Computational Simulation of Arc Heater Flows For Martian Atmosphere

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An existing computational fluid dynamics code which simulates a high enthalpy arc heater flow for air, named ARCFLO3, is updated to be able to calculate a high temperature carbonaceous flow. The flowfield is assumed to be in thermochemical equilibrium and the thermodynamic and transport properties for high temperature carbonaceous gas mixture are calculated though the Yos’ mixture rule by compiling the most updated set of collision integrals. The radiative transport in arc heater is calculated in a fully coupled manner with flow motion by using a 3-band radiation model developed in the present study. The upgraded code is used to calculate the operational characteristic parameters such as arc voltage, chamber pressure, heater thermal efficiency and mass-averaged enthalpy for existing 60MW arc heater geometry by using CO₂ as a test gas. The result shows that by specifying the wind tunnel operating conditions routinely used for air, the similar level of the operational characteristic parameters is obtained, and that a high enthalpy environment during a manned Martian atmospheric entry flight can be produced for the arc heater geometry.

Key Words: High enthalpy flow, carbonaceous gas, radiation, arc heater, CFD

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>Planck function, W/cm²-sr</td>
</tr>
<tr>
<td>B₂</td>
<td>Characteristic function at given λ, W/cm²-sr-μm</td>
</tr>
<tr>
<td>d</td>
<td>Characteristic distance in an escape factor, m, see Eq.(4)</td>
</tr>
<tr>
<td>E₂</td>
<td>Emission coefficient, W/cm³-sr-μm</td>
</tr>
<tr>
<td>Hav</td>
<td>Mass-averaged enthalpy, MJ/kg</td>
</tr>
<tr>
<td>I</td>
<td>Electrical current, A</td>
</tr>
<tr>
<td>I₂</td>
<td>Specific intensity, W/cm²-sr</td>
</tr>
<tr>
<td>Iₛ</td>
<td>Specific intensity at given λ, W/cm²-sr-μm</td>
</tr>
<tr>
<td>m</td>
<td>Mass flow rate, kg/s</td>
</tr>
<tr>
<td>qrad</td>
<td>Radiative heat flux, W/cm²</td>
</tr>
<tr>
<td>r</td>
<td>Radial direction, m</td>
</tr>
<tr>
<td>SR</td>
<td>Schumann-Runge</td>
</tr>
<tr>
<td>s</td>
<td>Coordinate along a radiation lay, cm</td>
</tr>
<tr>
<td>V</td>
<td>Arc voltage, V</td>
</tr>
<tr>
<td>Wₜ</td>
<td>Heat input by test gas injection, W</td>
</tr>
<tr>
<td>x</td>
<td>Axial direction, m</td>
</tr>
<tr>
<td>κ, κₛ</td>
<td>Absorption coefficient, m⁻¹</td>
</tr>
<tr>
<td>λ</td>
<td>Wavelength, μm or nm</td>
</tr>
<tr>
<td>σ</td>
<td>Electrical conductivity, mho/m</td>
</tr>
</tbody>
</table>

Because most of such arcjet wind tunnels are operating with air as a test gas, a new constrictor type arcjet wind tunnel may be designed and constructed, in which a carbonaceous gas is utilized as a test gas. Actually, it is planned that CO₂ is used in an arcjet wind tunnel named SCIROCCO placed in Italy. In addition, one can expect that an existing arc heater facility is applied to operate such a carbonaceous gas instead of air if such an operation is found to be feasible.

A computer code to be able to analyze the arc heater flowfield for a carbonaceous gas will be useful to minimize the cost for the design of a new arc heater or to examine the limitations of the hardware capabilities such maximum heat flux at a constrictor wall. In addition, the optimum operational characteristic parameters can be determined by using such a code to examine the performance for nominal arc heater geometry against an operating condition without experimental trial and error processes.

A computer code named ARCFLO3 has recently been developed to calculate the arc heater flow for air⁶. Unlike the ARFCLO computer program⁷, which was developed in 1970’s to calculate the flow only within the constrictor, the code calculates the flow in the arc heater from the upstream end of the heater to the nozzle throat. This aspect is important to analyze the arc heater flow fully theoretically. The ARCFLO3 code can predict the experimental data obtained in the existing large scale arcjet wind tunnels fairly accurately. It is believed that the ARCFLO3 code will be applicable to the arc heater flowfield analysis for carbonaceous gas with confidence by modifying the important physical modeling used in the code.

