Numerical Study on Abnormal Heat Flux Augmentation in High Enthalpy Shock Tunnel (HIEST)\(^*\)

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Unexpected heat flux augmentation in a free-piston high-enthalpy shock tunnel (HIEST) was numerically analyzed. Since a previous experimental study implied that the radiation heating from the shock layer caused the augmentation, a three-dimensional thermochemical non-equilibrium CFD code including radiation transport calculation in the shock layer was developed. This calculation was conducted under the following models: 1) Radiation heating from the air species in the shock layer was calculated by solving radiative transport equation using tangent slab approximation; and 2) Radiation heating from impurities such as carbon soot and metal particulates, which could be included in the upstream test gas, was calculated by assuming the shock layer as a grey body with averaged shock layer temperature for a trial calculation. The calculations were performed at the stagnation enthalpy and stagnation pressure from 7 to 21 MJ/kg and 31 to 55 MPa, respectively. For air species radiation, radiative heat flux was too small to contribute heat flux augmentation. On the other hand, for grey body assumption, we could find that abnormal heat flux augmentation could be expected by $\varepsilon T_{ave}^4$ for an engineering technique, where $\varepsilon$ denotes the emissivity $\varepsilon = 0.132$ and $T_{ave}$ was the average shock layer temperature.

Key Words: Hypersonic Flows, Shock Tunnel, Aerodynamic Heating, Radiation, Computational Fluid Dynamics

Nomenclature

| Symbol | Definition |
|--------|------------|
| $B_\lambda$ | Plank function at a given wavelength |
| $C_s$ | mass fraction of species $s$ |
| $c$ | speed of light |
| $D$ | diameter of test model |
| $H$ | total enthalpy |
| $h$ | Planck function |
| $I_\lambda$ | radiant intensity at a given wavelength |
| $k$ | Boltzmann constant |
| $M$ | Mach number |
| $n$ | number density |
| $q$ | heat flux |
| $r$ | direction of radiation propagation |
| $R$ | radius of test model |
| $Re$ | Reynolds number |
| $s$ | coordinate along the wall-normal direction |
| $S_t$ | Stanton number |
| $T_t$ | translational-rotational temperature |
| $T_v$ | vibrational-electronic temperature |
| $\varepsilon$ | emissivity |
| $\kappa_\lambda$ | absorption coefficient at a given wavelength |
| $\lambda$ | wavelength |
| $\psi$ | angle between the direction of radiation propagation and the wall normal direction |
| $\rho$ | density |
| $\phi$ | angle shown in Fig. 3 |
| $\sigma$ | Stefan-Boltzmann constant |
| $\Omega$ | solid angle |

Subscripts

- $0$: stagnated condition
- $\infty$: free stream condition
- $ave$: average
- $calc$: calculated
- $conv$: convective
- $exp$: experiment
- $max$: maximum
- $rad$: radiative
- $s$: species

1. Introduction

In designing a thermal protection system for atmospheric entry vehicles, accurate prediction of aerodynamic heating is crucially important. The High Enthalpy Shock Tunnel (JAXA-HIEST) at Kakuda Space Center aims to provide the required aerothermodynamics data on scale models of various space vehicles in the hypersonic flow region. In Fig. 1, the heat flux data along the centerline of the Apollo command module (CM) 6.4% scale model measured in HIEST\(^1\) are compared with the convective heat flux profiles given by a thermochemical non-equilibrium computational fluid dynamics (CFD) code.\(^2\) When the heat flux data is scaled by $S_t \times \sqrt{Re_\infty D}$ where $Re_\infty D$ is the Reynolds number based on the typical model dimension $D$, it is known that the convective heat flux should fall on a single curve for a laminar flow. Although the computed convective heat flux profiles fall on a single curve reasonably well, the experimental data obtained in HIEST show higher heat flux values. Moreover, one can find that the difference between the measured heat flux and the corresponding heat flux given by CFD becomes larger as the stagnation enthalpy of the test flow...
becomes higher. We note that such an anomalously higher heat flux as discussed above seems to be observed commonly in other high enthalpy shock tunnels.\textsuperscript{3–8} The effect of augmentation caused by the turbulence and surface catalysis were examined. By assuming fully turbulent flow or the super catalytic wall, calculated convective heat flux can reach the experimental values. However, the distribution could not be reproduced. The cause of such higher heat flux has not been clearly determined yet. In the HIEST experiments, such abnormal heat flux augmentation is larger than the one in other facilities. Therefore, the data in the HIEST experiments is useful for examining abnormal heat flux augmentation.

