N86-11438

CALCULATION OF PARTICLE DYNAMICS EFFECTS ON LASER VELOCIMETER DATA

R. H. Nichols
Arnold Engineering and Development Center
Arnold Air Force Station, Tennessee

PARTICLE EQUATION OF MOTION

In order to analytically assess the effects of particle dynamics on laser velocimeter measurements, the particle response to the fluid in which it is entrained must be modeled. At AEDC, the equation of particle motion derived by Maxey and Riley (Ref 1) is used to model the motion of the particle. The equation is derived from the Navier-Stokes equation under the assumption of unsteady Stoke s flow. It should be noted that the Stoke s flow eliminates the need for a far field boundary condition, and hence eliminates any normal (lift) forces.

$$
\begin{aligned}
m_p \frac{dV_i}{dt} = {} & (m_p - m_f)\, g_i + m_f \left.\frac{DU_i}{Dt}\right|_{\vec{Y}(t)} \\
& - \tfrac{1}{2}\, m_f \frac{d}{dt} \left\{ V_i(t) - U_i[\vec{Y}(t), t] - \frac{d^2}{40} \nabla^2 \left. U_i \right|_{Y(t)} \right\} \\
& - \frac{3m_f}{4d} C_D\, \omega_i\, |\omega| - \frac{3\pi}{2} d^2 \mu \int_0^t \frac{\left\{ \frac{d}{d\tau} \omega_i\, [\vec{Y}_i(\tau).\ \tau] \right\}}{\sqrt{\pi\nu\,(t-\tau)}}\, d\tau
\end{aligned}
$$

where

$$\omega_i = V_i(t) - U_i\,[\vec{Y}(t), t] - \frac{d^2}{24} \nabla^2 \left. U_i \right|_{\vec{Y}(t)}$$

$$|\omega| = \sqrt{\sum_i \omega_i^2}$$

$$\left.\frac{DU_i}{Dt}\right|_{\vec{Y}(t)} = \left.\left(\frac{\partial U_i}{\partial x_j} + U_j \frac{\partial U_i}{\partial x_j} \right)\right|_{\vec{Y}(t)}$$

$$\frac{d}{dt} \left\{ U_i\,[\vec{Y}(t), t] \right\} = \left.\left(\frac{\partial U_i}{\partial t} = V_j \frac{\partial U_i}{\partial x_j} \right)\right|_{\vec{Y}(t)}$$

DRAG LAW

To extend this equation to higher particle slip velocities, the Stokes drag is replaced with the particle drag law developed by Barnett and modified to include heat transfer effects by Nichols. The drag coefficient accounts for inertial, rarefaction, compressibility, shape, and heat transfer effects.

