ABSORPTION FILTER BASED OPTICAL DIAGNOSTICS IN HIGH SPEED FLOWS

Mo Samimy, Gregory Elliott, and Stephen Arnette
Ohio State University
Columbus, Ohio

Laser light scattered by molecules or particles in a flow contains significant information about properties of the flow. Two major scattering regimes are Mie scattering ($d/\lambda \sim 1$) and Rayleigh scattering ($d/\lambda < < 1$), where d is the diameter of the scatterer and λ is the wave length of the incident laser light. While Mie scattering is used to obtain only velocity information, Rayleigh scattering can be used to measure both the velocity and the thermodynamic properties of the flow. Over the years, Mie scattering based measurement techniques such as laser Doppler velocimetry (LDV), to measure flow velocity at a single-point, and phase Doppler particle analyzer (PDPA), to measure both velocity and the size of the scatterer, have been developed and are now routinely used in many laboratories. Further, until very recently, Rayleigh scattering based measurement techniques were only used for density or concentration measurements. However, absorption filter based diagnostic techniques, that were introduced by Miles et al. (1990) in Rayleigh scattering regime and by Komine et al (1991) in Mie scattering regime, have started a new era in flow visualizations, simultaneous velocity and thermodynamics measurements, and planar velocity measurements.

For the past several years, we have actively been pursuing absorption filter based flow diagnostics for flow visualizations, planar velocity measurements, and simultaneous velocity and thermodynamic properties measurements. We have used both Mie scattering and Rayleigh scattering for visualizations in mixing layers (Elliott et al., 1992 and 1995), boundary layers (Samimy et al., 1994 and Arnette et al., 1995), and jets (Reeder, 1994 and Reeder et al., 1995).

In a planar velocimetry technique that we call filtered planar velocimetry (FPV), we have modified the optically thick iodine filter profile of Miles et al. (1990) and used it in the pressure-

broaden regime. This technique provides filter tuning to accommodate measurements in a wide range of velocity applications. We initially used this technique for single-component planar velocity measurements (filtered planar velocimetry, FPV) in mixing layers (Elliott, 1993 and Elliott et al., 1994) and very recently used for two-component planar velocity measurements in boundary layers (Arnette, 1995). We are currently working to advance the technique to full three-component planar velocity measurements.

Measuring velocity and thermodynamics properties simultaneously, using absorption filtered based Rayleigh scattering, involves not only the measurement of Doppler shift, but also the spectral profile of the Rayleigh scattering signal. These measurements require scanning of the laser (for mean value measurements only), multiple observation/scattering angles, or several absorption filters. Miles et al. (1992) have used the first scheme, and Shirley and Winter (1993) have shown the feasibility of the second scheme. We have modified and advanced the technique developed by Shirley and Winter. Using multiple observation angles, we have made simultaneous measurements of one-component velocity and thermodynamics properties in a supersonic jet (Elliott and Samimy, 1995 a & b). Presently, we are extending the technique for simultaneous measurements of all three-component of velocity and thermodynamics properties.

ACKNOWLEDGEMENTS

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Elliott, G.S., Samimy, M., and Arnette, S.A., "A Study of Compressible Mixing Layers Using Filtered Rayleigh Scattering Based Visualizations," AIAA Journal, Vol. 30, No. 10, pp. 2567-2569, 1992.

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Elliott, G.S., Samimy, M., and Arnette, S.A., "The Characteristics and Evolution of Large Scale Structures in Compressible Mixing Layers," Physics of Fluids, Vol. 7, pp. 864-876, 1995.

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Elliott, G.S. and Samimy, M., "A Rayleigh Scattering Technique for Simultaneous Measurements of Velocity and Thermodynamics Properties," submitted to AIAA Journal, May, 1995b.

Komine, H., Brosnan, S.J., Litton, A.B., and Stappaerts, E.A., "Real Time Doppler Global Velocimetry," AIAA-91-0337, 1991.

Miles, R. and Lempert, W., "Flow Diagnostics in Unseeded Air," AIAA-90-0624, 1990.

Miles, R., Forkey, J.N., and Lempert, W., "Filtered Rayleigh Scattering Measurements in Supersonic/Hypersonic Facilities," AIAA-92-3894, 1992.

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Reeder, M.F., Samimy, M., and Elliott, G.S., "An Investigation of the Effect of Tabs on Jets Using Advanced Diagnostics," AIAA-95-0672, January, 1995.

Samimy, M., Arnette, S.A., and Elliott, G.S., "Streamwise Structures in a High Reynolds Number Supersonic Boundary Layer," Physics of Fluids, Vol. 6, pp. 1081-1083, 1994.

Shirley, J.A. and Winter, M., "Air-Mass Flux Measurements Using Doppler-Shifted Filtered Rayleigh Scattering," AIAA-93-0513, 1993.

OUTLINE OF PRESENTATION

O **ABSORPTION FILTER BASED OPTICAL DIAGNOSTICS**

    O   Filtered Rayleigh Scattering (FRS)

    O   Filtered Planar Velocimetry (FPV/PDV/DGV)

    O   Filtered Angularly Resolved Rayleigh Scattering (FARRS)

O **ABSORPTION FILTER BASED OPTICAL DIAGNOSTICS AT AODL**

    O   FPV in Compressible Mixing Layers and Supersonic Boundary Layers

    O   FARRS in Supersonic Jets

O **CURRENT ACTIVITIES AND NEAR FUTURE PLANS**

ABSORPTION FILTER BASED OPTICAL DIAGNOSTICS

O **FILTERED PLANAR VELOCIMETRY (FPV)**

    O   The Scattering Medium

        ▶   Particles(d ~50 nm)

    O   The Light Source

        ▶   Injection Seeded Pulsed Nd:YAG Laser @ $\lambda = 532$ nm

    O   The Molecular Filter

        ▶   Optically Thick & Pressure Broadened (Tuning Capability for the Velocity Range)

    O   The Recording Devices

        ▶   Scientific Grade ICCD Cameras

ABSORPTION FILTER BASED OPTICAL DIAGNOSTICS

O   FILTERED PLANAR VELOCIMETRY (FPV)

