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FLOW DIAGNOSTICS AND VISUALIZATION IN WIND TUNNELS AND FLIGHT

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[redacted] FLOW DIAGNOSTIC AND VISUALIZATION IN WIND TUNNELS AND FLIGHT

Personnel at the Langley Research Center are conducting research on a variety of flow diagnostic instruments and flow visualization techniques. The figure indicates some of the instruments and techniques being developed and the researchers involved. If additional information is desired on a given subject, the personnel noted should be contacted.

- Conventional testing techniques

Hot wire anemometry

P.C. Stainback
C.B. Johnson

Hot film anemometry

B.J. Holmes
C.J. Obara
D.L. Carraway
J.P. Stack

- Non-intrusive testing techniques

Laser velocimeter (LV)

J.F. Meyers
S.P. Wilkinson

Laser transit anemometer (LTA)

W.C. Honaker
P.L. Lawing

Coherent anti-stokes Raman scattering (CARS)

R.R. Antcliff
O. Jarrett, Jr.
R.C. Rogers

- Flow visualization

Sublimating chemicals

B.J. Holmes
C.J. Obara

FLOW REGIMES FOR HOT-WIRE ANEMOMETRY

At the present time, flow diagnostic work in hot-wire anemometry is being conducted in three flow regimes, namely, incompressible subsonic; compressible subsonic, transonic, and low supersonic (noted hereafter as transonic); and high supersonic and hypersonic (noted hereafter as supersonic) flow regimes. In the incompressible subsonic flow regime, multi-wire probes are used to measure the three components of the fluctuating velocity and total temperature fluctuations. In the transonic flow regime, the longitudinal velocity, density, and total temperature fluctuations are being measured. In the supersonic flow regime, the mass flow and total temperature fluctuations are measured, and for wind tunnel test section disturbances, pressure fluctuations can be computed from these results.

- Subsonic flows - $\tilde{u}$, $\tilde{v}$, $\tilde{w}$, $\tilde{T}_0$
- Transonic flows - $\tilde{u}$, $\tilde{\rho}$, $\tilde{T}_0$
- Supersonic flows - $\tilde{m}$, $\tilde{T}_0$

DATA ANALYSIS TECHNIQUES FOR HOT-WIRE ANEMOMETRY

Much of the hot wire data obtained at Langley is obtained using digital signal analysis techniques since these techniques are much more powerful than analog ones. For example, quantities can be obtained using digital techniques that would be impossible or impractical to obtain using analog methods.

Conditional sampling techniques are used when data are to be taken only when some predetermined condition is satisfied. Using this technique, detail fluctuating quantities can be measured which would otherwise be obscured by other fluctuations in the flow.

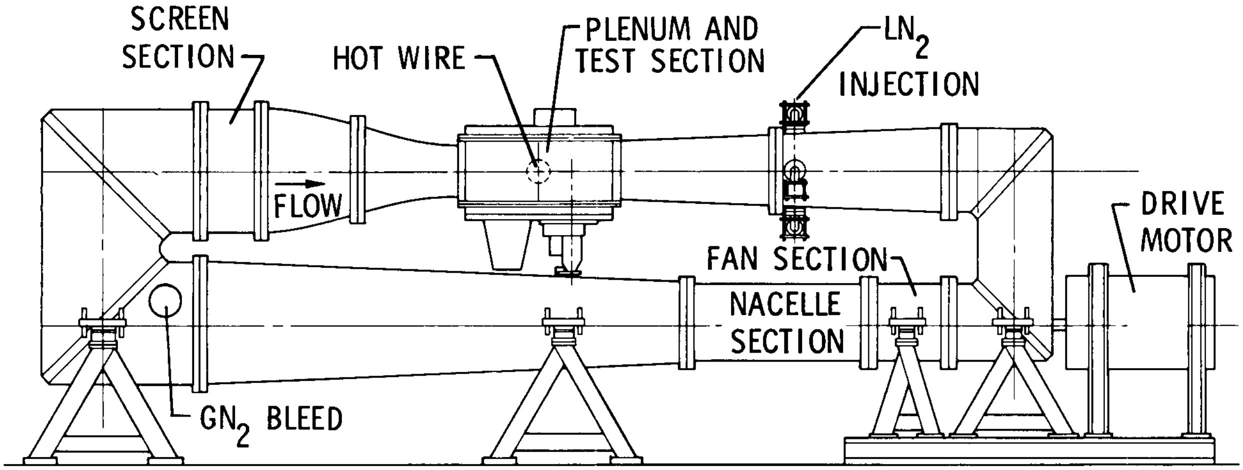
There are cases where assumptions have been made for hot-wire anemometry in order to make measurements in the transonic flow regime. Efforts are under way to determine possible errors introduced into the results using these assumptions.

When the signal-to-noise ratios are low, particularly in low disturbance facilities, methods have been devised in an attempt to separate the signal of interest from the noise.

- Digital signal analysis
- Conditional sampling
- Error analysis
- Correction procedures for electronic noise

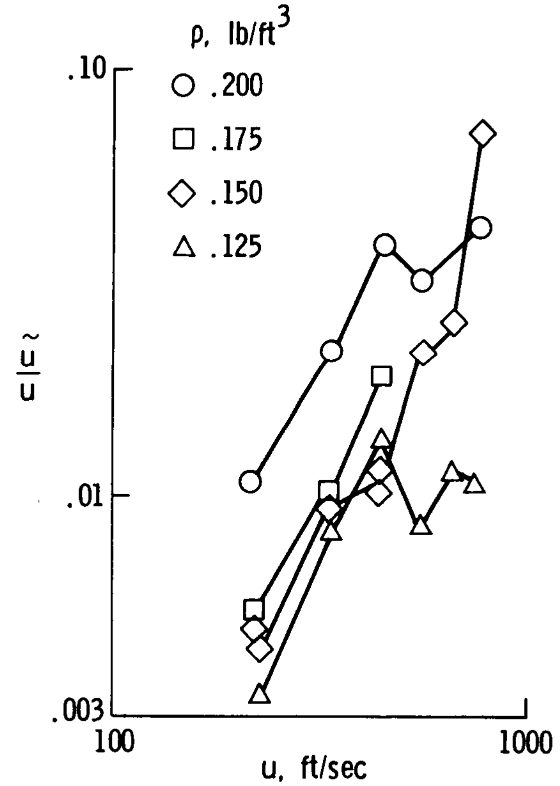
SCHEMATIC OF 0.3-METER TRANSONIC CRYOGENIC TUNNEL

Hot-wire measurements were made in the 0.3-Meter Transonic Cryogenic Tunnel. This facility is a closed-circuit wind tunnel driven by an axial flow fan. Cryogenic conditions are obtained by injecting liquid nitrogen into the circuit just downstream of the test section. The excess mass is removed from the circuit through an exhaust system located just upstream from the settling chamber. The tunnel operates over a Mach number range from about 0.1 to 0.9, a total pressure range from about 20 to 90 psi and a total temperature range from about 100 to 320 K.



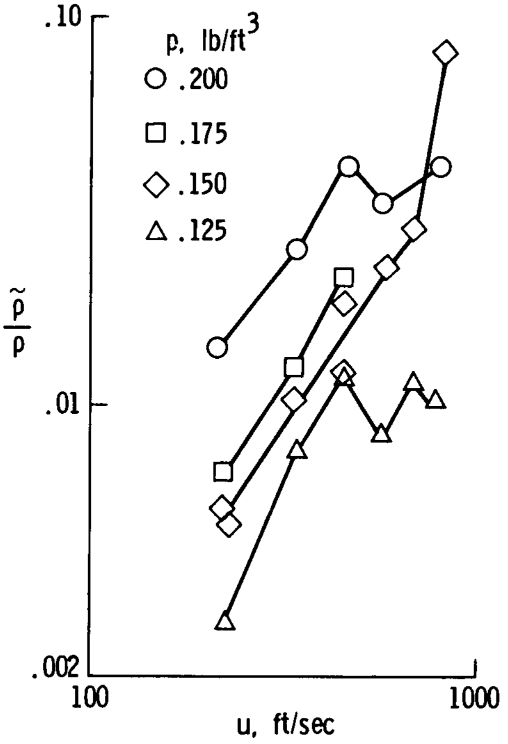
VELOCITY FLUCTUATIONS MEASURED IN THE TEST SECTION OF THE 0.3-METER TRANSONIC CRYOGENIC TUNNEL

Hot-wire measurements were made in the 0.3-Meter Transonic Cryogenic Tunnel using a three wire hot wire probe and using digital analysis techniques to reduce the data. This technique has made it possible to separate the three coexisting fluctuations of velocity, density, and total temperature. The velocity fluctuations increased with both increased velocity and density and the levels were high at the higher velocities and densities - ranging up to four percent.



