Analysis of flow-field and heat exchange for a blunted cone at hypersonic speeds

S M Drozdov and A S Rtishcheva
Central Aero Hydrodynamic Institute named after Professor N. E. Zhukovsky (TsAGI)
Russia, 140180 Zhukovsky, Zhykovsky st., 1

Abstract. The possibility of decoupled analysis of flow-field and heat transfer for a solid structure was investigated using numerical simulation of conjugate problem on hypersonic flow and heat transfer for a blunted cone made of heat-conducting material. The considered cones had semi vertex angle \( \varphi \approx 7^\circ \) and two radii of blunting: \( r_1 \) and \( r_2 = \frac{2}{3} r_1 \). This form is typical for noses of modern hypersonic aircraft. The ANSYS FLUENT software package was used to simulate a laminar flow with developed physicochemical models of nonequilibrium air (a five-component gas mixture was considered: \( \text{O}_2; \text{N}_2; \text{O}; \text{N}; \text{NO} \)) and S2S built-in model of radiative heat transfer. The accuracy of the decoupled analysis was evaluated as a result of comparison with the solution of the conjugate problem on flow-field and internal heat transfer.

1. Introduction
Numerical simulation of conjugate problems on flow-field and internal heat transfer in solid structures of modern hypersonic aircraft requires use of complex physicochemical models of nonequilibrium air, radiation heat transfer models, etc., which is possible only with large computing powers. Decoupling these tasks while maintaining high accuracy of the result is the only way to reduce the duration and cost of calculations.

This study considered a model problem on a streamlined blunted cone made of heat-conducting material (radius of blunting: \( r_1 \) and \( r_2 = \frac{2}{3} r_1 \)) with angle of semi vertex \( \varphi \approx 7^\circ \), that is a typical shape of nose part in modern hypersonic aircraft. The flow velocity was taken close to the first space velocity \( (\text{M}=25) \), which is typical for reentry vehicles at altitude of H=70000 m. In this condition, the nose part of hypersonic aircraft is subjected to the strongest thermal effect, as compared to the other parts of the structure.

The problem was solved using two approaches. According to the first approach, the flow-field was separately considered taking into account the equilibrium radiation of the blunted cone surface. Based on the obtained distribution of surface heat transfer coefficient, heat transfer inside the solid structure was simulated. In the case of the second approach, the conjugate problem on flow-field and internal heat transfer of blunted cone was solved. In this respect, the comparison of the levels of heat exposure and the equilibrium temperature near the front critical point attracted the most interest.
2. Problem definition
For numerical simulation of the problem of streamlined heat-conducting blunted cone, mesh models were created (Figure 1) to solve the problem within the two approaches described above.

![Mesh models to solve decoupled and conjugate problems on flow-field and internal heat exchange.](image)

Using the package of ANSYS FLUENT codes the laminar air flow was simulated where the real air was a mixture of five gases: \( \text{O}_2; \text{N}_2; \text{O}; \text{N}; \text{NO} \), and the following reactions were possible:

1. \( \text{O}_2 + \text{M} = \text{O} + \text{O} + \text{M} \) (\( \text{M} = \text{O}; \text{N}; \text{O}_2; \text{N}_2; \text{NO} \));
2. \( \text{N}_2 + \text{M} = \text{N} + \text{N} + \text{M} \) (\( \text{M} = \text{O}; \text{N}; \text{O}_2; \text{N}_2; \text{NO} \));
3. \( \text{NO} + \text{M} = \text{N} + \text{O} + \text{M} \) (\( \text{M} = \text{O}; \text{N}; \text{O}_2; \text{N}_2; \text{NO} \));
4. \( \text{N}_2 + \text{O} = \text{NO} + \text{N} \);
5. \( \text{NO} + \text{O} = \text{N} + \text{O}_2 \).

The kinetic model is a modification of the Dunn and Kang model proposed in TsAGI. It was shown in [1, 2] that it is the five-component models of real air that can be used to solve problems of hypersonic aircraft flow-field.

The problem was solved for two cone blunting radii: \( r_1 \) and \( r_2 = \frac{2}{3} r_1 \). At the entrance to the computational domain, the following boundary conditions were set: \( \text{M}=25; \ \text{p}=5.22 \ \text{Pa}; \ \text{T}=219.6 \ \text{K} \). Mass fractions of air components are: \( g(\text{O}_2)=0.23; \ g(\text{N}_2)=0.77 \). At the output of the computational domain, non-reflecting conditions were set with pressure \( \text{p}=5.22 \ \text{Pa} \).

The external surface of the solid structure was assumed to be non-catalytic, with emissivity factor \( \varepsilon=0.8 \). On the inner surfaces, which were a titanium insulated frame, the boundary conditions were set corresponding to the heat transfer due to natural convection: flow temperature far from the inner walls was \( \text{T}=300 \ \text{K} \) and heat transfer coefficient was \( \alpha_{in}=10 \ \text{Wm}^{-2}\text{K}^{-1} \). The design itself consisted mainly of heat-conducting material \( \lambda=50 \ \text{Wm}^{-1}\text{K}^{-1} \).

In the case of the first approach to solving problems, it was assumed that a convective heat flux obtained from solving the flow-field problem acted on the surface of the nose of hypersonic aircraft (blunted cone):

\[
q = \alpha(T_e - T_w),
\]

where \( T_e \) – representative temperature at the external edge of the boundary layer;
Tw – surface temperature of hypersonic aircraft (blunted cone).

The surface temperature of the blunted cone was determined with the balance condition of convective heat flux (1) and equilibrium heat radiation, for which the formula was used:

\[ q_{rad} = \varepsilon \sigma (T_w^2 - T_\infty^2), \]

where \( T_\infty = 219.6 \) K – undisturbed flow temperature at altitude \( H = 70000 \) m.