In the previous numerical study,\textsuperscript{2} we calculated the convective heat flux profile with a Baldwin-Lomax algebraic turbulence model.\textsuperscript{9} We assumed fully turbulent flow to determine whether or not turbulence could be the cause of higher heat flux. The computed heat flux increased only slightly in the shoulder region in the leeward side, while the experimental data indicated that the heat flux is increased rather in the entire surface. Therefore, it was difficult to explain the higher heat flux profile obtained in the experiment by the effect of turbulence.

In order to clarify the cause of higher heat flux, other aerodynamic heating measurements on small hemispheres were carried out in HIEST.\textsuperscript{10} The anomalously higher heat flux was insignificant for small models at the same stagnation enthalpy for which the higher heat flux did appear for the Apollo CM test model. In addition aeroheating measurements on a flat plate were conducted with optical filters, which can measure radiation and convective heat flux independently.\textsuperscript{11} Figure 2 shows the time history of pressure and heat flux at the stagnation point on the flat plate (shown in Fig. 7 in Tanno et al.\textsuperscript{11}). One can find that the radiation heat flux is delayed compared to the rising time of pressure and total heat flux, which was measured by thermocouples without optical windows. It indicates that the body surface received radiation after developing the shock layer. However, the source of the radiation is yet unknown.

The objective of the present paper is to clarify the mechanisms of the radiative heating and obtain an engineering technique to estimate the abnormal heat flux augmentation in HIEST. We focus on following two radiation heatings in the shock layer as the source of such anomalously higher heat flux: 1) The radiation heating from air species, and 2) The radiation heating from impurities like soot and metal which can be included in the test gas under the high stagnation temperature condition. First, we calculate the radiation heat flux from air species in the shock layer to show whether or not it can be the source of the enhanced heat flux. Then, we show some evidence that suggests radiation from impurities involved in the test flow can explain the elevated heat flux. However, the chemical species and amount of impurities are unknown. In this study, we assume the impurities as a grey gas for a trial calculation. In the following, numerical methods are described in Sec. 2, numerical conditions are shown in Sec. 3, and obtained results and related discussions are given in Sec. 4. The conclusions are finally stated in Sec. 5.

2. Numerical Methods

2.1. Flowfield calculation

The governing equations for the flow field calculation are the three-dimensional Navier-Stokes equations accounting for thermochemical non-equilibrium. We employ Park’s two-temperature thermochemical model.\textsuperscript{12} Five neutral air species (O, N, NO, N$_2$ and O$_2$) with the following chemical reactions are considered,

\[
\begin{align*}
\text{O}_2 + \text{M} & \leftrightarrow \text{O} + \text{O} + \text{M}, \\
\text{N}_2 + \text{M} & \leftrightarrow \text{N} + \text{N} + \text{M},
\end{align*}
\]
NO + M ⇔ N + O + M, \quad (1)
N_2 + O ⇔ NO + N,
NO + O ⇔ O_2 + N,

where M stands for collision partners. The forward rate coefficients are given by Arrhenius form, and the backward rate coefficients are determined by the equilibrium constant. The details of forward reaction rates and equilibrium constant are given in Park.\textsuperscript{12} The translational-vibrational relaxation term is given by the Landau-Teller model with Park’s two modifications\textsuperscript{12}; that is, introducing the limiting cross-section for the relaxation time of Millikan and White, and the bridging formula for the Landau-Teller equation. A preferential dissociation model is also included in the calculation.

