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An Experimental Study of the Flow of Subsonic Flat Mini and Micro Air Jets

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Abstract—We have experimentally studied subsonic submerged air jets emitted from flat mini and micro nozzles with characteristic dimensions from 22 to 600 μm in a range of Reynolds numbers 70–2600. The point of laminar–turbulent transition (jet penetration range) was determined using the flow visualization technique. It is established that the penetration range of micro jets can reach 100–300 nozzle calibers. The Reynolds number for the transition to turbulence in flat mini and micro jets reaches high values (1000–2600), which are two to three orders of magnitude greater than the Reynolds numbers for the loss of stability (3–10). Available experimental data are summarized and generalized based on the Reynolds number determined for the jet penetration range.

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An important modern area in hydrodynamics is related to the investigation of micro jets. The widespread practical use of small-size jets has been inspired by development of the technology of microelectromechanical systems. In particular, micro gas jets have numerous applications in micro jet engines, micropneumatic actuators and gasdynamic flow control devices, and cooling systems for microelectronics [1, 2]. In this context, an important practical task consists in determining the Reynolds number of laminar–turbulent transition and the coordinates of transition points in submerged subsonic mini and micro jets.

As is known, the critical Reynolds number for the loss of stability of a submerged jet amounts to Re_{cr} = 3–10 [3, 4]. At the same time, the Reynolds number for the transition to turbulence under these conditions varies within broad limits (from ~40 to 2000) and the transition point position changes from 10 to 500 nozzle calibers [2, 5]. This spread of parameters is related to the fact that the behavior of subsonic jet flows significantly depends on the initial conditions, which remain uncontrolled in most investigations.

Let us call the length of the laminar part of a jet (i.e., the distance from the nozzle edge to the point of transition to turbulence) the penetration range (L) of subsonic jets. Experimental investigation [6] of flat subsonic jets with transverse sizes b = 50–200 μm has revealed the influence of a scaling factor on the jet instability and penetration range. The jet penetration range is also strongly influenced by the acoustic action. Data on the effects of acoustic fields on the propagation of mini and micro jets have been reported in [7–9]. The penetration range of axisymmetric subsonic air jets with characteristic diameters within d = 0.5–8 mm was studied in [5].

The present work was aimed at determining the Reynolds number for the transition to turbulence and coordinates of the transition point in submerged flat subsonic mini and micro jets. In addition, we have also summarized and generalized the available experimental data.

In our experiments, flat jets were formed using nozzles of several types. The first variant was a subsonic nozzle with an input diameter of 15 mm that converged to an output slot of height b = 0.5 mm and a width of 15 mm connected to a flat channel. We have used a series of flat nozzles of this type with the same slot height and channel lengths l = 0.5, 15, 30, and 75 mm. The second variant was a cylindrical channel with a diameter of 15 mm with abrupt narrowing to a flat slot with height b = 0.5 mm and a width of 15 mm. The third variant was a flat channel with height b = 0.6 mm, a width of 16 mm, and a length of 70 mm without an input nozzle [5]. The fourth variant comprised micro jets with wedge-shaped confusers and output nozzle heights within b = 22–175 μm. The range of Reynolds numbers for air jets studied, calculated based on average flow rates U and nozzle heights b, was within $\mathrm{Re}_b = Ub/\nu$ = 70–2600.

