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Comparison of plexiglas and vespel materials for heat flux measurements by infrared thermography at hypersonic conditions

by C. O. Asma, F. Barbe, S. Paris, D. G. Fletcher

Aeronautics and Aerospace Department, von Karman Institute for Fluid Dynamics,
Chaussèe de Waterloo 72, B-1640 Rhode-Saint-Genèse, Belgium.
E-mail: asma@vki.ac.be

Abstract:

The aerodynamic heating rate on axisymmetric cone-flare models under hypersonic conditions (Mach 6) is investigated by using infrared thermography. The primary purpose of the work is to see the effects of different flow conditions. Tests with several unit Reynolds numbers are performed to obtain laminar, transitional and turbulent flows. Locations of separation and reattachment points are determined and detailed investigations on the magnitude of aerodynamic heating rate are carried out. Another purpose of this study is to evaluate the model material. Two different materials, Plexiglas and Vespel are used. It is observed that experiments with Vespel yield more reliable and more accurate results by infrared thermography, owing to its lower thermal diffusivity and its ability to withstand high temperatures with little changes in thermal properties.

1. Introduction

Aerodynamic heating has always been a problem during re-entry of space vehicles at hypersonic speeds. One of the critical areas in the design of hypersonic vehicles is the aerodynamic heating of control surfaces. The purpose of this work is to study transitional shock wave boundary layer interactions; i.e. cases where the boundary layer is laminar at separation and transitional or turbulent at reattachment (see Fig.1 for a typical flow pattern in hypersonic cases for the geometry studied) [1]. For this purpose, experiments have been performed in the Mach 6 Hypersonic H–3 Wind Tunnel Facility of the von Karman Institute. Axisymmetric cone-flare models with interchangeable nose sections (made of aluminum) suitable for this purpose were used to obtain fully laminar, fully turbulent and transitional reattachment flows. Infrared thermography was used to measure the surface temperature of the model during the tests.

2. Experimental set-up

Experiments are performed in the Mach 6 Hypersonic H–3 Wind Tunnel Facility. H-3 is a blowdown type Mach 6 hypersonic wind tunnel. The gas used for these tests is air. The stagnation pressure (which is the basic factor in the determination of the freestream Reynolds number) can range from 6 to 35 bars. The air is heated to avoid condensation within the test section, and the stagnation temperature ranges between 480K and 570K, which is still in the range of caloric perfection for air. The wind tunnel has an axisymmetric contoured nozzle of 15 cm exit diameter providing a uniform free jet airflow of approximately 12 cm diameter. This flow is swallowed by a diffuser and expelled through a supersonic ejector. The model is injected into and held in the freestream with a pneumatic support mechanism. A schematic description of the wind tunnel is shown in Fig. 2. The test section has a germanium window, which is suitable for the infrared camera measurements.

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The infrared camera used in this study is an Agema 900 equipped with a 20° × 10° field of view lens. The detector is cryogenically cooled with liquid nitrogen. It has a detectivity in the long wave spectral range corresponding to the mid-infrared (8 to 12 μm). As specified by the manufacturer, the infrared images are acquired at a frequency of 15Hz, the sensitivity is 0.08°C at 30°C and the accuracy is ±1°C or ±1% (absolute temperature measurements). The infrared camera is calibrated prior to the experiments. Second order curves are fitted to define temperature as a function of radiation intensity measured by the I/R camera. The average error of the calibration curves is estimated to be ±0.6°C within a confidence interval of 93%. Different calibration curves are used for black-painted and non-painted models.

Two different models are tested, one made of Plexiglas and the other made of Vespel [2], a plastic designed to withstand high temperatures and to have a low thermal diffusivity. The models have a conical half-angle of 7.5 degrees, a flare angle of 12.5 degrees (with respect to the cone), a total length of 68.5mm (excluding the nose) and a maximum radius of 32.5mm (at the base). Several noses (sharp to blunt) are used to achieve the desired flow: laminar, transitional or turbulent. The thermal properties of Vespel and Plexiglas are presented in Table 1.

