JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 38, No. 6, November–December 2001

Engineering Note

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Blowdown Arc Facility for Low-Density Hypersonic Wind-Tunnel Testing

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Introduction

THE blowdown arc facility[1] (50 kW) at Dipartimento di Scienza ed Ingegneria dello Spazio "Luigi G. Napolitano" in Naples, at first named High Enthalpy Blow Down Arc Facility (HEBDAF), was designed for simulating heat fluxes to a space vehicle during reentry, designing thermal protection systems, and carrying out basic research in the field of catalycity. The facility has been in operation for several years and is considered a pilot facility of the Scirocco Plasma Wind Tunnel (PWT; 70 MW) at Centro Italiano Ricerche Aerospaziali in Capua (Italy).

The HEBDAF has recently had technical improvements related to the development of the vacuum system (current minimum pressure in the test chamber is 0.01 torr; former minimum pressure was 1 torr), more efficient electronic equipment for data acquisition and control (current electronic channels are 32; former channels were 16), the installation of LABVIEW software allowing on-line monitoring of the tests and remote operations in the test chamber, and the incorporation of a "new" supersonic conical nozzle with a larger area ratio (exit section/throat). The diameter of the throat section of both the "old" and new nozzle is 11 mm. The diameter of the exit section of the new nozzle is 50 mm, and the length is 155.3 mm (the diameter of the exit section of the old nozzle is 22 mm; the length is 61 mm). The area ratio of the new nozzle is 20.7, and the nominal freestream Mach number is 4.9 (the area ratio of the old nozzle is 4 with a nominal freestream Mach number of 2.9).

Development of HEBDAF was initially aimed at improving heat-flux measurement capability. A larger cross section of the jet allows testing of larger models with a more precise definition of the stagnation point. For this reason the name of the tunnel has been changed from HEBDAF to the Small Planetary Entry Simulator (SPES). The improvements are also very important because they extend SPES operation in the transition regime between continuum and free molecule flow. Thus, SPES offers new opportunities in basic research of hypersonic, low-density flows, and applied problems like aeroassist missions for capsules and space vehicles.

The purpose of this Note is to verify the upgrade of SPES, quantify the level of flow rarefaction, and state the related test conditions. This task has been accomplished both numerically and experimentally. A computational code,[1] modeling the SPES jet, simulates the working of the arc heater, the chamber used to mix hot nitrogen (coming from the arc heater) and cold oxygen (if any), and the nozzle. The test gas is simulated in chemical and vibrational nonequilibrium. The code solves a one-dimensional, steady, inviscid flowfield; the accuracy of the code can be considered sufficient for the purpose of this Note, where only bulk thermo-fluid-dynamic parameters are required. Moreover, the code is computationally very cheap and provides immediate results.

The thermo-fluid-dynamic parameters and gas composition (mass fractions α) in the jet, which are the freestream conditions for the test, are those computed at the exit of the nozzle. Viscosity is computed, at the jet thermal conditions, by the Chapman–Enskog[2] theory for each chemical species. Viscosity of the mixture is evaluated by the Wilke[2] rule. This code also computes a number of rarefaction parameters and generates input data to the DS2G code,[3] based on the well-validated direct simulation Monte Carlo method.[4]

Experiments were conducted to measure the aerodynamic drag of a sphere, using a one-dimensional, strain-gauge balance (with a full-scale balance capacity of 2 N and an uncertainty of about ±0.02 N). Comparisons of data measurements were made with those reported in the published literature and with those computed using DS2G. In the 1960s and 1970s spherical configurations have been widely tested in the hypersonic low-density flow regime. The published data used for these comparisons were selected in such a way that the test conditions, as per the freestream Mach number M_∞, were as close as possible to the present test conditions.