    O   FPV Results in Compressible Mixing Layers & Comparison with LDV Results

    O   Uncertainty Assessment

    O   FPV Results in Supersonic Boundary Layers & Comparison with LDV Results

FPV RESULTS IN COMPRESSIBLE MIXING LAYERS
WITH $M_c = 0.86$ ($M_1 = 3$ & $M_2 = 0.5$)
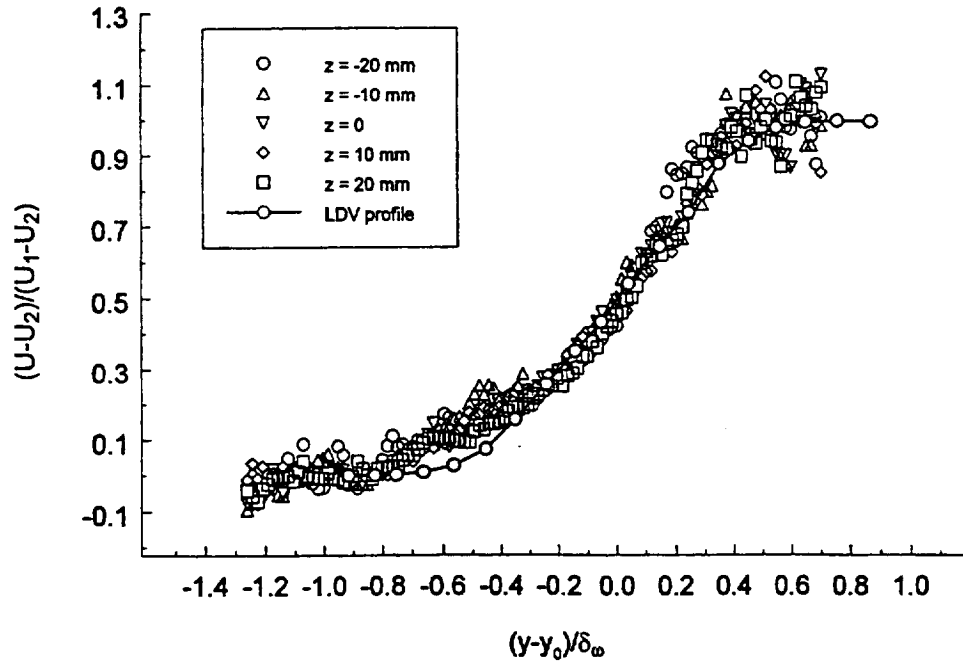## TWO-CAMERA/ONE-COMPONENT VELOCITY

