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Impingement of Rectangular Jets on a Ground Plane

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Nomenclature

D = rectangular nozzle exit width
H = nozzle exit height above ground
L = rectangular nozzle exit length
$\dot{M}$ = momentum flux
N = normal distance above ground
NPR = nozzle pressure ratio
R = radius measured from real or apparent jet impingement point
Re_D = Reynolds number based on rectangular nozzle exit width D
U = wall jet velocity
α_j = jet impingement angle in pitch (rotation about nozzle exit minor axis)
θ_j = jet impingement angle in roll (rotation about nozzle exit major axis)
ϕ = azimuthal angle measured around periphery of jet impingement region; if α_j or $\theta_j \neq 90$ deg, $\phi = 0$ deg in direction of horizontal component of free jet mean flow

Abstract

THE azimuthal distributions of wall jet radial momentum flux have been experimentally determined for the impingement of turbulent jets emanating from rectangular nozzles with exit area aspect ratios between one and eight. Data are presented for parametric variations in nozzle exit height above ground, nozzle pressure ratio, and jet impingement angle caused by rotation of the nozzle about the nozzle exit major and minor axes. The momentum flux distributions were found to be highly directional and sensitive to variations in the above parameters.

Contents

The design of multiple jet V/STOL aircraft for successful operation in ground effect requires a knowledge of the complex viscous flowfields resulting from the interactions of the lift jets, the ground, and the airframe surfaces. The behavior of turbulent flowfields produced by the interaction of multiple lift jets and a ground plane is strongly dependent on the lift jet nozzle geometry, nozzle exit spacing and orientation, jet exit conditions, and nozzle exit height above ground. For the purposes of modeling the mean flow features of these flowfields, much information is available in the literature concerning the impingement of turbulent jets emanating from circular nozzle exits, most notably the work of Donaldson and Snedecker.[1] This work was used extensively in the development of a prediction methodology for multiple jet V/STOL aircraft hovering in ground effect.[2]

However, recent interest in certain propulsive lift systems, such as thrust augmenting ejector systems and other concepts employing noncircular nozzles, has revealed a need for the understanding of the basic free jet and jet impingement characteristics of rectangular exit area nozzles. Consequently, two experimental programs[3,4] sponsored by the NASA Ames Research Center were undertaken to investigate the wall jet characteristics produced by the impingement on a ground plane of jets emanating from low and high aspect ratio rectangular exit area nozzles. The purpose of the studies was to experimentally determine the azimuthal distributions of wall jet radial momentum flux about the impingement points of these jets for rectangular nozzles with exit area aspect ratios (L/D) of 1, 2, 3, 4, 6, and 8 for both vertical and oblique impingement. These momentum flux distributions, together with the magnitudes of the total momentum flux emanating from each nozzle, establish the location and (momentum) strength of the fountains in the flowfield below the aircraft.

Figure 1 presents a qualitative view of the wall jet radial momentum flux ($\dot{M}$) distributions associated with impinging jets issuing from both axisymmetric and rectangular nozzles. As seen in the figure, the axisymmetric nozzle produces a uniform distribution in vertical impingement ($\alpha_j = 90$ deg). In oblique impingement, a peak occurs in the distribution in the $\phi = 0$ deg direction (corresponding to the direction of the horizontal component of the free jet mean flow), with the relative magnitude of the peak increasing with decreasing impingement angle, as shown by Donaldson and Snedeker. The rectangular nozzles in vertical impingement, on the other hand, produce a prominent peak of the momentum flux distribution in a direction normal to the long sides of the nozzle exit, as shown in Fig. 1 by the $L/D = 4$ nozzle. The primary effect of oblique impingement of the rectangular nozzle in pitch (rotation about the nozzle exit minor axis) is to shift the peak to an azimuthal location approximately coincident with the magnitude of the impingement angle. The $L/D = 1$ (square) nozzle exhibits characteristics similar to that

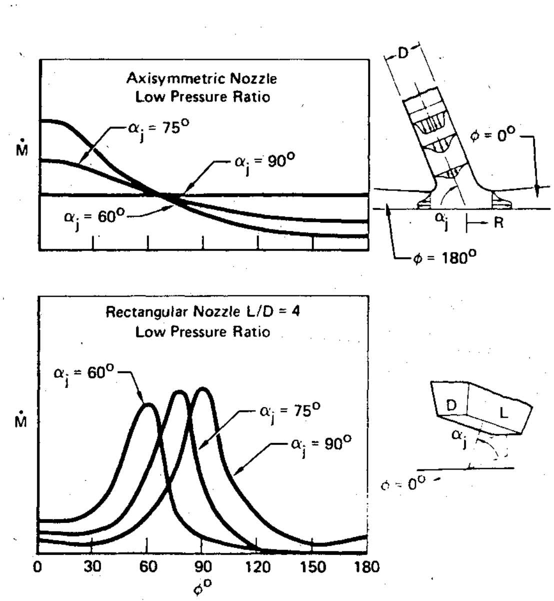

Fig. 1 Jet impingement flowfields.