Rarefaction Parameters

The Knudsen number Kn quantifies the rarefaction of a flowfield ($Kn = \lambda/L$, where λ is the free molecular path and L is the characteristic dimension of the flowfield). Many formulations of the Knudsen number are available, according to the specification of λ and L. For the purpose of this Note, two formulations have been considered:

1) The overall Knudsen number is as follows: $Kn_\infty = \lambda_\infty/D$, where λ_∞ is the freestream, mean free molecular path and D is the diameter of the sphere model. The mean free molecular path is computed[4] by

$$\lambda_\infty = 1\Big/\sqrt{2}\pi\bar{d}^2 n \tag{1}$$

where n [1/m^3] is the molecular number density and $\bar{d}$ [m] is the average diameter of each chemical specie, weighted with respect to the gas composition. According to the variable hard sphere model,[4] $\bar{d}$ is computed as a function of temperature. The overall, freestream Knudsen number Kn_∞ can also be computed by the Chapman–Enskog[5] theory as

$$Kn_\infty = 1.276\sqrt{\gamma}(M_\infty/Re_\infty) \tag{2}$$

where Re_∞ is the freestream Reynolds number based on the model diameter and γ is the ratio of specific heat at constant pressure and constant volume. Transitional regime for a sphere is defined[6] as $0.01 < Kn_\infty < 1$.

2) The local Knudsen number is as follows: $Kn_G = \lambda_\infty/L_G$, where L_G is the scale length of the macroscopic gradient of a generic flow variable G, such as density, pressure, and temperature (e.g., $L_G = G/|\mathrm{d}G/\mathrm{d}x|$, where for the present application x is along the nozzle axis). Requirements for the limitation of the Navier–Stokes equations and of the beginning of the discrete molecules regime[4] are stated by $Kn_G > 0.1$ and $Kn_G > 0.2$, respectively. A meaningful,

Received 22 March 2001; revision received 25 June 2001; accepted for publication 7 July 2001.

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Table 1 Test parameters

Test	$\dot{m}$, g/s	$h_{0\infty}$, MJ/kg	V_∞, m/s	ρ_∞, kg/m^3	λ_∞, m	n, 1/m^3	M_∞	T_w/T_0	α_{N2}	α_N
1	0.5	7.2	3484	7.31×10^{-5}	1.32×10^{-3}	1.72×10^{21}	5.2	0.12	0.8262	0.1738
2	0.75	6.6	3346	1.14×10^{-4}	8.28×10^{-4}	2.71×10^{21}	5.2	0.13	0.8124	0.1876
3	1	7.6	3558	1.43×10^{-4}	6.77×10^{-4}	3.31×10^{21}	5.1	0.12	0.8567	0.1433
4	1.5	9.3	3908	1.95×10^{-4}	5.16×10^{-4}	4.45×10^{21}	5.1	0.09	0.8874	0.1126
5	2	8.4	3753	2.71×10^{-4}	3.66×10^{-4}	6.31×10^{21}	5.2	0.10	0.8487	0.1513
6	0.5	7.8	3114	4.22×10^{-4}	2.74×10^{-4}	9.71×10^{21}	3.1	0.11	0.8714	0.1286

local rarefaction parameter that includes the scale length of density is the continuum breakdown parameter P by Bird[4]:

$$P = \left(\pi^{\frac{1}{2}}/2\right)s(\lambda/L_\rho) \tag{3}$$

where s is the speed ratio [$s = V/\sqrt{(2RT)}$]. The continuum breakdown in expansions starts from $P = 0.02$.

The Reynolds number behind a normal shock wave Re_2 is also an overall rarefaction parameter used in correlating sphere drag coefficients. The transitional regime for a sphere is stated[7] by $0.1 < Re_2 < 10^3$. A value of $Re_2 > 10$ identifies a continuum low-density regime, and a value of $Re_2 < 10$ identifies a near free molecule regime.[8]

Discussion of Test Results

Six tests were conducted with different mass flow rates $\dot{m}$ and different jet total enthalpies $h_{0\infty}$. The test gas used was nitrogen, and the relevant test and fluid-dynamic parameters are summarized in Table 1. No wall temperature T_w was measured in the present tests. Values of T_w/T_0 (T_0 is the stagnation temperature) were computed with $T_w = 700$ K. This wall temperature was formerly measured in SPES on a hemispherical calorimeter at similar test conditions. Tests 1–5 used the new nozzle. One test using the old nozzle (test 6) was made for comparison at the minimum allowable mass flow rate ($\dot{m} = 0.5$ g/s). Unfortunately, this value of the mass flow rate is fixed as a result of requirements for safe operation of the present arc heater. The diameter of the sphere model is 15.8 mm, and geometrical blockage ratios are 0.1 and 0.5 for the new and the old nozzles, respectively.