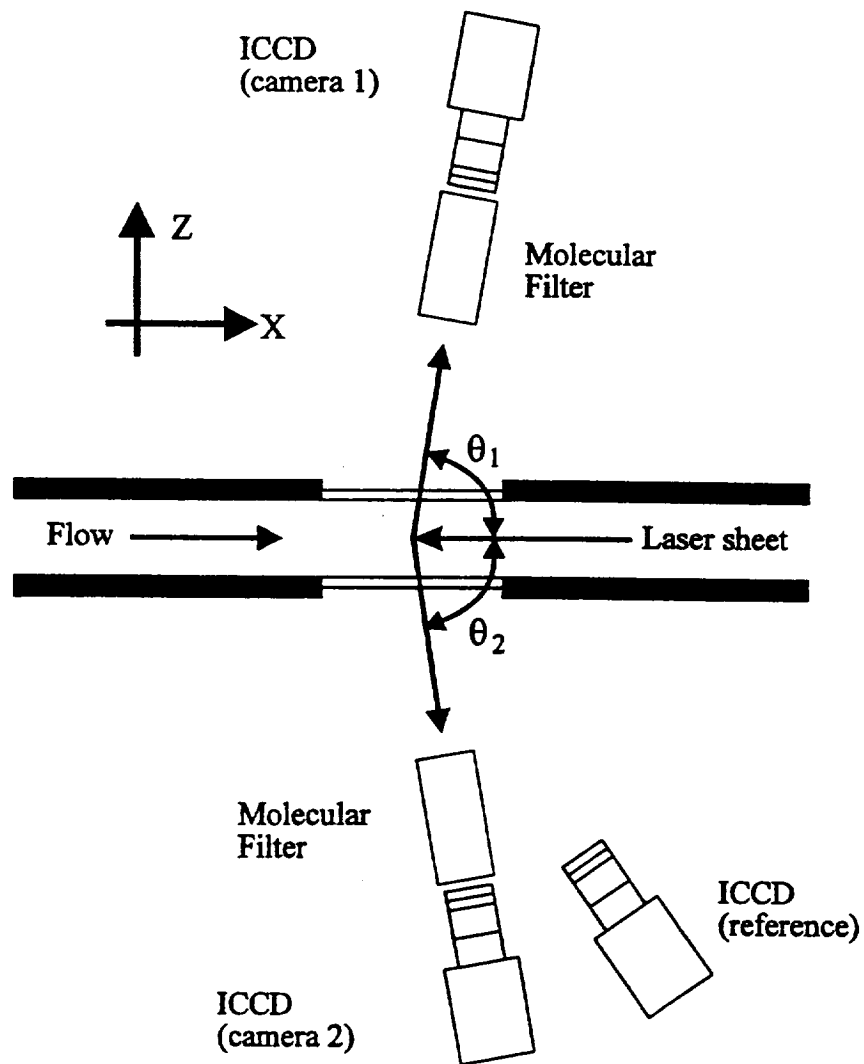# Laser and Camera Arrangement
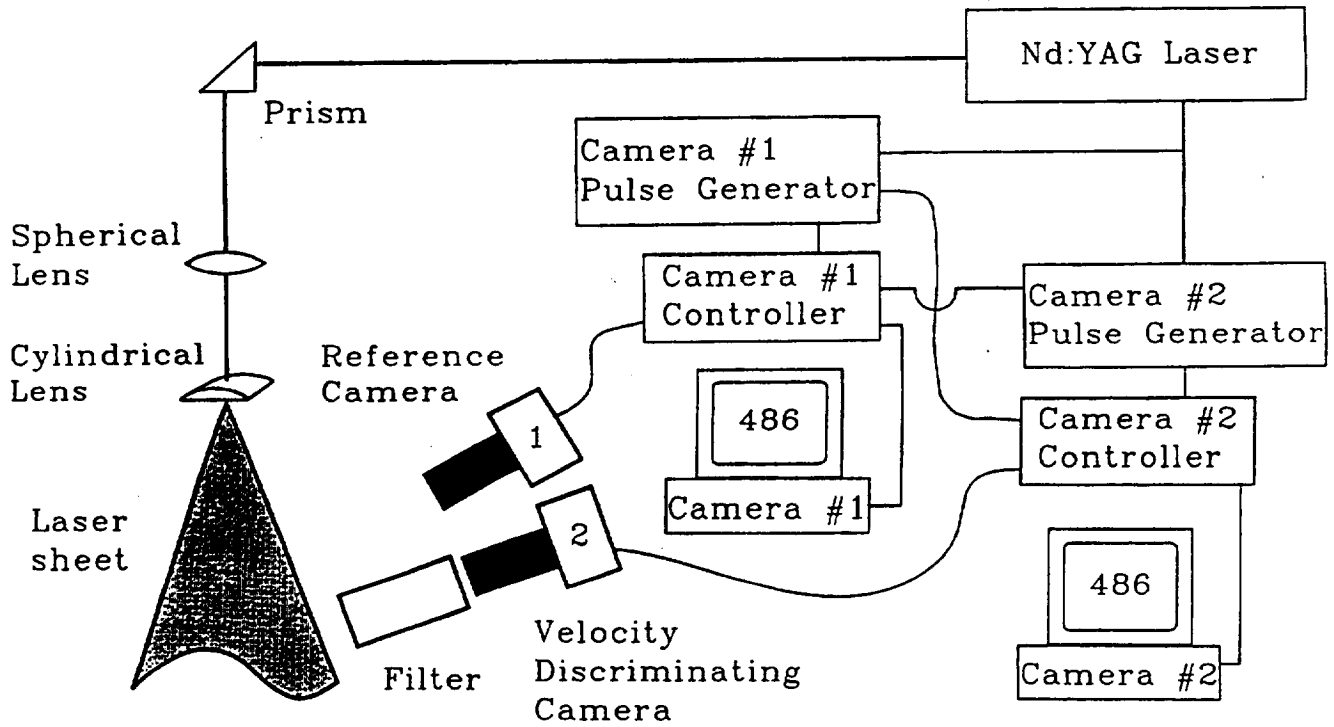
Reference and Velocity Images
$M_c = 0.86$, oblique view
