DIAGNOSTICS OF RAREFIED GASES USING HOT-WIRE ANEMOMETER

A. V. Bulgakov and V. G. Prikhod'ko

UDC 533.6.011.8

Hot-wire anemometry has been quite widely used in recent years to study low-density flows [1-3]. High sensitivity and good spatial resolution of the method make its application effective in flows with large gradients. The technique permits the determination of two thermodynamic quantities, the coefficient of heat transfer h and recovery temperature T_r. Relations coupling h and T_r with flow parameters were obtained in [4]. These relations were generalized in [3] for the case of unequal accommodation of translational and internal energy of molecules on the wire surface and nonequilibrium energy distribution in internal degrees of freedom. In order to obtain a more detailed information on the distribution of gasdynamic parameters, the hot-wire anemometer is, as a rule, used in conjunction with other diagnostic tools like the Pitot tube or electron beam [2]. The present work deals with the application of a twin-wire (perpendicular and parallel to the flow direction) hot-wire anemometer in rarefied flows without the benefit of other techniques. Furthermore, the influence of differences in the accommodation coefficients of translational and internal energies and the degree of rarefaction on the hot-wire anemometer is also investigated.

Consider the expressions for quantities determined by a hot-wire anemometer in the case of free-molecular equilibrium flow past a wire of length L and diameter d [3]. For the wire oriented perpendicular to the flow direction,

$$h_{\perp} = Anu/\varphi(S); \tag{1}$$

$$T_{r\perp} = \frac{T}{4+\nu/\alpha'}\left[5 + 2S^2 + \nu/\alpha' - \frac{1}{1+S^2(1+I_1/I_0)}\right]; \tag{2}$$

for the wire placed along the flow,

$$h_{\parallel} = A\sqrt{\frac{\pi k}{2m}}\, n\sqrt{T}; \tag{3}$$

$$T_{r\parallel} = T\left(1 + \frac{2S^2}{4+\nu/\alpha'}\right), \tag{4}$$

where n is the density of the number of particles in unit volume; u is the velocity; T is the gas temperature; $S = u/\sqrt{2kT/m}$ is the velocity ratio; m is the mass of the molecule; k is the Boltzmann constant; $\nu = \alpha''j$; α' and α'' are accommodation coefficients or translational and internal energy of the gas, respectively; j is the number of internal degrees of freedom; I_0 and I_1 are modified Bessel functions of the zeroth and first orders of the argument $S^2/2$; $A = kLd(4\alpha' + \nu)/2$; $\varphi(S) = 2\pi^{-1/2}S\exp(S^2/2)/[I_0 + S^2(I_0 + I_1)]$.

The flow parameters can be determined from experimental values of h and T_r: S is determined from the relation $h\ /h\ = 2S/\sqrt{\pi}\varphi(S))$, and from Eqs. (1) and (2) or (3) and (4), the quantities T, n, and u are determined if the accommodation coefficients α' and α'' are known. In their turn, accommodation coefficients are obtained from Eqs. (1), (2), and (4) using $T_{r\parallel}$, $T_{r\perp}$, and h, found in the flow with known parameters. Results of an experimental verification of the possibilities of the technique are described below.

Experiments with hot-wire anemometry were conducted in the low-density gasdynamic apparatus VS-2 [5]. The well-studied free jets of nitrogen and helium flowing from a sonic nozzle

---

Novosibirsk. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 5, pp. 126-130, September-October, 1986. Original article submitted July 5, 1985.

into a vacuum are chosen as the objects of investigation to develop the technique. Parameters of such jets can be easily determined using isentropic computation [6]. The diameter of the nozzle choke $d_* = 10$ mm. The hot-wire ($L = 2.4$ mm, $d = 8$ μm) is made of coated tungsten and fixed to steel supports having 0.2-mm diameter wire at weld location. The hot-wire anemometer is fed from the equipment TM-1M, which gives the wire resistance. The voltage drop across the wire was determined by voltmeter V7-21. The temperature of probe supports and the stagnation temperature were determined by thermocouples. Vacuum meter VDG-1 was used to measure the stagnation pressure.

The nozzle is mounted on a traversing mechanism that ensures the movement of the hot-wire along the jet axis. The hot-wire is mounted on a motor that makes it possible to place the wire normal to and along the axis without changing the position of the center of the wire. The free-stream pressure in all the experiments did not exceed 1 Pa. The technique used to determine heat loss and h and T_r is similar to that described in [7]. The coefficient of thermal resistance of the wire was ensured by calibration in a thermostat.

Results of the determination of h and h in a nitrogen jet (stagnation temperature $T_0 = 282$ K, stagnation pressure $P_0 = 3560$ and 734 Pa, points 1 and 2) and in a helium jet ($T_0 = 289$ K, $P_0 = 1600$ and 587 Pa, points 3 and 4) are shown in Fig. 1. Here x is the distance from the nozzle section and the quantity h/P_0 is the ordinate for normalizing experimental results relative to the stagnation pressure. The heat-transfer coefficients are also indicated here for the freely expanding jet, computed from Eqs. (1) and (3) using results of [6]: a and b refer to values of $h_\perp$ obtained with adiabatic indices $\gamma = 1.4$ and 1.667, c refers to values of $h_\parallel$ for $\gamma = 1.4$.

