JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 34, No. 6, November–December 1997

Experimental Rarefied Density Flowfields at Hypersonic Conditions over 70-Degree Blunted Cone

J. Allègre,* D. Bisch,† and J. C. Lengrand‡
Centre National de la Recherche Scientifique, 92190 Meudon, France

At rarefied flow regimes, flowfield investigations have been conducted in the SR3 wind tunnel on a 70-deg spherically blunted cone and density flowfields obtained by nonintrusive electron beam fluorescence measurements. The blunted cone, chosen as the test case model, has been the subject of extensive studies during the past few years. In addition to some limited results already presented at the Fourth European High-Velocity Database Workshop, the present research gathers density flowfields obtained experimentally at two rarefied hypersonic flow conditions. Experiments have been performed at a freestream Mach number close to 20 and for two Reynolds numbers, 1420 and 4175, calculated using freestream conditions and the cone base diameter. Density flowfields are presented for the two angles of attack, 0 and 10 deg, of the cone. In parallel to the experimental work presented, a number of flowfield calculations were executed by an international group of researchers for test conditions identical to SR3 test conditions. Flowfields were calculated using direct simulation Monte Carlo solutions, leading to comparisons between experimental and computational flowfields.

Nomenclature

d = base diameter, 50 mm
I = local gas fluorescence
i_v = intensity of beam primary electrons, A
K = calibration constant
Ma = nominal freestream Mach number
p_0 = stagnation pressure, bar
R_C = corner radius, mm
Re_d = Reynolds number calculated on the base diameter
R_n = nose radius, mm
T_0 = stagnation temperature, K
V = rarefaction parameter $Ma/(Re_d)^{0.5}$
X, Z = flow coordinates; X and $Z = 0$ for the model nose location
α = angle of attack, deg
α_1 = nitrogen fraction
ρ = local flow density, kg/m^3
ρ_q = quenching constant, kg/m^3
ρ_∞ = local freestream density, kg/m^3

Introduction

RAREFACTION effects are important for hypersonic applications. As far as the blunt body flow is concerned, the near wake involves complex flow interactions with significant implications for spacecraft and re-entry vehicles. The wake closure has to be investigated for planetary probes and aerobrakes because, for such vehicles, payloads must fit into the central part of the wake to minimize heating loads generally associated with reattachment of the separated near-wake flow. One main objective of this study is to build an experimental database on density flowfields. These flowfields are investigated around the blunted cone model, under rarefied and hypersonic flow conditions. This database is made available for comparisons between experimental and computational data, providing a support for code validation.

As part of AGARD, the Fluid Dynamics Panel and its Working Group 18 have chosen the 70-deg spherically blunted cone as the test case model. The forebody configuration is identical to that of the Mars Pathfinder probe. Some experimental data have been partly presented to the Fourth European High-Velocity Database Workshop.[1] In the present document one will find complete results on all density flowfields investigated. Experiments were performed at rarefied hypersonic conditions in the SR3 low-density wind tunnel of the Centre National de la Recherche Scientifique. Test conditions are characterized by a freestream Mach number close to 20 and by Reynolds numbers 1420 and 4175 calculated using freestream conditions and the cone base diameter. Density flowfields are presented for two rarefaction levels and for angles of attack 0 and 10 deg of the model. At the angle of attack of 10 deg, both the leeward side and the windward side have been investigated.

Cone Model and Density Measurement Technique

The model is an axisymmetric spherically blunted cone mounted on a cylindrical sting. Made of brass, the cone and its sting support are water cooled. Consequently, the wall temperature of the model remains close to 290 K during all measurements of density flowfields. Main dimensions of the model are specified in Fig. 1. Base and sting diameters are 50 and 12.5 mm, respectively. The useful length of the sting represents three times the cone base radius.

Density flowfields around the model are obtained by nonintrusive electron beam fluorescence measurements. This measurement technique is briefly described here. The principle of the measurement consists in sending a narrow electron beam of high energy through the flow. Collisions between electrons and gas molecules conduct to the gas fluorescence. The electron gun, bound to a three-axis and motorized support, is located inside the test chamber surrounding the open-jet test section. For the present experiments, the 25-keV electron beam is characterized by a beam intensity limited to 60 μA to avoid the surface alteration of model walls when they are intercepted by the beam.

