Experimental Investigation and Numerical Analysis of Hypersonic Compression Ramp Heat Transfer*


For blunt-nosed, ramped flat plates at angles of attack of 0°, 20°, 30° and 35°, the heat transfer and the flow field around the compression ramp have been investigated experimentally based on infrared thermography measurement and Schlieren photograph observation in the NAL 1.27m and ONERA S4MA hypersonic wind tunnel at $M_\infty = 10.0$ and $Re_n=1.5 - 2.3 \times 10^6$/m. We also compared CFD simulations using NAL and ONERA N. S. codes for the examination and comparison of the flow field and the magnitude of the heat transfer. The results showed an increase in heat transfer on the flat plate that was upstream from the corner and the reduction of heat transfer on the ramp when the leading-edge is blunt. An analytical study to obtain a single correlation for the measured heat transfer along the plates showed that ratio $x/r_n$ of $x$ distance from the leading-edge and the nose radius is a dominant similarity parameter for heat transfer distribution on the ramp downstream of the reattachment as well as on the flat plate part upstream from the ramp corner.

**Key Words:** Blunted Nosed Flat Plate, Hypersonic, Compression Corner Flow, Heat Transfer Measurement, CFD Calculation

1. Introduction

Accurate predictions for both pressure and heat transfer distributions over the deflected control surfaces of winged-reentry hypersonic vehicles are very important as the control effectiveness and the heating rate of deflected control surfaces are two critical issues in their design. The magnitude of the pressure and heat transfer distributions are significantly influenced by the occurrence of extensive separation in the vicinity of the vehicle hinge line which is caused by the interaction of an oncoming boundary layer with the shock wave.

The nose and leading-edge on the wing of re-entry vehicles must have some bluntness in order to reduce the heat load at the nose and the leading-edge stagnation flow region. A strong shock at the blunt leading-edge induces a high temperature shock layer near the nose and this causes a high temperature gas layer called the 'entropy layer' to develop along the vehicle's surface. The low Mach number and the unit Reynolds number flow nature of the outer entropy layer affects the surface pressure, heating, and the extent of separation region around compression corner(1).

The goal of this research is to analyze the heating characteristics around the compression corner with the nose bluntness effects. We conducted a series of wind tunnel tests and corresponding numerical calculations in order to obtain and examine these heating characteristics. We did an analysis to obtain a simple generalized correlation for predicting the heating rate around the compression corner. This experimental correlation is valuable, especially for a high angle of

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attack, as there is little experimental data and analytical research about this topics in spite of its importance for the predicting heat levels on the re-entry vehicle control surfaces.

Nomenclature

\( \begin{align*}
C_d &: \text{leading-edge drag coefficient} \\
c_p &: \text{specific heat} \\
d &: \text{leading-edge diameter} \\
h &: \text{heat transfer coefficient } q/(T_s - T_w) \\
M &: \text{Mach number} \\
p &: \text{static pressure} \\
q &: \text{heat transfer rate} \\
Re &: \text{Reynolds number} \\
r_s &: \text{Leading edge radius} \\
s &: (x/r_o) \cdot (M/\sqrt{Re}) \text{main}^{1,2} \\
St &: \text{Stanton number } h/\rho_w U_w C_p \\
x &: \text{distance from leading-edge along upstream plate direction}
\end{align*} \)

Subscripts

\(\begin{align*}
o &: \text{stagnation} \\
2 &: \text{wedge flow condition} \\
\epsilon &: \text{edge of boundary-layer} \\
w &: \text{wall condition} \\
oo &: \text{free stream value} \\
\text{main} &: \text{freestream conditions (for } a=0^\circ) \text{ or wedge flow conditions (for } a>0^\circ) \\
\text{Superscript} \\
* &: \text{Eckert reference}
\end{align*} \)

