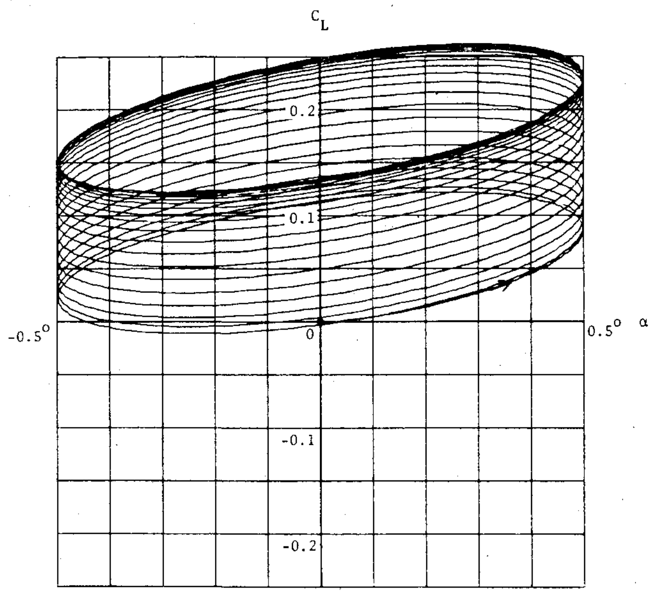

Fig. 4a NACA 64A006 airfoil, $M_\infty = 0.89$, $k = 0.2$, $N = 1 \sim 20$ cycles.

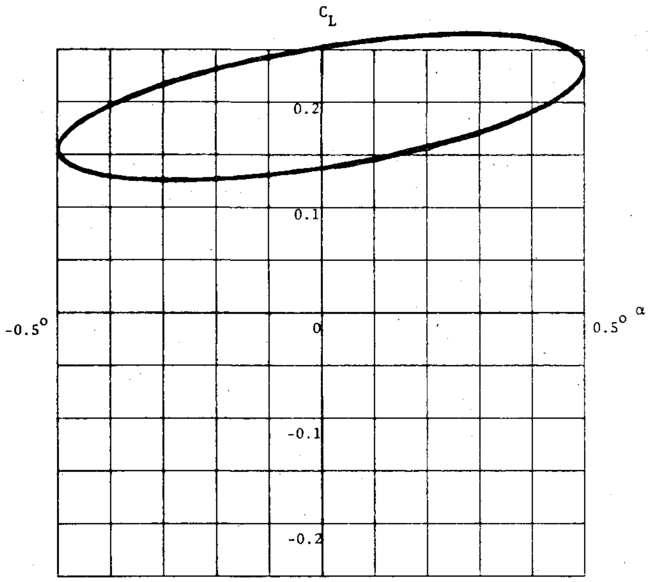

Fig. 4b NACA 64A006 airfoil, $M_\infty = 0.89$, $k = 0.2$, $N = 21 \sim 40$ cycles.

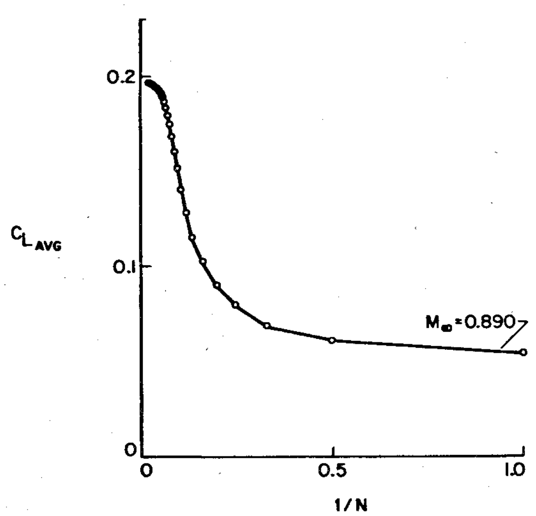

Fig. 5 Average lift vs inverse of the number of cycles of oscillations.

monotonically. The values of C_L at the end of cycles 6-12 were 0.1867 (6), 0.2010 (7), 0.2072 (8), 0.2118 (9), 0.2148 (10), 0.2169 (11), and 0.2181 (12). Hence, the conclusion is that at these flow conditions the symmetric steady flow is unstable and that a slight perturbation will cause the flow to evolve to a nonsymmetric stable state.