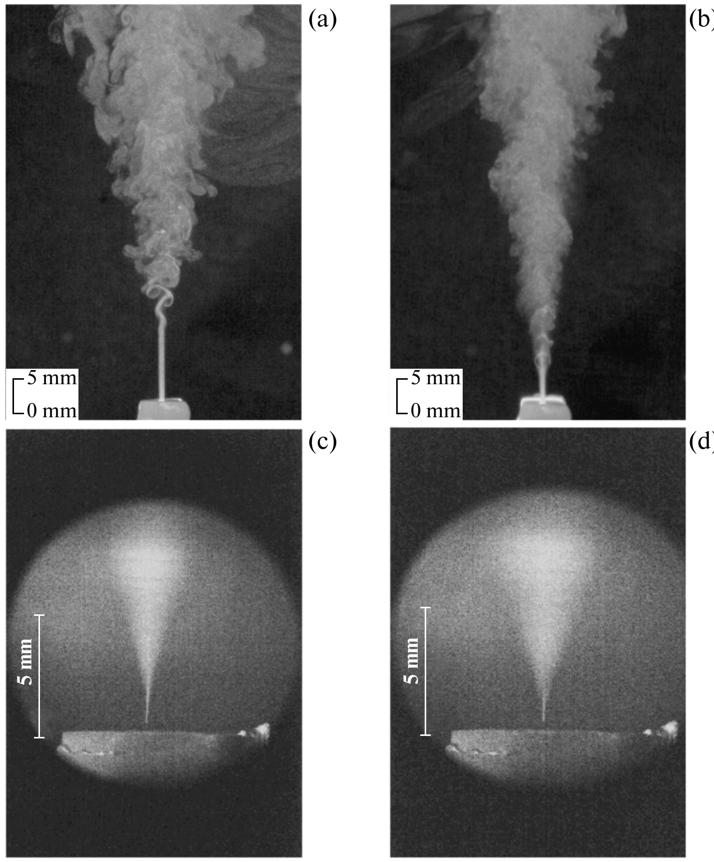

Fig. 1. Flow visualization in flat submerged (a, b) mini air jet with $b = 500$ μm at Re = (a) 410 and (b) and 2240 and (c, d) micro air jet ($b = 55.2$ μm) at Re = (c) 201 and (d) 274.

The investigations included imaging of mini and micro jet flow and hot-wire anemometer measurements. The flow of flat mini air jets (with nozzle heights of 0.5 and 0.6 mm) was visualized with the aid of an aqueous-aerosol generator (with a characteristic particle size of 1–2 μm). The pattern of flow was photographed by a Pentax digital camera (10 MPix matrix) at a frame exposure of 0.3–0.5 s under illumination with a pulsed laser radiation of 532-nm wavelength, 5-ns pulse duration, and 2-mm laser knife width. Hot-wire anemometer measurements were performed using a DISA 55M instrument equipped with a DISA 55P11 miniature probe (with 1-mm-long 8-μm-diameter tungsten wire).

In the case of micro jets, the size of aerosol generator particles used for the visualization of flow becomes comparable with the transverse dimensions of nozzles, which makes this method poorly applicable to investigation of micro jets. The flow of micro jets was imaged by the method of laser-induced fluorescence as proposed in [10]. This technique is based on the fluorescence of acetone vapor under the action of UV radiation. In our experiments, air was supplied via a flow rate controller to a vessel with acetone, passed via acetone and saturated with acetone vapor, and fed into a nozzle. The output air jet with acetone vapor was illuminated with a laser knife formed by radiation of an UV laser operating at 248-nm wavelength. The fluorescence of acetone vapor in the wavelength range of 400–550 nm was photographed via microscope with a digital camera at an exposure time of from 4 to 20 s.

Figure 1 presents photographs of mini and micro jet flows visualized with the aid of aerosol particles and laser-induced fluorescence, respectively. The flow was imaged in a central section of the jet, perpendicular to the large side of the nozzle. As can be seen, there are two clearly distinguishable parts of the jet: (i) initial region with almost constant width and (ii) wedge-shaped expanding region. The photographic images (see, e.g., Fig. 1a) show that the initial region of the jet is characterized by a laminar flow regime. Vortex formation then leads to the formation of developed turbulent flow that expands at some angle relative to the direction of jet propagation. The point of the laminar–turbulent transition was determined at the intersection of extrapolated boundaries of the expanded turbulent jet. The results of hot-wire anemometer measurements in mini jets showed that these data agree with the values of the penetration range determined from

