A STUDY OF THE TRANSITION FLOW REGION IN FREE GAS JETS

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Data are presented here which have been obtained in a study of transitions in gas jets and in flames. It is shown that the flow characteristics of gas jets and of hot flames remain the same as of jets of an incompressible fluid.

The transition flow region in submerged jets of an incompressible fluid has been analyzed by various authors [1, 2, 3, 4]. Less explored are the transition patterns in jets of variable density. It would be of considerable interest to establish the effect of the gas density to ambient medium density ratio on the transition when a light gas discharges into a heavier atmosphere or when a heavy gas discharges into a lighter atmosphere. With this in mind (extension of [3]), an experimental study was made concerning the propagation of a helium and a Freon jet discharging into air from long pipes ($l/d \approx 100$). In order to provide a complete picture of the process, a study was also made of the transition in a burning gas flame which forms when a hot gas mixture discharges into air from a specially profiled nozzle.

In those tests, the results of which will be presented here, the Reynolds number was varied within the 1600-34,000 range and the density ratio ρ_{med}/ρ_{jet} was varied from 7.15 to 0.25, ρ_{med} denoting the density of the medium and ρ_{jet} denoting the density of the jet.

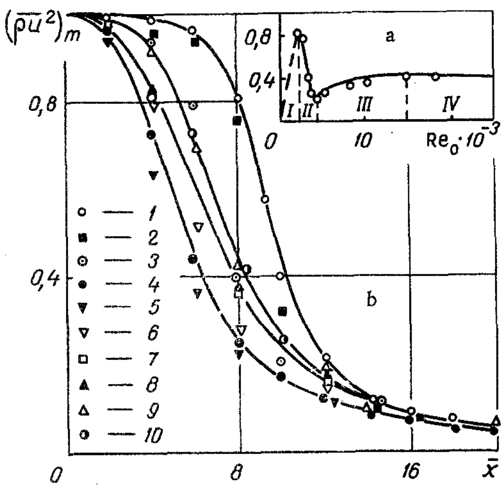

Fig. 1. Variation of $(\overline{\rho u^2})_m$ along the jet axis (a): $Re_0 = 2460$ (1), 2700 (2), 3220 (3), 3660 (4), 4050 (5), 4950 (6), 7950 (7), 10,950 (8), 16,650 (9), and 18,100 (10); as a function of the Re_0 number at $\bar{x} = 8$ (b). Both (a) and (b) are for helium discharging from a pipe.

In Fig. 1a are shown data on the variation of dynamic pressure $(\overline{\rho u^2})_m = (\rho u^2)_m/(\rho u^2)_0$ along the jet axis at various Reynolds numbers for helium discharging into air.

These data show that the rate at which $(\overline{\rho u^2})_m$ varies along the jet axis depends considerably (and nonmonotonically) on the Re_0 number. For Re_0 numbers from 1500 to 4000, an increase of the Re_0 number produces a larger $(\overline{\rho u^2})_m$ drop along the flow axis. As the Re_0 number increases further, $(\overline{\rho u^2})_m$ drops less along the axis until the axial distribution of $(\overline{\rho u^2})_m$ becomes almost independent of the Re_0 number for $Re_0 \geq 20{,}000$. The character of these variations is shown comprehensively in Fig. 1b, where the ralation $(\overline{\rho u^2})_m = f(Re_0)$ is plotted for a fixed value of $\bar{x} = x/d$. The graph reveals four distinct ranges of the $(\overline{\rho u^2})_m = f(Re_0)$ curve (as in the case of a submerged jet discharging into a gas of the same density [3]), which correspond respectively to a laminar flow (I), a transitional flow (II-III), and a fully developed flow (IV).

Typical of such transition inherent in free jets [3, 6] is that the laminar flow becomes unstable very suddenly. In consequence, the value of $(\overline{\rho u^2})_m$ drops below the constant level which corresponds to turbulent flow before reaching it (ranges II-III).

