Numerical Study of Two-Dimensional Impinging Jet Flowfields

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Abstract

THE Reynolds-averaged compressible Navier-Stokes, continuity, and energy equations are solved in conjunction with a two-equation ($K-\epsilon$) turbulence model for two-dimensional impinging jet flowfields relevant to VTOL aircraft. About the impingement region with free upper surface, turbulent flow is studied numerically. For the laminar impinging jet with upper flat plate, effect of height of the jet above the ground plane on the flow behavior is obtained. Beam and Warming implicit finite-difference scheme with implicit boundary treatment is introduced. To suppress numerical oscillations, explicit fourth-order and implicit second-order dissipation terms are employed. In order to confirm the accuracy and reliability of the present solution procedure, computed flowfield properties are presented, and comparisons are made with experimental data and related numerical results.

Contents

Jets impinging on a flat plate appear in various applications, such as heat transfer in industrial equipment, flowfield around Vertical-Takeoff-and-Landing (VTOL) aircraft, etc. For VTOL aircraft, an important consideration is the aerodynamic interaction between airframe under surfaces and the ground in the presence of the lift jets. To understand a less complex lift-jet-induced flow, the investigation of the flowfield created by a planar lift jet with/without an upper surface in ground effect is conducted by using a numerical approach in the present study. Without considering the cross-flow effect, the jet flowfield can be divided into three regions (Fig. 1). The first part is the free-jet region where the flow is the same as that of a jet issuing into an unbounded medium. The second part is the impingement region in which the large pressure enhances the change of flow direction. The third part is the wall-jet region where the flow moves over the ground plane with constant pressure. Besides the above descriptions, it is known that the fluid surrounding the jet is entrained at the boundaries of the three regions. About the turbulent impinging jet, the one-equation[1] and two-equation[2] models are employed, and the governing equations are written in stream function/vorticity forms and formulated by the finite-difference methods. In this paper, the nondimensional, conservative Reynolds-averaged forms of Navier-Stokes, continuity, and energy equations[3] in conjunction with a two-equation ($K-\epsilon$) turbulence model[2,4] are employed. In order to simulate the flow behavior, the grid system is generated by two independent algebraic coordinate transformations.[5] By using the Beam and Warming numerical scheme with three-point-backward temporal differencing, local linearization, and factorization, the governing equations are solved by the alternating-direction-implicit (ADI) sequence.[6] To stabilize the calculation, explicit fourth-order and implicit second-order dissipation terms are added.

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For the boundary conditions, the velocity and total temperature are prescribed within the nozzle entering jet, and the density is obtained from interior values. Along the upper flat plate and the ground plane, the no-slip, adiabatic conditions and one-sided difference of the y directional momentum equation are employed. On the jet centerline, symmetry conditions are imposed. For the impinging jet with upper flat plate, extrapolation of momentum flux with specified pressure is applied along the exit plane (right boundary). About the impingement region with free upper surface, the y component of the velocity is assumed to be zero, and the other flow properties are taken to be uniform with respect to the x direction. The boundary treatment of turbulent kinetic energy K and dissipation rate ϵ are the same as those of Ref. 2.

The impingement region, which is bounded by ABCD in Fig. 1, is employed to study the turbulent flow. In this case, the Mach number of the jet is equal to 0.1, and H is chosen to be 12.2. In addition, the fully developed jet velocity profiles along AB are specified as

$$v = v_{\text{jet}}(1-\tanh^2 C_1 x), \qquad C_1 = \tanh^{-1}(1/\sqrt{2}) \tag{1}$$

