PROPAGATION OF A JET OF VISCous LIQUID
IN A MEDIUM CONTAINING A DENSITY JUMP

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The results of an experimental investigation into the laws governing the propagation of a jet of viscous liquid in a medium incorporating a density jump are studied for a Reynolds number range of $25 \leq R \leq 20 \cdot 10^3$. In addition to jets normal to the jump surface (vertical jets), horizontal jets travelling along the interface between the heavy and light liquids (jump surface) are examined. Photographs are presented, together with dynamic pressure measurements, illustrating properties of the jets studied which are unusual for a uniform medium: the extinction of turbulence, the existence of a limiting jet length, anisotropy of the jet, etc. An approximate explanation (within the framework of boundary-layer theory) is given for the effects in question.

1. In this investigation we studied a problem which has as yet received little attention: the propagation of laminar and turbulent jets in a medium containing a density jump. In the experiments the jump arose at the interface between two immiscible liquids arranged in a stable manner, that with the greater density (water) being at the bottom and that with the lower density (diesel oil, density $830 \text{ kg/m}^3$) at the top.

As a preliminary stage we used the same apparatus to study the propagation of liquid jets in a medium of another density (water jets in diesel fuel and conversely). Although the visual and photographic observation of the jets was greatly eased by choosing immiscible liquids, special experiments with miscible liquids (water and salt solutions of different densities) showed that the qualitative picture of the phenomenon remained the same. Of particular interest is the possibility of clearly visualizing the extinction of turbulence when the denser liquid (water) passes in jet form through the density jump. Despite the comparatively slight discontinuity in the densities, approximately equal to a ratio of 0.83, the photographs presented below indicate a substantial smoothing of the pulsations. There are also some obvious effects associated with the anisotropy of the jet structure, and so forth. A theoretical explanation for the observed phenomena and a quantitative estimation of the effects are given at the end of this article.

2. The experimental apparatus was an open rectangular trough with a length, width, and height equal to 470, 254, and 310 mm, respectively, made of Plexiglas. Water and diesel fuel were poured into the trough to form layers. At the bottom and in one of the sides of the trough were apertures containing tubes of diameter $d = 2-4 \text{ mm}$ for supplying liquid from the pressure tank. The position of the latter relative to the tube could be varied so as to obtain any specified conditions of outflow of the jet. The Reynolds number determined from the outflow parameters was varied over the range $25 \leq R \leq 20 \cdot 10^3$. This enabled experiments to be carried out with laminar, transient, and developed turbulent flow in the jet at the outlet from the nozzle.

In our experiments we measured the dynamic pressure (along the axis of the jet and over the cross sections) and also took ordinary and motion pictures of the jet. Dye was introduced into the liquid in order to make the flow readily visible. The dye was introduced into the supply tube under steady-state conditions of flow. This enabled us to determine the velocity distribution in the jet by measuring the velocity of the

dye front or leading edge (although the time of observation was restricted to a few seconds). We studied vertical jets, traveling in a direction perpendicular to the interface between the light and heavy liquids, and also horizontal jets generated in the neighborhood of the density jump. When studying the horizontal jets, we placed a mirror in the trough so as to record the horizontal and vertical projections of the jet at the same time. The ordinary and motion pictures were taken with Zorkii-M and SKS-1 M cameras, respectively. The dynamic pressure was determined with a Pitot tube 0.8 mm in diameter.

3. Figure 1 shows some photographs of liquid jets of various densities propagating in a homogeneous medium (a—water in water; b—water in oil; c—oil in water). Under the photographs are the Reynolds numbers $R$. The photographs show that for comparatively small values of the Reynolds numbers ($R < 3000$) three characteristic regions may be distinguished in the field of flow, corresponding to laminar (cylindrical part of the jet), transient (zone of sharp increase in perturbations), and developed turbulent flow [1]. As the Reynolds number $R$ increases, the length of the cylindrical section shortens considerably and turbulization of the flow starts in the immediate neighborhood of the nozzle. When a jet of light liquid flows out into a denser one, turbulization of the flow takes place for considerably lower values of $R$. Hence, the developed turbulent mode sets in (for the same values of $R$) at a much shorter distance from the mouth of the nozzle, than when a jet of liquid with the same density as the surrounding medium is flowing. A qualitatively different picture is observed when a jet of heavy liquid propagates into a lighter one. In this case, for $R < 2500$ the forces of surface tension are sharply revealed—the photographs clearly show the formation of individual drops of heavy liquid. For large values