$$C_D = 24/Re\ F_1\ F_2\ F_3\ F_4$$

WHERE F_1 = INERTIAL (RE) CORRECTION

F_2 = COMPRESSIBILITY (M) CORRECTION

F_3 = RAREFACTION (KN) CORRECTION

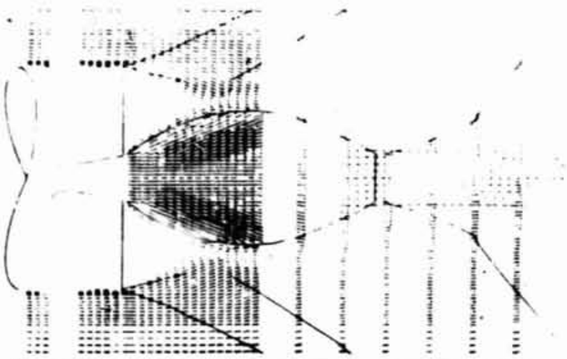
F_4 = SHAPE CORRECTION

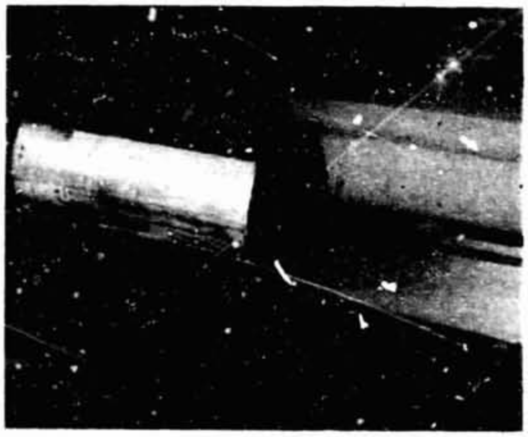
AND

$$Re = \frac{\rho_f\, d \sqrt{\sum_i (U_i - V_i)^2}}{\mu_{app}}$$

BASE FLOW EXPERIMENT

A test conducted in 1983 in the one foot transonic tunnel at AEDC emphasized the problems in the current seeding methodology. A missile base flow field was obtained at M = 1.4 and M = 2.7 at NPR of 50 and 150. Freestream, jet, and base flows were seeded separately with aluminum oxide particles.



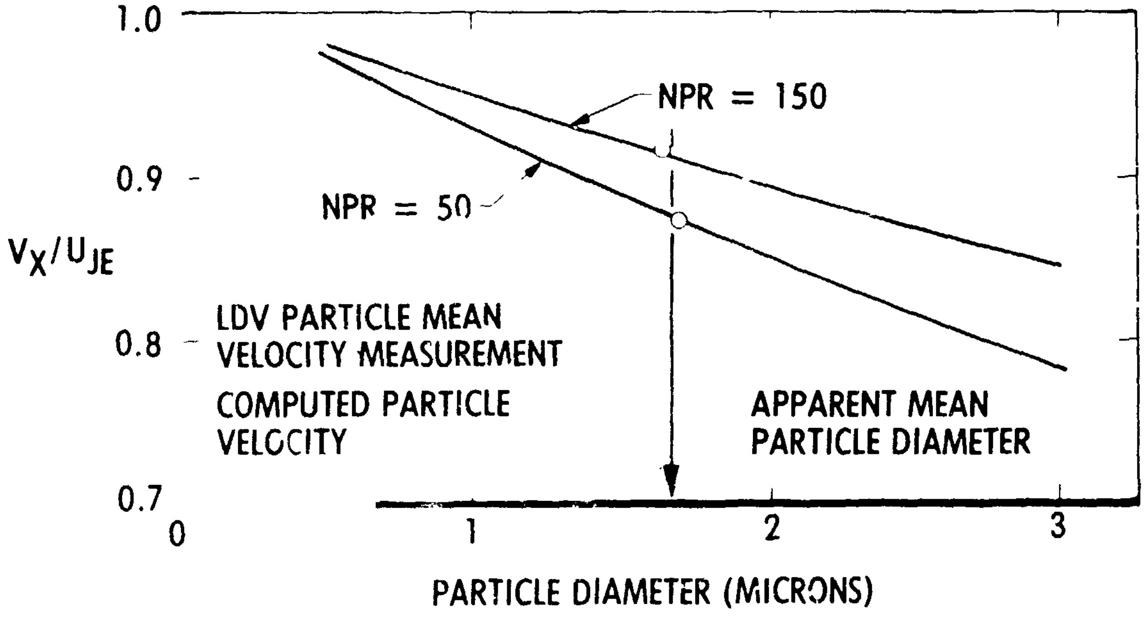


- **FLOWFIELD**
  - $M_\infty = 1.4$
  - $M_j = 2.7$
  - NPR = 50,150
- **SEEDING**
  - FREESTREAM - .3μAl_2O_3
  - JET - .3μAl_2O_3
  - BASE - .3μAl_2O_3, FLUORESCENT
- **MEASUREMENTS**
  - BACKSCATTER
  - SIMULTANEOUS
  - 2 COMP COUNTER
  - 2 COMP DFT

APPARENT PARTICLE DIAMETER

The velocity at the jet exit was much lower than expected from theory. In order to investigate this, particle lag calculations were made at the nozzle exit. These calculations indicated that the actual mean particle size on the centerline was 1.7 micron. Since the particle size limiting streamlines move closer to the nozzle wall as particle diameter decreases, it is expected that the centerline particle distribution will be weighted toward the larger particles. The apparent mean diameter is a function of the particle size distribution present in the flow and the transfer function of the laser velocimeter system.