The fluorescence intensity I of a given volume element of the beam is directly linked to the local gas density:

$$I = \frac{K i_v \alpha_1 \rho}{1 + \rho/\rho_q} \tag{1}$$

Measurements are performed in nitrogen gas flows, which correspond to a nitrogen fraction $\alpha_1 = 1$. The recorded beam fluorescence is emitted by nitrogen in the 00 band of the first negative system. An interference filter is mounted to select the corresponding wavelengths. Its passing band is 50 Å wide with a central wavelength of 3905 Å. Associated with the electron gun, an optical device, including lenses and photomultiplier, allows the local measurement of the fluorescence intensity coming from one fixed elementary section

Received Jan. 9, 1997; revision received July 3, 1997; accepted for publication July 11, 1997.

*Research Engineer, Department of Hypersonics and Rarefied Flow, 4 ter route des Gardes.

†Research Assistant, Department of Hypersonics and Rarefied Flow, 4 ter route des Gardes.

‡Head, Laboratoire d'Aérothermique, 4 ter route des Gardes. Member AIAA.

Table 1 SR3 wind tunnel, experimental test conditions

Flow conditions	Gas	Ma	T_0, K	p_0, bars	Re/cm	Re_d	$\bar{V}$	ρ_∞, kg/m^3
1	N_2	20.2	1100	3.5	284	1420	0.53	1.73×10^{-5}
2	N_2	20	1100	10	835	4175	0.31	5.19×10^{-5}

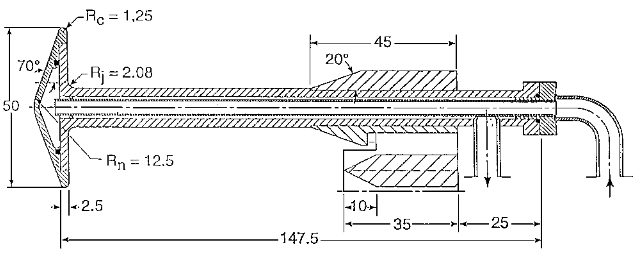

Fig. 1 Water-cooled model for density measurement. All dimensions are in millimeters.

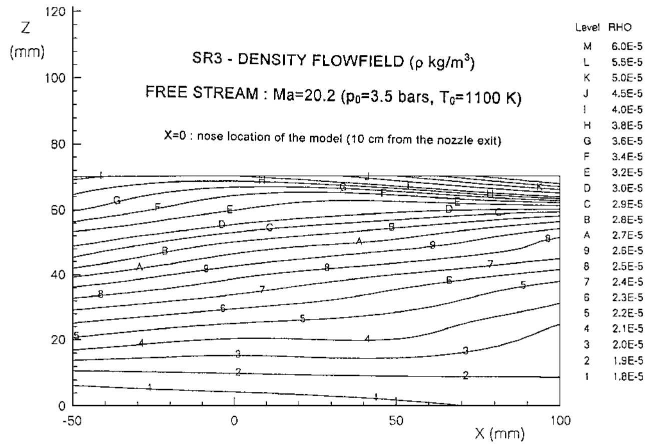

Fig. 2 Wind-tunnel freestream densities (first set of flow conditions).

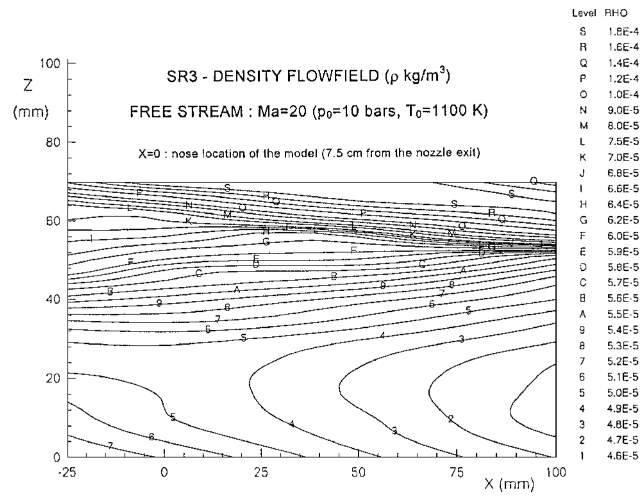

Fig. 3 Wind-tunnel freestream densities (second set of flow conditions).

