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An Accurate Prediction of Surface Temperature History in a Supersonic Flight

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***Abstract*—**In the present study, the surface temperature history of the adaptor part in a two-stage supersonic launch vehicle is accurately predicted. The full Navier-Stokes equations are used to estimate the aerodynamic heat flux and the one-dimensional heat conduction in solid phase is used to compute the temperature history. The instantaneous surface temperature is used to improve the applied heat flux, to improve the accuracy of the results.

***Keywords*—**Aerodynamic heating, Heat conduction, Numerical simulation, Supersonic flight, Launch vehicle.

I. Introduction

ONE of the major problems to be considered in high speed flights is temperature rise due to an aerodynamic heating [1]. The aerodynamic heat flux is sometimes so high that thermal protection systems such as ablative materials must be used to protect the inner systems or metal shell from thermal damages. Predicting the surface temperature requires the coupled solution of the flow field governing equations and solid phase energy equation. Such simulations are so much time-consuming processes and therefore the faster methods should be used instead. These methods are based on decoupling of the flow field and the solid phase governing equations.

Simulation of the flow field using constant temperature boundary condition results in predicting the heat flux which is applied to the body. This heat flux can be estimated during flight in different time intervals. Then the solid phase should be simulated using the predicted heat flux to calculate the temperature history within and on the shell. Increasing the number of these time intervals during flight improves the accuracy of results.

There are different methods for predicting the aerodynamic heating: the solution of full Navier-Stokes equations, the parabolized Navier-Stokes equations, or the viscous shock-layer equations [2]-[6]. There are other engineering methods that use the inviscid flow simulations to compute the heat flux according to the empirical relations.

In the present paper, the full Navier-Stokes equations are used to compute the heat flux during the supersonic flight for a typical geometry of two-stage different-diameter launch vehicle. Then the one-dimensional heat conduction in the solid phase is used to predict the surface temperature variation of the adaptor part of structure. The surface temperature effect on aerodynamic heat flux is considered.

II. Governing Equations and Numerical Simulation

Full Navier-Stokes equations governing the mass, momentum, and energy of the compressible flow are used to compute the heat flux. The commercial CFD program is used here to numerically solve these equations. The conservative forms of the governing equations in an axisymmetric mode are presented here [7]:

$$\frac{\partial U}{\partial t}+\frac{\partial(F+F_v)}{\partial x}+\frac{\partial(G+G_v)}{\partial y}+\frac{(G+G_v)+(G'+G'_v)}{y}=0 \tag{1}$$

where,

$$U=\begin{bmatrix}\rho\\ \rho u\\ \rho v\\ \rho e\end{bmatrix}\quad F=\begin{bmatrix}\rho u\\ \rho uu+p\\ \rho uv\\ \rho uh\end{bmatrix}\quad G=\begin{bmatrix}\rho v\\ \rho vu\\ \rho vv+p\\ \rho vh\end{bmatrix}\quad G'=\begin{bmatrix}0\\ 0\\ -p\\ 0\end{bmatrix}$$
$$F_v=\begin{bmatrix}0\\ -\tau_{xx}\\ -\tau_{xy}\\ q_x-u\tau_{xx}-v\tau_{xy}\end{bmatrix}\quad G_v=\begin{bmatrix}0\\ -\tau_{yx}\\ -\tau_{yy}\\ q_y-u\tau_{yx}-v\tau_{yy}\end{bmatrix}\quad G'_v=\begin{bmatrix}0\\ 0\\ \tau_{\theta\theta}\\ 0\end{bmatrix} \tag{2}$$

The stress terms are defined as:

$$\tau_{xx}=\mu\left(2\frac{\partial u}{\partial x}-\frac{2}{3}\nabla .V\right)\qquad \tau_{xy}=\mu\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)$$
$$\tau_{yy}=\mu\left(2\frac{\partial v}{\partial y}-\frac{2}{3}\nabla .V\right)\qquad \tau_{\theta\theta}=\mu\left(2\frac{v}{y}-\frac{2}{3}\nabla .V\right) \tag{3}$$

here

$$e=c_vT+(uu+vv)/2$$
$$q=-k\nabla T \tag{4}$$

To predict the heat flux on a surface, the constant temperature boundary condition is used. So the computed heat flux is a flux which applied to the surface due to the aerodynamic heating when the surface temperature is hold in that level. Therefore, it should be improved during the solid phase simulation.

The one-dimensional heat conduction equation in a solid phase is used to calculate the temperature-time history under the applied heat flux.

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$$\frac{\partial T}{\partial t} = \alpha_s \frac{\partial^2 T}{\partial \eta^2} \qquad (5)$$

It should be noticed that the computed heat flux is compared here with an empirical relation of Zoby to confirm the accuracy of the flow field simulations. This relation is presented as [8]:

$$q_w = 0.22\left(R_{e_\theta}\right)^{-1}\left(\frac{\rho^*}{\rho_e}\right)\left(\frac{\mu^*}{\mu_e}\right)\rho_e V_e (H_{aw} - H_w)(\mathrm{Pr}_w)^{-0.6} \qquad (6)$$

Here, the values of pressure, temperature, density, and the velocity are applied from the edge of boundary layer, using the inviscid flow simulations.

III. Results and Discussions

The two-stage different-diameter launch vehicle is considered here where the conical adaptor is used to connect two stages together. The heat flux is computed in twelve time intervals during ascending flight. The Mack number and altitude history from trajectory are shown in Fig. 1.

The variation of the maximum heat flux on the adaptor using constant temperature of 300 K is presented in Fig. 2. The heat flux is a result of the combination of the projectile's velocity and the atmospheric condition. So the maximum heat flux in this case is not applied when the flight's Mack number is in maximum level.