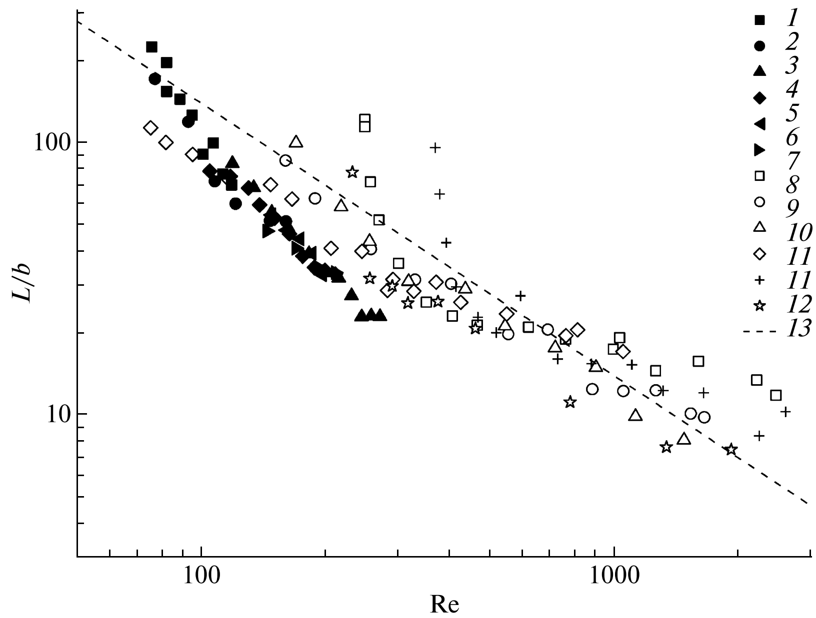

Fig. 2. Plot of the transition point coordinate vs. Reynolds number in submerged micro jets with b = (*1*) 22.3, (*2*) 34.5, (*3*) 52.5, (*4*) 83.3, (*5*) 130, (*6*), 175, and (*13*) 50–200 μm [6] and mini jets with b = 0.5 mm and l = (*7*) 0.5, (*8*) 15, (*9*) 30, and (*10*) 75 mm and abrupt narrowing (*11*), as well as (*12*) b = 0.6 mm [5].

the experiments with flow visualization. The error of penetration range determination fell within 5–18% and was related to a nonstationary character of the obtained patterns. In the experiments with mini jets, the data were averaged over four or five frames (with an exposure time equal to a laser pulse duration of 5 ns), while the penetration range of mini jets was determined from a single frame (with an exposure time of 4–20 s).

Figure 2 presents a summary of data for all variants of flat nozzles used in experiments. The dashed line shows a correlation relation obtained in [6]. As can be seen from these data, the values of the penetration range of subsonic flat micro and mini jets are mutually consistent. The results of various experiments plotted in logarithmic coordinates clearly reveal a linear dependence of the penetration range on the Reynolds number. The same tendency was pointed out in [6], but for a narrower interval (50–200 μm) of nozzle heights.

Another interesting result was the penetration range of jets emitted from subsonic nozzles with b = 0.5 mm and various lengths of the slot channel (0.5, 15, 30, and 75 mm). As is known, the distribution of velocities at the nozzle output has a top-hat character. Boundary layers formed at the channel walls merge together at a distance of about $l/b = 100$ from the nozzle input. By varying the nozzle channel length, we obtained different initial profiles of jet velocities: from top-hat at $l = 0.5$ mm ($l/b = 1$) to fully developed at l = 75 mm ($l/b = 150$). It was found that, for $\mathrm{Re}_b < 400$, the penetration range of jets formed for the initial top-hat velocity profile (l = 0.5 mm) and identical Reynolds numbers is greater than that of jets formed for the initial velocity profile close to the Poiseuille distribution (for l = 15, 30, and 75 mm). This tendency was also confirmed by data on the penetration range of jets emitted from a nozzle with abrupt narrowing. This rather unexpected result requires more thorough and detailed analysis, since the theory [11] claims that jets with parabolic initial velocity profiles possess a higher Reynolds number for the loss of stability than do jets with top-hat profiles. The scatter of data on the penetration range of mini and micro jets is probably related to the influence of initial conditions, including the initial velocity profile and level of turbulent pulsations of jet velocities. We failed to find any reported experimental data on the penetration range of flat macroscopic jets, which is a possible object for later investigations.