of the electron beam. The spatial resolution of the measurement is of the order of the beam diameter (1–1.5 mm) in the transverse direction and less than 1 mm in the beam direction. Density flowfield investigations are performed by computerized displacements of the electron beam across the analyzed region. Because of the low-density levels associated with the present tests, the working conditions of the electron beam are optimum. As will be discussed in the presentation of the density flowfields, the accuracy of density measurements is estimated to be better than 10% for all tested regions except for the portion of the shock wave located just ahead of the forebody, which is characterized by high-density gradients.

Test Facility and Flow Conditions

Experiments are performed in the SR3 facility. The wind tunnel is equipped with pumping systems in continuous operation. According to the required flow conditions and to the rarefaction level, two distinct pumping groups are used. At the lowest flow densities, which correspond to the present test conditions, the exhaust system is composed of rotary piston vacuum pumps, Roots pumps, and oil diffusion booster pumps, withstanding volume flow rates of air or nitrogen of about 40 m^3/s under working pressures up to 10^{-4} atm. The almost unlimited running time of the facility is particularly suitable for obtaining good stabilization of flow conditions prior to the experiments. It makes possible long time measurements such as density surveys by the electron beam technique, which require a large number of electron beam displacements through the investigated zone.

Density flowfields are performed at hypersonic and rarefied flow conditions for two rarefaction levels. The nominal operating conditions are indicated in Table 1. Nitrogen flows are issued from two different nozzles supplied with an electrical graphite heater. Divergent sections of the nozzles are conical and continued by cylindrical extensions providing the junction between the conical parts and the test section. Reynolds numbers Re_d and rarefaction parameters $[\bar{V} = Ma/(Re_d)^{0.5}]$ have been calculated assuming, as reference, the 5-cm-cone base diameter. The Sutherland viscosity law is applied for gas temperatures down to 100 K, and then a linear viscosity law is used at lower gas temperatures between 0 and 100 K. At high Mach numbers and at rarefied flow conditions, the use of conical divergent sections results in the existence of transverse and longitudinal density gradients through the test section. Freestream density distributions obtained by electron beam surveys are presented in Figs. 2 and 3 for the first and the second set of flow conditions, respectively. Coordinates X and $Z = 0$ correspond to the nose location of the blunted cone where the flow parameters are assumed to take their nominal values.

Experimental Density Flowfields

The particular shape of the investigated blunted cone makes difficult starting the wind tunnel when the model is initially located through the test section. To avoid this difficulty, the blunted cone and its sting support are mounted at the extremity of a streamlined transverse support actuated by a pneumatic jack. The model then can be introduced or removed from the test section within a fraction of a second. During the process of starting the nozzle flow, the model remains located outside the test section. The model is injected through the test section only after correct stabilization of stagnation pressure and temperature.

Density flowfields are obtained by displacing vertically the electron beam along 24 cross sections distributed around the model. For each of the cross sections, beam fluorescence measurements are performed, typically every 2.5 mm with 33 points of measurements for each investigated section. To get rid of possible variations of the beam intensity during the measurements, all transverse distributions of measured fluorescence are readjusted considering, as references, fluorescence measurements performed along a horizontal line. This line is located 35 mm above the model nose ordinate and crosses all 24 of the vertical sections. Density measurements were repeated along the horizontal line to ensure that identical distributions were found between two sets of experiments. Data reduction and beam displacements through the analyzed zone were controlled by microcomputer.