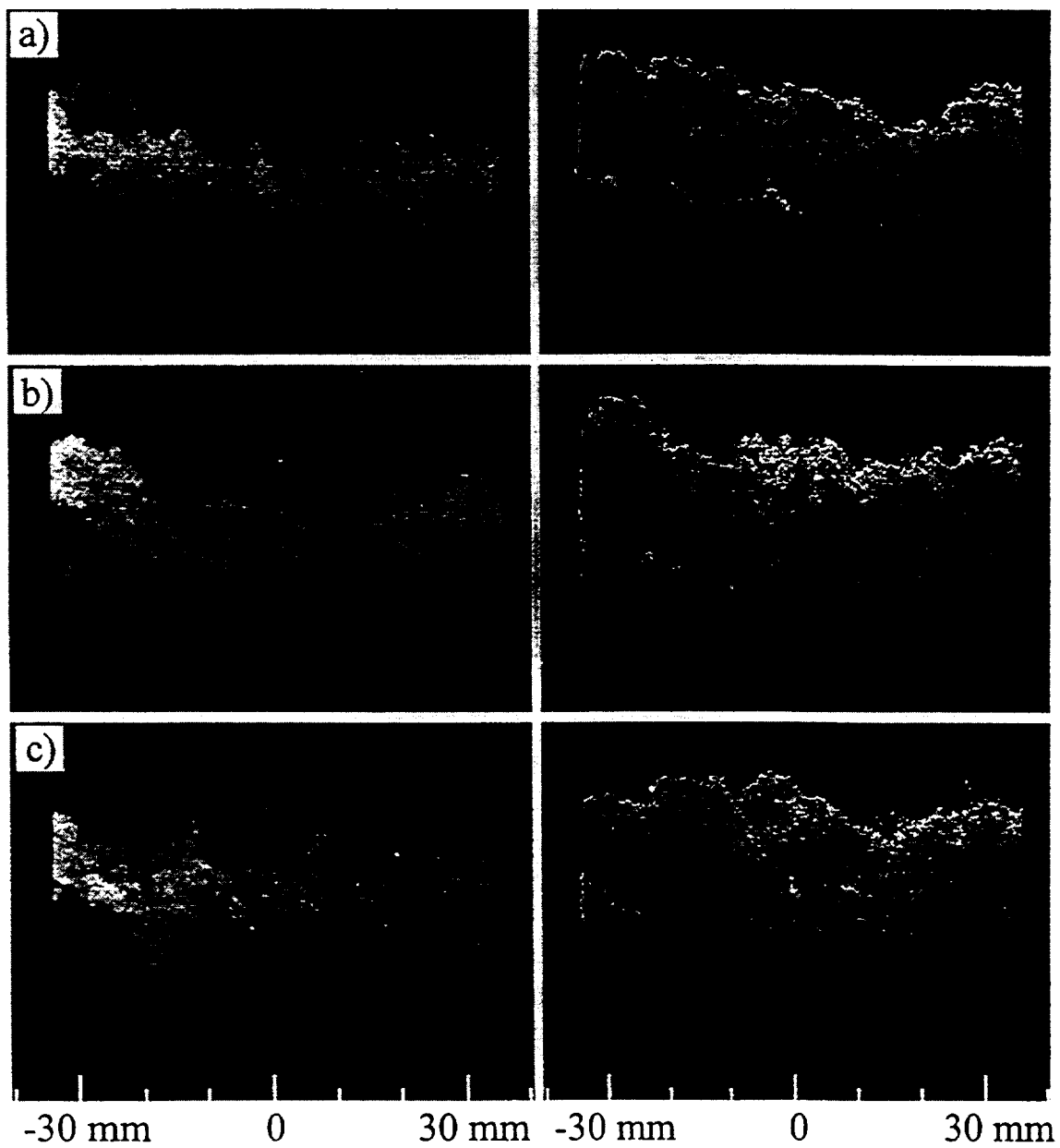
Normalized Streamwise Velocity
$M_c = 0.86$

Plot axes: y-axis $(U-U_2)/(U_1-U_2)$ ranging from -0.1 to 1.3; x-axis $(y-y_0)/\delta_\omega$ ranging from -1.4 to 1.0.