DS2G was run by dividing the axially symmetric flowfield around the model in a grid of 40 cells along the sphere surface and 50 cells along the local normal to the surface. A typical dimension of the cell was about 2.4×10^{-4} m. The time step used was 10^{-7} s, and the simulated time, to reach the steady-state condition, was 2×10^{-3} s. The interaction between molecules and model surface was fully accommodated at T_w.

Both the cell dimension and the time step satisfy the requirements by Bird[3] for proper runs of this code; the typical cell dimension should be less than the local mean molecular path, and the time step should be less than the mean collision time Δt_c. For tests 1–5 the cell dimension is less than the free molecular path in the jet (as shown in Table 1), and the time step is less than Δt_c, ranging between 2.4×10^{-6} and 6.1×10^{-7} s. Δt_c has been computed as the reciprocal of the collision frequency in the jet:

$$\Delta t_c = 1\Big/\pi \bar{d}^2 n \sqrt{2(k/\bar{m})T_\infty} \tag{4}$$

where k is the Boltzmann constant and $\bar{m}$[kg] is the average molecular mass of each chemical specie, weighted with respect to the gas composition.

Table 1 shows that the stronger expansion in the new nozzle reduces ρ_∞ and increases λ_∞ by one order of magnitude compared with those in the old nozzle. Figure 1 shows that the overall Knudsen numbers and the Reynolds number behind the shock wave are within the transitional range for both nozzles. Local Knudsen numbers do not provide the same indication as Kn_∞. Only Kn_p achieves values higher than 0.01, for the new nozzle and at mass flow rates of 0.5, 0.75, and 1 g/s. Parameter P (Fig. 2) overcomes the continuum breakdown limit, even inside the nozzle. In the old nozzle flow is not able to achieve a continuum breakdown condition, even at the minimum mass flow rate.

Drag coefficients, with the related error bars, are reported in Fig. 3 as a function of Re_2. The trend of the present drag co-

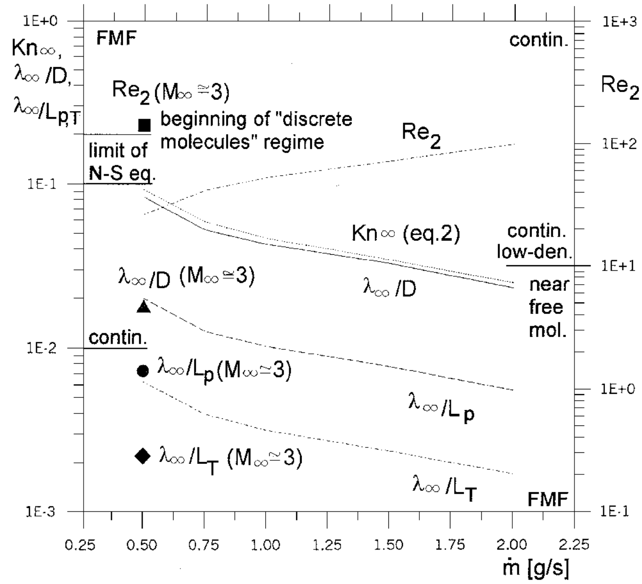

Fig. 1 Profiles of rarefaction parameters as a function of mass flow rate.

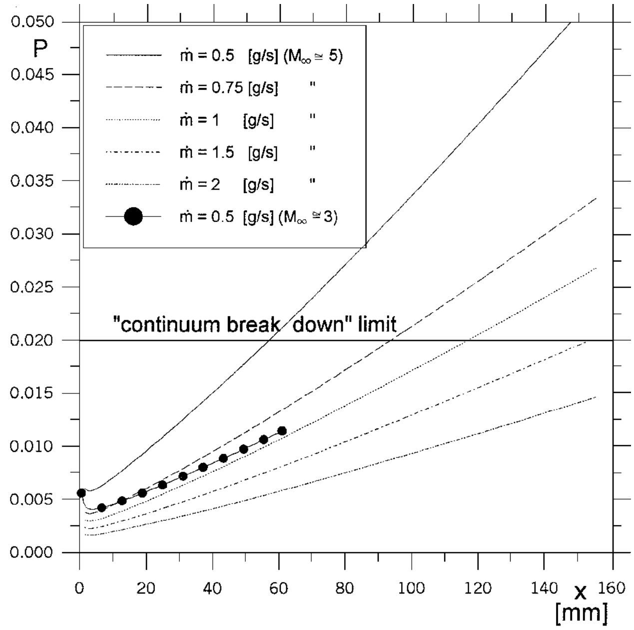

Fig. 2 Profiles of the continuum breakdown parameter along nozzle axis.

