas characteristics will greatly affect the aerothermodynamics environment on the hypersonic vehicles, that is, the rarefied gas effects and the physical and chemical processes in air are all required to be analyzed.

References

[1] V. Gusev, "The Investigation of the Hypersonic Vehicle Aerothermodynamics," *AIAA Paper*: 1990-5271, 1990.

[2] W. D. Goodrich, S. M. Derry, J. J. Bertin, "Shuttle Orbiter Boundary-Layer Transition: a Comparison of Flight and Wind Tunnel Data," *AIAA Paper*: 1983-0485, 1983.

[3] B. Boman, C. Babish, "Application of the STAPAT II Code to Hypersonic Vehicle Aerothermodynamics," *AIAA Paper*: 1991-5035, 1991.

[4] Y. Z. Cao, X. G. Qiu, *Experimental Heat Transfer*, National Defense Industry Press, 1998.

[5] Q. M. Tan, *Dimensional Analysis*, Chinese Science and Technology University Press, 2005.

Authors

Ruiqu Li
Graduated from Tsinghua University as a doctor and main interests in hypersonic aerothermodynamics, aero-optics and transition.