The molecular viscosity for each chemical species is given by Blottner’s model\textsuperscript{13} and the thermal conductivity by Eucken’s relation.\textsuperscript{14} The transport properties for the gas mixture are obtained from Wilke’s semi-empirical mixing rule.\textsuperscript{15} The diffusion coefficients are assumed to be constant for all air species with a constant Schmidt number of 0.5.

The numerical method is based on the cell-centered finite volume scheme. The convective numerical flux is calculated using the SLAU scheme.\textsuperscript{16,17} The viscous flux is evaluated by a central difference scheme. We employ the MUSCL approach\textsuperscript{18} to attain second-order spatial accuracy. In the time integration, the LU-SGS implicit method\textsuperscript{19} is employed. The diagonal point implicit method is utilized in order to improve stability in the integration of the source terms.\textsuperscript{20}

2.2. Radiation calculation

The radiative transfer equation is solved by tangent-slab approximation.\textsuperscript{14} In a one-dimensional local-thermodynamic-equilibrium medium, the radiative transfer equation is given by

\[ l \frac{dI_l}{ds} = \kappa_l(B_l - I_l), \quad (2) \]

where \( l = \cos \varphi \). The coordinate system is shown in Fig. 3. Radiation intensities at each cell boundary are obtained by solving Eq. (2) along only the cells that are normal to the wall surface in the tangent-slab approximation. The Planck function, \( B_l \), is a function of temperature \( T \) and is given by

\[ B_l = \frac{2hc^2}{\lambda^5} \exp\left(-\frac{hc}{\lambda kT}\right) \left[ 1 - \exp\left(-\frac{hc}{\lambda kT}\right) \right]. \quad (3) \]

The spectral radiation heat flux \( q_l \) is obtained by integrating over the solid angle.

\[ q_l = \int_4^{2\pi} I_l d\Omega = \int_0^\pi \int_0^{\pi/2} I_l \sin \varphi d\varphi d\theta = 2\pi \int_0^1 I_l dl. \quad (4) \]

The total radiation heat flux \( q_{\text{rad}} \) is then given by

\[ q_{\text{rad}} = \int q_l dl. \quad (5) \]

The flowfield calculation and radiative transport calculation are uncoupled. The radiative heat flux is calculated from the solution of steady-state flowfield.

2.2.1. Radiation from air species in shock layer

For calculating air test gas radiation, the absorption coefficient \( \kappa_l \) shown in Eq. (2) is expressed as a sum of those for individual species in the form of

\[ \kappa_l = \sum_i n_i \kappa_{lf}, \quad (6) \]

where \( s \) indicates radiation-contributing chemical species such as O, N, NO, O_2, and N_2. The wavelength region from 750 to 15,000 Å is considered with the local thermodynamic equilibrium assumption. The wavelength points are 10,000. The number density of each species \( n_i \) is obtained by the steady-state flowfield. The cross-section values \( \sigma_{lf} \) are prepared in advance curve-fitted formulae as follows,

\[ \sigma_{lf} = \exp\left(\frac{A_{l1}^f}{z} + A_{l2}^f + A_{l3}^f \ln(z) + A_{l4}^f z + A_{l5}^f z^2 \right). \quad (7) \]

where \( z = 10,000/T_v \). The five parameters \( A_{l1-5}^f \) are calculated using a multi-band model.\textsuperscript{21}

2.2.2. Radiation from particulates

In these calculations, radiative heat flux is computed by utilizing tangent slab approximation employed in the evaluation of radiation from air species in the shock layer. However, the chemical species of impurities in test flow and the amount of impurities are unknown, and therefore, we cannot determine the radiation intensity from impurities. In the HIEST experiments, strong emission is observed after the stagnation point in order to reproduce the experimental heat flux. The details are discussed in Sec. 4.2.

