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Research on Data Reduction Techniques of Phosphor Thermography in Gun Tunnel

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Abstract- Heat transfer to a hypersonic vehicle surface is one of the most important aerothermodynamic quantities and one that often remains difficult to predict using modern computational fluid dynamics. Ground wind tunnel testing plays an important preparatory role for flight testing of new hypersonic concept vehicles. Arrays of thin film resistance thermometer have been used to measure heat transfer on a model. However, due to the limited spatial resolution of the array, critical effects are often difficult or impossible to capture. Phosphor thermography provides a useful tool for quantitative global heat transfer diagnostics in hypersonic gun tunnels. Phosphor paint is a thin polymer layer doped with certain luminescent molecules for which the emission is sensitive to temperature. Therefore, once phosphor paint coated on a surface is calibrated, surface temperature fields can be measured by detecting the luminescent emission from phosphor paint. Digital cameras with optical filters are used to image phosphor paint. After a time sequence of the surface temperature fields is obtained from phosphor paint in a hypersonic tunnel, the main problem is how to accurately extract a heat flux field on a model surface. Heat transfer measurements using conventional local gauges such as thin-film resistance thermometer in hypersonic tunnels have been very mature. In contrast, methods for calculation of heat flux from phosphor thermography measurements are not given in a systematical and general fashion. Therefore, the heat transfer model and data processing method of phosphor thermography are analyzed in detail in this paper.

Keywords**:** Hypersonic vehicles, Phosphor thermography, Gun tunnel, Data reduction.

1. Heat transfer model

During the effective operating time（60ms）of hypersonic gun tunnel, there are two steps in the heat flux of aircraft surface. At present, most of the heat flux calculations are based on the second type of boundary conditions (heated by constant heat flux), But in the actual aerodynamic heating process, the wall is subjected to the heating from the gas in the high temperature boundary layer. It is more similar to the third type of boundary conditions (heat exchange with the flow of temperature T_∞).These two boundary conditions are discussed below.

The surface temperature under the second type of boundary condition is first calculated. Given the 200Kw/m^2(1-25ms)and 400Kw/m^2(1-25ms), the surface temperature of the aircraft is calculated as shown in figure1. It can be seen that there are great differences between the cures of temperature measured with time and the numerical simulation under the second boundary condition. In the experiment, there is a rapid temperature change after the flow field is established, and then rise gradually with a certain rule. But there is no such phenomenon in numerical simulation. On this basis, the third type of boundary condition is proposed. Assuming that the total temperature of the first step is 750K, and the total temperature of the second step is 1200K.As shown in Fig.3, the simulation results of the surface temperature of aircraft can be found by comparison. At this time, the surface temperature variation of the aircraft is consistent with the experimental results. As shown in Fig.5, the variation of surface heat flux can be seen as the same trend between the experimental measurements and the numerical simulation, which further shows that the assumption of the third type of boundary conditions is reasonable.

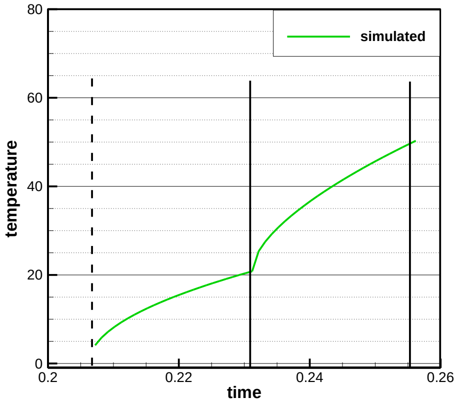

Fig. 1: Surface temperature under the second type of boundary conditions.

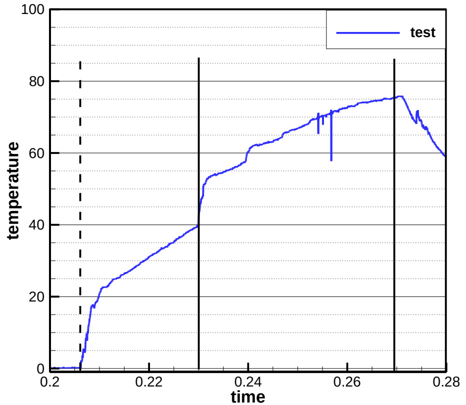

Fig. 2: Measurement results.

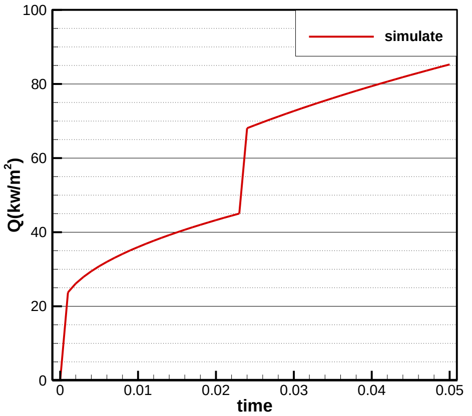

Fig. 3: Surface temperature under the third type of boundary conditions heat flux.

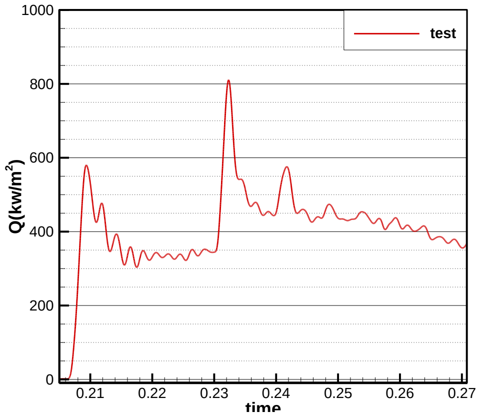

Fig. 4: Measurement results.