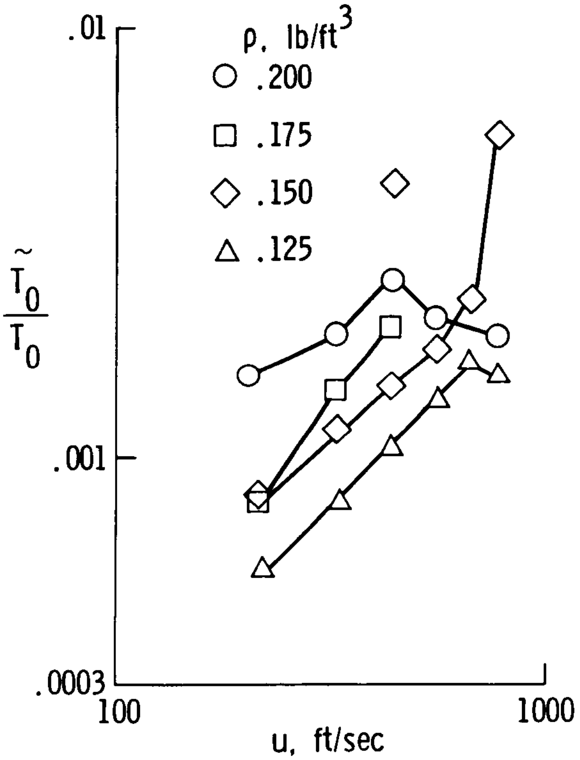
DENSITY FLUCTUATIONS MEASURED IN THE TEST SECTION OF THE 0.3-M TRANSONIC CRYOGENIC TUNNEL

The density fluctuations also increased with increasing velocity and density and had a variation and level very similar to those measured for the velocity fluctuations.



TOTAL TEMPERATURE FLUCTUATIONS MEASURED IN THE TEST SECTION OF THE 0.3-METER TRANSONIC CRYOGENIC TUNNEL

In general, the total temperature fluctuations also increased with increasing velocity and density; however, the levels of the total temperature fluctuations were about an order of magnitude lower than the velocity and density fluctuations. The total temperature fluctuations ranged from about .05 to 0.3 percent.



TESTING TECHNIQUES FOR HOT FILM ANEMOMETRY

Hot film anemometry is a very versatile technique and hot film anemometry has been applied to several fluid dynamic problems. Special probes have been procured to apply the three wire hot-wire technique to hot film anemometry. The probes have not been tested to date.

The hot film technique has been used extensively to detect boundary layer transition and the degree of intermittency in the transition region.

Hot films have been developed into a flow reversal measuring device to obtain data on the location of boundary separation and re-attachment.

If a hot film is properly sized and calibrated, shear stresses can be measured over the flow conditions for which the film is calibrated.

Finally, the hot film technique has also been developed into a cross flow vorticity measuring device. This device will measure the spacing of crossflow vortices, give some indication of the local velocity, and indicate when the vortices cause the laminar boundary to break down into a turbulent one.

- Fluctuating fluid quantities
- Transition detection
- Flow reversal
- Shear stress measurements
- Cross flow vorticity

MULTI-ELEMENT HOT-FILM TRANSITION SENSOR

The accurate measurement of the location where a laminar boundary layer breaks down to a turbulent one serves many purposes. In basic research and in developmental testing, this information is needed for validation of theory and design. For example, a complete understanding of performance and stability and control of a laminar flow airplane requires knowledge of transition locations on wing surfaces, empennage surfaces, fuselage, and nacelles.

One very useful device for large-scale wind tunnel and flight applications is the thin, surface-mounted hot-film gage. Hot films indicate transition responding to the different heat transfers in laminar versus turbulent flow. The advantages of these gages relate to installation flexibility and durability. Since the gages and associated wiring are entirely surface mounted, they may be used on test surfaces which do not permit through-the-surface types of instrumentation. Installed gage thicknesses will not be large enough to cause transition for testing at sufficiently large model scales.

The continuous multi-element hot-film transition gage has been developed by integrating the required number and distribution of hot-film sensing elements into a long, continuous thin sheet. Transition data acquisitions are accomplished using an electronic switching system which allows rapid switching of all sensing elements into the data recording system.

The continuous thin sheet of a particular length covers the area of interest for transition measurements beginning at the leading edge and continuing to downstream of the transition region. For example, on an airplane wing of 10-foot chord length, the gage may be as much as seven to eight feet in length. The leading edge of a gage mounted on the upper surface of a wing would wrap around, beneath, and downstream of the wing leading edge. In this fashion, no disturbance from the film leading edge will cause turbulent wedges to disturb the hot-film sensors in the transition region. For situations where the lateral edges could cause transition, the edges may be filled and faired to correct this difficulty.

The multi-element gages are planned for use on both the NASA Lear 28/29 viscous drag reduction flight experiments and the NASA OV-1 natural-laminar-flow engine nacelle flight experiments.

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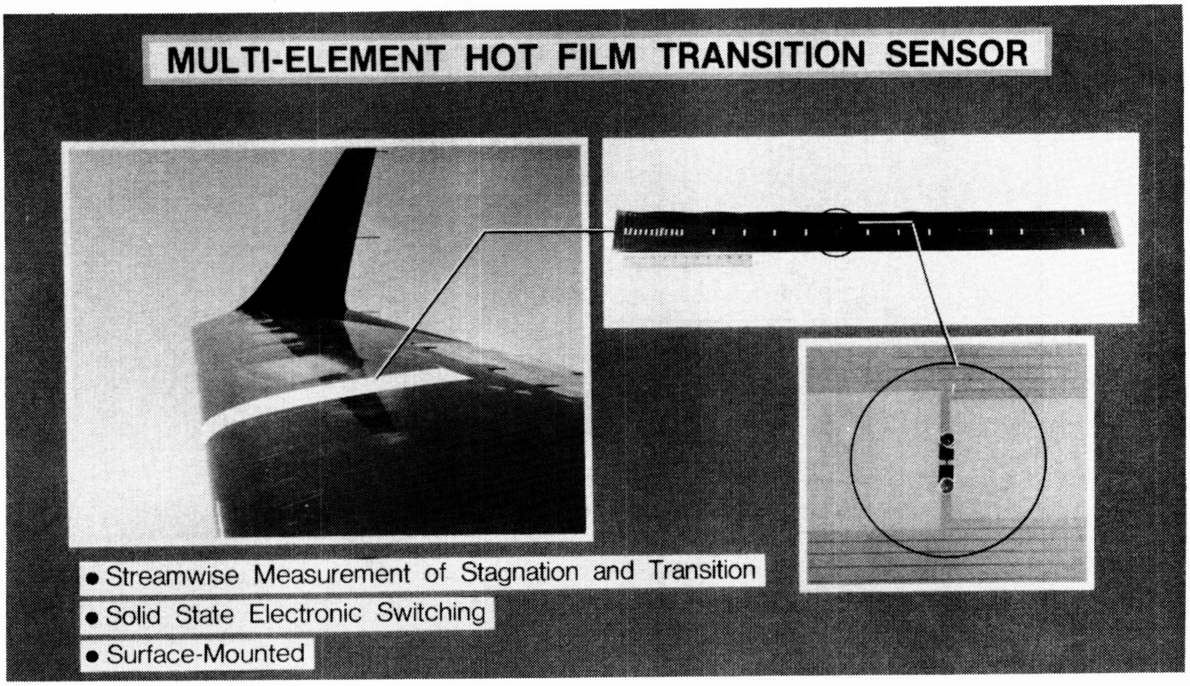


MULTI-ELEMENT HOT FILM TRANSITION SENSOR

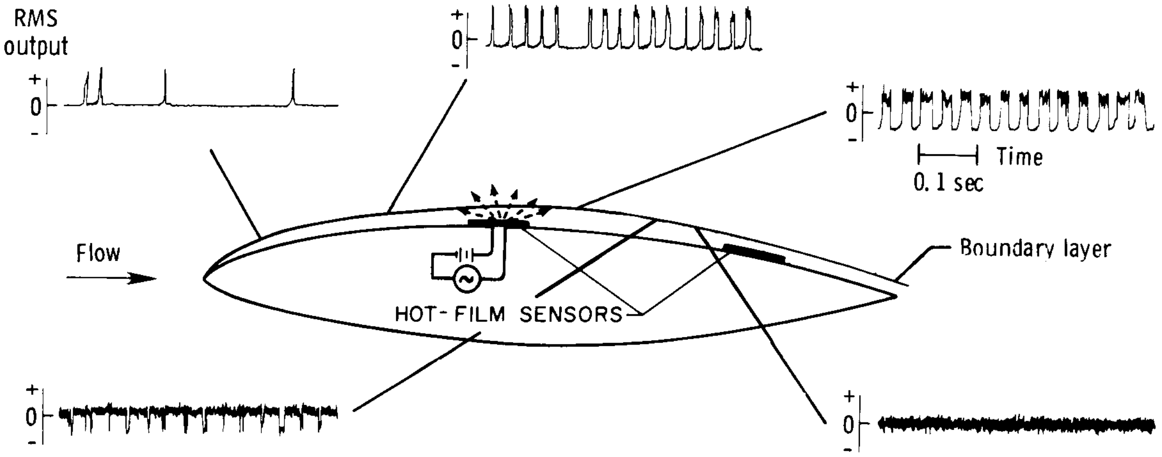
- Streamwise Measurement of Stagnation and Transition
- Solid State Electronic Switching
- Surface-Mounted