For this calculation the initial shock waves were located at 77% of the chord from the leading edge and the local Mach number just ahead of the shock was $M = 1.172$. During the course of the airfoil motion, the shock waves did not approach closer to the trailing edge than 92% chord location and the maximum local Mach number did not exceed 1.184. Therefore, the flow was consistent with the approximations of the unsteady transonic, small-disturbance theory used in LTRAN2. Also, the shock waves did not reach sufficiently close to the trailing edge that possible interference with the imposition of the Kutta condition might explain the anomalous flow.

Multiple solutions have also been found for the transonic *full potential steady* flow equation by Steinhoff and Jameson.[5] Steinhoff and I will be investigating these anomalous computed flows further with the use of more complete governing equations. The motivation behind this effort is to determine whether the shock wave instability in these calculations also occurs in the Euler equations. If such an instability is found, it could provide an inviscid mechanism for invoking the buffet phenomenon,[6] which also occurs over a narrow range of Mach numbers in the transonic regime.

Acknowledgments

This work was supported, in part, by AFOSR Grant 81-0213A. Dr. Anthony Amos is the Technical Monitor. The third author thanks George Kimberly, Summer Fellowship, NASA Ames Student, Space Biology Research Program, for performing the additional calculations with LTRAN2.

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Visualization of Flow Patterns Induced by an Impinging Jet Issuing from a Circular Planform

K. R. Saripalli*
McDonnell Douglas Corporation, St. Louis, Missouri

Introduction

THE development of high-performance V/STOL aircraft powered by lift jets requires knowledge of the complex

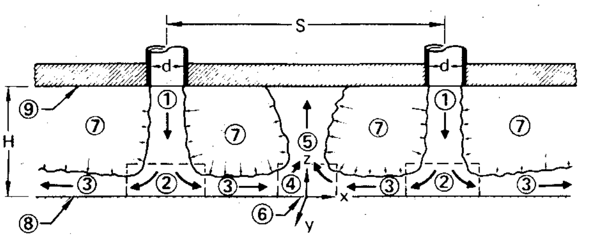
Received Aug. 30, 1982; revision received March 22, 1983.

*Research Scientist, McDonnell Douglas Research Laboratories. Member AIAA.

flowfield (Fig. 1) produced by these lift jets in ground effect. One of the important characteristics of this flowfield is the entrainment by the lift jets, the wall jets, and the fountain, which causes reduced pressures on the lower fuselage surface and the resultant downward "suckdown" force (lift loss) on the aircraft. Analysis of these lift losses due to entrainment is of critical importance for the design and development of V/STOL aircraft.

As the initial phase in determining the entrainment characteristics of the complex multijet impingement flowfield, the flow of a single impinging jet issuing from a planform simulating the fuselage was studied. Previous experimental efforts[1-5] devoted to the single jet impingement problem mostly have been directed to measurement of lift losses and pressure distributions on the lower surface of the planform (blocking plate), as summarized in Refs. 6 and 7.

Figure 2 shows schematically the possible flow patterns which may exist depending on the height of the jet exit above the ground H, the jet diameter d, the blocking plate diameter D_B, and the jet velocity. It is well established that for $H/D_B < \ll 1$ (Fig. 2a) the flow behaves similar to that in a channel[3,4] with a purely radial outflow at the edge of the



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 multijet impingement flow.

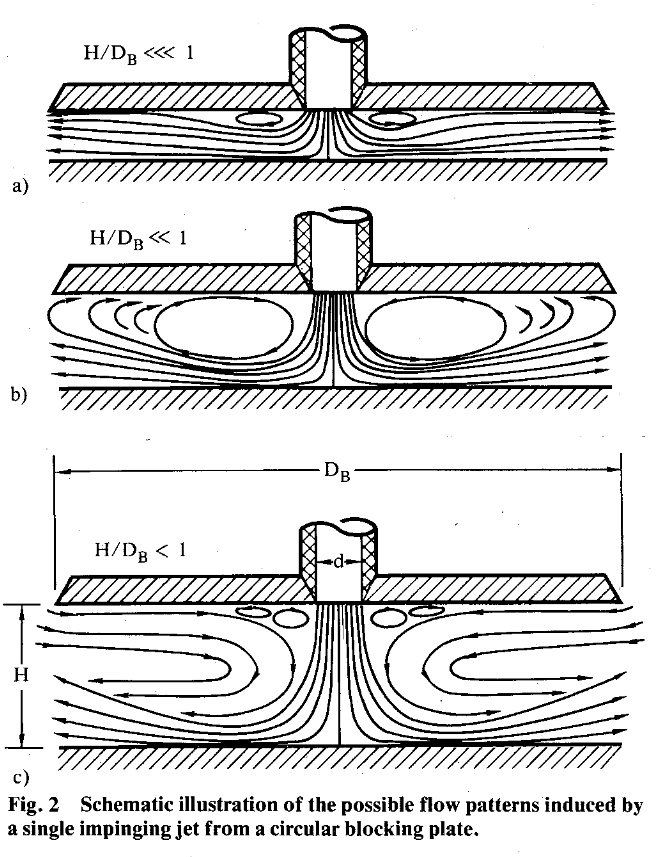


Fig. 2 Schematic illustration of the possible flow patterns induced by a single impinging jet from a circular blocking plate.