Legend:
- $\circ$ z = -20 mm
- $\triangle$ z = -10 mm
- $\triangledown$ z = 0
- $\diamond$ z = 10 mm
- $\square$ z = 20 mm
- —$\circ$—   LDV profile

Uncertainty for Filtered Planar Velocimetry

Sources of Error	Maximum % error in Vel.: $M_c = 0.51$	Maximum % error in Vel.: $M_c = 0.86$
I'	1.17	1.70
I_0	1.20	1.70
ϕ_D	1.74	0
γ_D	0	0.87
θ_D	2.46	0.87
b_A	6.17	5.41

FPV RESULTS IN SUPERSONIC BOUNDARY LAYERS
WITH $M_\alpha = 3$
THREE-CAMERA/TWO-COMPONENT VELOCITY
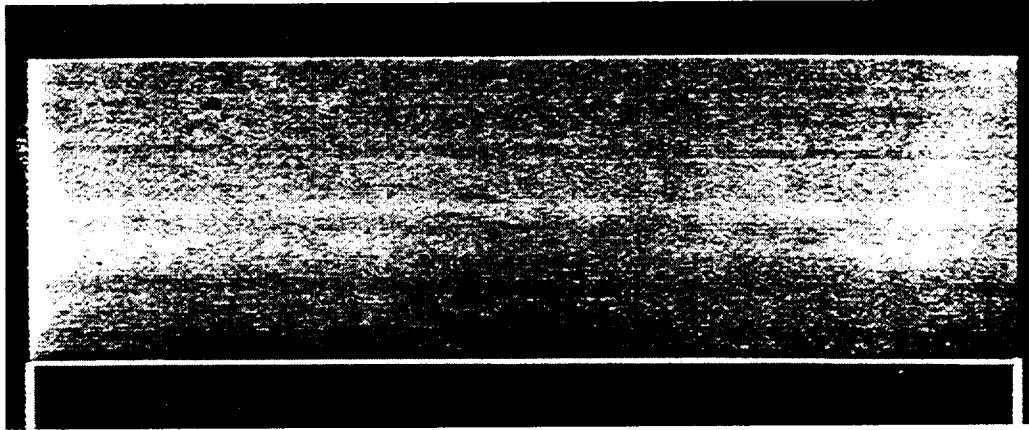
$s / \delta_0 = 0.0$ $s / \delta_0 = 8.8$
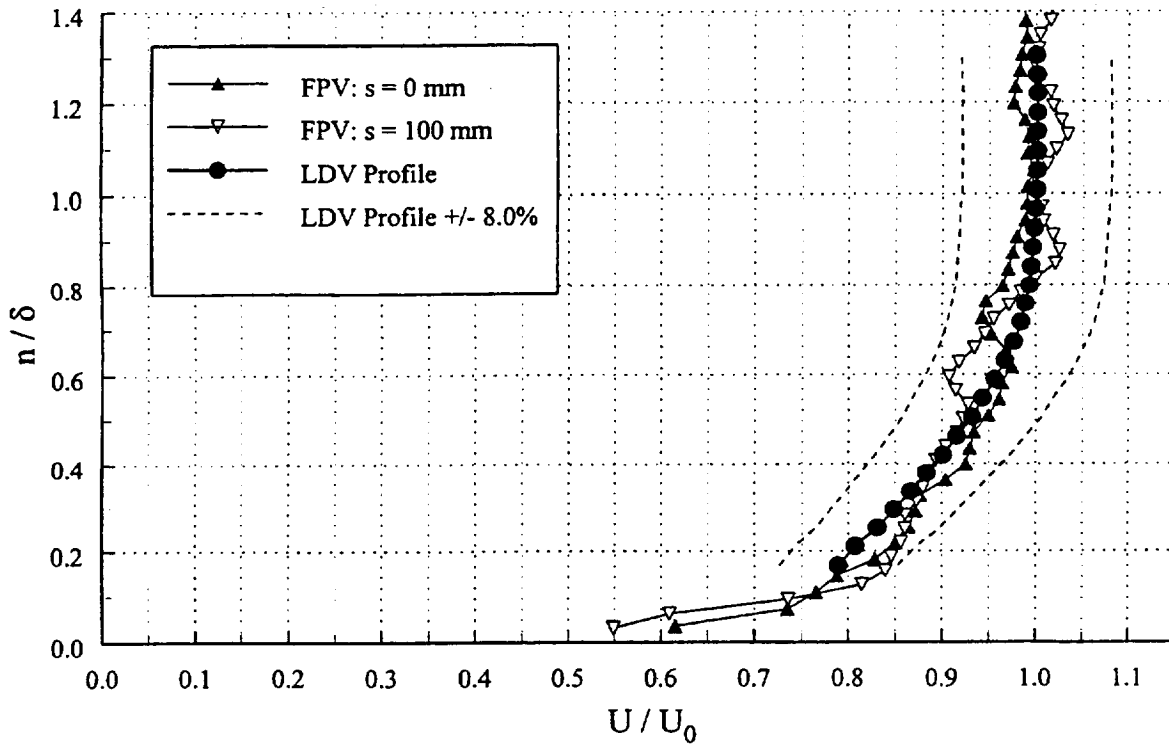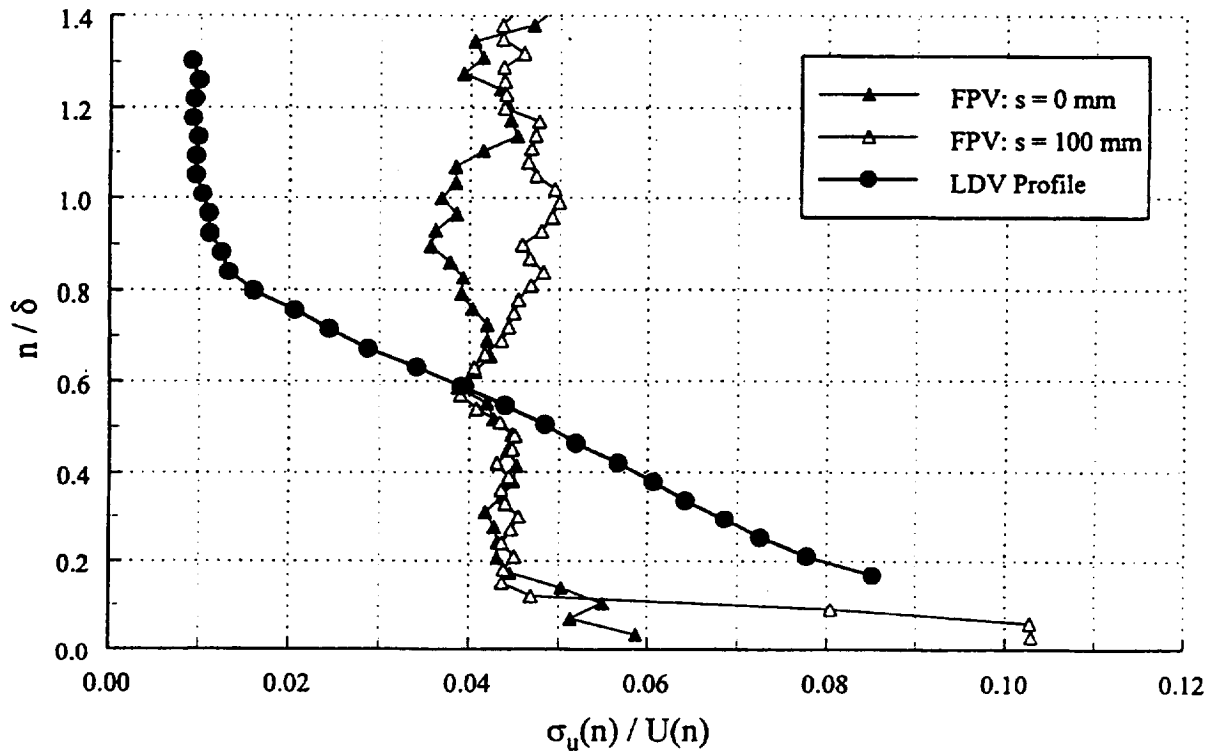
Figure: Plot of n/δ versus $\sigma_u(n)/U(n)$ with legend — FPV: $s = 0$ mm, FPV: $s = 100$ mm, LDV Profile.