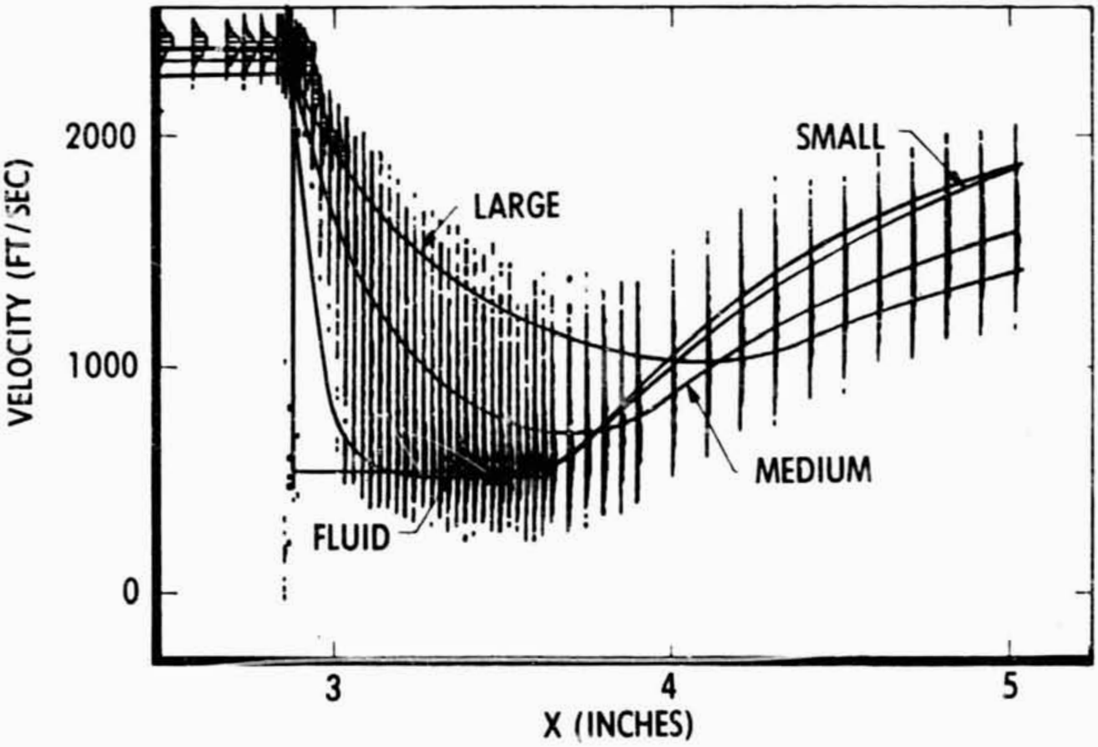
PARTICLE VELOCITY AT THE NOZZLE EXIT CENTERLINE FOR ALUMINUM OXIDE PARTICLES



EFFECTS OF BROAD PARTICLE SIZE DISTRIBUTION

Particle dynamics effects can also be seen when the jet centerline measurements are examined. As the flow continues to expand, the different size particles accelerate at different rates, producing a broad velocity distribution which is often misinterpreted as fluid turbulence. This particle size induced broadening of the velocity distribution is especially noticeable behind the normal shock. It is also interesting to note that in the reacceleration region behind the shock the particle velocity lines cross, again obscuring the real turbulence and the mean velocity.