In the present study, ARCFLO3 code is upgraded to be able to calculate the arc heater flow for carbonaceous gas. To do so, a radiation model is developed by applying the procedures used in a 3-band radiation model for air originally employed in ARCFLO3 code. It has shown that the radiation calculation is one of the most important aspects in the physical modeling to improve the accuracy of the computer code and to reduce its computing time.⁸ Best
available thermodynamic and transport properties for a high temperature carbonaceous gas mixture are implemented into the upgraded code.

The upgraded code is used to analyze the arc heater flowfield, showing the calculated operational characteristics parameters such as arc voltage, chamber pressure, heater thermal efficiency, and mass-averaged enthalpy for existing large scale arc heater geometry. In addition, parametric studies are performed to determine the arc heater operating conditions which can produce candidate Martian atmospheric entry flight environments to show the applicability of the existing arc heater to produce such high enthalpy levels.

2. Method of calculation

The numerical method is similar to the one employed in ARCFLO3 code. Therefore, the brief explanation for the numerical details will be made below. However, the procedures used to construct a radiation model will be explained in detail for completeness.

2.1. Governing equations and flow conditions

The arc heater flowfield is assumed to be 2D-axisymmetric viscous flow. The conservation equations for mass, momentum, and energy equations are solved. The Joule and radiative source terms are included in the energy equation. The equations are discretized using a finite volume method. The discretized equations are implicitly integrated in time to obtain a steady-state solution. A fully coupled radiation calculation with flow motion is made to obtain a steady-state solution. A spatial accuracy is second order. ARCFLO3 code needs two operational parameters of the arcjet wind tunnel: mass flow rates and electrical current. The other details of the numerical procedures in ARCFLO3 code are given in our previous work.

Thermochemical equilibrium is assumed to be valid up to the throat of the nozzle because a typical chamber pressure becomes more than 0.1013MPa for the conditions analyzed in the present study. CO\(_2\) is used as a test gas. In order to account for the high temperature thermochemical reactions of CO\(_2\), a following 10 gaseous species (C, O, O\(_2\), CO, CO\(_2\), C\(_2\), C\(_3\), O\(^+\), O\(^+\), e) are considered. Thermodynamic properties are calculated with Chemical Equilibrium with Applications (CEA) computer program. The transport properties including electrical conductivity are calculated with the Yos' mixture rule using the collision integrals. The collision integrals are compiled from the available literatures.

Calculations are carried out for the arc heater geometry of a 60MW arc heater facility at NASA Ames Research Center. The arc heater has a constrictor diameter of 8cm, and length of 3.9m. The diameter of the nozzle throat is 6.03cm. The number of computational grid is 240x40, which is the same grid size used for the calculations for air in our previous study. The computed results are presented mainly for the mass flow rates ranging from 0.1 to 0.8kg/s and for two electrical currents of 3,000, and 6,000A. The arc heater geometry used for calculation is given in Fig. 1, showing the temperature contour in the arc heater for the case of I=6,000A and \(m=0.2\)kg/s. For the purpose of comparison, calculations are carried out by using air as a test gas. It should be noted that the operating conditions are routinely used in the 60MW facility for air and that when air is used as a test gas for the same arc heater geometry, ARCFLO3 reproduces the measured operational characteristic parameters fairly well.

2.2. Radiation

The radiative transfer equation is solved in a cylindrical coordinate system. The emission and absorption of radiation are accounted for. The radiative systems included in the calculation are summarized in Table 1.

<table>
<thead>
<tr>
<th>Atomic lines</th>
<th>Molecular bands</th>
<th>Bound-free</th>
</tr>
</thead>
<tbody>
<tr>
<td>C and O</td>
<td>CO(4+), C(2S), O(_2)(SR)</td>
<td>O and O(_2)(SR)</td>
</tr>
</tbody>
</table>

A three band radiation model is used to calculate the radiative transfer equation. In the 3-band model, the non-gray nature of the high temperature gas within arc heater is represented by gray gas properties, that is, spectrally averaged radiative properties. A radiative property at a given wavelength is classified one of three non-gray gases. In the three band model, the total radiative heat flux is given by adding the three radiative heat fluxes as follows:

\[
\frac{dI}{ds} = -\kappa_i (I_i - B_i), \quad i = 1 \sim 3, \quad (1)
\]

\[
q_{\text{rad}} = \sum_{i=4}^{3} q_{\text{rad},i} = \sum_{i=1}^{3} \int_{0}^{\Omega} I_i \cos \theta d\Omega, \quad (2)
\]

where \(\theta\) is the angle between a radiation ray and the outward normal to the cylindrical surface and \(\Omega\) is the solid angle. The specific selection criteria used to determine into which group a given wavelength is classified are given by 1) \(\kappa > 3\)cm\(^{-1}\), and 2) \(\kappa < 3\)cm\(^{-1}\) for \(\lambda < 275\)nm, and 3) \(\lambda > 275\)nm, respectively. The procedures to determine these values will be explained later.