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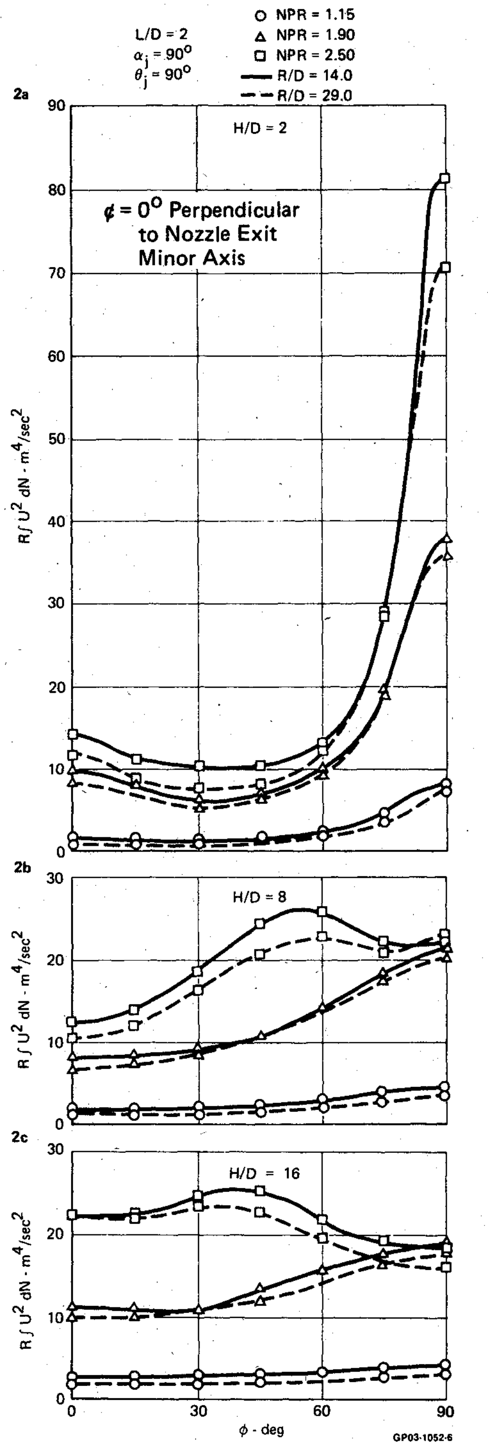

Fig. 2 Azimuthal distribution of wall jet radial momentum flux. $L/D = 2$ nozzle: vertical impingement.

of the axisymmetric nozzle at low pressure ratios. At high pressure ratios, however, the square nozzle exhibits characteristics common to both axisymmetric and rectangular nozzles with a primary peak occurring at $\phi = 0$ deg, as with axisymmetric nozzles, and a secondary peak occurring at an azimuthal angle approximately coincident with the jet impingement angle, as exhibited by rectangular nozzles.

The experimental test programs provided data for the determination of basic and integrated fluid flow properties associated with the impingement of turbulent jets over a range of parameters relevant to the operation of V/STOL aircraft in the hover mode in ground effect. Free jet surveys were performed for each of the nozzles to investigate the quality of the flow issuing from the nozzles and to verify exit flow symmetry. The nozzle exit flows were of low turbulence level and exhibited uniform velocity profiles due to the large contraction ratios of the convergent nozzles. The desired wall jet radial momentum flux distributions were determined by numerical integration of the wall jet velocity profiles, which were obtained by surveying the turbulent wall jets at azimuthal locations about the periphery of the jet impingement region. The wall jet surveys were performed by traversing a dual sensor "cross flow" hot film anemometer probe through a 0.508-cm (0.200-in.) hole in the ground board in a direction perpendicular to the ground board surface, thus allowing the determination of wall jet flow angularity in a plane parallel to the ground plane as well as mean flow velocities. At the radial stations surveyed in this investigation, the nonradial velocities were negligible; however, the azimuthal distributions of radial velocity and momentum flux were found to be highly directional (strong functions of azimuthal angle ϕ). Reynolds number effects (Re_D) were found to be negligible over the range investigated ($146{,}000 \leq Re_D \leq 722{,}000$).

Sample results for an aspect ratio 2 nozzle ($L/D = 2$) in vertical impingement are shown in Fig. 2. The remainder of the experimental data may be obtained from Refs. 3 and 4.

The distributions of wall jet radial momentum flux associated with the impingement of turbulent jets emanating from rectangular exit area nozzles in both vertical and oblique impingement are a strong function of the impingement angle, H/D and the NPR, with the relative peak magnitudes increasing with the decreasing H/D. An azimuthal shift of the wall jet radial momentum flux peak was observed for the case of highly underexpanded nozzle exit flow at the greater nozzle exit heights above ground.

Acknowledgments

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