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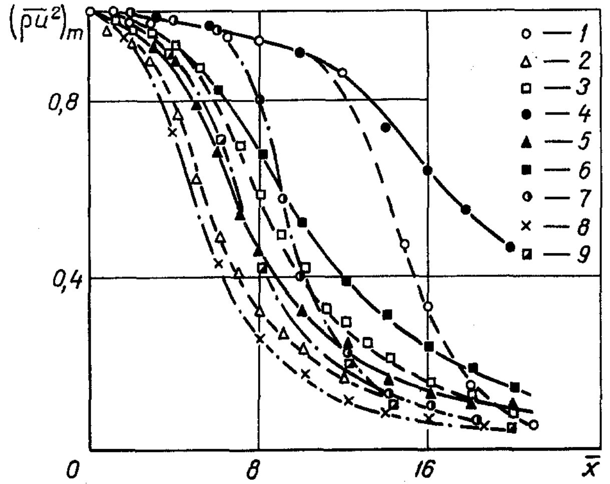

Fig. 2

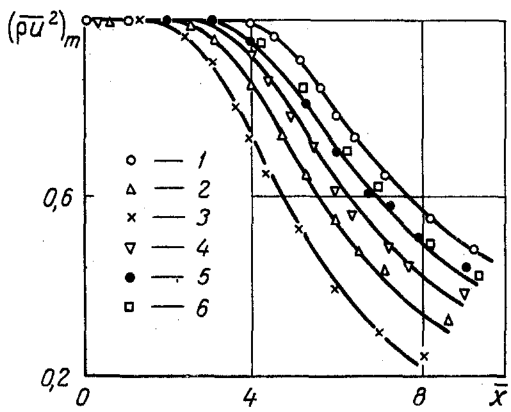

Fig. 3

Fig. 2. Variation of $(\overline{\rho u^2})_m$ along a jet axis: $Re_0 = 2700$ (1), 4000 (2), and 18,300 (3) for air (dashed line); $Re_0 = 2840$ (4), 4000 (5), and 18,100 (6) for Freon (solid line); $Re_0 = 2460$ (7), 3660 (8), and 16,550 (9) for helium (dashed-dotted line).

Fig. 3. Variation of $(\overline{\rho u^2})_m$ along a flame axis at different Re_0 numbers ($\alpha = 0.55$): $Re_0 = 3700$ (1), 5400 (2), 6900 (3), 8100 (4), 11,200 (5), and 15,00 (6).

An analogous pattern is observed when a heavy gas (Freon-22) discharges into air. Naturally, in both cases the maximum mixing rate (minimum point on the $(\overline{\rho u^2})_m = f(Re_0)$ curve at fixed values of x) corresponds to the same critical Re_0 number approximately 4000, as has been determined from the flow parameters ($Re_0 = u_0 d/\nu$).

Derivative data on the axial variation of $(\overline{\rho u^2})_m$ in gas jets with a variable or with a constant density are shown in Fig. 2. These data reveal the effect which the ratio of gas density in a jet to the density of the ambient medium in the direction of flow has on the variation of $(\overline{\rho u^2})_m$. This effect is most pronounced at a low discharge velocity. The $(\overline{\rho u^2})_m = f(Re_0)$ curves come closer together in the fully developed turbulence range, although the basic relation remain intact: $(\rho u^2)_m$ drops faster when $\rho_{med}/\rho_{jet} > 1$ and slower when $\rho_{med}/\rho_{jet} < 1$. The curve which corresponds to $\rho_{med}/\rho_{jet} = 1$ occupies an immediate position. As to the transverse distribution of ρu^2, here as well as in other cases a higher rate of jet attenuation along the axis corresponds to a rapid expansion of the mixing zone and to an increasing effective thickness of the boundary layer.