In each group, the wavelength averaged absorption coefficients are determined by using an escape factor concept. The escape factor \(\phi\) is defined as the probability that a photon emitted at a point is not absorbed during traveling the distance \(d\).


\[
\phi = \int E_\lambda \exp(-\kappa_\lambda d) d\lambda \int E_\lambda d\lambda. \tag{3}
\]

Assuming that an averaged absorption coefficient exists over a certain wavelength range, the average absorption coefficient can be calculated as

\[
\kappa = -\frac{\ln(\phi)}{d}. \tag{4}
\]

In order to determine the wavelength-mean Planck function, the following relation for a gray-gas approximation is used:

\[
B = \frac{I}{1 - \exp(-\kappa d)}. \tag{5}
\]

In Eq. (5), an incoming specific intensity is assumed to be zero at a boundary. For a distance \(d\), the total specific intensity \(I\) in the right hand side of Eq. (5) can be given by integrating the radiative properties in each group as follows:

\[
I = \int I_\lambda d\lambda = \int B_\lambda \left[1 - \exp(-\kappa_\lambda d)\right] d\lambda. \tag{6}
\]

The line-by-line portion of NEQAIR85 code\(^{12}\) is used with an expanded radiation data set to calculate spectral radiative properties given in Eqs. (3) and (6). In the line-by-line calculation, the wavelength region covers from 50 to 4,000 nm with 10\(^7\) wavelength points.

The values used in the selection criteria, and the characteristic distance \(d\) is empirically determined to reproduce the radiative heat flux distribution obtained by the line-by-line method. The distance \(d\) is set to be 3, 3, and 30cm for each group, respectively. For this purpose, the radial temperature and pressure distribution is calculated by using ARCFLO3 code for a typical operating condition. The radial distribution of the radiative heat fluxes obtained by using the 3-band method and the line-by-line method is compared at \(x/L=0.5\) where \(L\) denotes the length of the constrictor. The result is shown in Fig. 2. The temperature distribution is given in the same figure. From Fig. 2, the 3-band method can reproduce the result obtained by the line-by-line method fairly well. The difference of the radiative heat flux at the wall between the two methods is about 9%. The error is not so different for other conditions, though the result is shown here. The 3-band method can speed up the radiative transport calculation by a factor of 1,000 compared with the line-by-line method.

The averaged absorption coefficients and Planck functions are tabulated as a function of pressure and temperature to use the 3-band model in a CFD calculation. The range of pressure and temperature covers from 1,000 to 15,000K and from 0.1013 to 1.013 MPa, respectively.

### 3. Results and Discussion

#### 3.1. Heat flux

Fig. 3 shows the axial distributions of convective, radiative and total (convective+radiative) heat fluxes at the wall within the constrictor region for \(I=6,000A\) and \(m=0.2kg/s\). One can see that radiation is a main component of the heat flux in the upstream region. The convective heat flux increases toward the exit of the constrictor because the turbulent heat transfer becomes stronger to the downstream region. The heat flux value is found to be highest near the constrictor exit, and the value is about 1,300 W/cm\(^2\). The maximum heat flux value increases against mass flow rate for a constant electrical current value. For \(I=6,000A\), the maximum heat flux value becomes 1,800 W/cm\(^2\) at \(m=0.8kg/s\). The value is below the maximum allowable limit of the heat transfer rate (nominally 5,000 W/cm\(^2\)) for the constrictor disks.\(^{2}\) It is found that the heat transfer rate to the constrictor wall is kept below this allowable limit for all the operational conditions analyzed in the present study.

#### 3.2 Operational characteristics parameters

The operational characteristic parameters for arc voltage, chamber pressure, heater thermal efficiency, and mass-averaged enthalpy are shown for \(I=3,000\), and 6,000 A in Figs. 4 and 5, respectively. The data is plotted against mass flow rate. For the purpose of comparison, the calculated results for air are also shown in the figures.
The arc voltage is calculated as

\[ V = \int \frac{I}{2\pi r \, dr} \, dx. \]  

(7)

From Fig. 4(a), the arc voltage increases against mass flow rate. One can see that the calculated voltage value is nearly the same between two different electrical currents. This trend is due to the fact that the radial distribution of the electrical conductivity for CO\textsubscript{2} is the same level of that for air. In addition, it is found that the net energy level input to the test gas is nearly the same.

