Tracer Particle Flow in a Compressor Rotor Passage with Application to LDV

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Theme

LASER-Doppler velocimetry (LDV) is a noncontact optical technique for determining the velocity of fluids by measuring the velocity of tracer particles entrained in the fluid rather than by measuring the velocity of the fluid itself. To help identify application guidelines of the LDV technique for the aircraft turbomachinery field, a theoretical analysis was conducted of the dynamic behavior of micron-size particles moving in the three-dimensional flowfield of a rotating transonic axial-flow air compressor rotor. The particle-to-gas velocity ratio and angular deviation relative to the gas were determined as functions of particle diameter, mass density, and radial position. It was found that the particles move essentially on gas stream surfaces and that their radial position within the blade channel is independent of their size and mass density. Velocity and angular deviation generally less than 1% and 1° were achieved with 1 g/cc mass density tracer particles with diameters of 1μ or less.

Contents

The flow system analyzed is the three-dimensional gas-particle flow through a transonic axial-flow air compressor rotor. The rotor was designed for a weight flow per unit annulus area of 40.6 lbm/sec-ft^2, a tip speed of 1393 fps, a total pressure and temperature ratio of 1.601 and 1.162 respectively, and a tip solidity of 1.30. The rotor has 44 blades, a leading-edge tip diameter of 1.65 ft, a hub-to-tip radius ratio of 0.504, and a rotational speed of 16,100 rpm. Gas-particle flow was analyzed in a blade channel solution region which is bounded by adjacent blade surfaces and by upstream and downstream boundaries along which the flow is assumed to be uniform. The region extends from a radius of 60 to 94.3% of the blade span as measured from the rotor hub.

The flowfield was analyzed by first numerically[1] determining the magnitude and direction of the gas velocity at all points of the blade channel solution region. Once the gas flowfield was established, the path followed by a particle and its velocity along that path were determined by numerically integrating the equations which govern the relative motion of a particle moving through the blade channel. The force required to accelerate the particle results from the viscous drag and is expressed in terms of an empirically determined drag coefficient[2] which corrects the Stokes drag law for rarefaction, compressibility and inertial effects. It was assumed that the particles are noninteracting, uniformly distributed, and in sufficiently small concentration that they do not alter the gas properties.

To help establish application guidelines for LDV to the aircraft turbomachinery field, the dynamic behavior of several gas-particle mixtures was determined by varying the particle diameter and mass density over ranges encountered in current LDV gas dynamic applications. The particle diameter varied from 0.5-4μ and the particle mass density ranged from 1-4 g/cc. The gas flow was constant throughout the study with a mass flow rate, inlet mass density, and inlet pressure and temperature of 65 lbm/sec, 0.0527 lbm/ft^3, 10.13 psi and 518.4°R, respectively. The rotor speed was 16,100 rpm. The relative gas Mach numbers at the point of particle injection ranged from 1.15 at the 60% span point to 1.31 at the 94.3% span point. The particles had an initial velocity equal to 99% of the corresponding gas velocity and had zero initial angular deviation relative to the gas. Their velocities and trajectories were numerically determined as they progressed through the solution region thereby providing information from which the particle-to-gas velocity ratio and particle angular deviation were determined.

Results from the gas flowfield analysis show that the radial component of velocity is small relative to the axial and relative tangential components, and that the relative inlet flowfield is supersonic while the outlet flowfield is generally subsonic. There is a smooth turning of the flow through the blade channel except for angular deviations near the leading edge of the pressure surface and the trailing edge of the suction surface. The relative Mach number adjacent to the leading edge of the suction surface varies with radius from 1.28 to 1.69, and the relative Mach number adjacent to the trailing edge of the pressure surface varies from 0.346 to 0.687.

The tangential variation of particle-to-gas velocity ratio and particle angular deviation at the leading edge ($1/L = -0.5$), mid channel ($1/L = 0$), and trailing edge ($1/L = 0.5$) is illustrated in Figs. 1 and 2 for particles whose average path radius is 0.7211 ft. The abscissa is the normalized tangential position and is 0 at the suction surface and 1 at the pressure surface. The velocity ratio is defined as the magnitude ratio of the particle velocity to gas velocity V/U where V and U are the absolute particle and gas velocities respectively. Radial

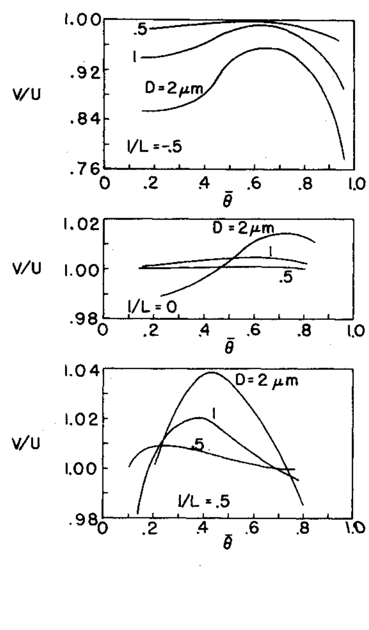

Fig. 1 Tangential variation of particle-to-gas velocity ratio as a function of particle diameter, $\bar{r} = 0.7211$ ft.

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Index categories: Subsonic and Transonic Flow; Nozzle and Channel Flow; Multiphase Flows.