For each point of measurement, the quantities recorded simultaneously are the point coordinates and the local gas fluorescence given by the photomultiplier. The absolute gas density ρ is deduced from the local gas fluorescence. When presenting the experimental density flowfields around the model, one may exhibit either the absolute density ρ or the relative density ρ/ρ_∞. The representation of the relative density ρ/ρ_∞ has the advantage of taking into account the density gradients through the freestreams even if the applied data reduction method is not completely satisfactory. The local absolute density ρ is measured with the model in the test section, whereas the local freestream density ρ_∞ is measured at the same point with the model removed from the test section. Both absolute and relative density flowfields are presented, offering two possibilities for comparing experimental and calculated flowfields. The first possibility is to consider experimental absolute density flowfields; then flow calculations must take into account existing density gradients through the test section (Figs. 2 and 3). The second possibility is to consider experimental relative density flowfields; then flow calculations may assume a uniform flow ahead of the model.

To present the experimental data, density flowfields around the blunted cone are plotted by means of the TECPLOT interactive data visualization program. From data files including measured coordinates and associated values of absolute and relative densities, the program allows the design of density contours through the analyzed region. For the two investigated flow conditions and the angles of

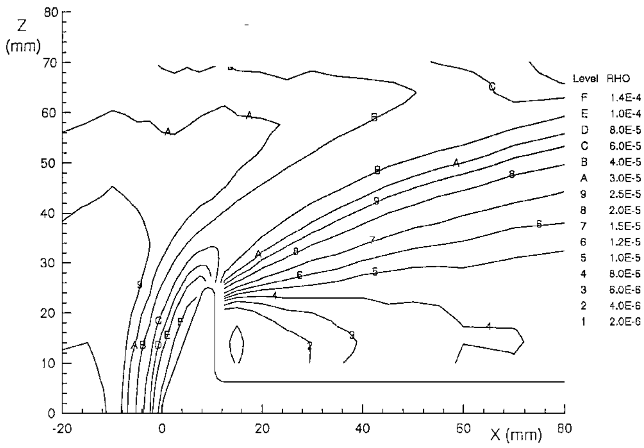

Fig. 4 Experimental absolute densities ρ (kg/m^3); *Ma* = 20.2, *Re*/cm = 284, and α = 0 deg (first set of flow conditions).

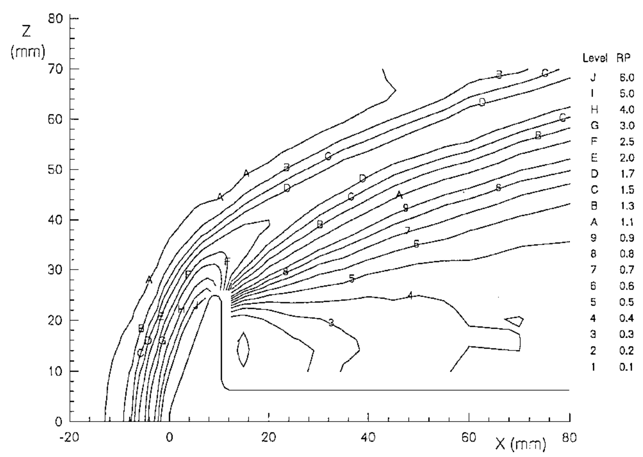

Fig. 5 Experimental relative densities ρ/ρ_∞; *Ma* = 20.2, *Re*/cm = 284, and α = 0 deg (first set of flow conditions).

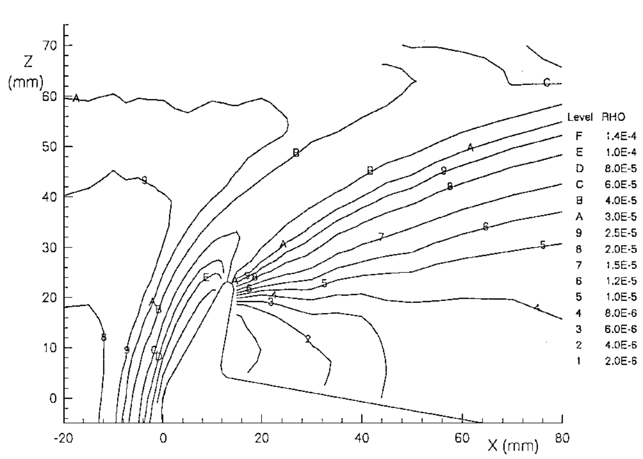

Fig. 6 Experimental absolute densities ρ (kg/m^3); *Ma* = 20.2, *Re*/cm = 284, and α = 10 deg (first set of flow conditions).