ABSORPTION FILTER BASED OPTICAL DIAGNOSTICS

O   FILTERED ANGULARLY RESOLVED RAYLEIGH SCATTERING (FARRS)

   O   The Scattering Medium

   ▶   Air Molecules

   O   The Light Source

   ▶   Injection Seeded Pulsed Nd:YAG Laser @ $\lambda = 532$ nm

   O   The Molecular Filter

   ▶   Optically Thick Filter

   O   The Recording Devices

   ▶   Scientific Grade ICCD Cameras

ABSORPTION FILTER BASED OPTICAL DIAGNOSTICS

O   FILTERED ANGULARLY RESOLVED RAYLEIGH SCATTERING (FARRS)

   O   Experimental Procedure for One-Component Velocity and Thermodynamics
       Properties Measurements

   O   Results in Supersonic Jets & Comparison with Theoretical Results

   O   Uncertainty Assessment

   O   Current Activities on Three-Component Velocity and Thermodynamics
       Properties Measurements in Supersonic Jets

Filtered Angularly- Resolved Rayleigh Scattering (FARRS)
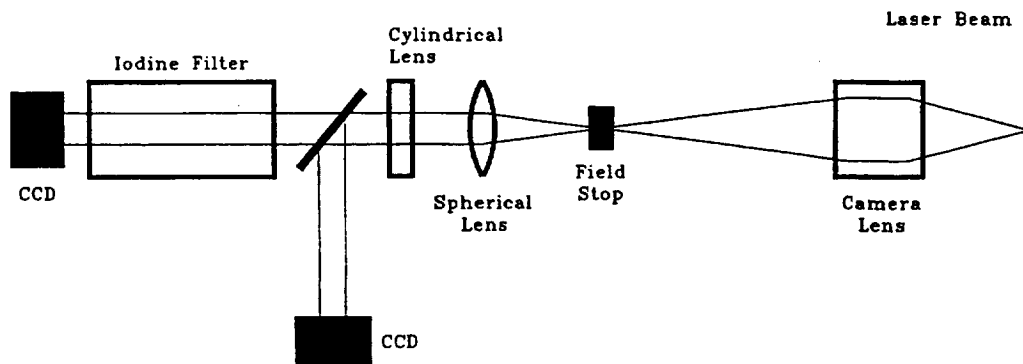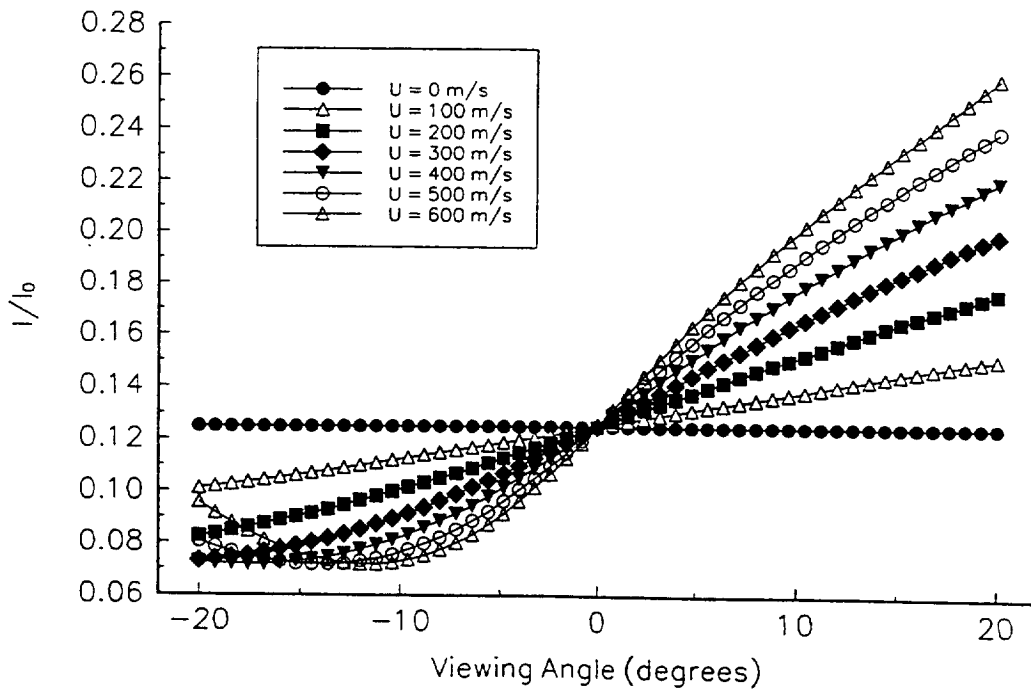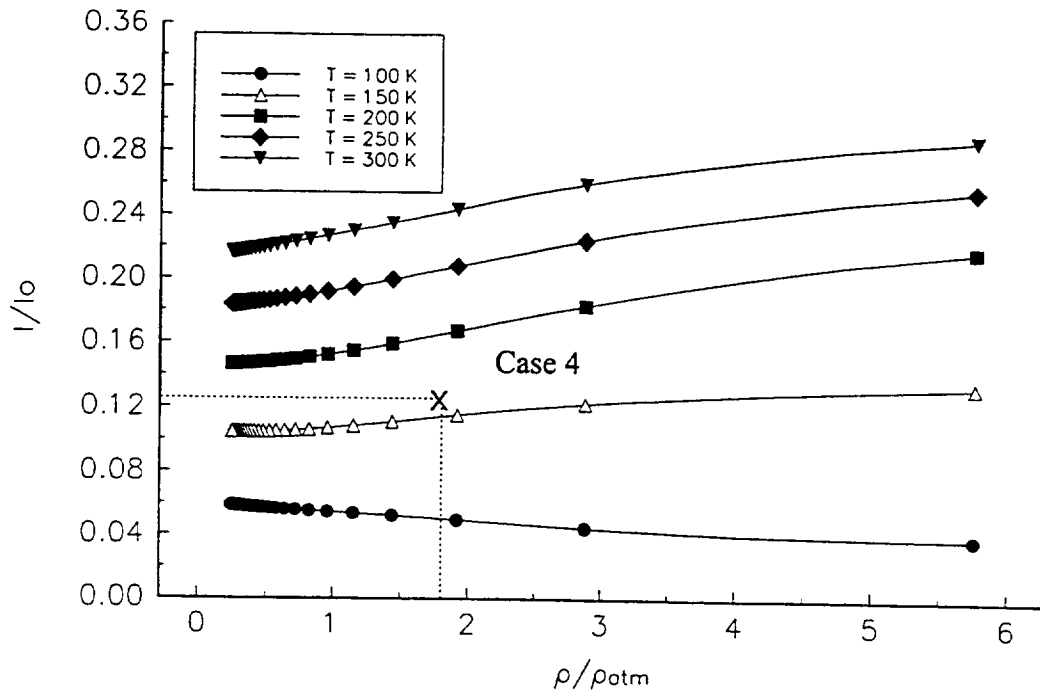
Image Processing

