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Utilization of an Electron Beam for Density Measurements in Hypersonic Helium Flow

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Abstract

SEVERAL methods have been investigated for making nondestructive measurements of various wind tunnel parameters. Herein is described a study to determine the feasibility of using an electron beam to measure the freestream static density of gaseous helium over a range of hypersonic flow conditions. Measurements were made for a range of stagnation pressures and temperatures which produced freestream number densities of 1.53×10^{23} to 1.25×10^{24} molecules/m^3 and static temperatures from 2 to 80 K. The results showed the collision quenching cross section to be 4.4×10^{-15} cm^2 at 1 K and to have a weak temperature dependence of $T^{1/6}$. Knowing these values, the freestream number density can be determined quite accurately. These results are reported in more detail in Ref. 1.

Contents

Density measurements using the electron beam technique depend on a linear relationship between the local gas number density and the spontaneous de-excitation (thus fluorescence) of excited atomic states. This linear relationship is disturbed by de-exciting collisions between excited and unexcited atoms. To study this effect and to develop a useful density measurement technique for a range of temperatures and pressures in helium, a number of tests were conducted and compared with pitot measurements.

Monoenergetic electrons (28 keV) were used to produce excited atomic states in helium. In this work only the 3^1p to 2^1S (5015.7 Å) transition was monitored. The spontaneous fluorescence was detected with a photo-optical system equipped with a narrow bandpass optical filter.

Gas number density measurements with the electron beam technique are based on a unique relation between the local number density and the spontaneous fluorescence of the beam-excited atomic states. A relation between the number density n and fluorescence has been derived theoretically and is discussed in detail in earlier works.[2,3] This relation, in terms of the photodetector output current I_{pm} produced by the detected fluorescence and normalized by the excitation beam current I_b is

$$\frac{I_{pm}}{I_b} = k\frac{An+Bn^2}{1+Cn} \tag{1}$$

where k, A, and B are constant and C is a function of temperature. The constant k is determined by the system optics and photodetector characteristics. The coefficient A is determined by the primary beam excitation cross section and spontaneous radiation transitions. The B term accounts for excited states produced by secondary electrons and nonradiative de-excitation process; for present work as well as earlier studies[2,3] it was neglected. The C term accounts for a state de-excitation through collisions with neutral atoms

$$C = 4\sigma_j \sqrt{\frac{kT}{\pi m}} \Big/ A_j \tag{2}$$

Where σ_j is the collision cross section of the jth excited electronic state and k is the Boltzmann constant. T is the static temperature, m mass of the helium atom, and A_j the sum of the radiation transition probabilities of the jth atomic state to all other states except the ground state.

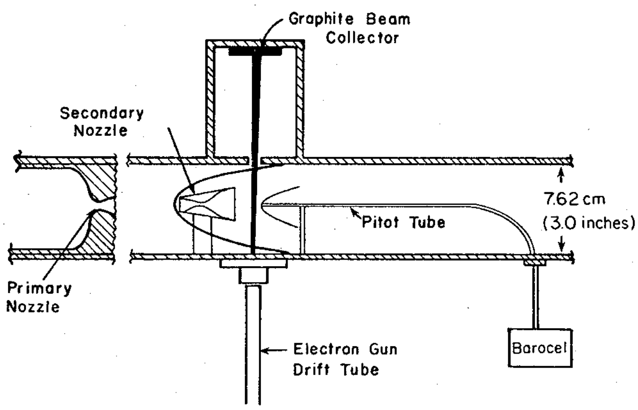

Fig. 1 Experimental setup at the 3-in. hypersonic helium tunnel.

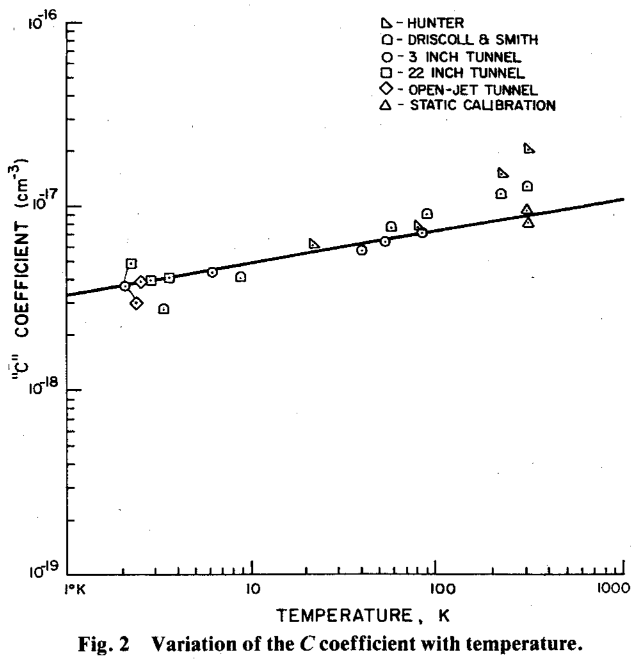

Fig. 2 Variation of the C coefficient with temperature.