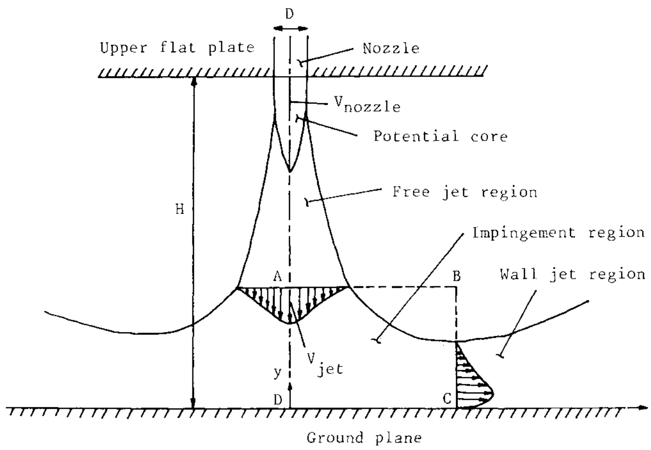

Fig. 1 Impinging jet system.

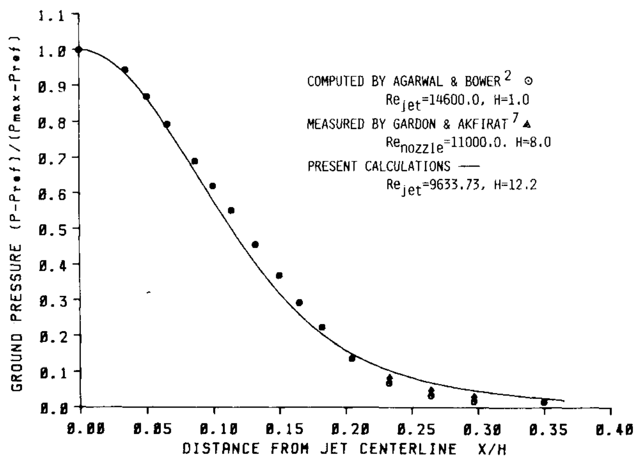

Fig. 2 Ground plane pressure distributions.

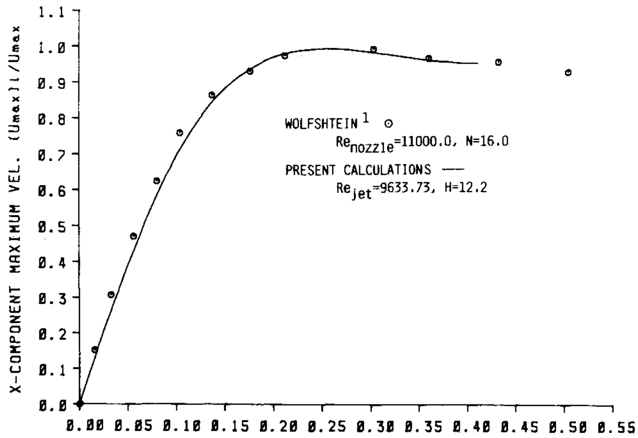

Fig. 3 Maximum velocity growth along the wall.

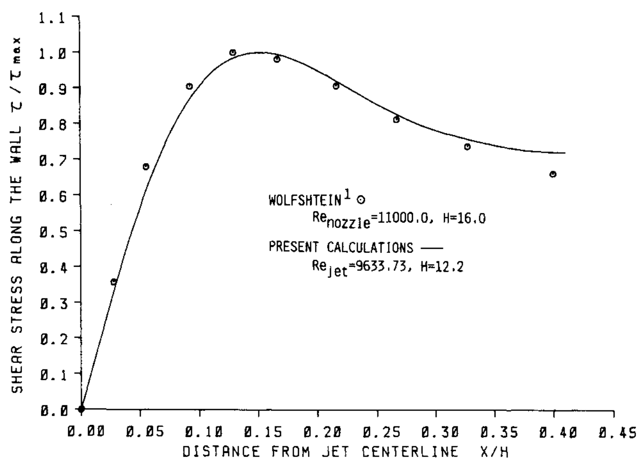

Fig. 4 Skin friction along the wall.

