Visualization of Multijet Impingement Flow

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Abstract

FLOW visualization experiments were conducted in water as the working medium to study multijet impingement flows with fountain formation. The visualization technique uses fluorescein-sodium, a fluorescent dye, as tracer fluid and illumination by a sheet of light obtained by spreading a laser beam. Streakline photographs were also taken using air bubbles as tracer particles. Stagnation-line patterns were recorded for the cases of two-, three-, and four-jet configurations and compared with theoretical predictions.

Contents

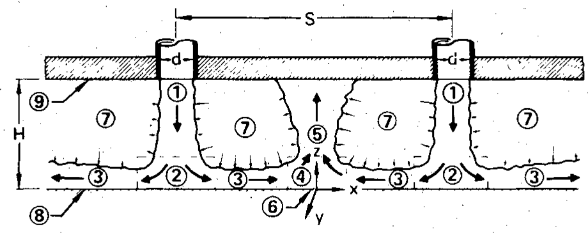
The design of efficient vertical-takeoff-and-landing (VTOL) aircraft equipped with powered lift-jet systems requires knowledge of the complicated flowfield produced by the impinging lift-jet streams when the aircraft is in proximity to the ground. The important characteristics of these jet impingement flows shown in Fig. 1 are 1) the fountain upwash produced by the colliding wall jets, and 2) entrainment of ambient air into the different regions of the flow. Accurate visualization of the multijet impingement flowfield on a laboratory scale provides valuable insight into these complex three-dimensional flowfields. Water as a working medium is more advantageous than air[1] since tracers suitable for use in water are more numerous, and the aerodynamic phenomena can be observed at a relatively slow speed in water for the same Reynolds number and model scale. In the present study, the multijet flow for normal impingement is described through photographs of the flow patterns in three mutually perpendicular planes using dynamic flow visualization techniques with water as the working medium. The present studies were conducted in a multijet impingement facility described in detail in Ref. 1.

In the principal flow visualization technique used, fluorescein-sodium, a fluorescent dye, which was found to be ideal for the present application,[1] is introduced as the tracer fluid directly into the primary jet streams. The second visualization technique is noncontaminating and uses air bubbles[1] as tracer particles to produce short streaks on the photograph, giving an indication of the streaklines. The source of illumination in both cases was a 3-W argon-ion laser, with approximately 1 W of power in the 488-nm line, which causes fluorescein-sodium to fluoresce a bright yellowish-green. By properly adjusting the optical-system components,[1] any desired cross section of the flow can be illuminated with a sheet of light obtained by spreading the laser beam.

Figures 2a-d show the basic flow patterns describing twin-jet impingement flow for equal jet diameters and jet momenta, m_{J2}/m_{J1}. The Reynolds number, Re, is based on the exit jet diameter and exit jet velocity. The free jets, wall jets, and the fountain formed by the colliding wall jets are visible in Fig. 2a. The fountain, located midway between nozzles, moves upward and spreads spatially by entraining the surrounding fluid. Figure 2b, obtained by using the air bubble technique, shows, apart from the features observed in Fig. 2a, entrainment of the surrounding fluid into the wall jets, free jets, and fountain. A radial flow pattern originating at the ground plane was observed in the fountain viewed in the y-z plane at $x/d = 0$.

Figures 2c and 2d demonstrate the effect on the fountain of reducing the spacing between the jets (S/d). For relatively distant spacing (Fig. 2a, $S/d = 12$), the fountain behaves as an independent plume of upward flow with no interaction with the main jets. However, for close-spaced jets, Figs. 2c and 2d indicate an interaction between the main jets and the fountain. The strength of the interaction increases with decreasing distance between the jets because the entrainment requirements of the fountain and the free jets move the free jets inward. The fountain for the case of $S/d = 4.1$, shown in Fig. 2d, was unsteady and oscillated between the jets.

Figures 3a and 3b show the effect of the ratio of the jet momenta, m_{J2}/m_{J1}, on the twin-jet impingement flow. As the momentum of one jet is increased relative to the other, the fountain inclines towards the jet with the lower momentum and the included angle increases with increasing difference in jet momentum. At a critical ratio of jet momenta, which depends on the height of the nozzle above the ground, a recirculation pattern develops between the lower-momentum jet and the fountain, with the resultant mixing of the fountain and the free jet flow. This recirculation pattern, shown clearly in Fig. 3b for $m_{J2}/m_{J1} = 0.25$, may be the result of the relatively small volume of fluid between the fountain and the free jet which cannot fulfill the entrainment requirements of both. For $m_{J2}/m_{J1} < 0.25$, the fountain deflects the lower-momentum jet away from the higher-momentum jet. The effect on the flow of unequal jet diameters was also studied, and it was observed that when the two jets have equal momentum, the fountain flow is vertical and centered. However, when the mass flows of the unequal-sized jets are



1. Lift jet flow
2. Jet impingement region
3. Wall jet flow
4. Fountain formation region
5. Fountain up-wash flow
6. Wall jet interaction stagnation line
7. Entrainment
8. Ground plane
9. Blocking surface

Fig. 1 Schematic illustration of twin-jet impingement flow.