Since Eqs. (1) and (3) contain the coefficient A that depends on accommodation coefficients of energy at the wire surface, it is possible to find agreement between experimental and computed results by matching its value. The curves shown were obtained for $4\alpha' + \nu = 5.3$ for N_2 and $\alpha' = 0.43$ for He. It is seen that there is good agreement between experimental results and isentropic values. The values of h for different stagnation pressures at identical x are proportional to P_0; the deviation from the computed result is apparently associated with the violation of free-molecular (based on wire diameter) flow conditions. The minimum Knudsen number $Kn = \lambda/d$ in the present experiment equals 0.7, where λ is the mean free path. A synthesis of the data obtained with reference to the effect of the degree of rarefaction on the hot-wire anemometer output resulted in the relation $h/h_f = 1 - 0.25/Kn$ ($Kn \geq 0.7$), where h_f is the heat transfer coefficient for $Kn \gg 1$ for the same free-stream parameters.

Results of measurements of recovery temperature are shown in Fig. 2a, b. Here the points 5 and 6 are obtained for $P_0 = 1240$ and 1320 Pa, and the other symbols are the same as in Fig. 1. For helium (Fig. 2a), values of T_r agree well with computations from Eq. (2) (line) for isentropic flow. In hypersonic flow ($x/d_* > 2$), the recovery temperature coefficient obtained in experiments $r = (T_r - T)/(T_0 - T) = 1.25$ agrees with the theoretical value for monatomic gas [4]. Deviation from computation at small x/d_* is, obviously, also associated with the violation of free-molecular conditions of the flow past the wire. It is more difficult to generalize the results on the effects of Kn because of the small range of variation in T_r; for the purposes of estimation, it is possible to use the relation $T_r/T_{rf} = 1 - 0.05/Kn$ ($Kn \geq 1$).

In nitrogen (Fig. 2b) the measured values of $T_{r\perp}$ and $T_{r\parallel}$ are above those computed for isentropic flow in the case $\alpha' = \alpha''$ (dashed lines); in hypersonic flow the measured value $r = 1.23$ instead of the theoretical $r = 1.167$. This condition, apparently, is associated with lower accommodation of rotational energy of molecules at the surface of the wire compared to translational energy, i.e., the part of energy of the forward motion of falling molecules does not "succeed" in converting into internal degrees of freedom of reflected molecules and is given out at the surface. Apparently, a similar effect was also found in [8] where, for the hypersonic flow of hydrogen, $r = 1.32$-1.35. The neglect of the difference in accommodation of translational and internal energy in measuring T_r in the molecular gas can lead to errors in the interpretation of results. For example, in [2] for air with $S = 1.67$, we obtained $T_r/T_0 \approx 1.2$, whereas theory [4] predicts 1.15.

Knowing the velocity ratio and values of $T_{r\perp}$ and $T_{r\parallel}$, it is possible to determine the ratio ν/α' from (2) and (4). By selecting the value of this ratio so as to obtain the best agreement between measured and computed values for isentropic flow (Fig. 2b, continuous lines), we get $\nu/\alpha' = 1.7$ for nitrogen. Since $4\alpha' + \nu = 5.3$ from measurements of h, the accommoda-

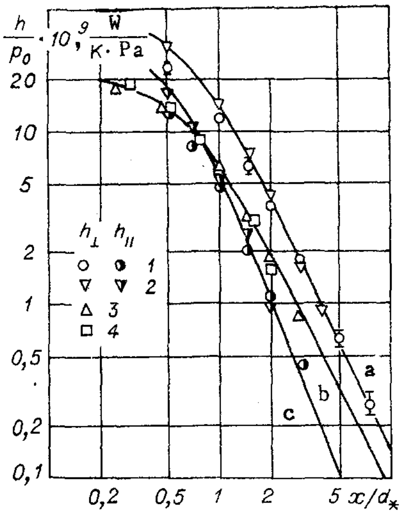

Fig. 1

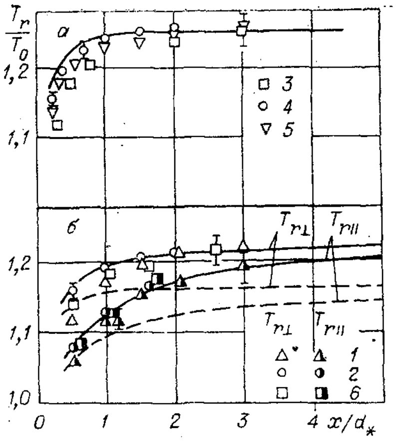

Fig. 2

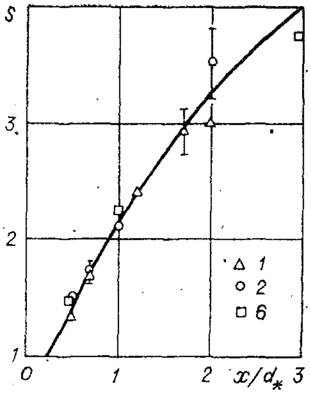

Fig. 3

tion coefficient of translational energy α' = 0.93 and the accommodation coefficient of rotational energy α'' = 0.79. We recall that α' = 0.54 was obtained for helium.