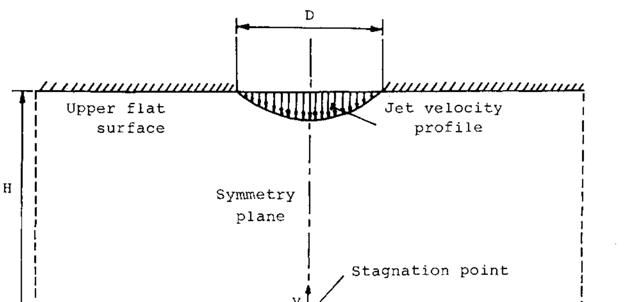

Fig. 5 Planar jet with upper flat plate configuration.

Computations of normal impingement of the turbulent jet on the ground plane have been carried out for one set of parameters corresponding to the experimental investigation of Gardon and Akfirat.[7] Based on the jet profile given in Eq. (1) and the relationship between v_{jet} and v_{nozzle} given in Ref. 1, the jet-entry conditions can be determined. For the pressure distribution, the growth of maximum velocity in the x direction and the skin friction along the ground plane are plotted in Figs. 2–4. It is clear that satisfactory agreement has been obtained.

A preliminary model of the VTOL lift-jet flowfield is given by a planar jet with a flat upper surface as shown in Fig. 5. The effect of height of jet above the ground plane for laminar flow is investigated. In this calculation, W is chosen to be 4.68. The velocity distribution of the entering jet is expressed as

$$v = v_{\text{jet}}, \quad x \leq 0.15$$

$$= v_{\text{jet}}(-1200x^2 + 360x + 120)/147, \quad 0.15 \leq x \leq 0.5 \tag{2}$$

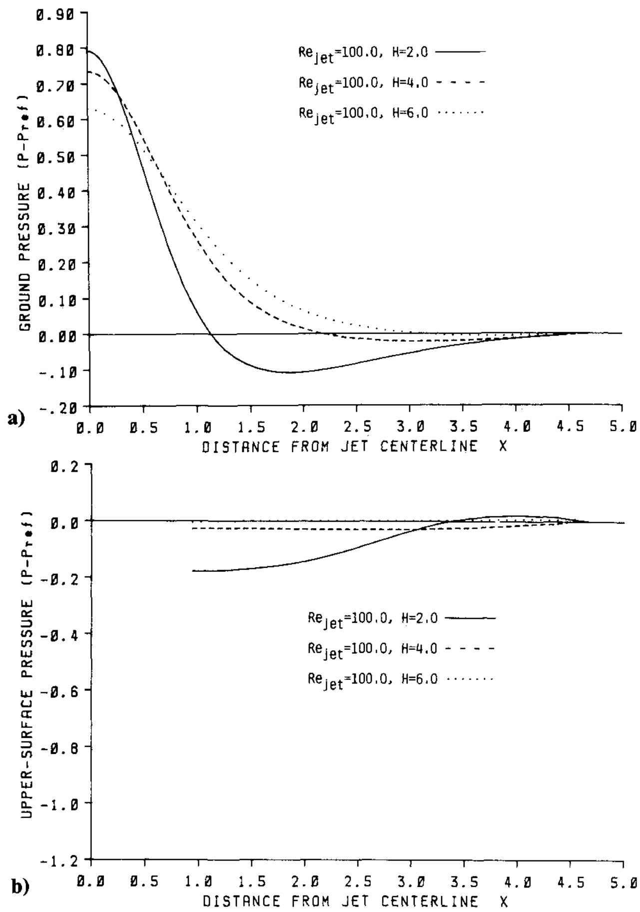

Fig. 6 a) Ground plane and b) upper flat plate pressure distributions for different height of jet above the ground plane.

For the different heights of the jet above the ground plane ($H = 2.0$, 4.0, 6.0), the pressure distributions along the ground plane and upper flat surface are plotted in Fig. 6. When the value of H becomes small, the static pressure at the stagnation point becomes high. The ground plane pressures on either side of the stagnation point are below ambient. These data suggest a strong acceleration in the impingement flow to either side of the stagnation point. Because of the negative pressures along the upper flat surface, the induced suck-down loads for VTOL aircraft are observed. The negative pressure distributions (with regard to ambient) along the upper flat surface become significant when the distance between the jet and ground plane are small.

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