3. Numerical Conditions

3.1. Upstream and wall boundary conditions

Table 1 summarizes the upstream conditions for the flow field calculation over the Apollo CM test model\textsuperscript{11} and small probes.\textsuperscript{10} These values were determined using a JAXA in-house code.\textsuperscript{22}

For the wall boundary conditions, an isothermal and fully-catalytic wall are assumed for all cases. Figure 4 shows the
dependence of the surface catalysis on the convective heat flux at Shot No. 1783 where the stagnation enthalpy is highest, and the surface catalysis is likely to affect the convective heat flux in all cases in Table 1. One can find that the difference is ignorable. The dependence of the wall temperature on convective heat flux is also investigated. Figure 5 shows the heat flux at the wall temperatures of 300, 500 and 700 K. The differences are negligibly small. Since the wall temperature becomes about 500 K in the experiment, the wall temperature is set to be 500 K.

### 3.2. Test models and computational grids

Three different test models, namely the Apollo CM model and two probe models of different size, referred to as D50R100 and D20R10, are employed in the heat flux measurements conducted in HIEST. Figure 6(a) shows the Apollo CM 6.4% scaled test model, which has a diameter of 250 mm and a nose radius of 300 mm, and is the largest among the models. On the other hand, small probe model D50R100 shown in Fig. 6(b) has a diameter of 50 mm and a nose radius of 100 mm. Though not shown, small probe model D20R10 has a similar shape with a diameter of 20 mm and a nose radius of 10 mm.

A typical example of the computational grid for the Apollo CM model at an angle of attack (AoA) of 30 deg is shown in Fig. 7. It is a structured mesh having 51 points in the normal direction from the surface toward the outer boundary, 51 points along the surface, and 65 points in the circumferential direction. The minimum grid spacing at the wall surface satisfies the cell Reynolds number of $Re_{cell} = 1$. Several mesh surfaces are clustered and aligned parallel to the shock wave using the solution adaptive technique which is critically important particularly when a structured mesh is employed in