blocking plate. Also, it is known that for large heights ($H/D_B < 1$, Fig. 2c), the ambient air is entrained into the jet flow, causing an inwardly directed entrainment flow at the edge of the blocking plate and reduced pressures on the blocking plate. However, the mechanism of transition from the flow pattern in Fig. 2a to that in Fig. 2c is not clearly understood, although Refs. 2-5 do suggest the existence of different flow features such as a trapped doughnut-shaped vortex (Fig. 2b), steady or unsteady annular separation bubbles, and a stationary ring vortex during the transition using smoke and tuft flow visualization. In the present work, the character of the various flow patterns was studied through flow visualization techniques using water as the working medium.

Experimental Techniques

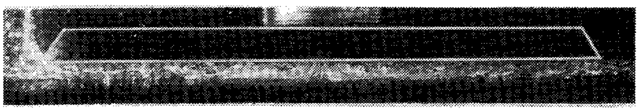
The present studies were conducted in a multijet impingement facility described in detail in Ref. 8. The facility has a recirculatory system with the water drawn from the main glass tank housing the ground plate and the nozzle unit pumped into a header tank which supplies the jet through the control valve and flowmeter. The water jet from the nozzle unit consisting of a settling chamber and detachable nozzle and blocking plate impinges on the ground plate held at a fixed height in the main tank. Three nozzles, with exit internal diameters of 6.35, 9.53, and 12.7 mm, and six blocking plates with diameters at the bottom edge of 5.08, 7.62, 10.16, 12.7, 15.24, and 17.78 cm, were used. The nozzle unit is designed such that the nozzle exit is flush with the undersurface of the blocking plate. The blocking plate is provided with a beveled edge for smooth flow around the edge. The position of the nozzle units can be adjusted with a traversing rig to vary the height of the blocking plate above the ground plate.

The source of light used to visualize the flow was a laser beam (488 nm wavelength) spread in the form of a thin sheet to illuminate a plane in the flow passing through the center of the blocking plate. By employing air bubbles as tracer particles, photographs with controlled exposure time were taken to produce short streaks which gave an indication of the velocity field. Additional details of the apparatus, illumination system, and the flow visualization technique are given in Ref. 8.

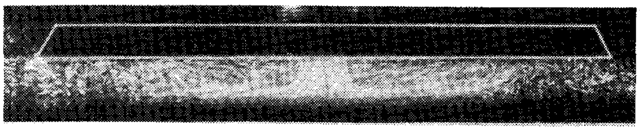
Results

Flow streakline patterns were photographed for the six blocking plates of different diameters and for each of the three nozzles at various heights above the ground. Figure 3 shows the flow patterns representative of those observed in all cases. The instantaneous flow pattern was photographed for the heights where the flow was unsteady. At distances close to the ground, flow between the blocking and ground plates is purely radial (Fig. 3a) and similar to that in a channel, as found in earlier observations.[3,4] A small separation bubble exists at these heights but is confined to a narrow region near the jet entrance.

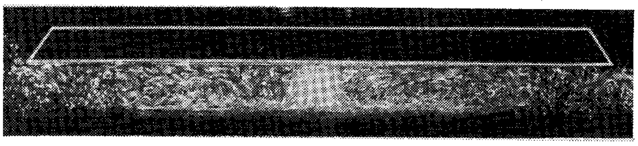
As the height is increased, the size of the annular separation bubble increases. Here, the wall jet formed by the primary jet impingement rolls back with a complete direction reversal (Figs. 3b and 3c), defining the boundaries of the separation bubble which may be termed a doughnut vortex. The upper edge of this recirculation region opens to the surrounding fluid at irregular intervals and at different positions on its circumference, and the velocities in the region outside the doughnut vortex are otherwise relatively insignificant. The abovementioned flow feature related to the region of the separation bubble can be explained on physical grounds in the following manner: The entrainment requirements of the primary jet and the wall jet formed by its impingement on the ground are considerable, resulting in a low-pressure region around the jet. Since the ambient fluid has no access to this region at low heights, the wall jet rolls back on itself to fill the low-pressure region and thereby meet the entrainment



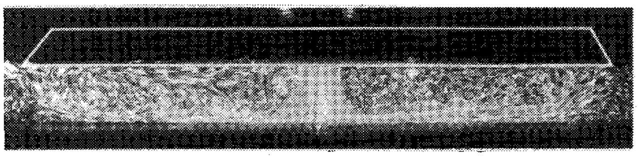
a) $H/d = 0.4$, $H/D_B = 0.033$.