LAMINAR AND TURBULENT FLOW INDICATED BY HOT FILMS

Near the leading edge of an airfoil where the boundary layer is laminar, the output from the hot film is very low. As the flow progresses along the wing, the Tollmien-Schlichting waves break down into localized turbulent bursts. These bursts produce a positive voltage spike in the output from the anemometer. Farther down the airfoil, the rate of turbulent bursts increases until the flow is approximately fifty percent laminar and fifty percent turbulent. After this, the flow becomes almost completely turbulent with an occasional laminar burst. Finally, the boundary layer becomes completely turbulent.

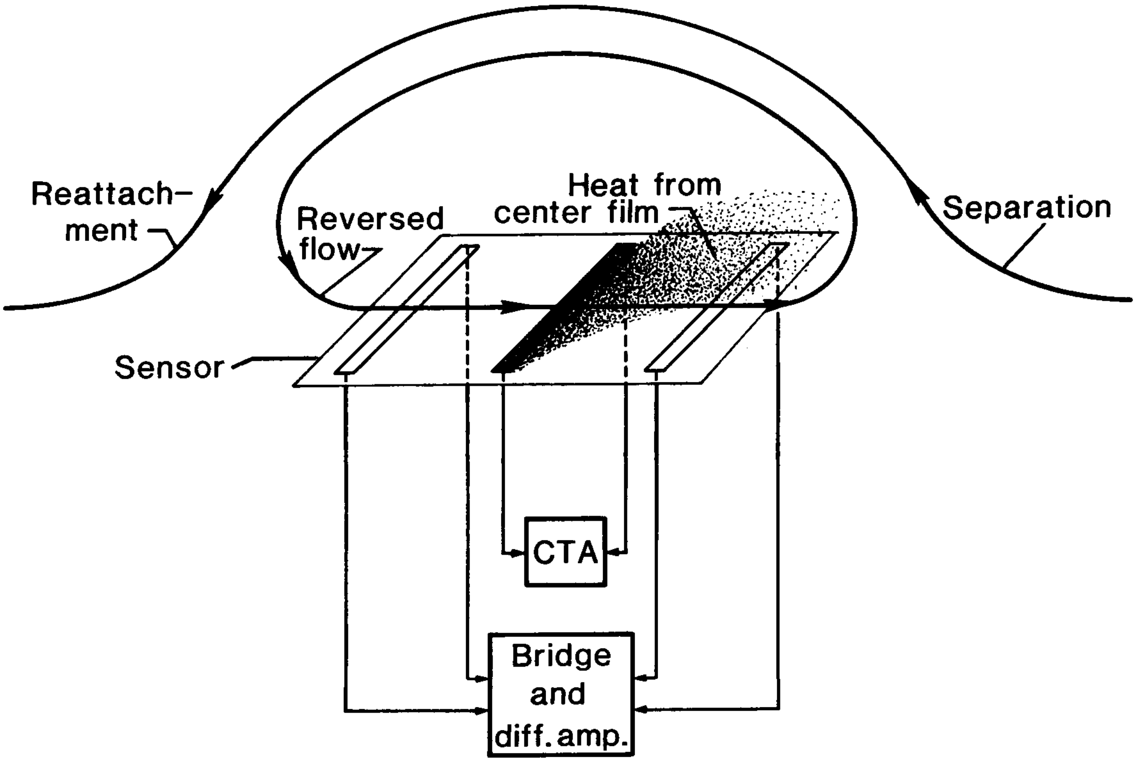
The "beginning" and "end" of boundary layer transition can be determined from RMS values of the output signal from the anemometer where the minimum RMS value represents the beginning of transitions and the maximum value represents the end of the transition process.

The degree of turbulent intermittency can be obtained through the transition process by measuring the rate of occurrence of turbulent bursts.



LAMINAR BOUNDARY LAYER SEPARATION SENSOR

The laminar boundary layer separation sensor (BLS sensor), used to detect flow separation and flow reversal, consists of a flush array of three parallel thin films. The center film is electronically heated by a constant temperature anemometer (CTA). The outer films are incorporated into two legs of a bridge for use as resistance thermometers. When the sensor is exposed to airflow, heat is transferred from the center film to either the upstream or downstream film, depending on the direction of the flow. The change in temperature (according to the change in resistance) of the upstream or downstream films is measured by the bridge and differenced by a differential amplifier to determine the direction of the flow, and hence, separation.



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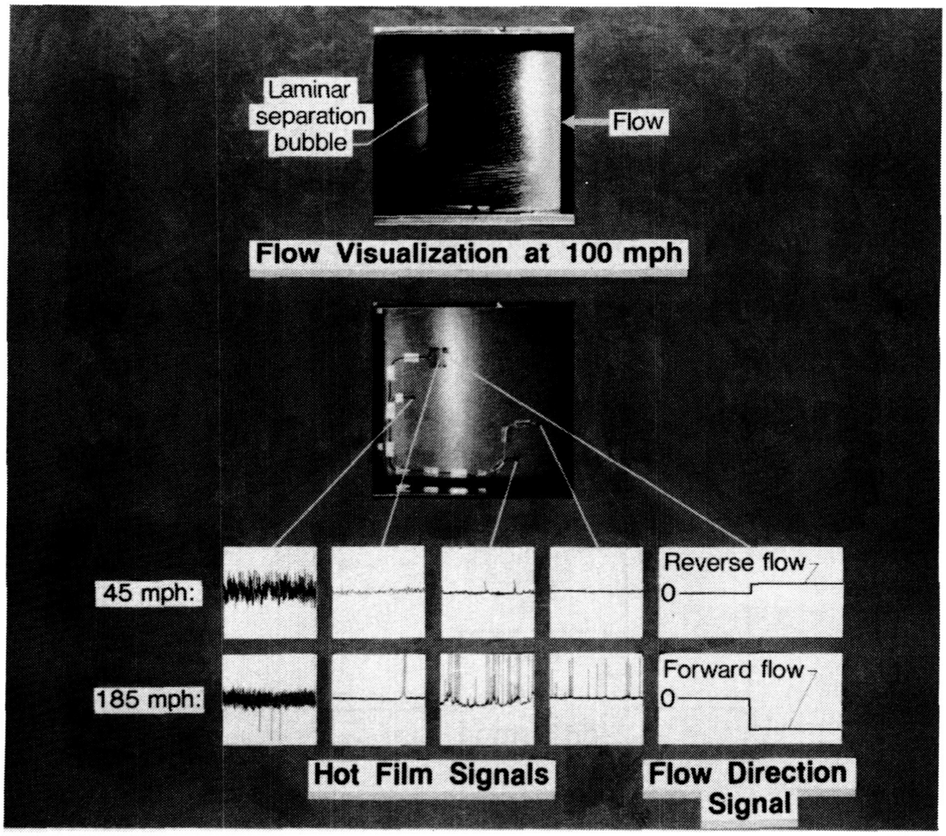
BOUNDARY LAYER MEASUREMENTS OBTAINED WITH A BOUNDARY LAYER SEPARATION SENSOR