The calculations were performed in a two-dimensional axisymmetric formulation.

3. Results of study of blunted cone flow-field

Figures 2 and 3 show the results of analyzing flow-field of cone with blunting radius \( r_2 \) at angle of attack \( \alpha = 0^\circ \).

![Figure 2. Calculation results on flow-field of blunted cone, radius \( r_2 \).](image)
The thickness of the shock layer near the forward stagnation point was \( \delta/r_2 = 0.113 \). In this condition, the temperature in the shock layer was \( T=15704 \) K and the pressure at the forward stagnation point was up to \( p/p'_0=1.03 \). The pressure value was related to the total pressure behind the direct shock wave \( p'_0=4203.1 \) Pa. High temperature was only in a narrow segment behind the shock wave. The entropy layer generally had temperature \( T\approx6000–8000 \) K, which leads to the manifestation of real air properties in the form of intense chemical reactions of decomposition of nitrogen and oxygen molecules and the formation of N, O, NO. The effective heat capacity of the mixture of components increased, which reduced the heat capacity ratio \( \gamma=c_p/c_v \) to value \( \gamma=1.2 \) and led to the approach of the shock wave to the surface of the frontal blunting.

The maximum heat flux density was seen at cone surface temperature \( T_w=300 \) K and made \( q_{max}=237.8\cdot10^4 \) Wm\(^{-2}\), which is 33% lower than the heat flux density calculated by the Fay-Riddell formula for a sphere without real air properties [3].

The maximum heat flux density obtained by analyzing flow-field of blunted cone, taking into consideration equilibrium radiation (\( \varepsilon=0.8, T_\infty=219.6 \) K), was \( q_{max}=174.9\cdot10^4 \) Wm\(^{-2}\). The temperature at the front critical point was \( T_{w_{max}}=2492.1 \) K.

For the cone with blunting radius \( r_1 \), in comparison with the previous case, the mass fractions of N and NO components in the vicinity of the anterior critical point were slightly higher (by 19% and 10%,
respectively). The result of large-scale effect was that chemical reactions at a greater distance were more complete.

The maximum heat flux density was seen at cone surface temperature $T_w=300\, \text{K}$ and amounted to $q_{\text{max}}=169.0\times 10^4\, \text{Wm}^{-2}$, which is 42% different from the heat flux density calculated by the Fay-Riddell formula for a sphere without taking into account the real properties of air.

The maximum heat flux density obtained by analyzing flow-filed of blunted cone, taking into consideration equilibrium radiation ($\varepsilon=0.8$, $T_\infty=219.6\, \text{K}$), was $q_{\text{max}}=126.2\times 10^4\, \text{Wm}^{-2}$. The temperature at the front critical point was $T_{w\text{max}}=2296.6\, \text{K}$.

4. Accuracy check of decoupled analysis of flow-field and internal heat exchange for a blunted cone

The obtained distribution of heat transfer coefficients to the surface of the blunted cone was set as a boundary condition for solving the problem of internal heat transfer.

Figure 4 shows the comparison of temperature distribution over the surface and inside the solid structure based on two approaches for a cone with blunting radius $r_2$.

![Thermally insulated titanium frame](image1)

- a) The first approach (decoupled solution of problems on flow-field and heat transfer for a solid structure)
- b) The second approach (a conjugate problem on flow-field and internal heat transfer)

![Thermally insulated titanium frame](image2)

- c) Temperature $T_w$, K distribution on the cone surface near the front critical point

**Figure 4.** Comparison of the calculation results for decoupled and conjugate problems on flow-field and internal heat transfer for a cone with blunting radius $r_2$

Solving the problem on heat transfer inside a solid structure demonstrated that due to thermal conductivity, the temperature at the front critical point of the blunted cone decreased to $T_{w\text{max}}=2229.8\, \text{K}$.

The solution of the conjugate problem on flow-field and internal heat transfer for a blunted cone showed that the maximum temperature at the front critical point was $T_{w\text{max}}=2233.9\, \text{K}$, and the maximum value of the heat flux (taking into account the thermal conductivity of solid materials) was $q_{\text{max}}=185.0\times 10^4\, \text{Wm}^{-2}$. 
Solving the heat transfer problem inside a solid structure for a cone with blunting radius $r_1$ demonstrated that due to thermal conductivity, the temperature at the front critical point decreased to $T_{w\text{max}} = 2077.6$ K.

The solution of the conjugate problem on flow-field and internal heat transfer for a blunt cone showed that the maximum temperature at the front critical point was $T_{w\text{max}} = 2079.9$ K, and the maximum value of the heat flux (taking into account the thermal conductivity of solid materials) was $q_{\text{max}} = 132.1 \cdot 10^4$ Wm$^{-2}$.

5. Conclusions

The investigations of hypersonic flow-field around a blunted cone and its internal heat transfer showed that the decoupling of these problems gives a discrepancy with the solution of the conjugate problem in heat flux values of not more than 6%, and in temperature values not more than 5 K. Therefore, the use of the decoupled analysis method is justified and allows significant savings in computing resources.

It was shown that the heat flux density decreased whereas the blunting radius of the cone increased: for $r_2 = \frac{2}{3} r_1 - q_{\text{max}} = 185.0 \cdot 10^4$ Wm$^{-2}$; for $r_1 - q_{\text{max}} = 132.1 \cdot 10^4$ Wm$^{-2}$.

It should be noted that modeling the properties of real air is a necessity for analyzing hypersonic flows. The study showed that the estimates of the heat flux obtained using the Fay-Riddell formula and omitting the real properties of air were significantly overestimated.

References

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