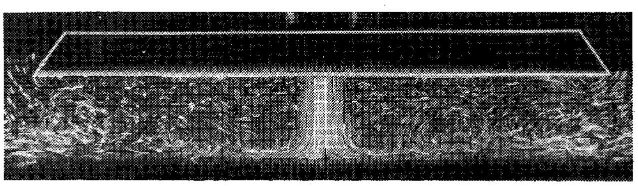
b) $H/d = 0.8$, $H/D_B = 0.067$.



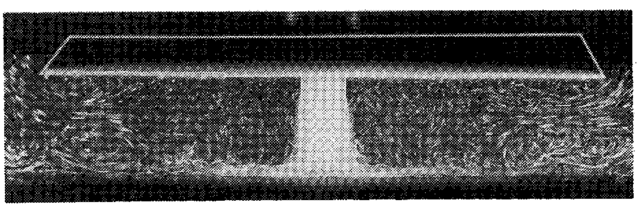
c) $H/d = 1.0$, $H/D_B = 0.083$.



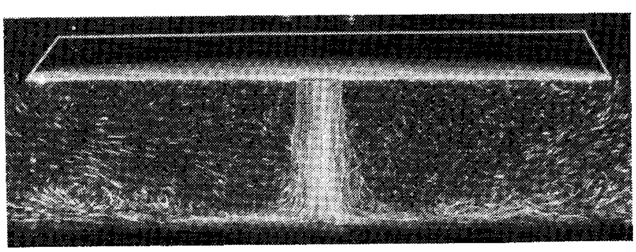
d) $H/d = 1.2$, $H/D_B = 0.1$.



e) $H/d = 1.8$, $H/D_B = 0.15$.



f) $H/d = 2.2$, $H/D_B = 0.183$.



g) $H/d = 3$, $H/D_B = 0.25$.

Fig. 3 Flow patterns induced by a single impinging jet issuing from a circular blocking plate: $d = 12.7$ mm; $D_B/d = 12$, $Re = 21{,}140$.

requirements. However, the primary jet is constantly pumping fluid into the space between the plates, and this fluid must eventually be forced out of the doughnut vortex to conserve mass. Hence, the upper edge of the vortex opens periodically to expel fluid. The existence of a similar unsteady separation bubble was suggested in Ref. 3 with a shifting point of reattachment that was attributed to the pumping action of the jet, resulting in the spreading jet sealing against the blocking plate, collapsing, and repumping.

As the height of the blocking plate is increased further, a condition is reached where the outer edge of the separation bubble moves closer to the edge of the blocking plate (Fig. 3d). At still greater heights, the wall jet no longer rolls back on itself; rather, it remains attached to the ground plate and flows radially outward, and the ambient fluid is entrained through the gap between the edge of the blocking plate and the wall jet as shown in Figs. 3e-g. The height at which the entrainment of the ambient fluid first occurs and the flow pattern in Fig. 3d changes to that in Fig. 3e is termed the transition height. The velocity at which the ambient fluid is entrained through the gap decreases as the height is further increased above the transition height; however, gross features of the flow pattern still remain as shown in Figs. 3e-g.

An interesting observation is that the transition height varies linearly with the blocking plate diameter according to the relation

$$(H/d)_{\text{transition}} = 0.125\ (D_B/d)$$

for a given jet diameter and jet Reynolds number (based on jet diameter and jet velocity). The transition height was also observed to be independent of the jet diameter and increase slowly as the jet velocity decreases.

An estimate of the average entrainment velocity, and hence the entrainment mass flow, necessary for the theoretical analyses such as the one presented in Ref. 6, can be obtained from the length of bubble streaks at the edge of the blocking plate. In conclusion: a range of complicated flow patterns exists in the range of heights of practical interest, and this fact, especially the presence of an unsteady doughnut vortex up to a considerable height above the ground, should be considered in theoretical modeling of the subject flows.

Acknowledgments

This research was conducted under the McDonnell Douglas Independent Research and Development Program. The author wishes to acknowledge K. T. Yen of the Radnor Graduate Center of The Pennsylvania State University for suggesting this problem.

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