USE OF TOTAL HEAD TUBE AND MASS-FLOW HEAD TO DETERMINE THE DENSITY AND VELOCITY OF A RAREFIED GAS STREAM

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Results are given of an experimental determination of the density and velocity of a rarefied gas stream in the range of M_∞ from 3.1 to 9.0 and of $Re_{\infty 1\,cm}$ from 45 to 1500.

From the local mass-flow rate $(\rho_\infty u_\infty)$ of a gas and the stagnation pressure behind a normal shock (P_0'), one can determine the local values of density and velocity of a gas stream issuing from a nozzle, without the postulate of flow isentropy [1]. Comparison of these quantities with the velocity and density determined on the assumption of isentropic expansion of the gas in the nozzle is a check on the accuracy of determination of the flow parameters.

The literature has a limited number of papers dealing with measurement of local mass-flow rate, amongst them [1-3].

In the present work the local mass-flow rate of a gas was determined by use of a mass-flow-rate head with a sharp leading edge and an diverging inner channel (semiopening angle $\varphi = 25°$) to avoid the formation of detached shock waves, since only then do we have $\rho_\infty u_\infty = G/F$ (Fig. 1).

A previously calibrated sonic nozzle was used to measure the mass-flow rate of gas through the head. The nozzle diameter was chosen from the condition that the head should start up, i.e., that the shock wave should pass inside the intake. With an intake diameter of 4 mm, the nozzle diameter was chosen to be 3 mm. A photograph of the flow over the head (Fig. 2), taken by the glow discharge method, shows that there is no detached shock for one of the modes. A similar picture was observed over the whole range of pressures investigated. In calibrating the head the forward section was connected to a burette filled with vacuum oil, and the rear section to a vacuum reservoir. Then a supercritical pressure drop exists over the nozzle. The pressure ahead of the nozzle is fixed, while that behind it, both in calibration and during the tests, remained at the level of 10^{-3} mm Hg. The mass-flow rate of gas through the burette was determined by the constant-pressure method [4] from the rate of rise of the oil in the burette.

An experimental determination of the local mass-flow rate and stream density and velocity was performed in a low-density wind tunnel for the flow parameters shown in Table 1. The flow parameters were determined from the total head-tube readings and the parameters of the gas in the stagnation chamber, on the assumption of isentropic flow. This assumption was verified by investigating the transverse variation of P_0'. The flow Mach number M_∞ was determined from the ratio P_0'/P_0. A correction was made for the effect of viscosity according to the data of [5]. The pressure in the total-head tube was measured by means of a type MT-6 thermal manometer with an instrument error of ±10%, the pressure in the stagnation chamber was measured by means of a U-tube manometer to an accuracy of from ±0.5 to ±5%. Thus, the error in determining M_∞ was ±2 to ±3%.

The gas-flow rate through the diverging head during the experiment was determined from the measured pressure drop in the measuring nozzle, using the results of calibration. The maximum error in determining the flow rate was ±15%.

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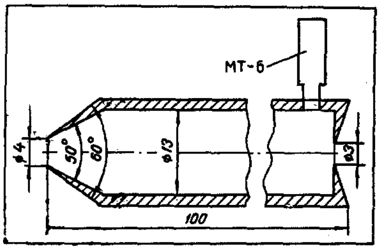

Fig. 1. A sketch of the mass-flow-rate head.

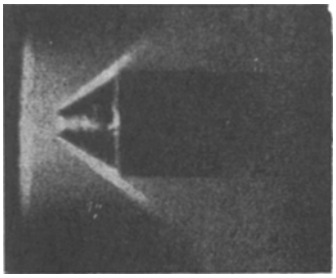

Fig. 2. Photograph of flow over the mass-flow-rate head.