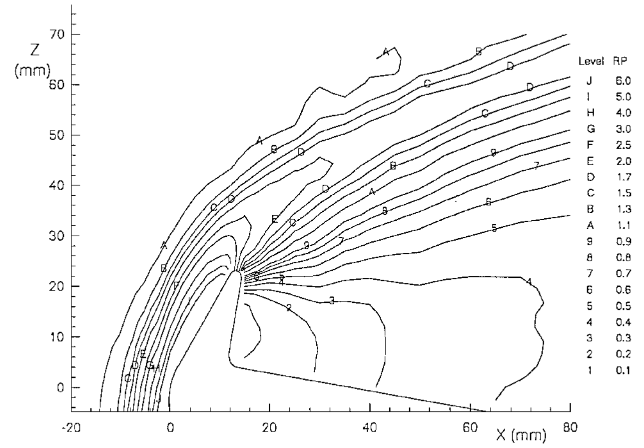

Fig. 7 Experimental relative densities ρ/ρ_∞; *Ma* = 20.2, *Re*/cm = 284, and α = 10 deg (first set of flow conditions).

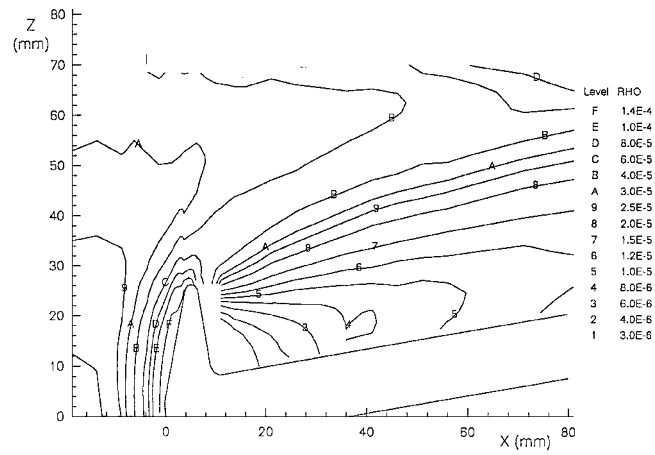

Fig. 8 Experimental absolute densities ρ (kg/m^3); *Ma* = 20.2, *Re*/cm = 284, and α = −10 deg (first set of flow conditions).

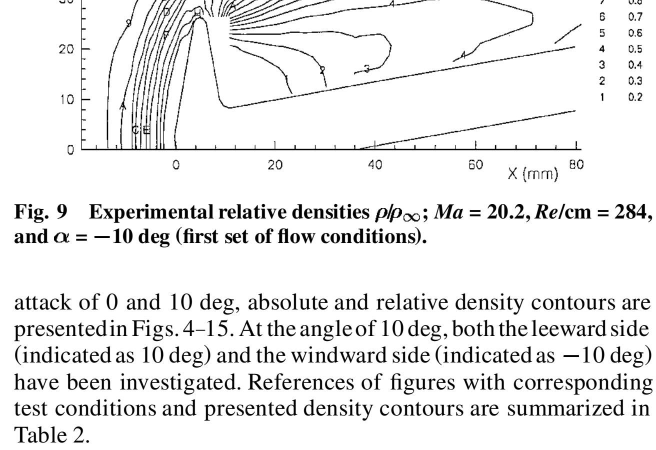

Fig. 9 Experimental relative densities ρ/ρ_∞; *Ma* = 20.2, *Re*/cm = 284, and α = −10 deg (first set of flow conditions).

attack of 0 and 10 deg, absolute and relative density contours are presented in Figs. 4–15. At the angle of 10 deg, both the leeward side (indicated as 10 deg) and the windward side (indicated as −10 deg) have been investigated. References of figures with corresponding test conditions and presented density contours are summarized in Table 2.