PARTICLE RESPONSE IN THE REACCELERATION REGION BEHIND A NORMAL SHOCK

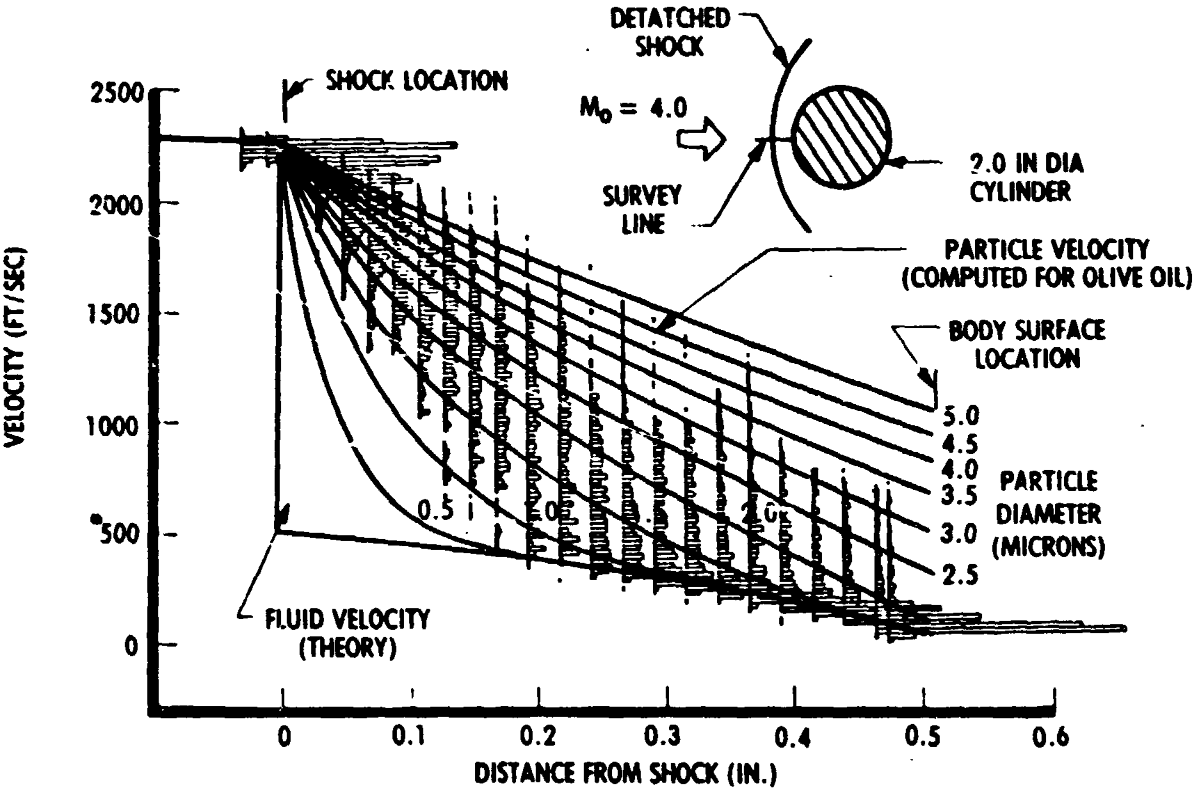


SUPERSONIC TUNNEL LV APPLICATIONS

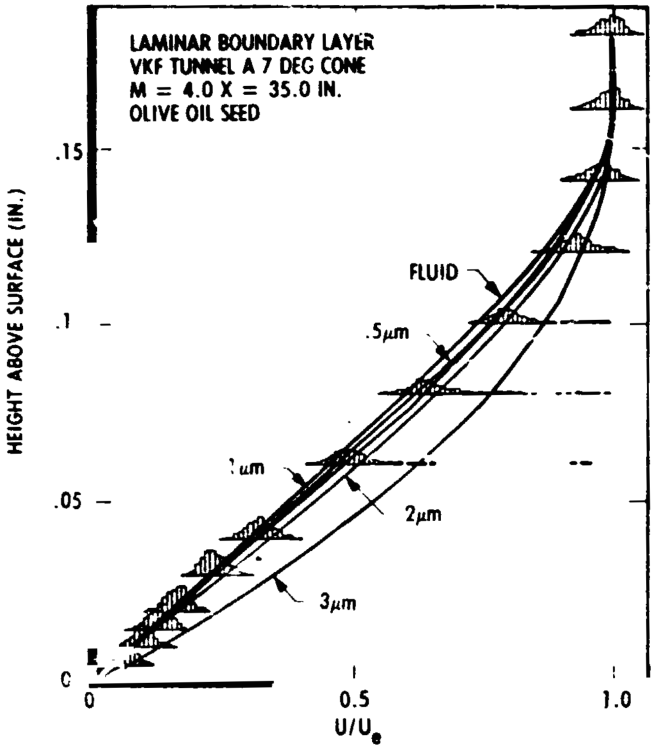
LDV measurements were also obtained in AEDC Tunnel A at M_∞ = 4.0, Re = 0.6 x 10^6/Ft, and 0° angle of attack across the bow shock from a circular cylinder placed normal to the flow. Seeding was done using olive oil in a TSI Model 9306 seeder and in an AEDC developed laskin nozzle seeder. Calculations of particle lag were made to attempt to quantify particle size. The measurements indicate a broad particle distribution with an apparent mean about 1.5 micron. The calculations also indicate that a particle diameter of 0.5 micron would yield adequate mean flow velocity data for the boundary layer, but that a much smaller particle diameter is required for the bow shock measurements. It is interesting to note that the maximum particle lag in the boundary layer occurs in the middle rather that at the bottom of the boundary layer. The calculations did not include particles which had hit the surface and reflected back into the flowfield.