2. Experimental Method

2.1 Facilities

In order to evaluate heat transfer measurement techniques, we conducted tunnel-to-tunnel heat transfer measurement tests of blunt-nosed, ramped flat plate models using IR thermography in NAL/1.27m and ONERA/S4MA hypersonic tunnels which are similar Mach 10 blow-down type tunnels with exit diameters of 1.27m and 1.0m, respectively. The NAL new 1.27m hypersonic wind tunnel which was built parallel to the existing 50cm tunnel (Fig. 1) has been operational since March 1995. The performance of the NAL hypersonic wind tunnel can be summarized as follows:

\[
\begin{array}{|c|c|c|}
\hline
\text{Test section} & 50cm Leg (Free-jet) & 1.27m Leg (Free-jet) \\
\hline
\text{Test medium} & \text{Dry air} & \text{Dry air} \\
\hline
\text{Mach number} & 5, 7, 9, 11 (Inter-changeable nozzles) & 10 (Fixed nozzle) \\
\hline
\text{Reynolds number} & 0.7 \sim 5 \times 10^5/m & 0.3 \sim 4.5 \times 10^5/m \\
\hline
\text{Total pressure} & 1 \sim 9.8 \text{ Mpa} & 1 \sim 9.9 \text{ Mpa} \\
\hline
\text{Total temperature} & 600 \sim 1300 \text{ K} & 1000 \sim 1200 \text{ K} \\
\hline
\text{Test times} & 60\text{sec} \times 2 & 30\text{sec} \times 2 \\
\hline
\end{array}
\]

Figure 2 shows a description of the S4MA facilities. Compressed air is stored in tanks under 270 bar of pressure. Before the test is conducted the accumulation heater, which contains 11 tons of alumina pebbles, is heated by propane combustion. During the run the air from the heater, dry and nonvitrified, is passed through a 10 µm mesh dust filter. The characteristics of the test sections for the three interchangeable nozzles are:

\[
\begin{array}{|c|c|c|c|}
\hline
\text{Nozzle} & \text{Mach 6.4} & \text{Mach 10} & \text{Mach 12} \\
\hline
\text{Outlet diameter} & 0.685 \text{ m} & 0.994 \text{ m} & 0.994 \text{ m} \\
\hline
\text{Throat diameter} & 75.43 \text{ mm} & 36.61 \text{ mm} & 21.53 \text{ mm} \\
\hline
\text{Useful running time} & 40 \text{ to } 90 \text{ sec} & 25 \text{ to } 85 \text{ sec} & 25 \text{ to } 85 \text{ sec} \\
\hline
\end{array}
\]

We performed the tests under the same test conditions of stagnation pressure of \( p_o = 25 \) and 60 bar at angles of attack \( a=0^\circ \) and \( 35^\circ \). We conducted additional tests at \( p_o = 40 \) bar and \( a=30^\circ \) in NAL, and the extensive pitot pressure and total temperature calibration in both tunnels.

2.2 Models

The same models were used in the present studies for comparison. The models consists of the central Vespel \textsuperscript{®} plates and a holder to hold and protect them (Fig. 3). Vespel is a high temperature-resisting and low thermal diffusivity engineering plastic whose properties are shown in Table 1. We prepared 4

![Fig. 1 View of the NAL hypersonic wind tunnel system](image1)

![Fig. 2 Description of the S4MA facilities](image2)
interchangeable leading-edge parts of plates with different nose bluntness ($r_n = 0.3, 3, 6, 12$ mm) in order to obtain nose bluntness effect data. A fixed compression corner angle of 15° was used. The model aspect ratio ($A_e = w/x_c$) should be $A_e > 1$ in order to satisfy the limit that can hold two-dimensionality in a compression ramp region and in order to minimize the three dimensional effects on the measured heat fluxes. The ramp was made long enough so that the ramp will terminate many boundary layers with a thickness aft.
of the reattachment region, and will yet not exceed the maximum permissible blockage of the tunnel. As a result, we selected $A_o=1.15$ as the largest aspect ratio for a given configuration and flow conditions. A picture of the model is presented in Fig. 4.

2.3 Experimental method and data reduction

2.3.1 Apparatus and instrumentation In order to obtain a time history of the models surface temperature, we used infrared imaging systems for both tunnels; we used systems for AGEMA® 900LW and Thermovision® 782LW infrared (IR) cameras in the NAL and S4MA tests, respectively. The camera framing rates are 15 frames per second and the temperature resolutions are 12bit and 10bit for AGEMA® 900LW and Thermovision® 782LW, respectively. We observed the model's windward surface temperature images through the Ge and the ZnSe windows. Cameras were placed within an atmospheric pressure box in the test chamber of the tunnel and outside the test chamber in the NAL and ONERA tests, respectively.