3. Experimental Results

Experiments are performed with a Plexiglas model painted black for high emissivity [3, 4, 5] and with a Vespel model [6]. The models are inserted into hypersonic flow and the temperature histories are recorded by infrared camera with a frequency of 15Hz. Having the surface temperature history of the models during the experiment (see Fig. 3), it is possible to see the temperature field on the model at any time (see Fig. 4), and to calculate the heat flux on the centreline of the model. A modified Stanton number distribution (non-dimensional heat flux) for each case is calculated based on the following formula:

$$St = \frac{\dot{q}_w}{C_p \cdot \rho_\infty \cdot U_\infty \cdot (T_0 - T_w)} \qquad (1)$$

where $\dot{q}_w$ (W/m^2) is heat flux, C_p (J/kg.K) is the specific heat for air, ρ_∞ (kg/m^3) and U_∞ (m/s) are freestream density and velocity respectively, T_0 (K) is the total temperature and T_w (K) is the wall temperature. For the calculation of the heat flux, the governing heat flux differential equation is solved by numerical integration, assuming one-dimensional heat transfer [7]. Since it is well known that Stanton number is inversely proportional with $\sqrt{\mathrm{Re}_{\infty,x}}$ [1, 7], $St \cdot \sqrt{\mathrm{Re}_{\infty,x}}$ plots are presented to compare tests with different unit Reynolds numbers.

3.1 Results with Plexiglas Model

Initial experiments were performed with a Plexiglas model, with several noses of different bluntness radii. Typical experimental results of $St \cdot \sqrt{\mathrm{Re}_{\infty,x}}$ are presented in Fig. 5 [4], where a blunt nose of 2.5mm radius is used. Keeping in mind that the flow is laminar at reattachment point for the smallest Reynolds number case (Re_u=8.9×10^{6}m^{-1}), and turbulent on the flare for the highest Reynolds number case (Re_u=20.8×10^{6}m^{-1}), the evolution of Stanton number while passing from laminar flow to turbulent flow can be seen on this figure. One of the two important conclusions of the research of [3, 4] is that the maximum Stanton number is observed at transitional conditions rather than turbulent flow

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conditions; the second conclusion is that the location of maximum heating for a transitional case may be different than those of laminar and turbulent cases: For laminar and turbulent cases, the maximum Stanton number location is very close to the reattachment point. From Stanton number distribution, one can also locate the separation point. The point where the Stanton number starts decreasing with a higher slope is considered to be the separation point (in Fig. 5, separation point is at $x \cong 0.075$m).

3.2 Results with Vespel Model

A number of experiments were also performed with a Vespel model, at the various flow conditions (laminar, transitional and turbulent) on the flare. These results could be compared with those of the Plexiglas model. Also, the black paint effect on infrared measurements was investigated. Because Vespel has a relatively high emissivity (unlike Plexiglas), it is possible to take infrared measurements from a Vespel model without painting it black. Typical $St \cdot \sqrt{\mathrm{Re}_{\infty,x}}$ curves for the Vespel model with a blunt nose of 2.5mm radius are presented in Fig. 6 [6]. Keeping in mind that the flow is laminar for the smallest Reynolds number case ($\mathrm{Re}_u = 9.5 \times 10^6 \mathrm{m}^{-1}$), and it is turbulent on the flare for the highest Reynolds number case ($\mathrm{Re}_u = 25.7 \times 10^6 \mathrm{m}^{-1}$), the evolution of the Stanton number distributions from laminar flow to turbulent flow can be studied on this figure. The conclusions derived for the Plexiglas model are seen for Vespel model as well.