When applying the automatic smoothing procedure to density contours, noticeable changes in density values were found, especially through the shock layer induced by the model. For that reason, the experimental flowfields presented have not been treated by any kind of smoothing procedure. The useful core of the nozzles is

Table 2 Experimental density flowfields

Flow conditions	Angle of attack, deg	Absolute density	Relative density
$Ma = 20.2$, $Re_d = 1420$	$\alpha = 0$	Fig. 4	Fig. 5
	$\alpha = 10$	Fig. 6	Fig. 7
	$\alpha = -10$	Fig. 8	Fig. 9
$Ma = 20$, $Re_d = 4175$	$\alpha = 0$	Fig. 10	Fig. 11
	$\alpha = 10$	Fig. 12	Fig. 13
	$\alpha = -10$	Fig. 14	Fig. 15

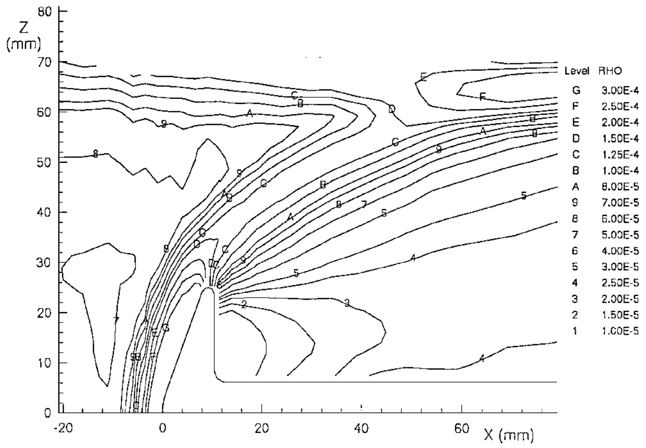

Fig. 10 Experimental absolute densities ρ (kg/m^3); *Ma* = 20, *Re*/cm = 835, and α = 0 deg (second set of flow conditions).

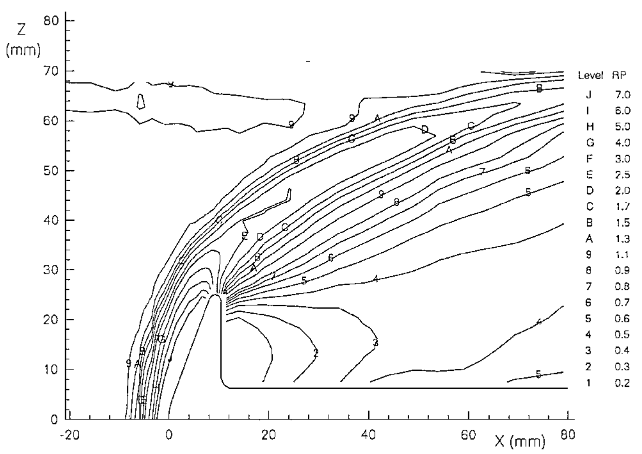

Fig. 11 Experimental relative densities ρ/ρ_∞; *Ma* = 20, *Re*/cm = 835, and α = 0 deg (second set of flow conditions).

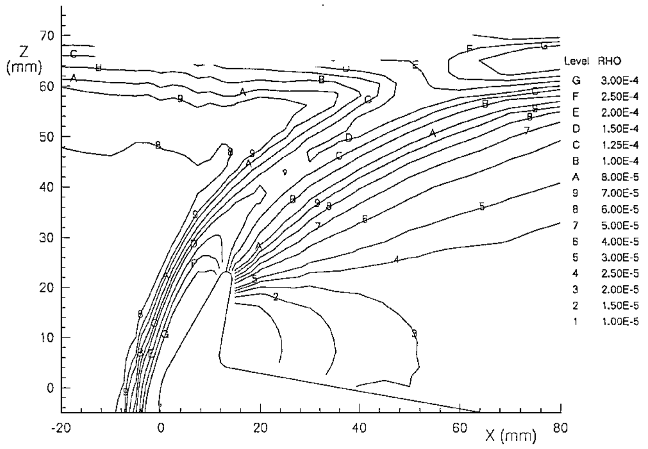

Fig. 12 Experimental absolute densities ρ (kg/m^3); *Ma* = 20, *Re*/cm = 835, and α = 10 deg (second set of flow conditions).