Image without Filter
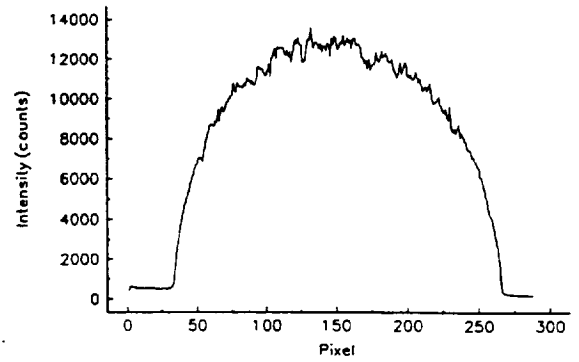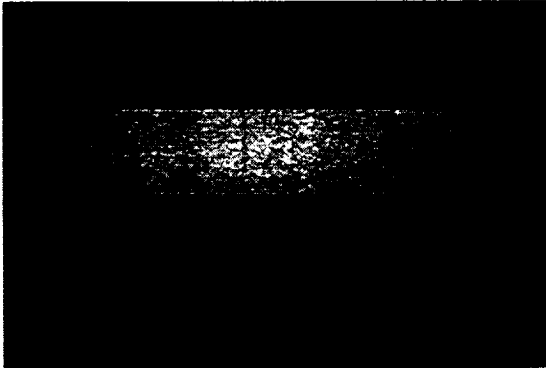
Image with Filter
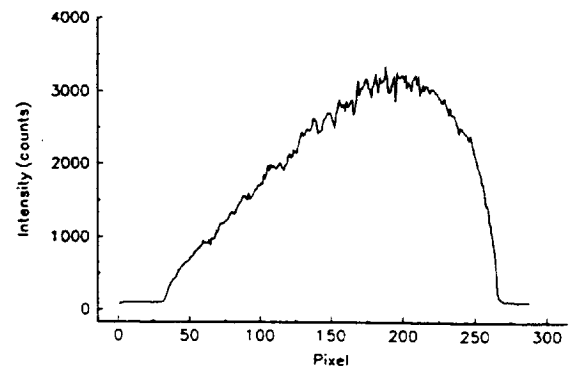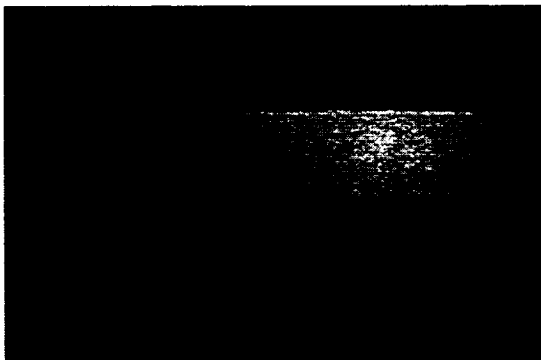
Normalized Image
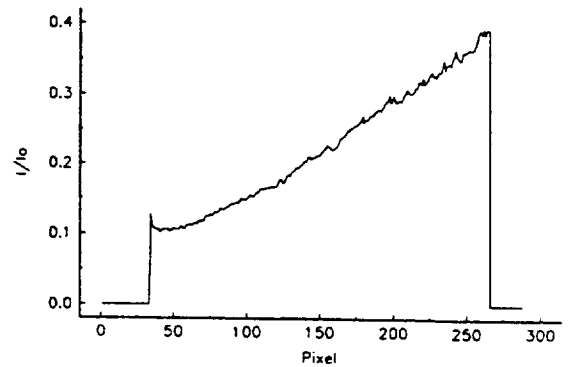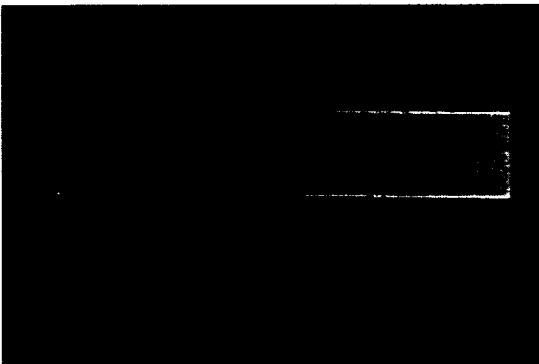
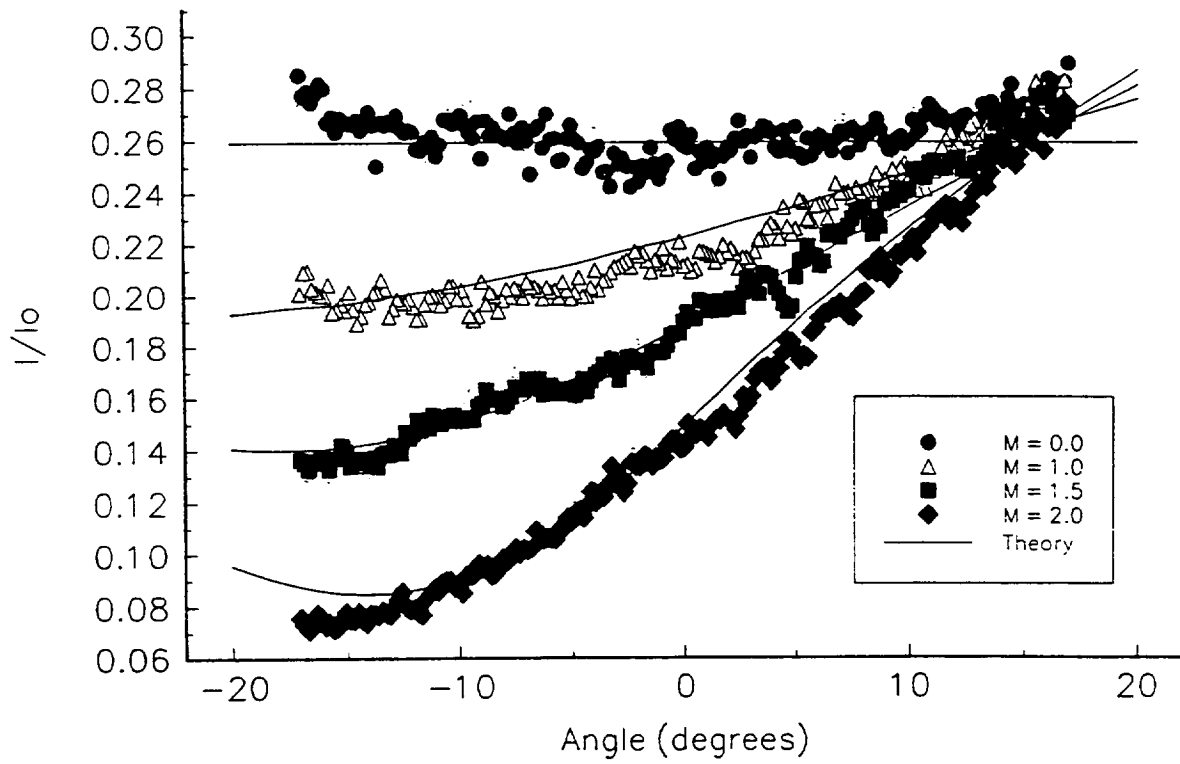# RESULTS IN SUPERSONIC JETS & COMPARISON WITH THEORETICAL RESULTS
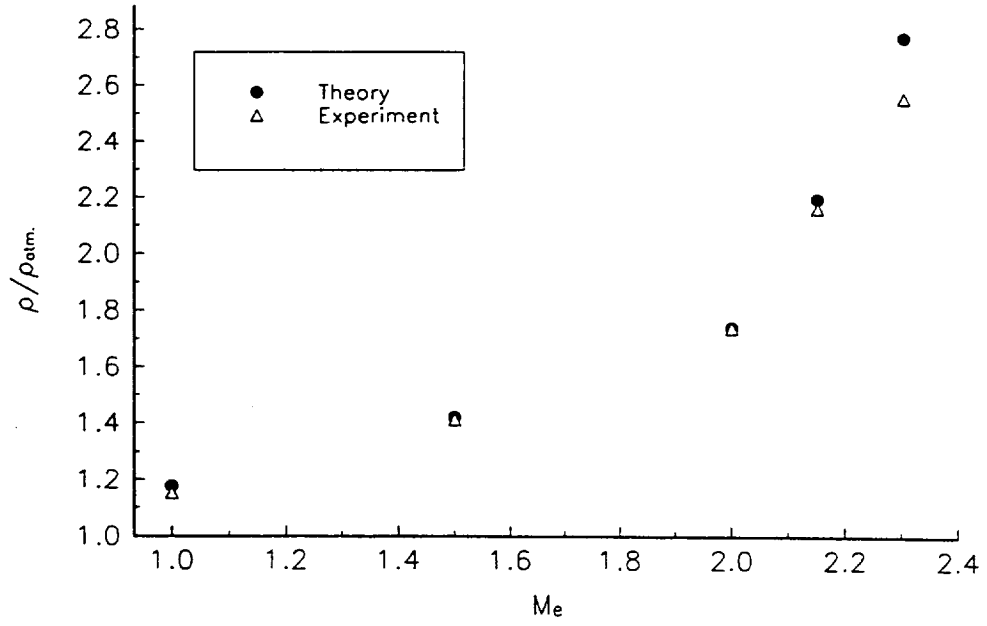## FULLY EXPANDED M = 1, 1.5, & 2
UNDEREXPANDED M = 2 @ 2.15 & 2.3