4. Discussion

4.1 Material Effects on Stanton Number

As a first conclusion, it can be said that the values of $St \cdot \sqrt{\mathrm{Re}_{\infty,x}}$ are greater for the Vespel model, compared to those of the Plexiglas model, under similar unit Reynolds number conditions. Even for transitional cases, where the Stanton number is proportional to Reynolds number (unlike laminar and turbulent cases), it is seen that the Vespel model has a higher Stanton number distribution than the Plexiglas model, although the Reynolds number for the experiment with the Vespel model is slightly less than that of the experiment of the Plexiglas model. The fact that the thermal properties of Vespel change very little with temperature, compared to those of Plexiglas suggests that the heat flux results obtained from a Vespel material are much more reliable, because the heat flux is determined assuming that these properties are independent of temperature [7]. A sensitivity analysis on this subject has shown that a 5% change in one of the thermal properties of the material causes approximately a 2.5% change in heat flux [6].

Comparing Fig. 5 and 6, it can also be said that the Stanton number curves at low unit Reynolds number have similar trends for the different materials. However, for higher Reynolds number, slightly different trends are observed on the flare section.

4.2 Black Paint Effects on Stanton Number

As mentioned before, the experiments with the Vespel model were done initially without black paint. Later, some experiments were repeated after painting the model black. Comparing these results did not show a significant change in the $St \cdot \sqrt{\mathrm{Re}_{\infty,x}}$ curves. Both the magnitude and the slopes of Stanton number curves downstream of the reattachment point are slightly smaller for black painted cases, although the difference seems not to be very important. This can be explained by the fact that black paint can play a role as a heat conductor that makes the temperature distribution more homogeneous. The differences between Stanton numbers are more obvious in transitional and turbulent cases than in laminar cases. This is believed to be due to the disturbances created by black paint on the model. The fact that turbulent flow appears at a lower Reynolds number for black painted cases also supports this hypothesis [6].

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4.3 General Evaluation of Experimental Results

The experimental results obtained from different models with several different noses are in good agreement not only with the previous tests done on this subject but also with the theoretical and numerical results [3, 5]. The separation and reattachment points that were determined from Stanton number distributions are in good agreement with numerical results [3, 5]. Calibration of the infrared camera has been repeated several times, to assure that the calibration curve has not changed. The experimental results have an average uncertainty of ±12% on Stanton number, mainly caused by the relatively high uncertainty on unit Reynolds number, which is ±7% [3, 7]. However, it is observed that the repeatability of the tests is good, especially for laminar and turbulent conditions. The tests with transitional flows have lower repeatability, mainly because of the sensitivity of transitional flow to any disturbance as well as to Reynolds number. This is supported by the relatively better repeatability of tests with non-painted Vespel models under transitional flow conditions.

5. Conclusion

Extensive experiments testing a cone flare model in the view to investigate the local heat transfer rate have been carried out in the H-3 Mach 6 Hypersonic Wind Tunnel facility of von Karman Institute. Models made of Plexiglas and Vespel are used with different noses having different bluntness radii. The Infrared thermography technique is used to measure the wall temperature and to calculate the Stanton number distribution along the symmetry axis.

The experimental results are consistent and repeatable. It is possible to detect the locations of separation and reattachment points by looking at the Stanton number distributions. The magnitude and location of maximum heating rate, which are very important parameters for high-speed flights, are studied under different flow types. Moreover, the effect of Reynolds number, nose shape and material are studied within the scope of this work.

It can be concluded that Vespel is a suitable material for infrared measurement technique, owing to its low thermal diffusivity and to its ability to withstand high temperatures without having significant changes in its thermal properties.

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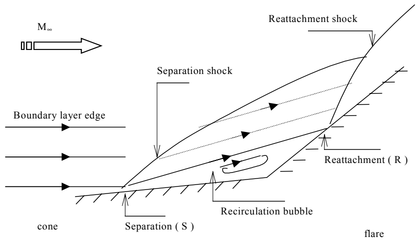