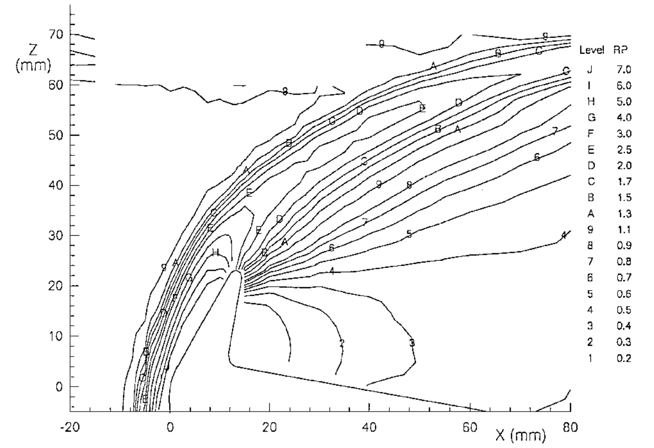

Fig. 13 Experimental relative densities ρ/ρ_∞; *Ma* = 20, *Re*/cm = 835, and α = 10 deg (second set of flow conditions).

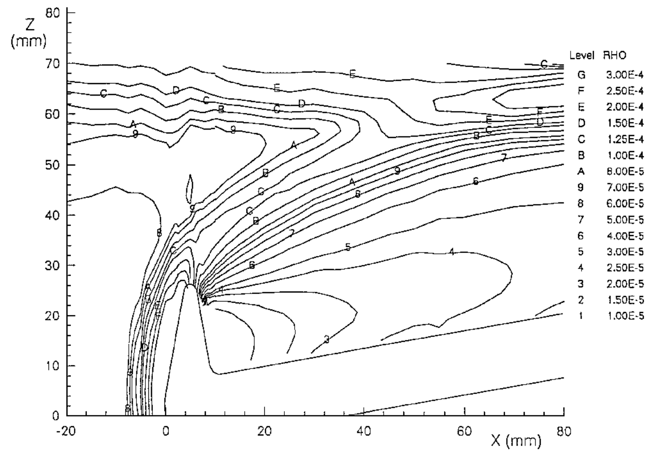

Fig. 14 Experimental absolute densities ρ (kg/m^3); *Ma* = 20, *Re*/cm = 835, and α = −10 deg (second set of flow conditions).

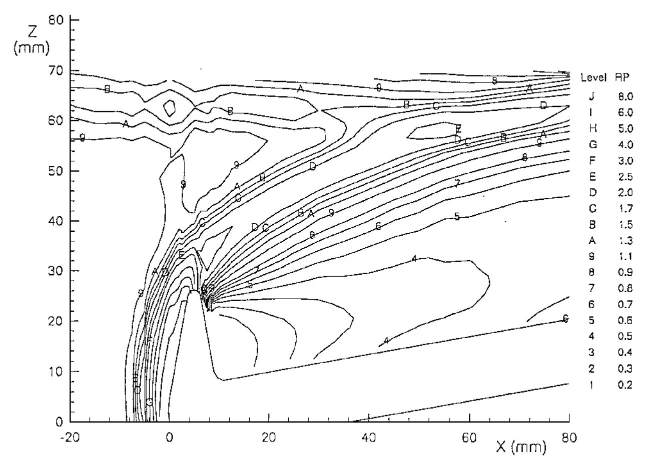

Fig. 15 Experimental relative densities ρ/ρ_∞; *Ma* = 20, *Re*/cm = 835, and α = −10 deg (second set of flow conditions).

limited to ordinates less than $z = 55$ or 60 mm around the symmetry axis. Consequently, on the density flowfields, one should disregard the density contours located beyond the ordinate limit of 55 or 60 mm.