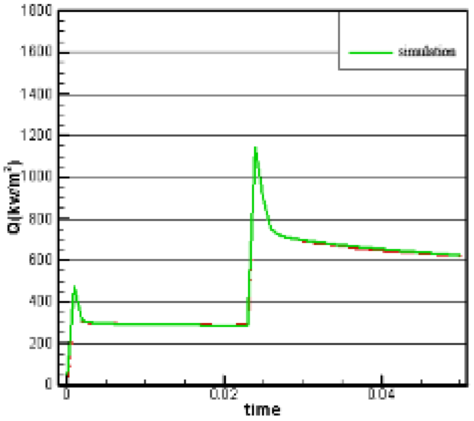

Fig. 5: Simulation results of heat flux.

2. Discussion

In the gun tunnel, the heat transfer process on the surface of the vehicle satisfies the one dimensional and semi-infinite assumption, and the convection heat transfer between the air around the aircraft and the wall of the aircraft is carried out. From Newton cooling formula：

$$q_w = h(T_{aw} - T_w) \tag{1}$$

Where q_w is the wall heat flux, h is the convective heat transfer coefficient between the surrounding air and the wall surface, which is related to the physical properties of the fluid, the fluid flow state and the surface condition of the aircraft, $T_{aw}$is the adiabatic wall temperature, and $T_w$is the surface temperature. Assuming the initial wall temperature is T_0, then:

$$q_w = h[(T_{aw} - T_0) - (T_w - T_0)] = h(\theta_{aw} - \theta_w) \tag{2}$$

Laplace transforms

$$\bar{q}_w = \frac{h\theta_{aw}}{s} - h\bar{\theta}_w \tag{3}$$

Simplified to:

$$\bar{\theta}_w = \frac{h\theta_{aw}}{s(h+\sqrt{s}\sqrt{\rho ck})} \tag{4}$$

$$\bar{\theta}_w = \theta_{aw}\frac{\frac{h}{\sqrt{\rho ck}}}{s(\frac{h}{\sqrt{\rho ck}}+\sqrt{s})} \tag{5}$$

Laplace reverse transformation:

$$\frac{\theta_w}{\theta_{aw}} = 1 - \exp\left(\frac{h^2}{\rho ck}t\right)\operatorname{erfc}(\frac{h}{\sqrt{\rho ck}}\sqrt{t}) \tag{6}$$

Erfc is the error function。

Set A=h, B= θ_{aw} ,The above formula can be turned into:

$$\theta_w = B（1 - \exp\left(\frac{A^2}{\rho ck}t\right)\operatorname{erfc}(\frac{A}{\sqrt{\rho ck}}\sqrt{t})） \tag{7}$$

$$q_w = A(B - \theta_w) \tag{8}$$

We can use the least squares method to solve the optimal A and B values, and then by Equation.1 we can find the heat flux distribution at different times.

The comparison of results of phosphor thermography and thin film sensor as shown in figure 6, it shows that there is a good agreement between the two methods, which shows that the heat flux calculation method is useful and reliable.

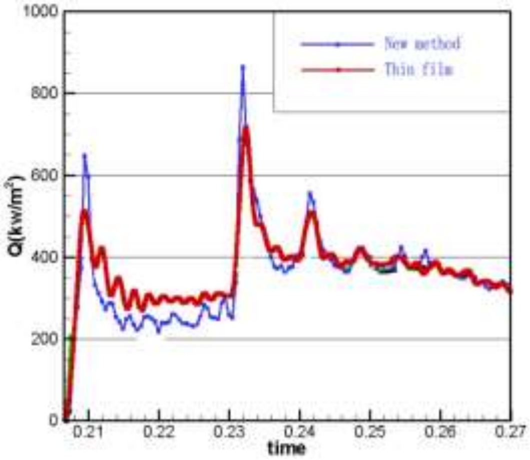

Fig. 6: comparison of thin film sensor and phosphor thermography.

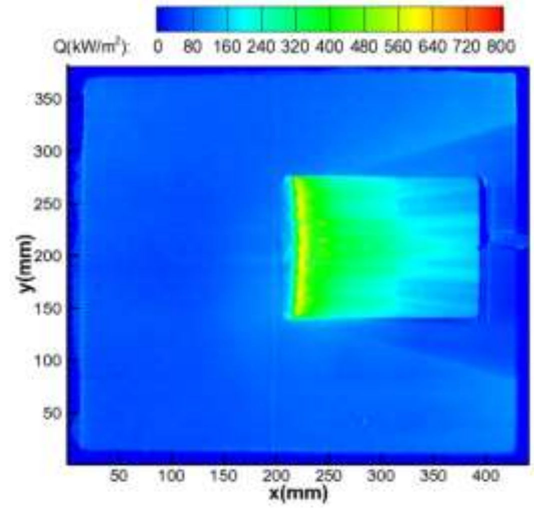

Fig. 7: Measurement results of Corner Model by phosphor thermography.

3. Conclusion

Numerical simulation and experiments show that the heat transfer process on the surface of aircraft in the gun tunnel is closer to the third type of boundary condition (heat exchange with the fluid with temperature t_∞). The data processing method based on the least squares method is suitable for the heat flux calculation of the thermography under the condition of the gun tunnel, which can obtain higher calculation accuracy and efficiency.

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