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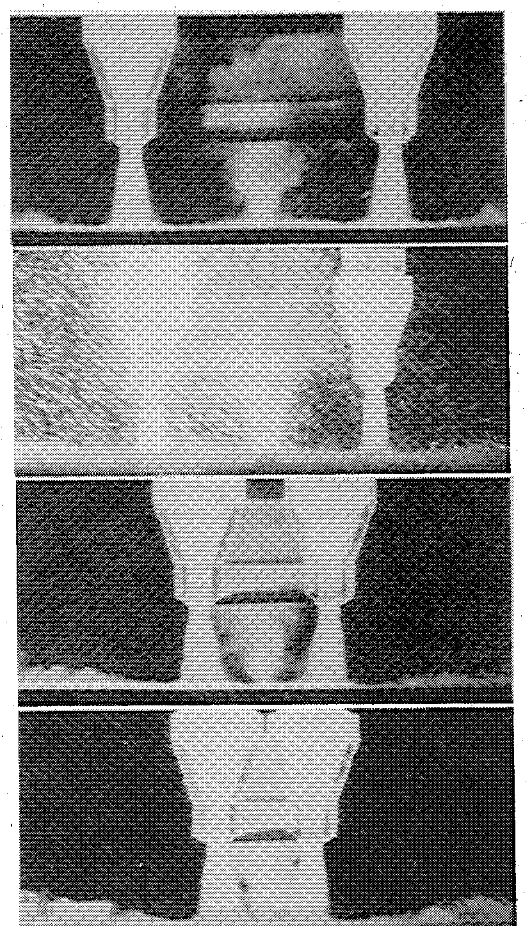
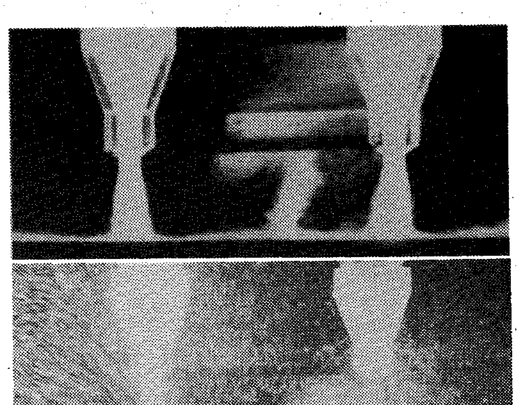


a) b) c) d)

Fig. 2 Basic flow patterns describing twin-jet impingement; $H/d=4$, $d_2/d_1=1$, $m_{J2}/m_{J1}=1$, and $Re=23\ 780$. x-y plane, $y/d=0$. a) $S/d=12$, dye technique; b) $S/d=12$, air bubble technique; c) $S/d=6$, dye technique; d) $S/d=4.1$, dye technique.

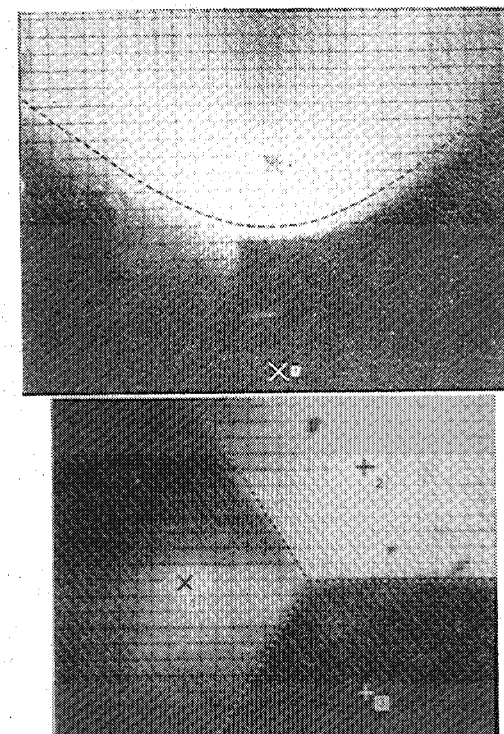


a) b)

Fig. 3 Effect of the ratio of jet momenta m_{J2}/m_{J1} on the twin-jet impingement flow: $S/d=12$, $H/d=4$, and $d_2/d_1=1$; x-y plane, $y/d=0$. a) $m_{J2}/m_{J1}=0.419$, dye technique; b) $m_{J2}/m_{J1}=0.25$, air bubble technique.

equal, the fountain is inclined towards the larger jet and mixes with it.

Figures 4a and 4b show typical ground stagnation-line patterns for two- and three-jet configurations obtained by illuminating a plane parallel and close to the impingement surface and selective dye addition in the jet streams. In the case of twin-jet impingement (Fig. 4a), the stagnation line becomes curved; its position shifts toward the weaker jet and its curvature increases as the ratio of jet momenta m_{J2}/m_{J1} is decreased. A comparison of the photographed stagnation-line



a) b)

Fig. 4 Stagnation line patterns for two- and three-jet impingement flow; $H/d=4$ and $d_1=d_2=d_3$. The dotted line indicates the calculated stagnation line. a) Two jets, $m_{J2}/m_{J1}=0.196$; 2) three jets, $m_{J1}=m_{J2}=m_{J3}$.

shapes with those predicted from the momentum-flux-density methodology reported in Ref. 2 indicates good agreement, as illustrated in Fig. 4a. A similar prediction method was also reported in Ref. 3. Additional stagnation-line shapes for different ratios of jet momenta can be found in Ref. 1. The individual segments of the stagnation-line patterns for the three-jet case illustrated in Fig. 4b are straight lines because the jets are of equal momentum. The present flow visualization techniques were also used to observe the stagnation-line patterns in the case of four-jet[1] impingement.

The specific advantages of the present flow visualization techniques in water compared with those (e.g., smoke and oils) in air are 1) clearly defined description of all features of the flow and nonintrusive fountain observation, even at jet Reynolds numbers in the range of 25,000; 2) the ability to illuminate any desired cross-section specific flow features, such as vortex patterns and stagnation lines in the recirculating regions; and 3) dynamic visualization, which provides unsteady features such as oscillating stagnation-line patterns. Examples of some of the quantitative data that can be obtained with these techniques are spreading characteristics, inclination angle and trajectory of the fountain, entrainment velocities from the air bubble streaks, position of the stagnation lines, and the local flow direction in the fountain upwash.

Acknowledgment

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