Run Conditions for Perfectly Expanded
and Underexpanded Axisymmetric Jet

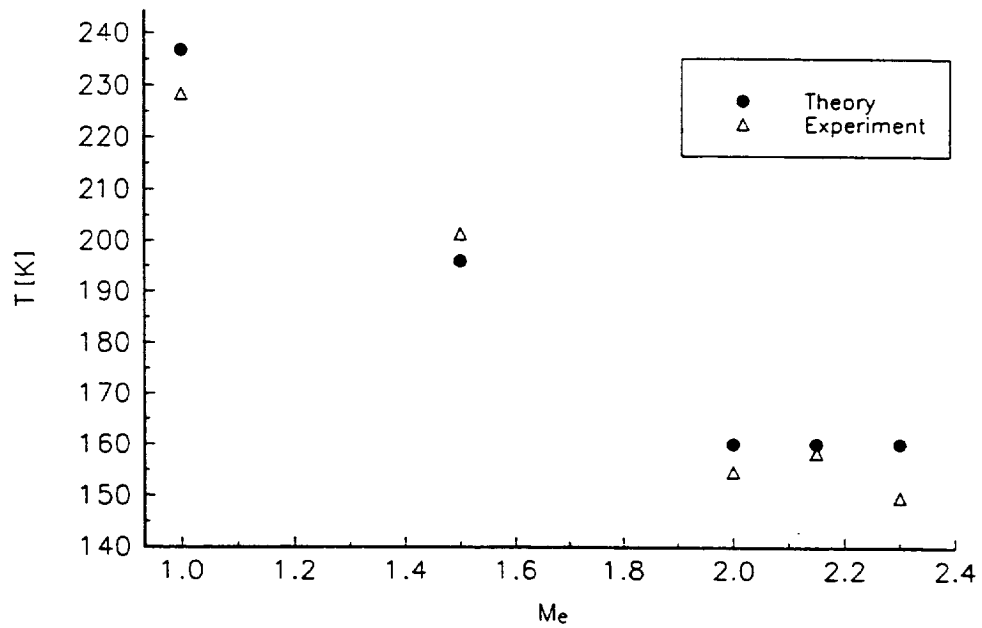| Case	M_e	T_0 [K]	P_0 [kPa]	U [m/s]
1	0.0	288	0.0	0.0
2	1.00	288	191.8	308.4
3	1.50	288	372.0	420.8
4	2.00	288	793.0	507.1
5	2.15	288	1002.0	507.1
6	2.30	288	1266.9	507.1

Intensity Profiles
Perfectly Expanded Jet
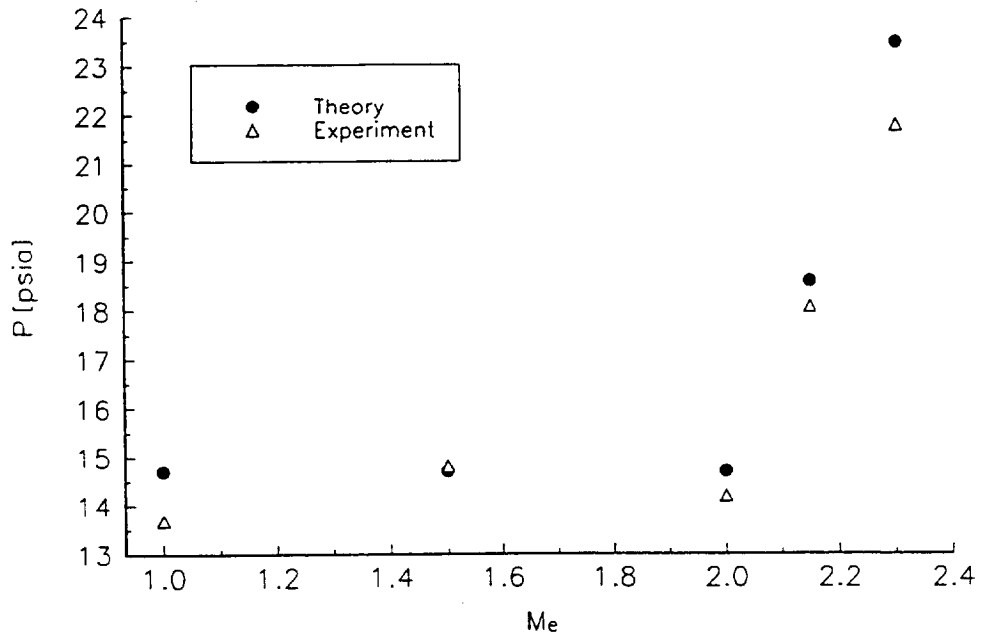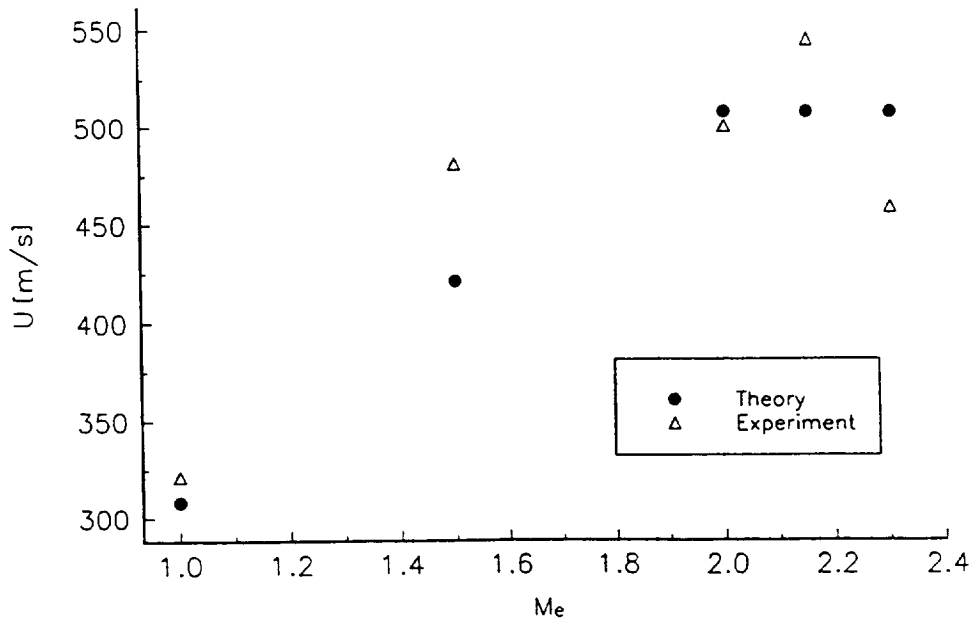
Density

Temperature

Pressure

Streamwise Velocity

Uncertainty for velocity an thermodynamic properties.

Error Source	Maximum Error in U %	Maximum Error in T %	Maximum Error in ρ %	Maximum Error in P %
I	1.5	1.2	4.0	1.2
α	0.07	0.01	-	0.01
ρ	3.1	0.44	-	3.6
f_0	9.5	5.63	-	5.6
A_i	1.3	0.60	-	0.55
Total	9.7	5.7	4.0	6.2

CURRENT ACTIVITIES

O   Extending FPV to Three-Camera Configuration for Simultaneous Measurements of all Three Components of Instantaneous Velocity on a Plane

O   Extending FPV to Three-Camera Configuration for Simultaneous Measurements of all Three Components of Instantaneous Velocity and Thermodynamics Properties on a Point

O   Improving Accuracy and Robustness of the Techniques

NEAR FUTURE PLANS

O   To Advance FRS & FPV to Real-Time Visualizations and Measurements