| Shot No. | Test model | $H_0$ [MJ/kg] | $T_{in}$ [K] | $T_{wall}$ [K] | $\rho_{0}$ [kg/m$^3$] | $M_{\infty}$ | $C_{D_{\infty}}$ | $C_{N_{\infty}}$ | $C_{N_{O_{\infty}}}$ | $C_{D_{O_{\infty}}}$ | $C_{N_{O_{\infty}}}$ |
|----------|------------|----------------|--------------|-----------------|------------------------|-------------|----------------|-----------------|----------------|----------------|----------------|
| 1781     | Apollo     | 6.849          | 662.4        | 679.2           | 0.01978               | 6.721       | 2.45 x 10$^{-3}$ | 4.33 x 10$^{-12}$ | 5.94 x 10$^{-2}$ | 2.01 x 10$^{-1}$ | 7.37 x 10$^{-1}$ |
| 1782     | Apollo     | 17.275         | 1861.1       | 1864.9          | 0.01686               | 5.945       | 7.77 x 10$^{-2}$ | 5.31 x 10$^{-7}$ | 4.78 x 10$^{-2}$ | 1.31 x 10$^{-1}$ | 7.54 x 10$^{-1}$ |
| 1783     | Apollo     | 21.537         | 2158.9       | 2163.1          | 0.01216               | 5.890       | 1.41 x 10$^{-1}$ | 5.61 x 10$^{-7}$ | 3.39 x 10$^{-2}$ | 7.46 x 10$^{-2}$ | 7.51 x 10$^{-1}$ |
| 1784     | Apollo     | 19.554         | 2035.2       | 2038.2          | 0.01457               | 5.909       | 1.09 x 10$^{-1}$ | 2.04 x 10$^{-6}$ | 4.10 x 10$^{-2}$ | 1.10 x 10$^{-1}$ | 4.78 x 10$^{-1}$ |
| 1785     | Apollo     | 21.059         | 2143.0       | 2146.8          | 0.01315               | 5.885       | 1.31 x 10$^{-1}$ | 4.51 x 10$^{-6}$ | 3.60 x 10$^{-2}$ | 8.33 x 10$^{-2}$ | 7.50 x 10$^{-1}$ |
| 1787     | Apollo     | 8.094          | 841.7        | 849.5           | 0.02643               | 6.496       | 3.82 x 10$^{-3}$ | 4.48 x 10$^{-12}$ | 6.03 x 10$^{-2}$ | 1.99 x 10$^{-1}$ | 7.37 x 10$^{-1}$ |
| 1791     | Apollo     | 6.759          | 649.7        | 668.1           | 0.01919               | 6.739       | 2.40 x 10$^{-3}$ | 4.40 x 10$^{-12}$ | 5.93 x 10$^{-2}$ | 2.01 x 10$^{-1}$ | 7.37 x 10$^{-1}$ |
| 1886     | Apollo     | 13.471         | 1455.9       | 1461.8          | 0.01633               | 6.108       | 4.14 x 10$^{-1}$ | 4.20 x 10$^{-6}$ | 5.57 x 10$^{-2}$ | 1.63 x 10$^{-1}$ | 7.40 x 10$^{-1}$ |
| 1889     | D20R10     | 8.596          | 908.7        | 915.8           | 0.02717               | 6.440       | 4.79 x 10$^{-3}$ | 5.82 x 10$^{-12}$ | 6.05 x 10$^{-2}$ | 1.98 x 10$^{-1}$ | 7.37 x 10$^{-1}$ |
| 1891     | D50R100 Apollo | 8.318        | 869.9        | 877.3           | 0.02702               | 6.479       | 4.14 x 10$^{-3}$ | 4.74 x 10$^{-12}$ | 6.04 x 10$^{-2}$ | 1.99 x 10$^{-1}$ | 7.37 x 10$^{-1}$ |
| 1893     | D50R100 Apollo | 20.048       | 1946.4       | 1952.3          | 0.01050               | 6.013       | 1.30 x 10$^{-1}$ | 3.30 x 10$^{-6}$ | 3.65 x 10$^{-2}$ | 8.32 x 10$^{-2}$ | 7.50 x 10$^{-1}$ |
the evaluation of heat flux profiles.\textsuperscript{23)} Figure 8 shows the computed convective heat flux using solution adaptive mesh and no adaptive mesh at Shot No. 1791. For the no adaptive mesh, the grids are not clustered or aligned parallel to the shock wave. One can find that the heat flux distribution by the no adaptive mesh oscillates near the stagnation region. However, numerical errors appeared at \( x = y = z = 0 \text{ m} \). This is due to the singularity of the grid. Since this error does not affect heat flux in the other region, treatment for this error is out of the scope of this study.

4. Results and Discussion

4.1. Radiation from air species in shock layer

Figure 9 shows the radiation heat flux profiles from air species in the shock layer for Shot Nos. 1781 and 1783, with associated convective heat flux profiles. Although radiation heat flux becomes larger in the higher enthalpy condition, it is negligibly small compared to the corresponding convective heat flux. It should be noted that tangent slab approximation generally gives a higher radiation heat flux incident on the surface of blunt bodies. Nevertheless, the computed radiation heat flux is far smaller than that of convective heat flux. This concludes that radiation from air species in the shock layer cannot explain the augmented heat flux observed in HIEST.