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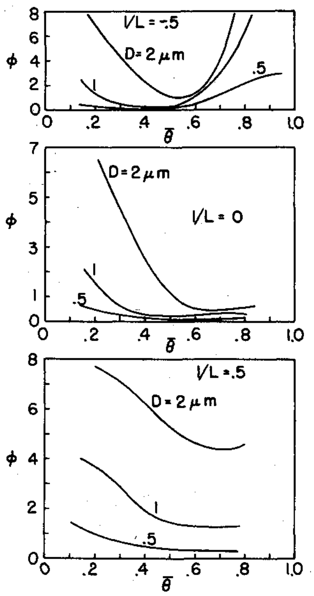

Fig. 2 Tangential variation of angular deviation as a function of particle diameter, $\bar{r}=0.7211$ ft.

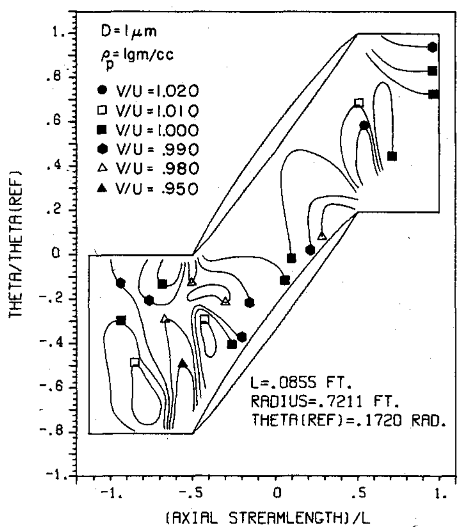

Fig. 3 Contours of constant particle-to-gas velocity ratio.

velocity components are not included in V and U since an LDV system normally views the blade channel from the radial direction. Particle angular deviation ϕ is defined as $\phi = |\alpha_p - \alpha_g|$. The angles α_p and α_g denote the flow angles of the particles and gas, respectively, and are based upon the absolute axial and tangential velocity components. LDV applications typically require that $0.99 < V/U < 1.01$ and $\phi < 0.5°$. Figures 1 and 2, and similar curves in the full paper, indicate that particle velocity lag and angular deviation generally decrease when either the particle diameter decreases, or when the middle of the blade channel is tangentially approached from either blade surface, or when the radial position increases. Results also indicate that velocity lag and angular deviation are more sensitive to a change in particle size than to a corresponding change in mass density. A 2:1 increase in particle size was found to have essentially the same

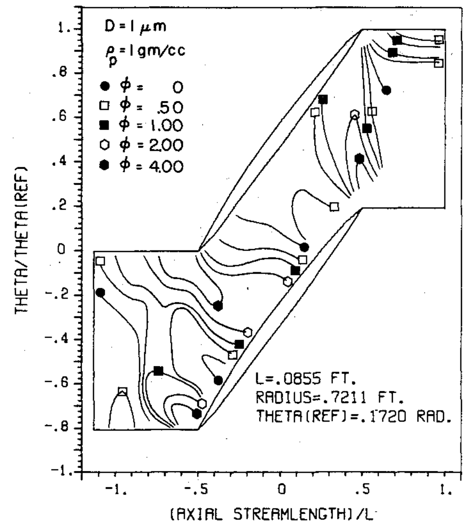

Fig. 4 Contours of constant angular deviation.

effect on particle tracking as a 4:1 increase in mass density. Plotting of particle trajectories on the axial-radial plane shows that the particles move essentially on gas stream surfaces and that their radial position within the blade channel is independent of particle size and mass density.

Figures 3 and 4 illustrate the tracking capability of 1μ diam particles whose average path radius is 0.7211 ft. Tracking is shown by lines of constant velocity ratio and angular deviation. The regions of greatest velocity lag (high and low V/U) occur adjacent to the leading and trailing edges of the suction surface, immediately in front of the pressure surface, and in a narrow oblique area in front of the blade channel. Minimum velocity lag and angular deviation generally occurs near the entrance to the flow region where the gas-particle mixture was introduced, and in the central portion of the blade channel near the pressure surface. The regions of greatest angular deviation occur near the trailing edge of both blade surfaces and near the trailing edge of the suction surface.

While the results illustrated in Figs. 1-4 are quantitatively applicable to the particle diameters and mass densities noted, the results and trends are qualitatively applicable to the entire range of particle properties investigated. The results of the study indicate that LDV applications employing particles with 1 g/cc mass densities and diameters greater than 1μ experience velocity and angular deviations generally greater than 1% and 1°, respectively. These conclusions are very similar to those in a previous study[3] involving subsonic gas flow through a stationary cascade of turbine stator blades.

References

[1]Kurzrock, J. W. and Novick, A. S., "Transonic Flow Around Compressor Rotor Blade Elements, Vol. I: Analysis, Volume II: Digital Program User's Manual," AFAPL-TR-73-69, Aug. 1973, Air Force Aero Propulsion Lab., Wright-Patterson Air Force Base, Ohio.

[2]Carlson, D. J. and Hoglund, R. F., "Particle Drag and Heat Transfer in Rocket Nozzles," *AIAA Journal*, Vol. 2, Nov. 1964, pp. 1980-1984.

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