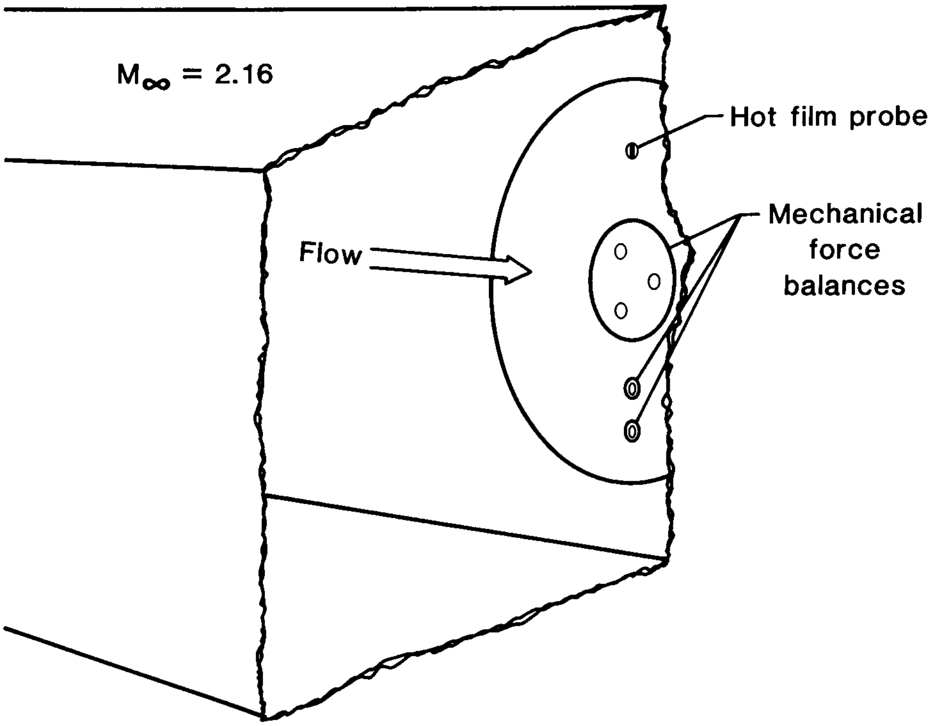
A preliminary test of the sensor was conducted in the Instrument Research Division's (IRD) small calibration tunnel on a laminar-flow airfoil model. A flow visualization made at 100 m.p.h. indicated the existence and location of a laminar separation bubble, characterized by flow separation, reversal, and reattachment. Subsequent tests were run over a range of tunnel speeds from 45 m.p.h. to 185 m.p.h. with a BLS sensor in the area of the bubble and with other hot-film sensors mounted in various other locations on the model. The results of the tests were favorable. At 45 m.p.h., the polarity of the BLS sensor is positive, indicating reversed flow across the sensor (the presence of a bubble). As the velocity of the tunnel was increased to 185 m.p.h., the polarity of the output changed, indicating the bubble had moved slightly aft of the sensor.



SKIN FRICTION GAGE

A thin film sensor has been calibrated in the Unitary Plan Wind Tunnel at Langley for use in shear stress measurements. A .000127-inch wide by .040-inch long thin film sensor was mounted flush with the tunnel wall in close proximity to a static force-type balance. The heat transfer of the film was measured and compared to shear force data taken simultaneously with the force-type balance.

UPWT Test Setup



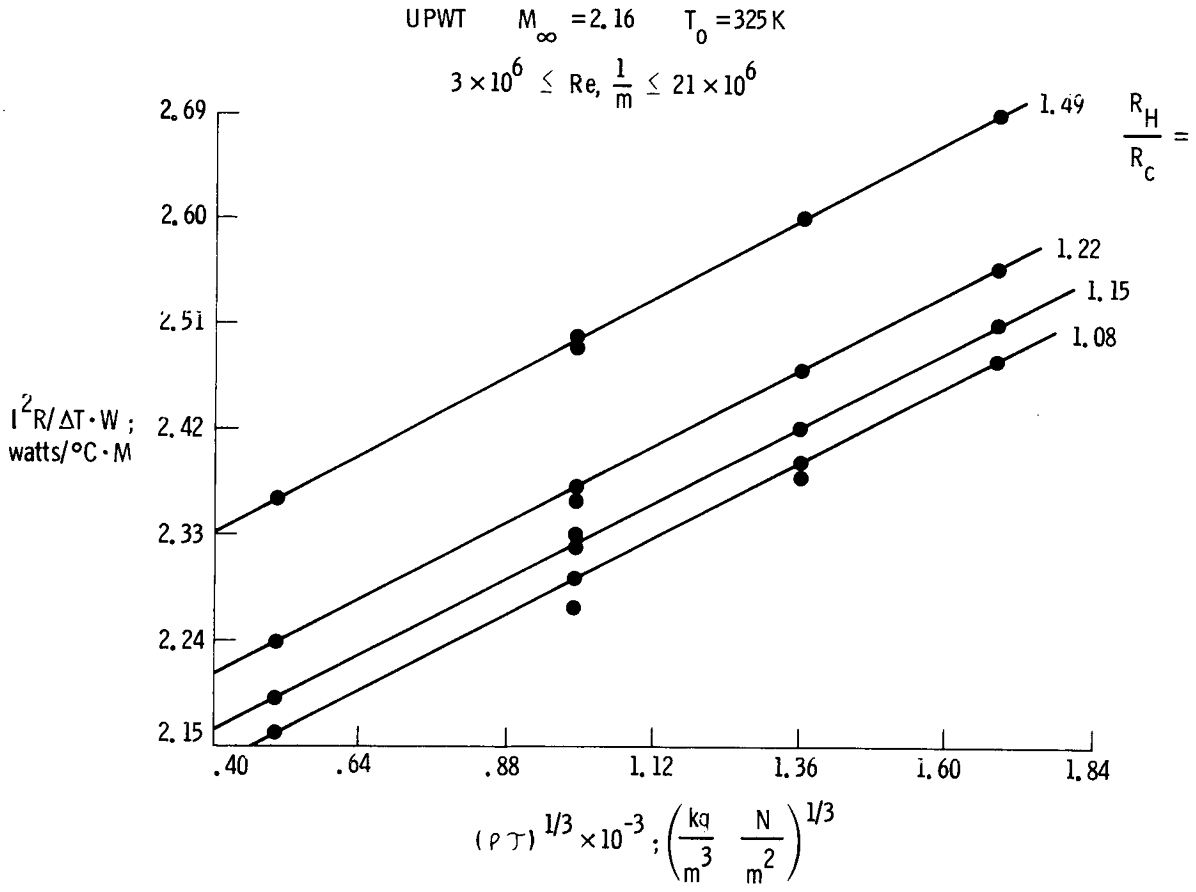
THIN FILM SKIN FRICTION GAGE CALIBRATION

Data were taken at Mach 2.16 over a range of Reynolds numbers from 1 X 10^6 per foot for four different film overheat ratios (film temperatures) from 1.08 to 1.49 (50°C to 180°C).

The results were in good agreement with theoretical analysis for this case which states that the heat transfer of the film is linearly proportional to the cube root of the product of density and shear stress $(\rho\tau)^{1/3}$. The calibration was subsequently repeated, and the worst error in heat transfer for a given shear stress was 0.7 percent.

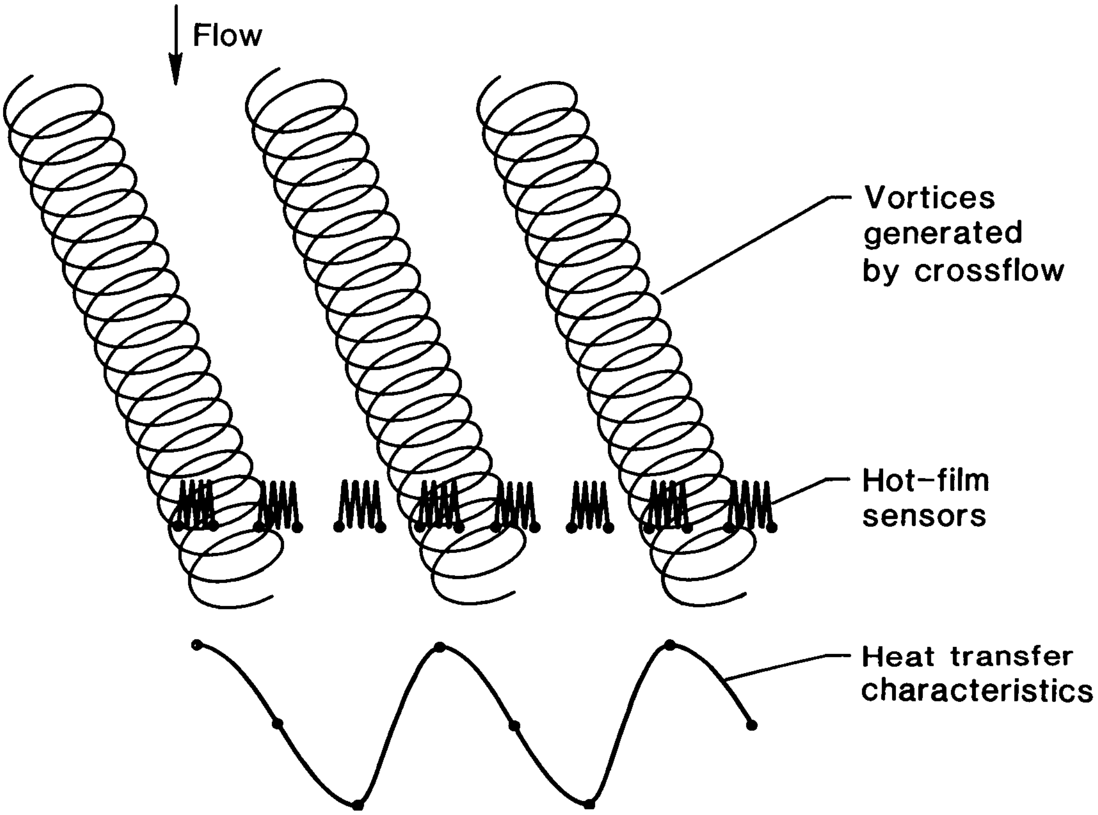
Some of the current research objectives in this area are:

1. Uniformity between sensors to lessen the amount of calibrations and instrumentation
2. Sensors which can fit various surface contours
3. Sensors for high Reynolds number flow
4. Rugged and reliable sensors for flight and cryogenic applications



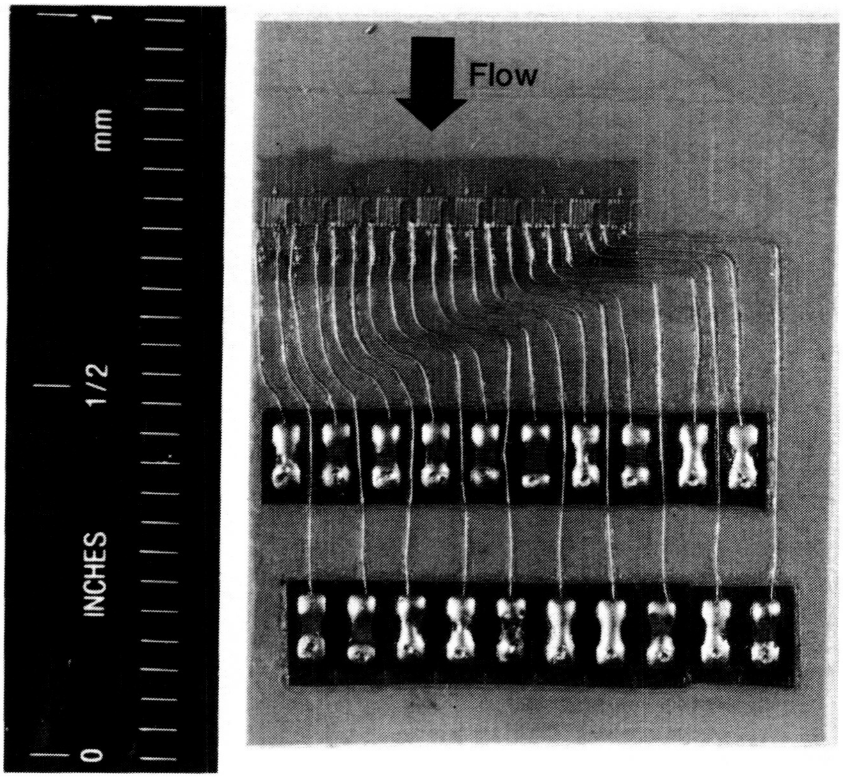
CROSSFLOW VORTICES

When a wing is swept with respect to the incoming velocity vector, a crossflow component of velocity is formed in the boundary layer. In a laminar boundary layer, this crossflow generates vortices in the boundary layer, and the vortices can cause premature transition from laminar to turbulent flow conditions. A schematic of these vortices is shown in the figure. The vortices are narrow and closely spaced, and in general, are aligned in the direction of the freestream velocity vector. The vortices produce high and low shearing stresses and high and low heat transfer rates which can be detected with a heated thin film. Since the vortices can cause transition, it is important that information be obtained on their nature if extensive amounts of laminar flow are expected on swept wings.



CROSSFLOW VORTEX SENSOR

The thin film crossflow vortex sensor detects the large variations in local heat transfer and skin friction caused by crossflow vortices. An array of several hot-film elements is electronically heated by a constant temperature anemometer. When exposed to the airflow, the elements respond to the local heat transfer in the boundary layer. Depending on the size and spacing of the elements, the sensor will detect not only the existence of crossflow vortices but will also obtain good resolution of the wavelengths of the vortices.



LASER VELOCIMETER SYSTEMS AND FACILITIES

In recent years, the Laser Velocimeter (LV) has been developed into a valuable flow diagnostic tool. At the present time, the Langley Research Center has two- and three-component systems in operation. These systems have been used to make mean and fluctuating velocity measurements in flows which range from low-speed pipe flows to transonic flow speeds. There are dedicated LV systems located in three facilities: the 4- by 7-Meter Tunnel, the 16-Foot Transonic Tunnel, and the Vortex Facility. A portable system is available for exploratory measurements in other facilities.

- Two and three component systems
- Test facilities
  - Pipe flow
  - Vortex facility
  - 4 × 7 - m tunnel
  - LTPT
  - 16 - ft transonic tunnel

PHOTOGRAPH OF A THREE-COMPONENT LASER VELOCIMETER SYSTEM

The laser velocimeter (LV) was an orthogonal three-component fringe-type system used in an off-axis, forward-scatter mode. For the purposes of the present study, only one component was used to compare with the results from the hot wire. A Bragg cell was not used in the LV in order to maintain compatibility with the hot wire, since the hot wire is not sensitive to flow reversal. A 5.0 W Argon ion laser was used as the light source with the 496.5 nm output line being selected. The output power at 496.5 nm was set to 0.2 W. The focal length was 0.38 m and the cross beam angle was 7.52 degrees which yielded a fringe spacing of 3.78 micrometers with a sample volume diameter of 160 micrometers. The collecting optics were rotated 37 degrees off of the optical centerline in the plane of the laser beams, which reduced the sample volume length, (measured to the points where the collected scattered light intensity value was $1/e^2$ of the peak), to 0.62 mm. The receiving optical system had a focal length of 0.38 m with a 7.5 cm clear aperture. The collected light was converted to electrical energy using a photomultiplier with a quantum efficiency of 0.21. This configuration yielded signal levels of approximately 0.2 V, peak-to-peak, from 0.35 - 0.55 micrometer polystyrene particles.

The output signals from the photomultiplier were processed by a high-speed burst counter which contained a double threshold triggering circuit and a 5:8 count comparison error detection circuit set to two percent. The digital output from the counter was input to a high-speed buffer memory which will accept up to 4096 velocity measurements, and the associated measured interarrival times. The data contained within this buffer system were then transferred to a 16-bit minicomputer for data processing and analysis.

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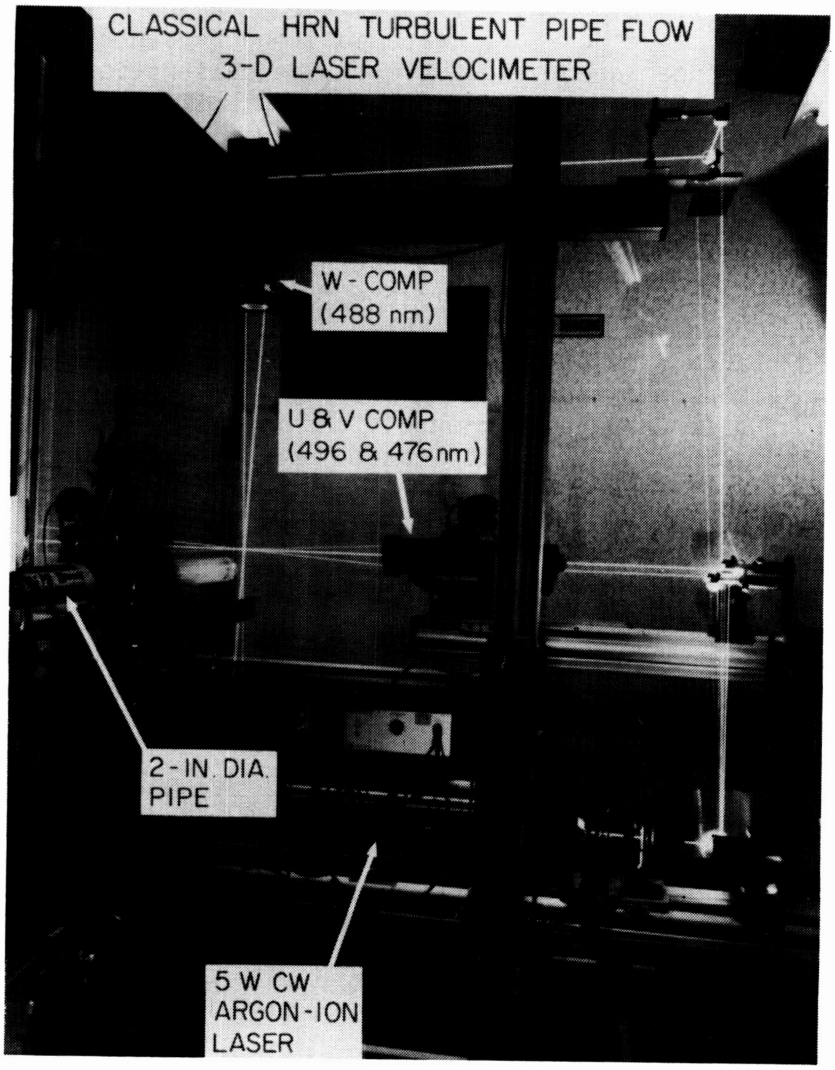
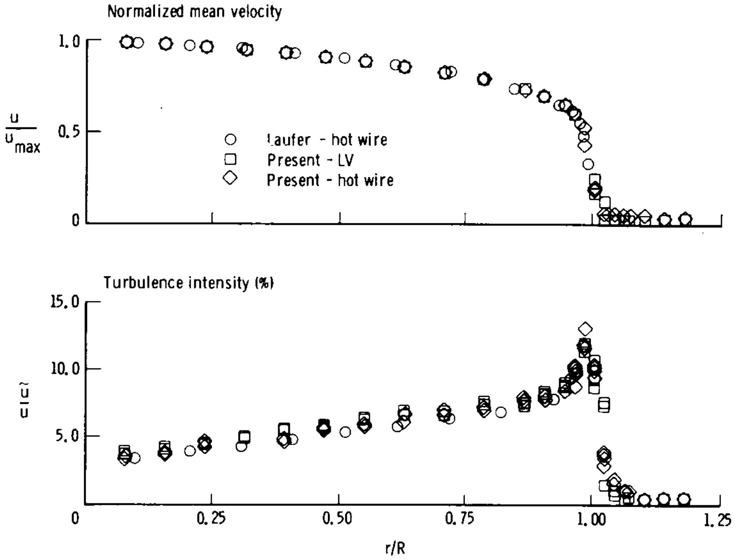