Descriptions of supersonic axisymmetric jets widely employ the Reynolds number calculated for the distance from a nozzle to the Mach disk, rather than for the nozzle diameter. The characteristic Reynolds number of the laminar–turbulent transition in a first-barrel mixing layer of supersonic underexpanded jets amounts to 10^2–10^4 [12]. In this context, Fig. 3 shows a proposed variant of generalization of the available experimental data in coordinates $\mathrm{Re}_L = f(\mathrm{Re}_b)$, where Re_b is the Reynolds number calculated for nozzle height b and Re_L is that for the coordinate of the transition point in submerged jets. The dashed line shows an empirical correlation obtained in [6]. As can be seen from Fig. 3, the data on the penetration range obtained for various nozzles with variable height and Re_b values plotted in these coordinates are mutually

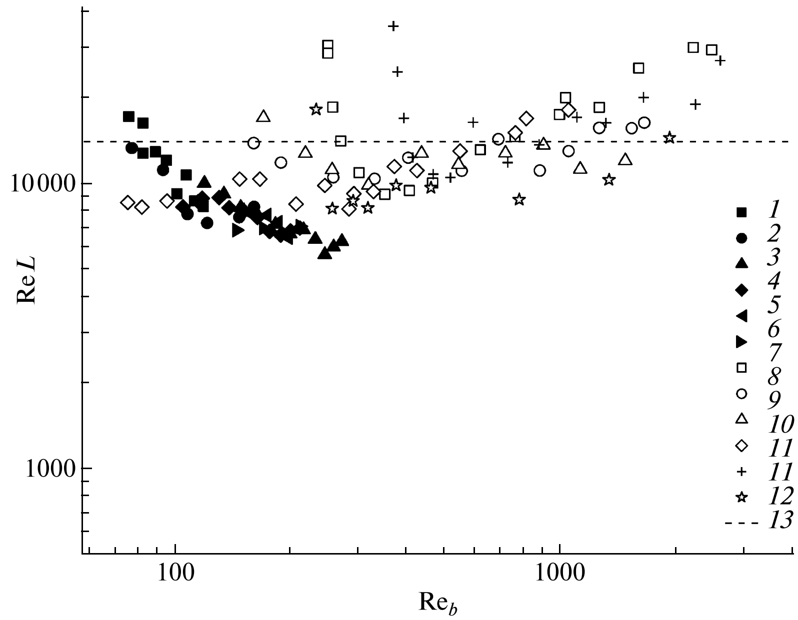

Fig. 3. Plot of the Reynolds number for turbulent transition in submerged jets. Notation of points is the same as in Fig. 2.

consistent. Thus, to a first approximation, the coordinate of the transition to turbulence can be determined with respect to Re_L, which falls in the interval of $\mathrm{Re}_L = 8 \times 10^3$–$1.5 \times 10^4$ and coincides in order of magnitude with the Reynolds number for the transition in a mixing layer of supersonic underexpanded jets.

Thus, it is established that the length of the laminar part of mini and micro jets can amount to 100–300 nozzle calibers. Plots on a logarithmic scale reveal linear correlation between the relative penetration range (L/b) and Reynolds number of the jet (Re_b). The Reynolds numbers of the transition to turbulence in flat mini and micro jets can reach high values (Re_b = 1000–2600), which are two to three orders of magnitude greater than the Reynolds numbers for the loss of stability (Re_{cr} = 3–10). It has been shown that the length of the zone of laminar–turbulent transition can be estimated using the Reynolds number Re_L determined from parameters of the initial jet section and its linear size (the coordinate of transition to turbulence). To the first approximation, this criterion falls in the range of $\mathrm{Re}_L = 8 \times 10^3$–$1.5 \times 10^4$ and is independent of the conditions of formation of flat submerged mini and micro jets and of the jet Reynolds number determined for the nozzle height.

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