Fig. 1. Typical Flow Field

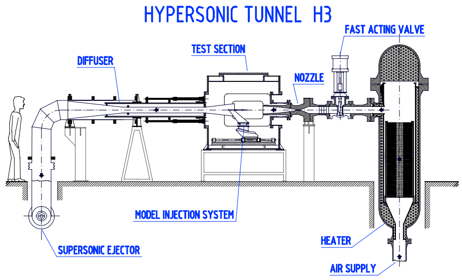

***Fig. 2.** Experimental Set-up*

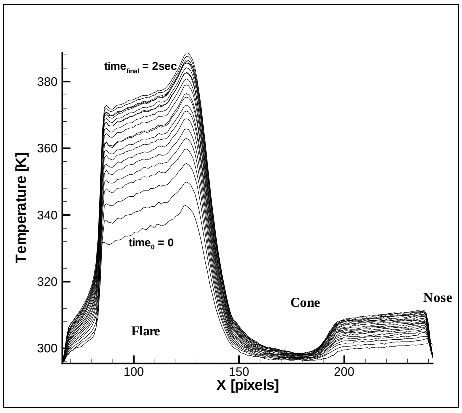

***Fig. 3.** Sample Temperature Profile History (Turbulent Flow)*

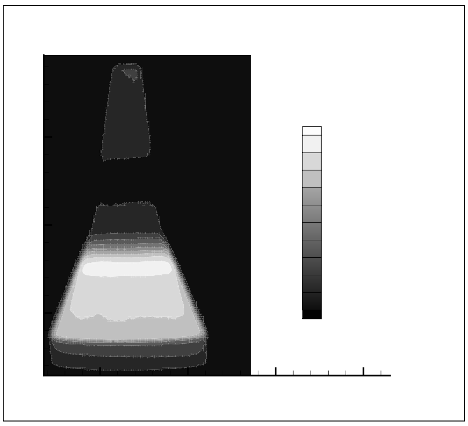

***Fig. 4.** Sample Temperature Contours (Turbulent Flow)*

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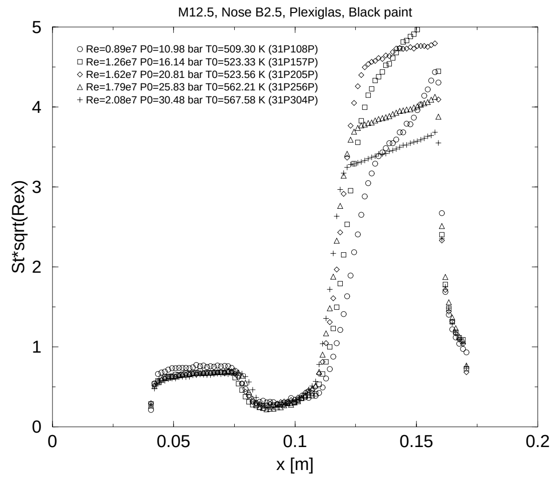

Fig. 5. *Stanton Number Curves for Plexiglas Model*

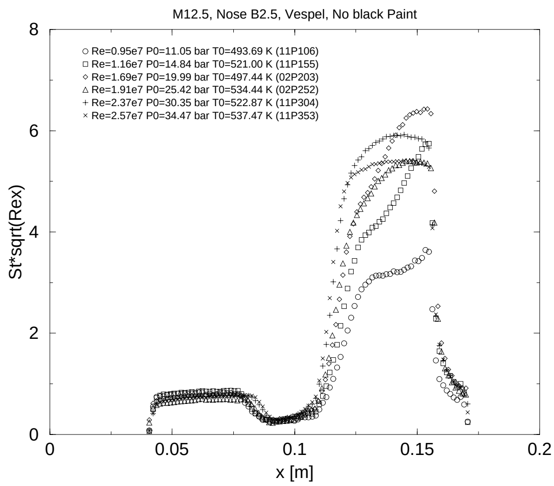

Fig. 6. *Stanton Number Curves for Vespel Model*

Table 1: *Thermal Properties of Vespel and Plexiglas at Ambient Temperature*

	Vespel	***Plexiglas***
λ **[W.m^{-1}.K^{-1}]**	0.35	0.184
Cp [J.kg^{-1}.K^{-1}]	1130	1440
ρ **[kg.m^{-3}]**	1420	1180