COMPARISON OF HOT-WIRE AND LV MEASUREMENTS

The investigations conducted in the turbulent jet flow from a two-inch pipe were to determine the characteristics of the laser velocimeter when used to measure turbulence quantities. The investigations consisted of comparisons of simultaneous measurements of turbulence with a single-component hot wire and a three-component laser velocimeter. The hot wire was approximately the same size as the laser velocimeter sample volume and located two millimeters downstream of the sample volume. The data from the hot wire were collected by a digital oscilloscope at a sample rate of 1000 data points per second and converted point-by-point via a spline fit calibration curve to velocity. The calibration was performed in a low-turbulence jet (one percent) with the mean velocities determined by the laser velocimeter. The calibration jet was seeded with the same 0.5 micron diameter polystyrene particles as the two-inch pipe to account for the effects of the seed material on the hot-wire heat transfer.

The flow from the two-inch pipe was adjusted to a Reynolds number of 50,000 to match the test conditions used by Laufer (ref. 1). Although the primary comparisons were between the U-component in the laser velocimeter and the hot wire, the remaining two components in the laser velocimeter were used to monitor the flow for large flow angles, which would invalidate the hot-wire measurements. Comparison measurements were made of mean velocity, turbulence intensity (circles - Laufer's data, diamonds - hot wire, and squares - laser velocimeter), and turbulence power spectra at several downstream locations.



LASER TRANSIT ANEMOMETER SYSTEMS AND FLOW REGIMES

In addition to LV systems, Laser Transit Anemometer (LTA) systems are also under development. At the present time only two component systems are in operation and they have been used in flow regimes which range from subsonic to supersonic speeds. The LTA systems are used to measure mean flow velocities under conditions where it would be difficult or impossible to make these measurements using conventional methods.

- Two component systems
- Test facility flow regimes
  - Subsonic
  - Transonic
  - Supersonic

LASER TRANSIT ANEMOMETER

The LTA was developed to handle applications where conventional Laser Doppler Velocimetry (LDV) was difficult to apply. The LTA measures the transit time of particles that crosses two focused laser beams. The optical package shown here forms "two spots" in space and detects light scattered from particles passing through them. The detected signals are correlated in time and this auto correlation allows an estimate of the average transit time, t. This average transit time in conjunction with the known spot separation, d, provides a measurement of the velocity, V, of the particles by

$$V = d/t$$

LTA system control, data acquisition and data processing are performed by microprocessor-based computer system.

The optics package is designed so that the plane formed by the optical axis of the two beams may be rotated about an axis that is equal distance from and parallel to the two beams. This capability permits the determination of the flow angularity using a "best angle" search. The procedure is to make a velocity magnitude measurement at several spot rotation angles at fixed preselected incremental steps. A plot is then made of "two spot" angular position against contrast, where contrast is defined as

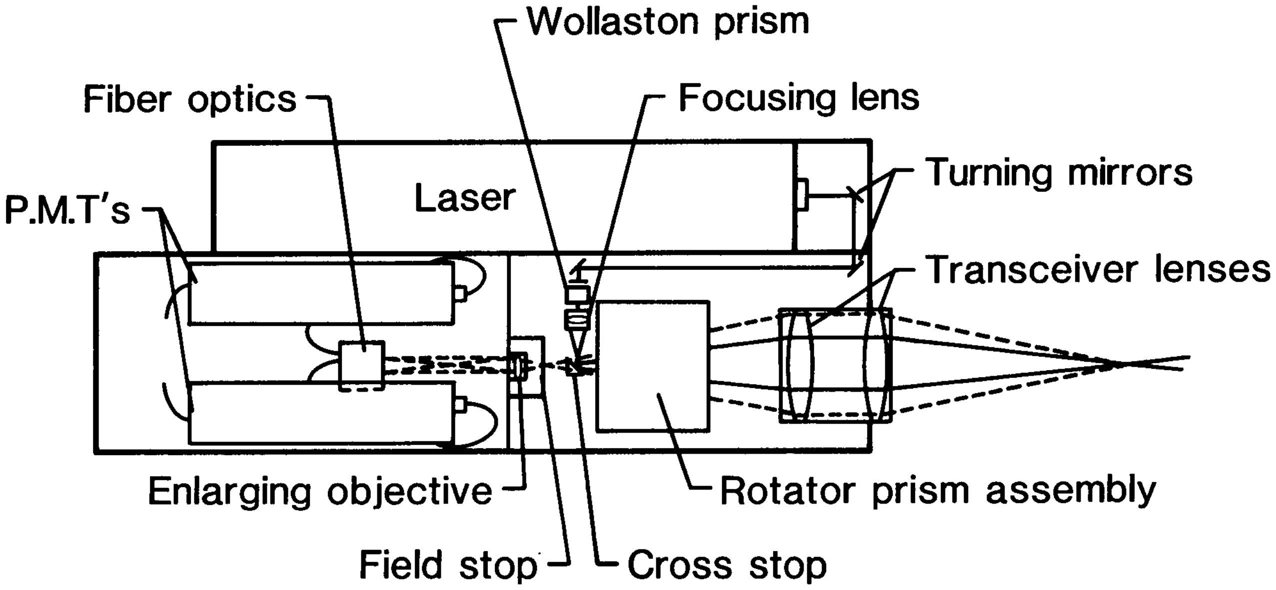
$$(h - b)/\text{sqrt } b$$

where h is the value in the peak store and b is the background level. A least-squares fit of a parabolic equation through the maximum three adjacent points is performed and the abscissa of the parabolic vertex is taken to be the mean flow angle or best angle. Finally, the system is positioned at this angle and a velocity magnitude measurement is performed. This calculation assumes a constant particulate concentration.

The Spectron Development Laboratory (SDL) model 104 LTA system has a specified accuracy of 0.1 degrees for flow angle and 0.1 m/s in velocity. Both measurements are affected by diameter to separation distance ratio as well as local turbulence intensity levels.

LASER TRANSIT ANEMOMETER

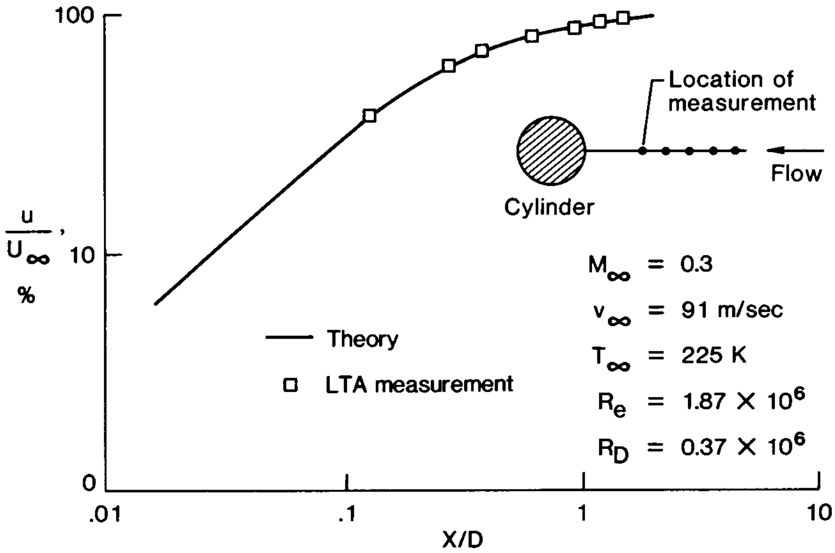
Electro-optics Head



STAGNATION LINE SURVEY

One of the major objectives of a recent 0.3-m Transonic Cryogenic Tunnel entry was to make measurements in the flow field of a cylinder. The size of tunnel windows did not permit a complete scan into the free stream, but with the "D" window rotated 90 degrees from the normal position a vertical scan was made to locate the stagnation line. This could be accomplished by searching for the location with zero degree flow angle, which occurs on the stagnation line of this model.