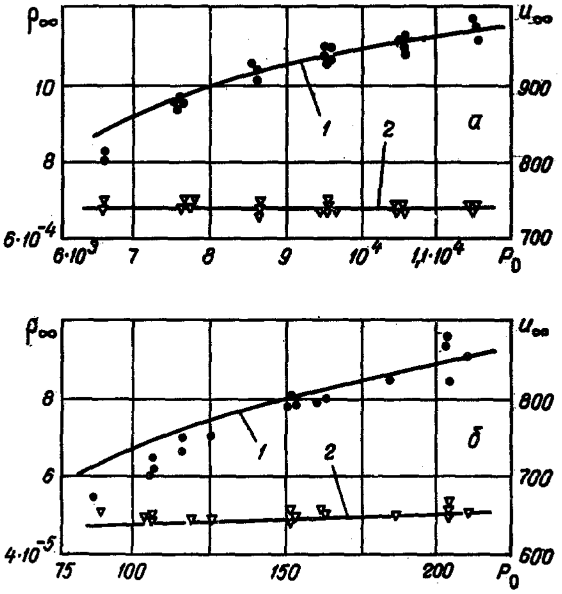

Fig. 3

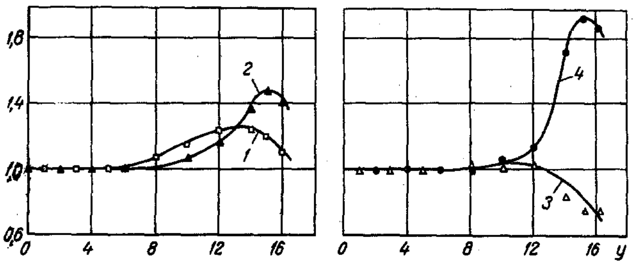

Fig. 4

Fig. 3. Dependence of the velocity u_∞, m/sec and of density ρ_∞, kg/m³, of the gas on the stagnation pressure for $M_\infty = 8.2$–9.0 (a), and $M_\infty = 3.1$–3.8 (b): 1) ρ_∞; 2) u_∞.

Fig. 4. Transverse profiles at the nozzle rim: 1) $P_0'/P_{0\,y=0}'$; 2) $\rho u/(\rho u)_{u=0}$; 3) $u/u_{y=0}$; 4) $\rho/\rho_{y=0}$.

TABLE 1. Experimental Conditions

P_0, N/m²	T_0, °K	M_∞	$Re_{\infty 1\,cm}$
60—240	290	3,1—3,8	45—120
5,3 ·10³—1,15·10⁴	290	8,2—9,0	410—690
6,65·10³—2,40·10⁴	290	7,0—8,9	800—1500

Knowing the local flow rate and the stagnation pressure behind the normal shock we could determine the local gas velocity and density. In fact, we have

$$P_0' = \frac{2\left(\frac{\varkappa+1}{2}\right)^{\frac{\varkappa+1}{\varkappa-1}}}{\varkappa^{\frac{\varkappa}{\varkappa-1}}}\left(1-\frac{\varkappa-1}{2\varkappa}\,\frac{1}{M_\infty^2}\right)^{-\frac{1}{\varkappa-1}}\frac{\rho_\infty u_\infty^2}{2}. \tag{1}$$

For $M_\infty \gg 1$, with $\varkappa = 1.4$,

$$\rho_\infty u_\infty^2 = 1.08 P_0'\left[1+\frac{1}{2\varkappa}\,\frac{1}{M_\infty^2}+o\left(\frac{1}{M_\infty^2}\right)\right]. \tag{2}$$

i.e., the quantity $\rho_\infty u_\infty^2$ can be calculated from the stagnation pressure behind the normal shock. Therefore, from the value of $\rho_\infty u_\infty$ determined by the flow-rate head, we can determine ρ_∞ and u_∞.

The values of density and velocity determined in this way are shown in Fig. 3. For $M_\infty > 7$ the calculation of $\rho_\infty u_\infty^2$ was done from the formula $\rho_\infty u_\infty^2 = 1.08\, P_0'$, while for $M_\infty = 3.1$ to 3.8 the value of M_∞ determined from P_0'/P_0 was used in Eq. (2). The solid lines in the figures show the results of calculation on the assumption of isentropic flow in the nozzle. Some of the discrepancy in the results is clearly due to errors both in the experimental and the calculated values of ρ_∞ and u_∞.

The mass-flow head was moved across the flow to determine the transverse density and velocity profiles in the isentropic flow core region. Figure 4 shows results of determining transverse profiles of $\rho_\infty u_\infty$, P_0', ρ_∞, and u_∞ for an off-design condition of nozzle discharge:

$$(P_k/P_\infty = 3.5;\quad M_\infty = 8.6;\quad P_0 = 2 \cdot 10^4\ \mathrm{N/m^2}).$$

It can be seen that both the stagnation pressure behind the normal shock and the local flow rate begin to vary simultaneously, the increase of P_0' in the off-design condition with increasing distance from the nozzle axis being accompanied by an increase of local mass-flow rate. At the same time, the gas density begins to increase and the velocity to fall off, which indicates the presence of a compression region between the isentropic flow core and the nozzle boundary layer.

Thus, the use of the mass-flow head has enabled us not only to determine ρ_∞ and u_∞ for an isentropic expansion in a nozzle but also to conduct flow diagnostics in quite a thick boundary layer at $M_\infty > 1$.

NOTATION

ρ, u, P, T	are, respectively, the density, velocity, pressure, and temperature of the gas;
G	is the mass-flow rate of the gas through the nozzle;
F	is the area of the intake;
M	is the Mach number;
Re	is the Reynolds number.

Subscripts

∞	denotes parameters of the oncoming stream;
k	denotes parameters of the gas in the working section;
0	denotes parameters of the adiabatically stagnated gas;
$'$	denotes parameters behind the normal shock.

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