One can see also from Fig. 4(b) that the calculated chamber pressures are almost the same between the two different test gases and that the pressure values are kept below 1.013MPa over the mass flow rates calculated. As will be shown later, the arc heater geometry used in the present study can produce the impact pressure level in the dissociated or ionized flow regime encountered during the Martian atmospheric entries.

From the figure, the \( H_{av} \) value becomes highest at \( m = 0.2 \) kg/s. The value is about 25MJ/kg for \( I = 6,000 \) A and about 16MJ/kg for \( I = 3,000 \) A, respectively. The \( H_{av} \) value decreases against mass flow rate. From the comparison of the data with air, the \( H_{av} \) value is lower for \( CO_{2} \) than for air by about 25% for \( I = 3,000 \) A and by about 15% for \( I = 6,000 \) A, respectively. This result is due to the fact that the turbulent heat loss at the constrictor wall is larger for \( CO_{2} \) than for air while the radiative heat loss is lower for \( CO_{2} \) than for air under the same operational condition. It should be noted that the heat input is nearly the same between the two test gases, as was seen in Fig. 4(a).

From Fig. 5(b), the \( H_{av} \) value is calculated by

\[ H_{av} = \frac{IV + W_{mj}}{m \eta}. \]  

(9)

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From Fig. 5(b), the \( H_{av} \) value is calculated by

\[ H_{av} = \frac{IV + W_{mj}}{m \eta}. \]  

(9)
1.5. The ratio of the centerline enthalpy to the mass-averaged enthalpy is unchanged so much against mass flow rate for $I=6,000\text{A}$; the ratio is about 2.0 for $I=3,000\text{A}$.

3.3. Application of the present code

The developed code is used to deduce the operating conditions necessary to produce the stagnation point heating environment during a manned Martian atmospheric entry flight.\(^{[15]}\) In that work, an entry velocity into the Martian atmosphere is given against the altitude of Mars. The altitude can be related to the freestream density, and pressure. By using the velocity, density, and pressure values, the enthalpy and the stagnation point pressure values are calculated through the relations using a hypersonic approximation.\(^{[14]}\) The envelope for the flight conditions so evaluated is shown in Fig. 7, in which the entry velocity is denoted by $U$, and the altitude is denoted by $h$, respectively.

The developed code is used to find the operating condition to enclose the envelope for the selected flight conditions. The calculated centerline enthalpy value is used as the enthalpy of the arcjet freestream in the test section. It should be noted that because the heat loss in the expanding nozzle region is small compared with the one in the arc heater, the centerline enthalpy value is changed only slightly in the downstream of the nozzle throat. In order to deduce the impact pressure value, the expansion process of the arcjet flow on the centerline downstream of the nozzle is assumed to be isentropic. The calculated chamber pressure value is used as a reservoir pressure. The conical nozzle geometry is taken from an existing one with a cone half angle of 10 degree, and its diameter at the exit location is 15.2cm\(^{[15]}\). The geometrical area ratio at an assumed measurement point, $x_{mp}$, which value is given in Fig. 7, is given by extending past the physical exit location. The impact pressure is estimated by using the Rayleigh pitot-tube formula.

The calculated result is given in Fig. 7. From the figure, one can find that the stagnation point heating environment for the candidate Martian atmospheric entries is able to be produced by the arc heater used in the present study by choosing the operating conditions appropriately. It should be noted that the operating conditions so chosen are well within the routinely used values.

4. Conclusion

By using the developed code, the high enthalpy arc heater flowfield for both air and carbonaceous gas is able to be analyzed. The proposed 3-band radiation model, which was originally developed for the radiation calculation of air, can be successfully applied to calculate the radiative transport in the high temperature carbonaceous gas. The ability of the upgraded code is demonstrated by calculating the arc heater flows with existing large scale arc heater geometry. The result shows that it is possible to produce the high enthalpy environment during a candidate Martian atmospheric condition by specifying the operational parameters routinely used in the arcjet run with air within the limitation of the hardware capabilities for an existing arc jet heater facility.

References


Fig. 7 Pitot pressure and flow enthalpy calculated by using the present method equivalent to the Martian entry flight conditions\(^{[15]}\)\(^{[15]}\)