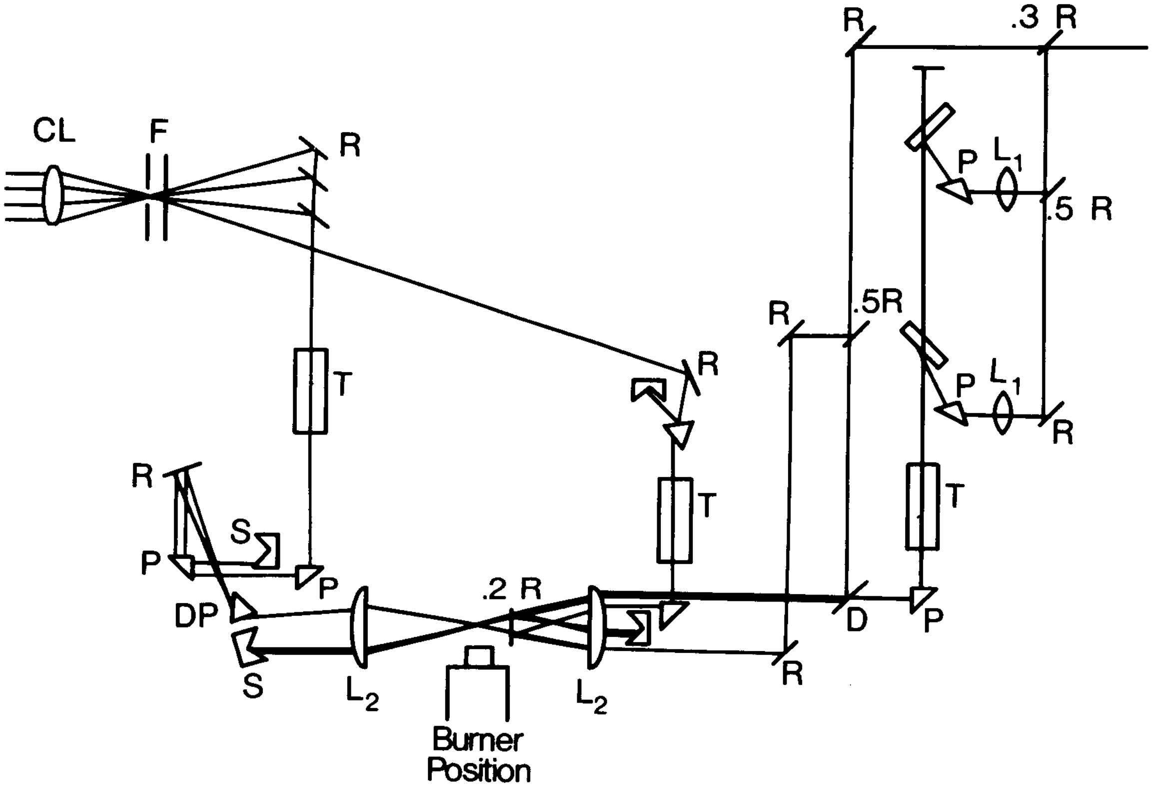
The plot shows the ratio of the velocity at each data point position to free-stream velocity as a function of x/D where x is the distance from the model surface and D is the model diameter. For this scan the 0.3-m Transonic Cryogenic Tunnel was operated at a temperature of 225K and a Mach number of 0.3: U was 91 meters/sec and the Reynolds number was 1.87 x 10^6. The solid line is calculated using potential flow theory and the symbols are measurements taken with the LTA system. All errors associated with the measurements are encompassed by the size of the symbols. From a position 3.56 cm (1.4 inches) in front of the model a horizontal scan was made along the flow direction to a point 0.32 cm (0.125 inches) from the model surface. The velocity varied from 86.6 m/sec to 34 m/sec along this streamline and these velocities agreed very well with theory.



CARS SYSTEM FOR TURBULENT FLAME MEASUREMENTS

Coherent Anti-Stokes Raman Spectroscopy (CARS) is a non-intrusive diagnostic technique which can measure the temperature and density of a gas in a flame. In the configuration shown here, called BOXCARS, high spatial (a few microns diameter by a millimeter length) and temporal (a complete data event in 10 nanoseconds) resolutions are achieved. In addition, CARS has high conversion efficiency and a laser-like signal; thus simple optics may be used to collect the strong signal. The process is Anti-Stokes in character, thus avoiding interference from the laser beams used to create the signal and any naturally occurring fluorescence.

The spectral shape of the CARS signal is temperature dependent; temperature is determined by fitting the CARS signal to a library of previously calculated spectra (typically nitrogen). The intensity of the CARS signal is density dependent; a partial reflector is used to create a second CARS signal in room air. The ratio of the two signals is used to calculate density.



CARS optical schematic including arrangements for referencing and dynamic range enhancement. Symbols: R= total reflector, L= lens, p= 90 deg. prism, T= telescope, D= dichroic mirror, S= beam sink, DP= dispersion prism, F= filter, CL= cylinderical lens.

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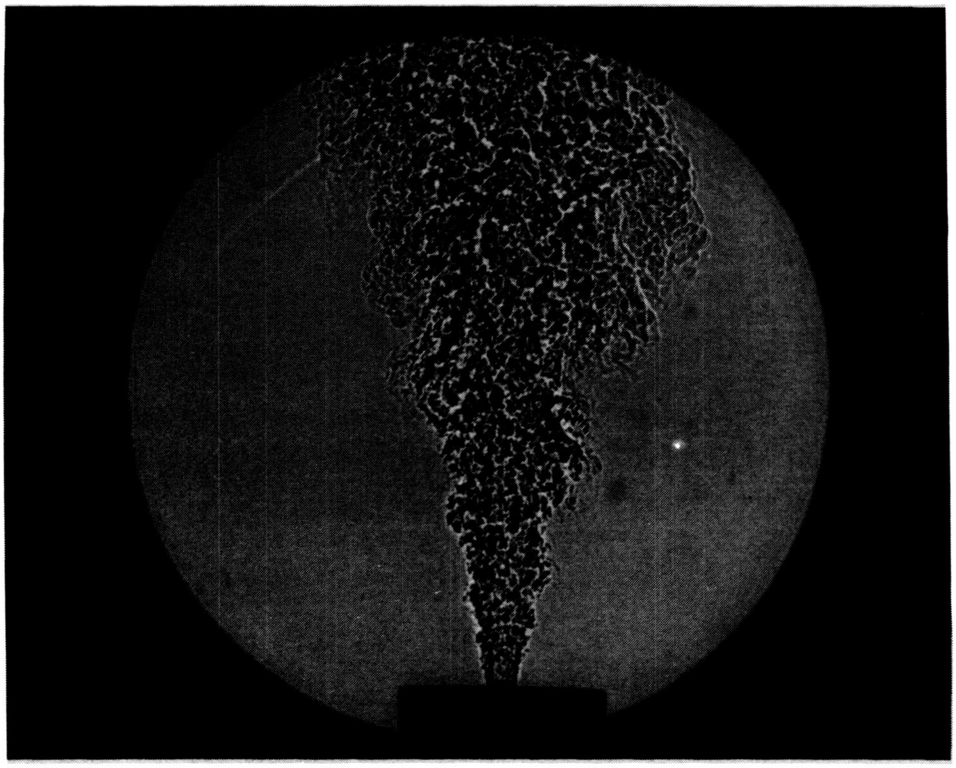
SHADOWGRAPH OF COAXIAL DIFFUSION FLAME

A subsonic coaxial diffusion flame was investigated with the CARS system. A comparison of the distribution of temperature and nitrogen density measured with the CARS system was made with modeled results. The combustion was modeled using: parabolized Navier-Stokes equations, a marching finite difference algorithm, a two equation (κ-ε) turbulence model, hydrogen oxygen equilibrium chemistry, and initial velocity profiles from hot-wire measurements in air.