To avoid an initial heating disturbance from the shear layer around mainstream, high speed injection systems were used in both tunnels. The injection speeds were 0.18 sec and 1.5 sec for NAL and ONERA tests, respectively. We performed a Schrielen system observation in order to analyze interacting flow patterns.

2.3.2 Surface heating rate reduction We extracted the Heat flux for each pixel of the image assuming one-dimensional conduction by modified Jones–Hunt methods and the finite difference method in NAL and ONERA data reduction, respectively. As Vespel has low thermal conductivity and thermal diffusivity properties, we expected small lateral conduction effects in the tests. Therefore, the reduction methods were adequate for the task at hand except for certain local extremely severe peak heating regions.

The use of correct thermal physical properties are necessary for the accurate quantitative extraction of heat flux. The temperature dependent material properties were used in ONERA data reduction. On the other hand, constant thermal physical properties at 50°C were used in NAL data reduction. In the case of the constant thermal properties, because of the relatively large temperature dependency of Vespel's thermal properties and the large temperature increase in the reattachment point heating region, it was necessary for us to study the effect of temperature dependency of thermal properties on the reduced heating rate.

In order to find suitable constant thermal properties and to examine the accuracy of measured IR heat flux data, we simultaneously measured heat flux by reference sensors (3 Gardon gauges and 3 slug calorimeters) at 6 points on the model in the NAL tests.

3. CFD Studies

3.1 Numerical analysis method

In the NAL computation, we used a flux-split upwind TVD thin-layer Navier–Stokes CFD code; "HYPER 2D". Computations using this code are primarily done for a model b configuration at angles of attack from 0 to 35 degrees. The computational mesh consists of 230 points in the streamwise and 100 points in the normal body direction. Grids are generated by using hyperbolic partial differential equations and grid lines intersect at almost right angles on the flat plate surface. This grid characteristics was very important in obtaining accurate heat transfer distribution in regard to the present analysis of the thin-layer assumption.

ONERA CELHYO is a two dimensional or axisymmetric Navier–Stokes code. The CELHYO solver deals with ideal mixtures of perfect gas. For thermochemical nonequilibrium flows, it usually assumes five neutral species. The chemical reaction model which we used for air is Gardner's. It consists of 15 dissociation and 2 reaction exchanges. Vibrational relaxation of the diatomic species occurs through V–T transfers which are modeled following Landau–Teller's rule. The mixture viscosity is calculated after Armaly Sutton's model. In this paper, we used a perfect gas version. The CELHYO code solves the Navier Stokes balance equations taking physical modeling on curvilinear structured meshes into account by using a fully implicit finite volume method. The viscous part is discretized according to a central differencing procedure, while a quasi–second order accurate upwind scheme yields an approximation for the inviscid operator. Upstreaming is achieved by using the Hybrid Upwind Splitting for upwind bias. We achieved second order accuracy by using a MUSCL approach that was written in primitive variables.

4. Results and Discussion

4.1 Infra-red thermography results

An example of an image of the heat transfer rate distribution on the flat plates that was obtained from the IR thermography is shown in Fig. 5. For a zero angle of attack, a two dimensional surface flow field is adequate as is shown in Fig. 5(a). However, for a 35° angle of attack, the flow field was three dimensional. Fig. 5(b) shows two heat peaks on the ramp, a peak near reattachment point, and peak heating from the
shear layer impingement as induced by bow-shock/separation-shock interaction.

A comparison of the IR measurement and the sensor data showed agreement within a 5% margin of error in each runs, as is shown in Fig. 6. This shows that the use of constant material properties in the data reduction scheme for relatively short tests (within 3 seconds of flow exposure) does not produce a significant level of error, provided that the material properties are suitable. At peak heating regions as the surface temperature became larger than 200°C, it will be necessary to analyze using the temperature depending thermal properties.