An aerodynamic analysis of the transition flow region in a gas flame was performed with a test apparatus consisting of a straight-flow burner with a profiled nozzle 18 mm in diameter and with a 4:1 adjustment range. The fuel (propane) and the oxidizer (air) were fed into a mixing chamber located at a considerable distance from the nozzle. This arrangement ensured a uniform gas mixture at the burner outlet. Steady burning was ensured by means of a stabilizer ring located 2 mm away from the nozzle throat. It was ascertained by appropriate measurements that the stabilizer did not introduce any significant distortions into the dynamic pressure distribution within the flame.

Measurements of $(\overline{\rho u^2})_m$ made along the flame axis at different Re_0 numbers (with a constant mixture ratio) are shown in Fig. 3. In a hot flame, as also in a gas jet, the relation $(\overline{\rho u^2})_m = f(Re_0)$ is not a monotonic function at any section of the jet, i.e., at any specified $\bar{x}$. When the Re_0 number is relatively low, an increase in discharge velocity results in a higher mixing rate and a correspondingly faster drop along the flame axis. The flow momentum intensity is attenuated at the maximum rate when the Re_0 number is in the 6000-7000 range. As the Re_0 number increases further, $(\overline{\rho u^2})_m$ drops along the flame axis at a slower rate. The $(\overline{\rho u^2})_m$-distribution becomes independent of the Re_0 number in the fully developed turbulent flow region.

In this way, the flow characteristics of the transition region are qualitatively identical in hot flames and in gas jets.

Some data describing the effect of the Re_0 number in a flame on the variations in $(\overline{\rho u^2})_m = f(Re_0)$, also on the variations in temperature, are shown in Fig. 4. They indicate the critical transition mode

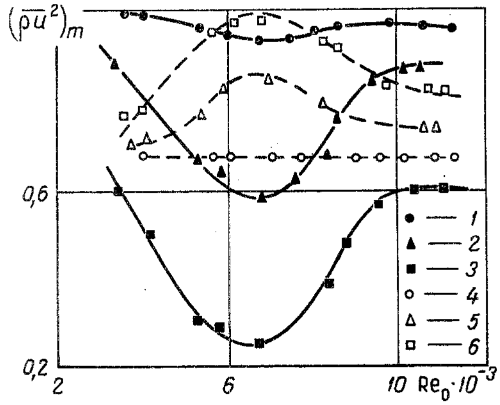

Fig. 4. Jet parameters at fixed points along a flame axis, as a function of the Re_0 number (α = 0.56): solid lines refer to $(\overline{\rho u^2})_m$ at $\bar{x}$ = 3 (1), 5 (2), and 7 (3); dashed lines refer to $\Delta\bar{T}_m$ at $\bar{x}$ = 3 (4), 5 (5), and 7 (6).

being reflected in the profiles of all characteristic parameters. Moreover, the function $\Delta\bar{T}_m = f(Re_0)$ ($\Delta\bar{T}_m = (T - T_0)/(T_f - T_0)$ with T_f and T_0 denoting the flame and the ambient temperature respectively) passes through a maximum as a consequence of an intensified heat transfer in the critical range of Re_0 numbers. This process is depicted by the nonmonotonic $\bar{l}_f = f(Re_0)$ curve of relative flame length as a function of the Re_0 number, with a characteristic minimum within the range of Re_0 numbers which corresponds to the region of intensive mixing in the jet.

It has been indicated earlier that at low Re_0 numbers in a jet of incompressible fluid the flow becomes turbulent within a narrow zone at some distance from the nozzle throat. In this zone the value of $Re_{x,cr} = u_m x/\nu$ is constant. Measurements have shown that the value of $Re_{x,cr}$ in a flame is quite close to its value in a jet of incompressible fluid*.

The overall results show that the critical mode of transition from laminar to turbulent flow is the same in free jets of an incompressible fluid or gas and in a hot flame. The transition region is represented on a nonmotonic curve of basic flow parameters (velocity, temperature, and others) with two characteristic extremum points: at the end of the laminar range and in the transition range. The extremum in the latter corresponds to the highest rates of momentum, heat, and mass transfer.

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*In gas jets $Re_{x,cr}$ could not be determined, since the concentration profile was not measured.