An example of the distribution of S in a freely expanding jet obtained from experimental values of $h_\perp$ and $h_\parallel$ in a nitrogen jet is shown in Fig. 3, where the lines refer to computation for isentropic flow [6] (symbols are the same as in Figs. 1 and 2). A satisfactory agreement between experimental and computed values is observed.

The range of measured values of heat-transfer coefficients is $(0.70\text{-}80)\cdot10^{-6}$ Watt/K and is limited at the lower end by an increase in measurement error at small values of h [3]. Corresponding minimum (determined with errors not worse than 25%) values of nu ≈ 10^{19} and $3\cdot10^{19}$ $(\text{cm}^2\cdot\text{sec})^{-1}$ in N_2 and He, and $n\sqrt{T} \approx 3\cdot10^{15}$ $\text{cm}^{-3}\text{K}^{1/2}$. The error in the determination of T_r (from 1 to 5%) depended principally on measurement error in h and probe-support temperature. Reliable ranges for characteristic values of parameters are given in Figs. 1-3. A reduction in error and an increase in working range of h and T_r is possible either by decreasing the diameter or by increasing the wire length if possible (sensitivity of the method is proportional to L^2/d [3]), or by heating the supports and maintaining their temperature at the wire temperature in the flow, as in [2]. It should also be mentioned that the sensitivity of the method is improved in high-molecular gases since, according to (1) and (3), the heat-transfer coefficient is proportional to the number of degrees of freedom of molecules.

Thus, the low-density free jet example has been used to demonstrate the possibility of measuring gasdynamic parameters with the help of two mutually perpendicular hot-wires. Satisfactory agreement of the experiment with computation makes it possible to conclude that within measurement errors accommodation coefficients do not depend on the orientation of the surface (which agrees with [8]), and the supports of the hot-wire do not introduce significant disturbances in the flow even for the wire oriented along the flow. The hot-wire technique may be of independent interest as a means of the determination of accommodation coefficients of translational and internal energy of the flow.

In conclusion, the authors acknowledge A. K. Rebrov for useful discussions stimulating development of studies with hot-wire anemometry.

LITERATURE CITED

1. S. K. Matu and K. Brandin, "Measurement of flow field in the near wake of spheres in hypersonic flow at low Reynolds numbers," in: Rarefied Gas Dynamics [Russian translation], Mir, Moscow (1976).
2. L. Gottesdiner, "Hot-wire anemometry in rarefied gas flow," J. Phys. E: Sci. Instrum., 13, 908 (1980).
3. A. V. Bulgakov, "Application of hot-wire anemometry for high-molecular low-density flows," in: Molecular Physics of Nonequilibrium Systems [in Russian], Novosibirsk (1984).
4. D. R. Stalder, G. Gudvin, and M. O. Kriger, "Heating of bodies in high-speed flow of rarefied gases," in: Problems of Heat Transfer [in Russian], Gosenergoizdat, Moscow (1959).
5. A. A. Bochkarev, V. A. Kosinov, et al., "Structure of supersonic jet of nitrogen—helium mixture in vacuum," Prikl. Mekh. Tekh. Fiz., No. 5 (1970).
6. V. A. Zhokhov and A. A. Khomutskii, A Chart of Supersonic Flows of Freely Expanding Ideal Fluid from Axisymmetric Nozzle [in Russian], Tsentral. Aero-Gidrodinam. Inst., Moscow (1970).
7. R. G. Lord, "Hot-wire probe end-loss correction in low-density flow," J. Phys. E: Sci. Instrum., 7, 56 (1974).
8. H. Legge, "Recovery temperature determination in free molecular flow of a polyatomic gas," in: Proc. 14th Int. Symp. Rarefied Gas Dynamics, Vol. 1, Tokyo (1984), pp. 117-126.

INFLUENCE OF ACOUSTIC DISTURBANCES ON THE BLOWING OF SOLID PARTICLES

A. Azizov*

UDC 532.529;631.459

The process of blowing of solid particles by an airstream is initiated and evolves within the limits of boundary-layer flow over a surface and depends on the nature of the flow in the layer. However, when the airstream moves over a natural surface, it encounters various obstacles and roughness elements, which disturb the flow pattern and generate acoustic oscillations, i.e., vortex sounds of various frequencies.

It has been shown [1-4] that the nature of the flow in a boundary layer depends essentially on the frequency of the acoustic oscillations existing in the flow.

When the boundary layer is irradiated by sound at a definite intensity and frequency, the laminar-to-turbulent transition is accelerated. A variation of the degree of flow turbulence is known to have a stronger influence on the blowing and entrainment of particles [5]. Consequently, the impingement of solid particles on a surface can affect the evolution of the erosion process.

The problem of the influence of acoustic disturbances on the blowing and entrainment of particles has been covered very meagerly in the literature. The present article reports

---

*Deceased.

Tashkent. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 5, pp. 130-132, September-October, 1986. Original article submitted August 26, 1985.