4.1.1 Heat transfer distribution at a zero angle of attack Figure 7 shows the measured centerline heat transfer distribution for an angle of attack of 0°, 35°. For a model with a nose radius \( r_s \) of 3, 6, 12mm (model b, c, d, respectively), Fig. 7(a) shows that the extent of the separated flow region is almost the same and that heating level increases slightly with increasing nose bluntness in the entire flow region that is upstream from the compression corner. For a small leading-edge \( (r_s=0.3 \text{ mm}) \), model a) case, the separated flow region is larger than that of the blunt nose cases. The upstream heating level is lower than the level of the larger blunt nose cases and approximately 10% larger than the sharp-flat-plate Stanton number based on Van Driest’s theory\(^6\). At the downstream region of the reattachment point, the heating level is higher than that of blunt nose cases. For small nose model a (symbol \( \vee \) in Fig. 7(a)), as the nose region plate was made of stainless steel, we omitted a seemingly very low heating rate at the nose and at the following flow region of leading-edge part.

4.1.2 Heat transfer distribution at a 35° angle of attack For 35° angle of attack cases, heat transfer distribution by IR camera observation and the Schlieren observations showed complex flow fields with bow-shock/embedded-separation-shock interaction.

The measured centerline heat transfer distribution for an angle of attack of 35° is shown in Fig. 7(b). The extent of the separated flow region decreases slightly with an increase in nose bluntness. The heat transfer coefficient on the ramp shows that, after the peak heating associated with separated flow reattachment, there are second peak heating regions that are associated with bow-shock/separation-shock interaction. The magnitude of this interacting peak heating decreases with an increase in the nose bluntness. The position of the peak heating moves backward with an increase in nose bluntness. This is caused by the backwards movement of the bow-shock/separation-shock interaction point according to the outward movement of the bow shock waves with an increase in nose bluntness.

4.2 Analysis of heat transfer measurements In order to appropriately evaluate the measured heat transfer data, other reliable data or good analytical methods that can validate the magnitude of the measured data are necessary. In this paper, we at first analyzed the effect of leading-edge bluntness on the measured heat transfer rate by correlating experimental flat plate data results as well as by comparing the measured data and the CFD calculations, as is shown in Section 4.3.
4.2.1 Heating at the flat plate area  As was described in section 4.1, the dependency of the obtained heating magnitude and the flow separation on nose bluntness which may come from the effects of the entropy layer were consistent with previous research \(^{(7)}\). Approximate empirical expressions for heat transfer distributions that were far from the stagnation point on a blunt-nosed flat plate are given for an example with zero incidence as in Eq. (1) \(^{(9)}\).

\[
S_{le}(R_{e,m}) = A\left(\frac{u_0}{u_0 + u_a}\right)^n \left(\frac{T_0}{T^*}\right)^{1.2} C^{0.6} \left(\frac{H_T - H_0}{(\rho r)^{0.5} (H_T - H_0)}\right)
\]

where \(A=0.332\) and \(n=0.5\) for laminar flow, and \(A=0.0296\) and \(n=0.2\) for turbulent flow.

However, Eq. (1) was not adequate for the blunt nosed cases and is not applicable to present experiments for angles of attack, as Eq. (1) has been used for the prediction of heat transfer at far from the nose for flat plate at zero angle of attack.

In this paper, we attempted to analyze the main flow effects by including test cases at angles of attack. We analyzed the relation between \(x/r_n\) and heat flux by assuming that \(x/r_n\) will be effective as a similarity parameter for flow field presentation after a blunt nosed configuration \(^{(9)}\). We correlated the measured heat flux and \(x/r_n\) by using local Stanton number \(S_{le}\), \(Re_m\) based on local flow properties \(u_0, \rho_c\) and \(T_{in}\). We estimated boundary layer-edge velocity \(u_0\) and pressure \(p_0\) from \(p_s\) and \(p_{in}\) assuming an isentropic flow expansion from the nose to the boundary layer edge and constant static pressure in the boundary layer, i.e., \(p_{in} = p_{o}\) and \(p_r = p_s\). We also assumed the nose bluntness to be large enough so that the total pressure at the boundary layer edge can be estimated following normal shock conditions of \(p_{o}\).