PARTICLE RESPONSE TO SHOCK

VKF TUNNEL A $M_\infty = 4.0$



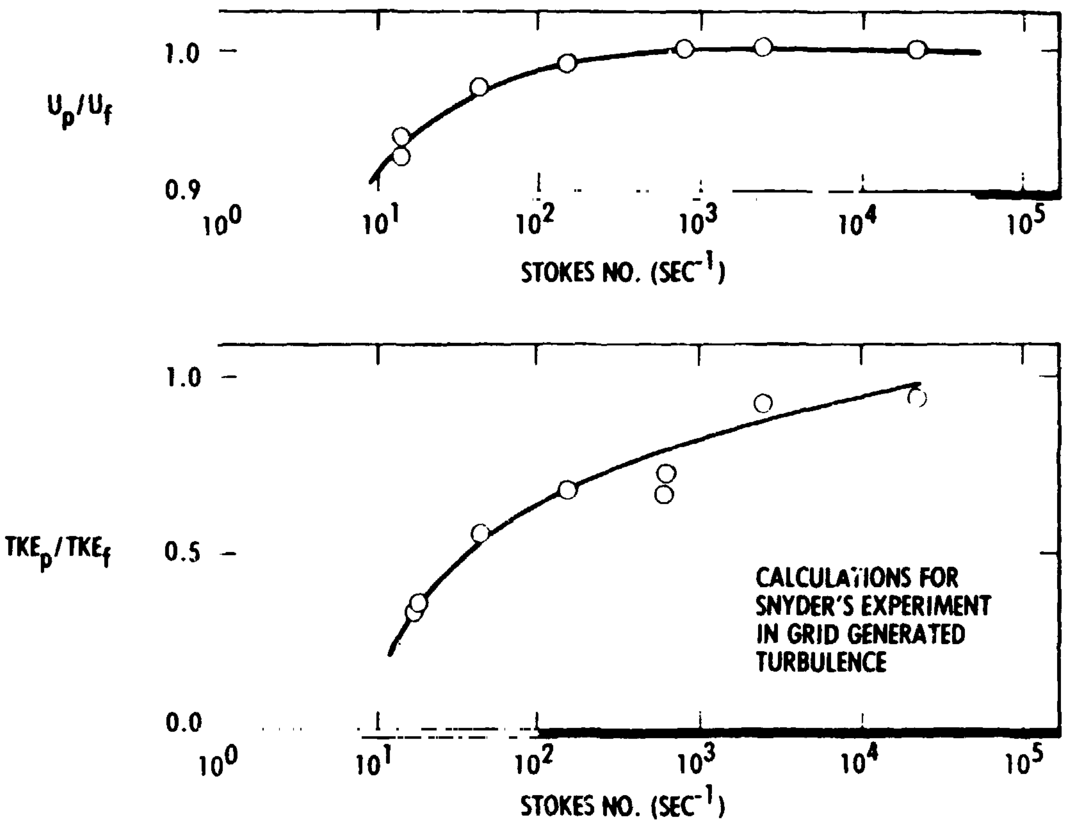
PARTICLE CALCULATIONS AND LDV VELOCITY DISTRIBUTIONS



TURBULENCE MEASUREMENT PARTICLE SIZE REQUIREMENTS

As noted earlier, a broad particle size distribution creates a high apparent turbulence in the presence of a velocity gradient if particle lag occurs. Although a monodisperse particle distribution would alleviate this problem, the diameter must still be chosen so as to assure the particle responds properly to the turbulence. Calculations in low speed grid generated turbulence modeled from Snyder's experiment (Ref 2) indicate that particles may not properly reproduce the turbulent velocity fluctuations even when the mean flow particle lag is zero. For a water particle in air these calculations indicate that while the mean flow velocity can be measured to within less that one percent accuracy with a 46.5 micron particle, the measurement of turbulence quantities to the same level of accuracy would require a 4 micron particle.

PARTICLE SIZE REQUIREMENTS FOR MEAN AND TURBULENT FLOW MEASUREMENTS



CALCULATIONS FOR SNYDER'S EXPERIMENT IN GRID GENERATED TURBULENCE

PARTICLE LAG CORRECTION SCHEME

Under the assumption that only the drag term of the particle equation of motion is relevant, it is theoretically possible to correct LV measurements for particle lag. The correction should be applied along particle path lines calculated from LV measurements. This also requires some method of determining fluid properties. The correction technique is only valid for a known monodisperse particle size, making its application impractical at this time. The technique can be useful in identifying regions of particle lag in a measured flowfield.