efficients agrees both with data reported in literature, Phillips and Kuhlthau[9] ($M_\infty \cong 8$–10, $T_w/T_0 \cong 1$), Kussoy and Horstman[10] ($M_\infty = 15$, $T_w/T_0 \cong 0.03$), and Wegener and Ashkenas[11] ($M_\infty \cong 4$), and with the results computed using the DS2G code; drag coefficients decrease with increasing Re_2 or decreasing the flowfield rarefaction. Unfortunately, the drag measurement from test 4 appears to be inaccurate. (Therefore, no error bar is reported.) The drag coefficient, for this flow rarefaction level ($Re_2 = 72$), should be higher than the present measurement ($C_D = 0.84$). Wegener measured $C_D = 1.28$ (at $Re_2 = 76$) and DG2G computed $C_D = 1.26$.

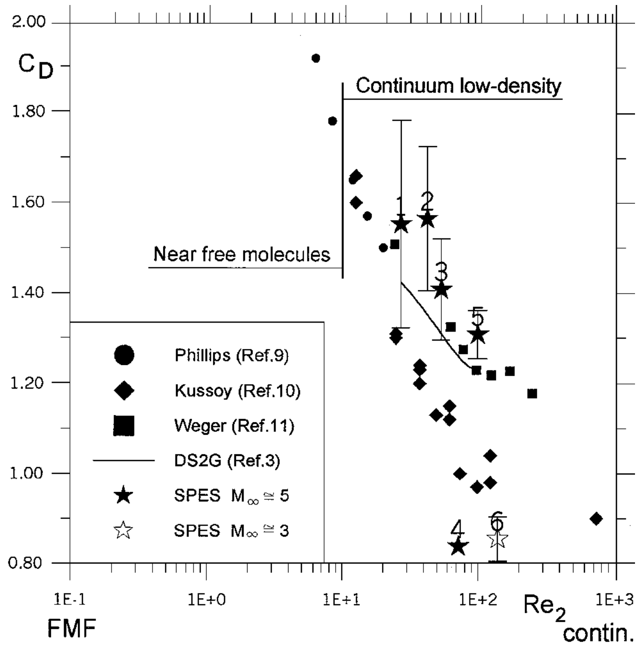

Fig. 3 Sphere drag coefficients as a function of the Reynolds number behind normal shock wave.

Drag measurements from tests 1 and 6, namely at the extreme rarefaction levels, are meaningful and very probative for the purpose of this Note because both tests were conducted at similar mass flow rates and jet total enthalpy. The drag coefficient from test 1, $C_D = 1.55$ ($Re_2 = 26$), matches that measured by Phillips and Kuhlthau,[9] $C_D = 1.50$ ($Re_2 = 20$), and Wegener and Ashkenas,[11] $C_D = 1.51$ ($Re_2 = 24$), and is comparable with the value computed by DS2G, $C_D = 1.44$. The drag coefficient from test 6 is $C_D = 0.85$ ($Re_2 = 139$). Its value is comparable with those measured by Kussoy and Horstman[10]: $C_D = 0.97$ ($Re_2 = 98$) and $C_D = 0.98$ ($Re_2 = 122$). Thus, the present tests verify that for the new nozzle at $\dot{m} = 0.5$ g/s, SPES is able to approach the border of the near free molecule, hypersonic regime.

Conclusions

Improvements to the blowdown SPES arc facility have been described. This Note has been aimed at verifying the SPES capability of extending its operations to the low-density, hypersonic regime, approaching the near free molecule regime, and to summarize the related test conditions.

Meaningful comparisons were made and assessed by the computation of rarefaction parameters and the comparison of measured sphere drag coefficients with data from the literature and with coefficients computed by a direct simulation Monte Carlo code.

The success of these tests suggests a future campaign of measurements for studying the dynamics of a space vehicle for various entry conditions. For this purpose a model of a sphere-cone capsule with a cross-section dimension of 20 mm is being considered. Even with this dimension the rarefaction parameters ($Re_2 \cong 33$ and $\lambda_\infty / D \cong 6.6 \times 10^{-2}$) are close to the near free molecule regime. The present tests also provided useful information related to the design and construction of a three-component strain-gauge balance.

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Associate Editor