We estimated the surface pressure distribution with a combination of blast wave and weak interaction theory.

\[
p_{o}/p_{o}=1 \text{ (for } \alpha=0^\circ) \text{, or } p_{o}/p_{o}=p_{o}/p_{o} \text{ (} \alpha>0^\circ \text{)}
\]

\[
p_{o}/p_{o}=0.117 M_o^{2.5} (x/d)^{-2.5} + 0.732 - 1.0
\]

\[
p_{o}/p_{o}=1 + 0.078 x - 1.0
\]

\[
p_{o}/p_{o}=p_{o}/p_{o} + p_{o}/p_{o} + p_{o}/p_{o}
\]

We used Eq. (2) for sharp nose surface pressure without viscous interaction effect \(p_{o}\). Eqs. (3) and (4) \(^{(7,10)}\) were used to obtain a pressure increase based on blast wave and weak interaction theory \(p_{o}\) and \(p_{o}\), respectively. We obtained the surface pressure \(p_{o}\) with combination of the above types of pressure, using Eq. (5). We also corrected surface pressure that is caused by a small angle of attack offset by the oblique shock relationship using hypersonic parameter \(M_0=\theta\), although this effect was small (for a 0.2\(^\circ\) angle of attack for a nominal angle of attack).

Figure 8(a) shows that \(S_{le} =\sqrt{Re_{c,m}}\) (local stanton number \(S_{le}\) with a combination of the local Reynolds number based on nose bluntness) is proportional to \((x/r_n)\) and viscous parameter \((M/\sqrt{Re})\) \(_{\text{main}}\), where the viscous parameter is evaluated at the wedge flow conditions of outside of the boundary layer–edge. The following heat transfer correlation was obtained:

\[
S_{le} = 0.022 \cdot (x/r_n)^{-0.5} \cdot (M/\sqrt{Re})^{0.6}_{\text{main}}
\]

or

\[
S_{le} = 0.022 \cdot (M/\sqrt{Re})^{0.6}_{\text{main}}
\]

The above results may be used as an unified correlation of the heat transfer for the blunt flat plates except for the area very close to the nose flow region. Figure 8(b) shows the correlation between \(S_{le} =\sqrt{Re_{c,m}}\) and \((x/r_n)^{-0.5} \cdot (M/\sqrt{Re})^{0.6}_{\text{main}}\) for high angle of attack cases. This high level of correlation indicates that correlation of Eq. (6) will be also applicable to cases with different angles of attack and different Reynolds numbers.

4.2.2 Ramp region heating  Although the above correlation (Eq. (6)) is for the upstream of the corner flow, Fig. 8 shows that the magnitude of the

\[
\begin{align*}
\text{(a) } & \theta = 0^\circ \\
\text{(b) } & \theta = 35^\circ
\end{align*}
\]

Fig. 8 Blunt nosed flat plate heating rate correlation
interaction peak heat flux was also proportional to parameter $s = (a / r_w) \cdot (M / \sqrt{Re})_{max}^{1.2}$. This relationship will be used to predict the level of heating on a ramp with a blunt nose configuration. However, surface pressure distribution on the ramp surface is needed in order to obtain relationship between corner flow properties $Ma$, $u_s$ and $p_b$ at angles of attack of $0^\circ$ and $35^\circ$. Inviscid oblique shock theory will not be able to predict down stream ramp pressure $p_b$ which was attained at the end of the reattachment compression, as there is a pressure loss effect from curved bow shock. In particular, in regards to a $35^\circ$ angle of attack, bow–shock/separation–shock interaction increases the peak pressure and heating in addition to the common double shock or triple shock compression effects on corner heating. Therefore, more research is necessary for a more complete analysis of blunt nosed flat plate ramp heating in order to obtain an empirical correlation between peak heating and pressure as for a sharp flat plate of a two dimensional interaction\[11\].

4.3 Comparison between CFD and experimental results

4.3.1 Comparison with experiments when $a=0^\circ$

We performed simulations at ONERA with the CELHYO N.S. code. They are in reference to the ONERA tests at a $0^\circ$ angle of attack at $M = 9.77$. The following table shows the computational conditions.