At the present flow rarefactions, the working conditions of the electron gun are satisfactory. The most severe conditions correspond to the survey of flow regions characterized by the highest densities encountered through and behind the shock portion located just ahead of the forebody. Close to the stagnation point, local flow densities may exceed six times the value of the freestream density. Considering the data reduction, flow density distributions have been

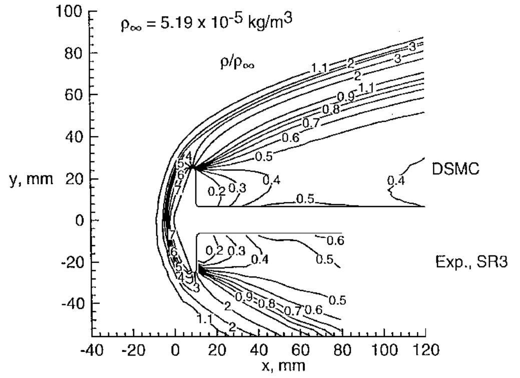

Fig. 16 Comparison of measured and calculated density (from Ref. 2).

deduced from intensities of gas fluorescence. To convert the gas fluorescence into gas density, a freestream point of known density has been used as the calibration point and necessary corrections were made to account for quenching effects [Eq. (1)]. When the electron beam is approaching the model surface, some parasitic reflections between the beam and the surface may occur within a distance of about 1 mm surrounding the model wall. These reflections lead to disturbances in the local density measurement. Consequently, the measurement of local fluorescence is not considered valid and is eliminated for distances less than 1–1.5 mm from the model surface. The accuracy of measured densities is difficult to quantify ahead of the forebody for the flow region, which is characterized both by the highest densities and by the highest flow gradients. In all other parts and, in particular, in the wake region where experimental density flowfields are subject to comparisons with calculated flowfields, the accuracy of measured densities is estimated to be better than 10% both for absolute and relative densities.

Comparisons Between Experimental and Calculated Density Flowfields

In parallel to the present experimental work, a number of flowfield calculations were executed by an international group of researchers for test conditions identical to SR3 test conditions. Flowfields were calculated using a direct simulation Monte Carlo solution (DSMC). An extensive number of computations have been made for the flow condition characterized by $Ma = 20$ and $Re_d = 4175$ because it was a test case at the Fourth European High-Velocity Database Workshop.[1] Nine computed entries were submitted for the 0-deg angle of incidence and two entries for the three-dimensional angle of incidence case. The results were included at the workshop and were indicative of the good agreements achieved between computation and experiment for most of the contributions. A synthesis of the workshop results for this test case was given by Coron and Harvey.[1]

As part of the AGARD Fluid Dynamics Panel and its Working Group 18, the blunt-body/wake closure problem has been studied both for high-enthalpy tests obtained with impulse facilities and for rarefied tests performed in rarefied low-enthalpy facilities. The SR3 wind tunnel, due to its long running time and to its movable electron beam, is the only facility that allowed complete investigation of density flowfields. A number of comparisons between computed density flowfields and experimental density flowfields have already been presented.[2,3] To illustrate flowfield comparisons, Fig. 16 taken from Moss et al.[2] shows in the upper part lines of constant density calculated by DSMC and in the lower part lines of constant density obtained experimentally in the SR3 wind tunnel.

Conclusions

Various sets of experiments have been performed recently on test case models to provide an experimental database at hypersonic flow conditions. Under rarefied and hypersonic flow regimes, investigations have been concentrated on a blunted cone model with the series of measurements presently focused on density flowfields. Experimental data on density flowfields around the blunted cone located at the two angles of attack, 0 and 10 deg, are presented.

Experiments have been performed in the SR3 wind tunnel, at a freestream Mach number close to 20 and for Reynolds numbers 1420 and 4175 calculated using freestream conditions and the cone base diameter. The present investigation on density flowfields contributes to a better understanding of the wake flow structure and makes information available for comparisons between experimental and computational data. The complementarity of the experimental and computational activities produces a database that can be helpful for code validation purposes.

Acknowledgments

This work was supported by the European Space Agency (ESA-ESTEC) under Contracts 132622 and 133790.

References

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I. D. Boyd
Associate Editor