4.2. Abnormal heat flux augmentation and radiation from impurities in shock layer

The augmentations of heat flux at various stagnation enthalpy conditions and test models are plotted in Fig. 10(a) and (b) in terms of the average vibrational temperature and maximum vibrational temperature, respectively. Figure 11 shows the translational temperature and vibrational temperature profiles along the stagnation stream line at Shot Nos. 1781 and 1783. To define the average temperature, we take into account the vibrational temperature in the shock layer except the low-temperature region near the wall surface. The location of the maximum vibrational temperature is immediately behind the shock wave. The augmentations of heat flux, and the average temperature and maximum vibrational temperature are summarized in Table 2. For the lower enthalpy conditions such as Shot No. 1781 shown in Fig. 11(a), the maximum vibrational temperature is higher than the average temperature. On the other hand, for higher enthalpy conditions such as Shot No. 1783 shown in
Fig. 11(b), the maximum vibrational temperature is comparable to the average temperature. The impurities that are heated due to the high temperature in the shock layer can emit radiation at the temperature of the heated impurities. We assume that the temperature of impurities equilibrate with the average vibrational temperature or the maximum vibrational temperature. The relation between the augmentation of heat flux and these temperatures is investigated. Using the average temperature $T_{\text{ave}}$, augmentation is fairly well fitted by $/C_{27}T_{\text{ave}}^4$ where $\sigma$ denotes the Stefan-Boltzmann constant. In Fig. 10(a), the emissivity is determined as $\varepsilon = 0.132$.

Using this fitted emissivity, the sum of the convective and radiation heat fluxes, referred to as the total heat flux, is com-

![Table 2. Heat fluxes at the stagnation point and the related quantities.](image)

**Table 2. Heat fluxes at the stagnation point and the related quantities.**

| Shot No. | Test model | $H_0$ [MJ/kg] | $\dot{q}_{\text{exp}}$ [MW/m²] | $\dot{q}_{\text{calc}}$ [MW/m²] | $\dot{q}_{\text{exp}}/\dot{q}_{\text{calc}}$ | $\Delta \dot{q}$ [MW/m²] | $T_{\text{ave}}$ [K] | $T_{\text{max}}$ [K] |
|----------|------------|----------------|------------------|------------------|------------------|----------------|----------------|----------------|
| 1781     | Apollo CM  | 6.849          | 3.74             | 2.17             | 1.72             | 1.57          | 3958.6        | 4688.1        |
| 1782     | Apollo CM  | 17.275         | 22.47            | 8.98             | 2.50             | 13.49         | 6654.1        | 6678.0        |
| 1783     | Apollo CM  | 21.537         | 27.32            | 10.86            | 2.52             | 16.46         | 7057.4        | 7090.1        |
| 1784     | Apollo CM  | 19.554         | 37.45            | 15.79            | 2.37             | 21.66         | 7133.9        | 7164.4        |
| 1785     | Apollo CM  | 21.059         | 36.63            | 14.79            | 2.48             | 21.85         | 7273.0        | 7321.0        |
| 1787     | Apollo CM  | 8.094          | 8.40             | 5.12             | 1.64             | 3.28          | 4466.8        | 5102.6        |
| 1791     | Apollo CM  | 6.759          | 4.67             | 2.92             | 1.60             | 1.75          | 4024.4        | 4590.5        |
| 1886     | Apollo CM  | 13.471         | 15.23            | 5.97             | 2.55             | 9.26          | 6001.8        | 6206.1        |
| 1891     | Apollo CM  | 8.318          | 6.33             | 3.54             | 1.79             | 2.79          | 4428.4        | 5228.0        |
| 1893     | Apollo CM  | 20.048         | 28.33            | 9.33             | 3.02             | 18.89         | 6844.6        | 6870.0        |
| 1889     | D20R10     | 8.596          | 23.62            | 20.36            | 1.16             | 3.26          | 4804.5        | 5397.1        |
| 1891     | D50R100    | 8.318          | 9.92             | 6.95             | 1.43             | 2.97          | 4558.7        | 5300.4        |
| 1893     | D50R100    | 20.048         | 31.22            | 17.30            | 1.80             | 13.92         | 6821.5        | 6870.0        |