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Table 1 Tunnel condition, calculated, and measured number densities

P_t, N/m^2	T_t, K	M_∞	N_∞ (mole/m^3) (Calculated)	N_∞ (mole/m^3) (Measured)
8.07 x 10^5	297.2	16.41	2.28 x 10^{23}	2.40 x 10^{23}
1.49 x 10^6	294.4	17.51	3.49 x 10^{23}	3.68 x 10^{23}
2.14 x 10^6	291.7	18.18	4.55 x 10^{23}	4.51 x 10^{23}
2.84 x 10^6	289.4	18.69	5.62 x 10^{23}	5.69 x 10^{23}
3.56 x 10^6	291.1	19.11	6.45 x 10^{23}	6.50 x 10^{23}
4.31 x 10^6	297.2	19.45	7.36 x 10^{23}	7.33 x 10^{23}
4.98 x 10^6	294.4	19.71	8.20 x 10^{23}	8.26 x 10^{23}
5.58 x 10^6	291.7	19.92	9.00 x 10^{23}	8.78 x 10^{23}
6.32 x 10^6	302.8	20.15	9.92 x 10^{23}	9.62 x 10^{23}
6.96 x 10^6	291.7	20.32	1.07 x 10^{24}	1.07 x 10^{24}
7.01 x 10^6	300.0	20.33	1.06 x 10^{24}	1.04 x 10^{24}
7.69 x 10^6	299.4	20.50	1.18 x 10^{24}	1.23 x 10^{24}
8.38 x 10^6	300.0	20.66	1.25 x 10^{24}	1.25 x 10^{24}
*7.18 x 10^6	302.6	20.25	1.04 x 10^{24}	1.04 x 10^{24}
*5.14 x 10^6	303.9	19.45	8.62 x 10^{23}	8.66 x 10^{23}
+6.89 x 10^6	316.7	21.09	8.68 x 10^{23}	8.43 x 10^{23}
+1.38 x 10^6	316.7	12.62	7.93 x 10^{23}	8.47 x 10^{23}
+5.52 x 10^6	312.8	4.59	1.53 x 10^{23}	1.66 x 10^{23}
+5.52 x 10^6	312.8	3.78	2.47 x 10^{23}	2.59 x 10^{23}
+5.52 x 10^6	312.8	3.01	4.27 x 10^{23}	4.18 x 10^{23}

*Open-Jet Tunnel
+3-Inch Tunnel

A number of tests were conducted in the 22-in. leg, the open jet leg of the hypersonic helium tunnel and the 3-in. calibration helium tunnel with static temperatures between 1.9 and 3.3 K. The higher temperatures (3.3-82 K) were all obtained in the calibration tunnel using the secondary nozzle technique as shown in Fig. 1. The secondary nozzles (25.5 mm long and 12.7 mm exit diam) were mounted on knife-edge struts in the center of the flowfield and were point designs to produce the local conditions desired. The tunnel primary shock broke over the front of the secondary nozzle. $P_{t,2}$ from this shock wave, as measured by a 0.76-mm (inside diameter) pitot tube, now becomes the new $P_{t,1}$ for the secondary nozzle and the new $P_{t,2}$ was measured with the same pitot tube. The pitot tube could be moved axially along the tunnel centerline to determine the static pressure at any point in front of or behind the secondary nozzle. The electron beam traversed the 3-in. tunnel 6.35 mm downstream from the secondary nozzle; the maximum electron beam diameter was 1.5 mm.

The C coefficient and its temperature dependence was studied in the facilities noted previously. The problem was to solve Eq. (1) for the C coefficient, neglecting the B coefficient as previously noted. The ratio I_{pm}/I_b was measured for each tunnel run condition. The A coefficient could be determined by static calibration or actual tunnel tests since it was a function of the geometry, gain of the photo-optical system, and excitation cross section.

The freestream Mach number, number density, and static temperature were calculated using $P_{t,1}$, $P_{t,2}$, and T_t. With these values and the I_{pm}/I_b ratio the C coefficients for the various run conditions could be calculated. Figure 2 is a log-log plot of the experimental values of C vs static temperature for the current research and of earlier work by others. Using this plot the a and b parameters of the following relation was determined with the a value determined at the 1 K intercept.

$$C = aT_\infty^b \tag{3}$$

$$C = 3.33 \times 10^{-18} T_\infty{}^{0.167} (\text{cm}^3) \tag{4}$$

An equivalent collision quenching cross section for the 3^1p to 2^1S transition was calculated based on simple kinetic collision theory, i.e., Eq. (2). A numerical value of approximately 4.4×10^{15} cm^2 was determined at 1 K.

A subsequent series of tests were conducted using the aforementioned C coefficient. The test conditions and results are tabulated in Table 1. The precision of the number densities measured with the electron beam is estimated to be $\pm 1.5\%$.

The quenching cross section and its temperature dependence shows some disagreement with data presented in Ref. 2 and with data presented in Ref. 3, as seen in Fig. 2. The parameters determined were $a = 1.83 \times 10^{-18}$ and $b = 1/3$. This disagreement could be attributed to impurities in the static chamber that condensed out at lower temperatures in Ref. 2, and in Ref. 3 an insufficient slit width in the optics or beam current measuring problems due to Faraday cup size.

In summary, the utility of the electron beam density measurement technique has been increased through the determination of an appropriate fluorescence quenching relationship. Although the results presented here do not agree with previous published results, the ability to obtain consistent C coefficient temperature dependent parameters for a wide range of tunnel conditions provides a basis for a reasonable level of confidence.

References

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[2]Hunter, W. W. Jr., "Temperature Dependence of the 3^1P Excitation Transfer Cross Section of Helium," *Journal of Chemical Physics*, Vol. 58, Feb. 1973, pp. 941-947.

[3]Driscoll, J. F., "Development of the Electron Beam Fluorescence Technique for Measurements in a Hypersonic Turbulent Flow," Ph. D. Thesis, Princeton Univ., 1975.