1. ASSUMPTIONS:
   - A. ALL TERMS BUT DRAG TERM NEGLIGIBLE
   - B. KNOWN MONODISPERSE PARTICLE SIZE
2. CALCULATE PARTICLE PATHS FROM LDV DATA
3. ITERATIVELY SOLVE FOR FLUID VELOCITY, DENSITY, TEMPERATURE FROM:

$$U_i = V_i + \frac{d^2}{18}\,\frac{(\varrho_p + \frac{1}{2}\,\varrho_f)}{\mu\,\Sigma\,F_i}\,V_i\,\frac{dV_i}{dx_i}\Bigg|_{\text{PATHLINE}}$$

$$G = \frac{\nabla \vec{U}}{\sum\limits_i \left(\frac{U_i}{\Delta x_i}\right)\Bigg|_{i-1}}$$

$$\varrho_i = \frac{\varrho_{i-1}}{1 + G}$$

$$T = T_T - \frac{|U^2|}{2Cp}$$

CONCLUSIONS

- INTERPRETATION OF LDV MEASUREMENTS REQUIRES THE CAPABILITY OF ANALYTICALLY EXAMINING PARTICLE DYNAMICS EFFECTS
- BROAD PARTICLE SIZE DISTRIBUTIONS PRODUCE "ARTIFICIAL TURBULENCE" AND SHOULD BE AVOIDED
- MINIMUM ACCEPTABLE PARTICLE SIZE FOR TYPICAL AEDC LDV MEAN VELOCITY MEASUREMENTS IS LESS THAN 0.5 MICRONS
- ABSOLUTE MINIMUM ACCEPTABLE PARTICLE SIZE IS PROBABLY DRIVEN BY TURBULENCE, NOT MEAN FLOW, REQUIREMENTS
- CORRECTION FOR MEAN FLOW PARTICLE LAG MAY BE FEASIBLE FOR MONODISPERSE SEED PARTICLES

REFERENCES

1. MAXEY, MARTIN R. AND JAMES J. RILEY, EQUATION OF MOTION FOR A SMALL RIGID SPHERE IN A NONUNIFORM FLOW, PHYS OF FLUIDS, VOL 26, NO. 4, PP. 883-889, APRIL 1983.

2. SNYDER, W. H. AND J. L. LUMLEY, SOME MEASUREMENTS OF PARTICLE VELOCITY AUTOCORRELATION FUNCTIONS IN A TURBULENT FLOW, J. FLUID MECHANICS, VOL 48, PART 1, PP. 41-71, JULY 1971.