![Fig. 12. Convective heat flux profiles, total heat flux profiles and corresponding experimental heat flux data are plotted for the Apollo CM test model at an AoA of 0 deg. The emissivity is $\varepsilon = 0.132$. (a) Shot No. 1781 ($H_0 = 6.849$ MJ/kg), (b) Shot No. 1782 ($H_0 = 17.275$ MJ/kg), and (c) Shot No. 1783 ($H_0 = 21.537$ MJ/kg).](image)
pared with the measured heat flux profiles obtained in HIEST. In Fig. 12, the computed convective and total heat fluxes are plotted for the Apollo CM model with an AoA of 0 deg using the corresponding experimental data. One can find that the computed total heat flux profiles agree fairly well with the experimental data over the entire surface. Similarly, in Fig. 13, the convective, total and the corresponding experimental data are plotted for an AoA of 30 deg. Reasonable agreements are also obtained with the same emissivity. Therefore, this indicates that the augmentation of heat flux can be estimated using \(0.132\frac{\tau_{ave}}{C^{27}T^{4}}\).

The ratio of measured and calculated heat flux \(q_{exp}/q_{calc}\) is shown in Fig. 14 (summarized in Table 2). The abnormal heat flux augmentation was not remarkable for small probe models. However, when heat flux augmentation is defined as \(\Delta q = q_{exp} - q_{calc}\) at the stagnation point, it is nearly identical as the stagnation enthalpies are close. For example, the surplus heat fluxes in Shot No. 1891 for the Apollo CM model and D50R100 probe model are 2.79 MW/m² and 2.97 MW/m², respectively, even though the computed shock stand-off distance for the Apollo CM model (=26 mm) is significantly larger than that for D50R100 probe model (=7 mm). Furthermore, the surplus heat flux in Shot No. 1889 for the D20R10 probe model is 3.26 MW/m², which is close to that in Shot No. 1891 for the Apollo CM model and D50R100, while the stagnation enthalpy in both Shots is also close. The shock stand-off distance in Shot No. 1891 for the Apollo CM test model (=26 mm) is 26 times larger than that in Shot No. 1889 for D20R10 (=1 mm). A similar trend can be observed for the Apollo CM model in Shot No. 1783, the Apollo CM model in Shot No. 1893 and D50R100 probe model in Shot No. 1893, where the surplus heat fluxes are 16.46 MW/m², 18.89 MW/m² and 13.92 MW/m², respectively. The surplus heat fluxes for the Apollo CM model are only 1.18–1.36 times larger than those for the D50R100 probe model. The above results suggest that the augmentation depends only on stagnation enthalpy. Because the convective heat flux becomes substantially higher for small nose radii, the resulting ratio of \(q_{exp}/q_{calc}\) becomes almost unity for small probe models. These results also indicate the reason why the abnormal heat flux augmentation becomes remarkable in HIEST. In HIEST, a larger test model can be used and the \(q_{exp}/q_{calc}\) ratio becomes smaller.

For such situations, one can point out that the amount of
heat flux augmentation should depend on the thickness of the shock layer, model size and stagnation enthalpy. It is the present scenario that the shock layer is optically thick due to impurities, and the radiation from impurities that exist in the relatively high temperature region near the edge of the boundary layer reaches the wall surface. The reason why the fitted emissivity ($\varepsilon = 0.132$) becomes smaller than a black body ($\varepsilon = 1.0$) may be that the specific wavelength region is only optically thick. In order to identify the source of radiation, spectroscopy analysis in the shock layer is needed.

5. Conclusion

The abnormal heat flux augmentation observed in HIEST was numerically analyzed. The analysis revealed the following. (1) Radiation from air species was too small to contribute to heat flux augmentation. (2) The engineering technique to estimate the abnormal heat flux augmentation was obtained, though the test campaign for spectroscopy in the shock layer is required to clearly determine the source of the radiation. The abnormal heat flux augmentation could be estimated using $0.132\sigma T_{av}^4$ and the computed total heat flux profiles agreed fairly well with the experimental data.

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