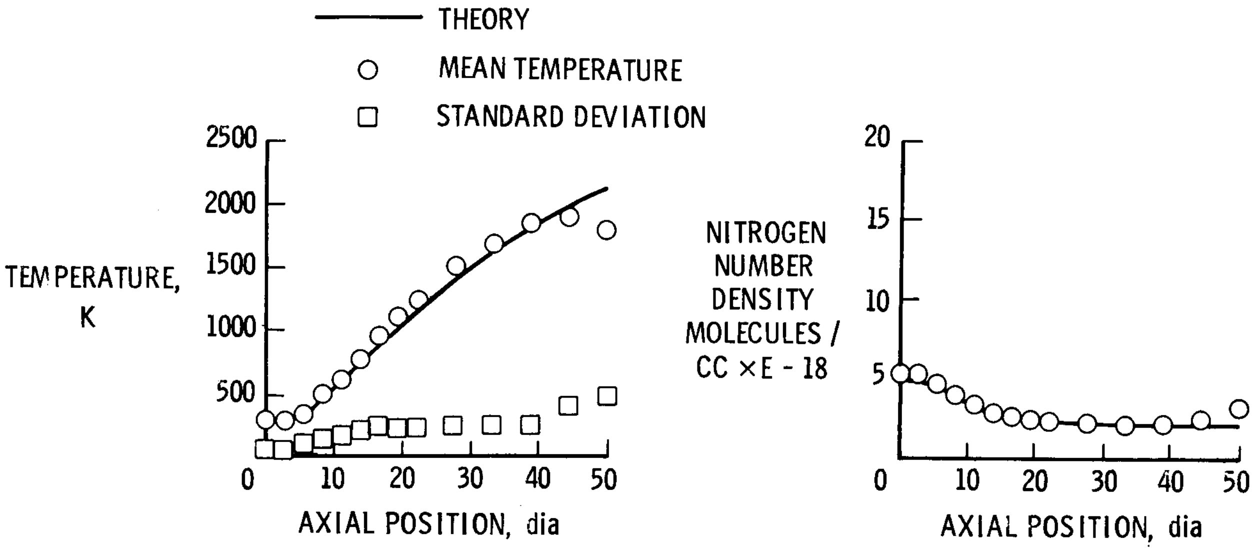
The spark shadowgraph of the flame also shows the tubes which provided the flow. Hydrogen seeded with 20% nitrogen flowed through the central 1/4-inch diameter tube at an average velocity of 100 m/s. Air flowed through the annulus between the 1/4 inch and the 1-inch tube at an average velocity of 15 m/s. Surveys were taken along the centerline and radially at 1 inch and 4 inches from the exit.



AXIAL VARIATION OF TEMPERATURE AND N_2 NUMBER DENSITY

Good agreement was demonstrated between CARS temperature and density measurements and the modeling results. The inherent standard deviations in the CARS temperature measurements are less than 100 degrees, thus, the larger values shown here are an indication of the variation of temperature due to turbulent mixing of hot and cold gases.

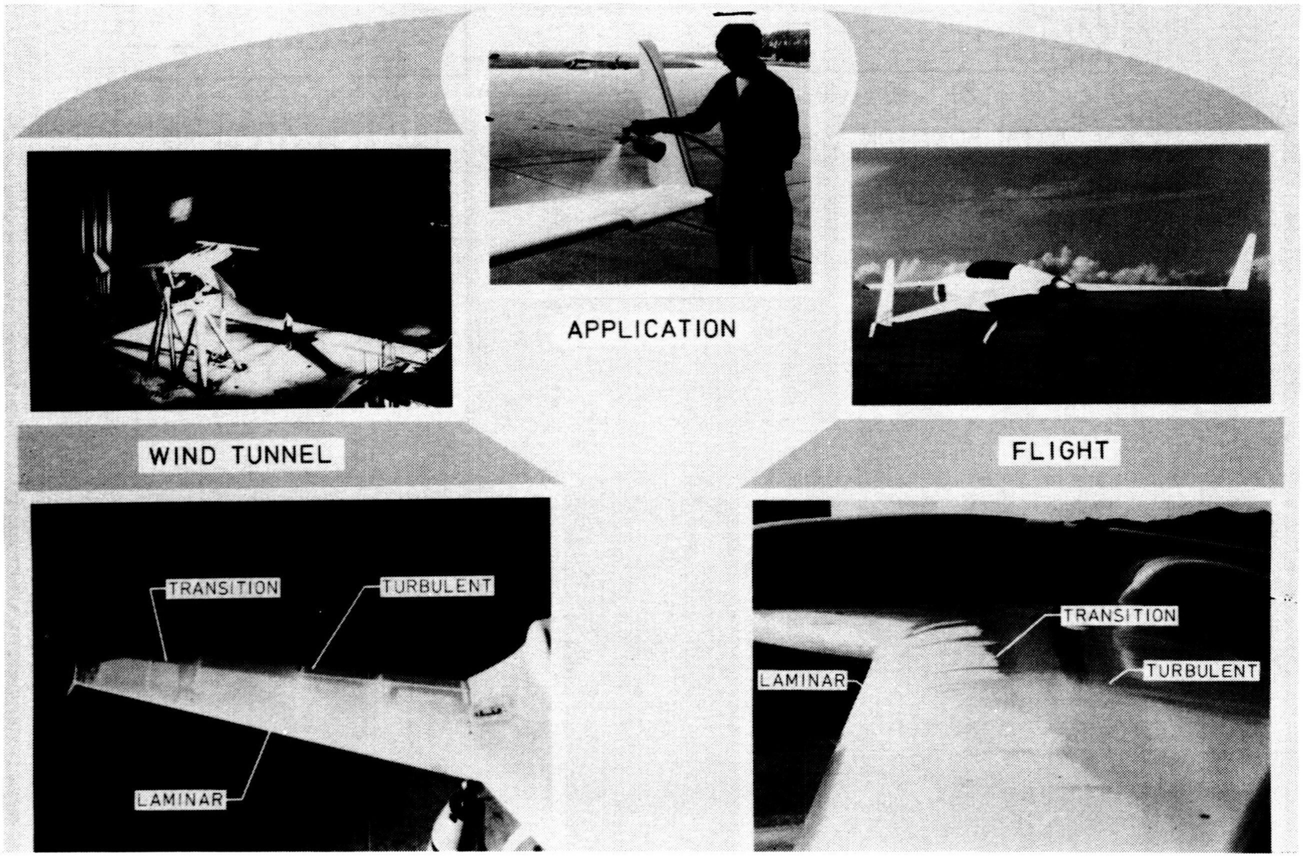
Measurements such as those shown here can be used to validate the results of modeling of computational fluid dynamics, as demonstrated here (see bibliography).



SUBLIMATING CHEMICALS FOR BOUNDARY LAYER TRANSITION VISUALIZATION

Recent developments which have lead to the practical application of natural laminar flow (NLF) for high performance airplanes require special test techniques for the aerodynamicist. The sublimating chemical method offers an accurate, reliable, low-cost technique for indicating transition from laminar to turbulent flow.

References 2, 3, and 4 discuss the original development of the sublimating chemical technique at the Royal Aircraft Establishment. Refinements by NASA Langley personnel (ref. 5) produced improvements in the simplicity and operational flexibility of the technique which involves coating the surface (using standard paint spraying equipment) with a thin film of volatile solid chemical. When exposed to the airstream, the chemical sublimates more rapidly in the turbulent boundary layer due to higher shear stresses. The chemical coating remains relatively unaffected in the laminar region because of lower shear stresses thus indicating the end of transition at the downstream edge of the remaining chemical coating. Typical sublimation times range from a few minutes to an hour, depending on the chemical selected, ambient temperature, and air speed. For flight testing, use of a slower sublimating chemical at ambient temperatures between 30°F and 90°F (at test altitude) offers the capability of flying to low test altitudes (<20,000 ft), stabilizing the sublimating chemical pattern at the test conditions, and returning to the ground with the chemical pattern unaffected by the off condition portions of the flight required for climb to and descent from the test altitudes. Sublimating chemicals are equally valuable when used for wind tunnel research.



CONCLUSIONS

The Langley Research Center has a concentrated and directed effort under way to develop both conventional and non-intrusive diagnostic instrumentation. These instruments are being developed to operate over large Mach number, total temperature, and total pressure ranges. Efforts are being made to evaluate the measurements made by the various instruments to determine the most accurate and reliable instrument to be used under a given flow environment. Although only one flow visualization technique was described, there are many different types presently being used at the Langley Research Center.

- Developing conventional and non-intrusive diagnostic instrumentation
- Suitable for all Mach number, total temperature and total pressure ranges
- Compare results from different techniques
- Multi-flow visualization techniques

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