<table>
<thead>
<tr>
<th>S4MArun n°</th>
<th>model</th>
<th>$P_b$ (bar)</th>
<th>$T_2$ (K)</th>
<th>$T_e$ (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2360</td>
<td>b</td>
<td>25.2</td>
<td>1028</td>
<td>300</td>
</tr>
<tr>
<td>2361</td>
<td>d</td>
<td>25.3</td>
<td>1015</td>
<td>300</td>
</tr>
<tr>
<td>2340</td>
<td>b</td>
<td>60.0</td>
<td>1016</td>
<td>300</td>
</tr>
</tbody>
</table>

The computational mesh, shown in Fig. 9, is composed of three blocks ($70 \times 80$), with a refinement near the wall in order to capture the boundary layer. The results of computations with CELHYO code are presented in Fig.10 for the above tests condition. Comparison of flow field between CFD computations and Shlieren photo shows that the flow fields appear to be adequately resolved, and showing that the shock

Fig. 9 Computational mesh used for CELHYO code

Fig. 10 ONERA/CFD simulations of flow field ($a=0^\circ$, $p_b=25$ bar)

Fig. 11 Comparison of the measured and computed heat transfer distributions (ONERA/NAL CFD, $a=0^\circ$)
shapes and the locations of the separation points appear to have been correctly computed. The computed heat transfer distributions are compared to the measured data in Fig. 11. The NAL code results for the NAL test conditions (Run 114; $M = 10.04$, $p_o = 25.0$ bar, $T_o = 1098$ K) and for the ONERA test conditions (Run 2340) are also plotted in Fig. 11(a) and (b), respectively. A comparison between the measured data and the CFD simulations shows that the separated flow regions seem to be of the same size. However, there were discrepancies of 10 to 20% in magnitude between the ONERA and the NAL experiments/computations. The discrepancies observed between the CFD predictions and the heat transfer distributions cannot be explained at present, although a small portion of it comes from the differences in the NAL/ONERA test conditions.

4.3.2 Comparison with experiments when $\alpha = 35^\circ$ When the angle of attack is $35^\circ$, heat transfer distribution from IR and Schlieren observations show complex flow fields with bow-shock/embedded-separation shock interactions. Figure 12 shows a Schlieren photograph for an example with small nose bluntness (model a) at an angle of attack of $35^\circ$ which shows the clearest flow field without any loss of visibility of the shear layer due to the small effects of the entropy layer on the density of the flow field. An estimated bow-shock/separation-shock interaction flow field from Schlieren observation is shown in Fig. 13. Second peak heating as is shown in Fig. 6, 7(b) is the result of a Type V shock/shock interaction.

Figure 14 shows the NAL code simulation of the pressure counter of a flowfield for the models b ($r_n = 6.0$ mm) at a $35^\circ$ angle of attack. We also observed Type V shock/shock interaction at a high Reynolds number in the CFD flow field calculation, which was very close to the Schlieren observation at low Reynolds numbers.

As the CFD calculations in this comparison are two dimensional and the IR heat transfer distribution data were three dimensional at a $35^\circ$ angle of attack, there were some discrepancies in the comparison of the experimental results and the CFD simulations.

5. Conclusions
Our research about blunt nosed, ramped flat plates showed the effects of nose bluntness on heat transfer. On the flat plate region that was up stream from the corner, the heat transfer for the blunt leading-edge configuration had a higher heating rate than for a small bluntness leading-edge configuration. In the ramp region, the results showed a reduction in heat transfer rate as the leading edge bluntness increased. The effect of nose bluntness on the extent of separated flow region showed that an increase in nose bluntness had little effect on change in the extent of the separation region, although the extent of separation for cases with small bluntness was larger than the blunter ones. In tests at angles of attack of $35^\circ$, we observed peak heating which was caused by bow-shock/separation-shock interaction. Type V interaction was confirmed by Schlieren observations and CFD simulations.
An analysis of the magnitude of heat transfer at flow regions upstream from the corner showed that the heat transfer distribution of the blunt-nosed flat plate that was modified by a viscous parameter $(M/\sqrt{Re})_{\text{main}}$ is proportional to $(x/r_n)^{a_5}$. This dependency was true for the all test cases with different nose bluntness configurations at different angles of attack. The heat transfer on the ramp downstream from the reattachment also showed the same dependency characteristics.

A comparison of the heat transfer distribution between the test results and the CFD simulation shows that a quantitatively high level of agreements was obtained for the entire surface region for flat plate models b and d ($r_n=3$ and 6 mm, respectively) configurations and complicated shock/shock interaction patterns (Type V) were captured in CFD and an experiment at an angle of attack of $\alpha=35^\circ$.

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