Now, the heat conduction to the adaptor must be studied. It is assumed to be built by aluminum with 8mm thickness. If the computed temperature rise shows a critical level, thermal protection coating should be used there. Fortunately, the assumed flight trajectory is so that the aerodynamic heat flux is not high. The surface temperature history of the adaptor is shown in Fig. 3. It should be noted here that the instantaneous surface temperature is used to improve the applied heat flux.

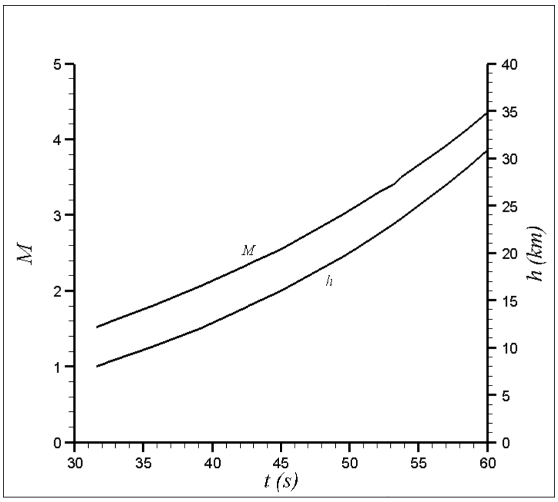

Fig. 1 Flight data history

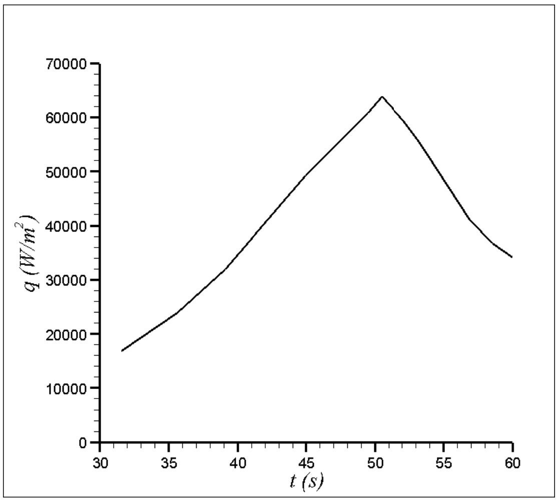

Fig. 2 Heat flux history

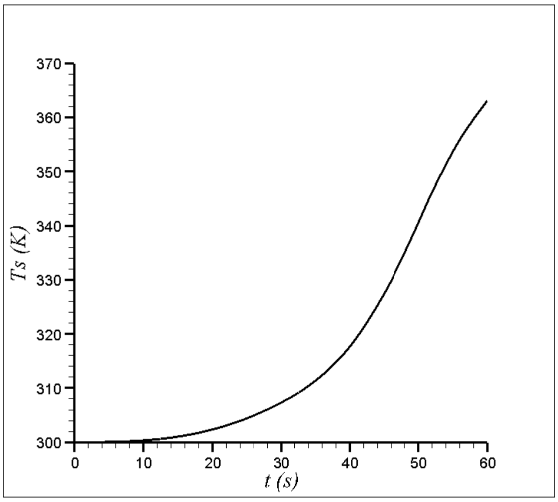

Fig. 3 Accurate surface temperature history of adaptor

The result shows that the shell temperature reaches 90 degrees centigrade. If this value is not proper for the equipment near this surface, it should be protected.

Here, some numerical experiments are done to study the sensitivity of results. They are based on these conditions: the error in heat flux calculation, not considering the surface temperature effect on heat flux, and applying the maximum heat flux during analysis. Fig. 4 shows this analysis.

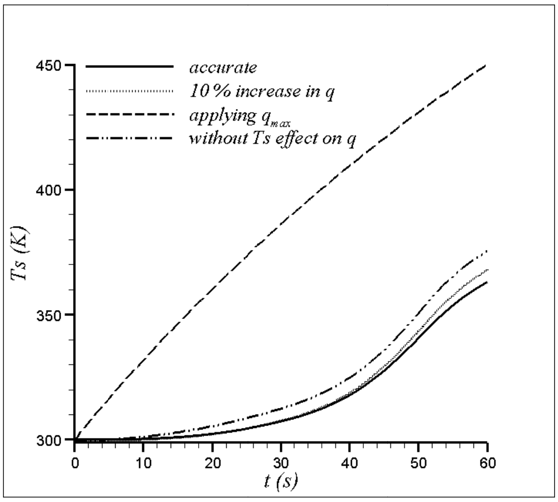

Fig. 4 Temperature history analysis

The results demonstrate that the heat flux time-variation has intense effect in temperature history and applying the maximum heat flux imposes much error in surface temperature prediction. If the surface temperature is not considered in the applied heat flux, the surface temperature is calculated higher than the real value because the computed initial heat flux is based on the constant initial temperature and increasing the surface temperature will reduce the real heat flux. There is a little change in results due to applying 10 percent changes in applied heat flux.

IV. Conclusion

The surface temperature history of a metal shell of an adaptor in a two-stage supersonic launch vehicle is accurately computed. The aerodynamic heat flux during flight in different intervals is predicted using the full Navier-Stoke simulation. The constant temperature boundary condition is used to predict the heat flux in flow field simulation, so the instantaneous surface temperature is considered to improve the real applied heat flux. The one-dimensional heat conduction equation is used to calculate the temperature time history in solid phase. The results show that increasing the number of time intervals and considering the surface temperature effect in heat flux computation will result in accurate temperature history, which is used in structural analysis or selecting the proper thermal protection systems.

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