Modern Experimental Techniques for High-Speed Flow Measurements

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Introduction

WITHIN the last few years there has been a marked increase in interest in supersonic and hypersonic flow regimes. This has been partly as a result of the establishment of a transatmospheric vehicle and the National Aerospace Plane (NASP) program. Addressing the technology problems for these future systems will provide a significant challenge for the aerospace community. Supersonic and hypersonic air-breathing vehicles are highly integrated systems involving strongly coupled technologies. The conceptual design process for various components requires analytical and experimental tools. The flowfield regimes include the internal combustion of propulsion systems, the external flow of the vehicle, and the overall performance of the system.

The rebirth of interest in high-speed flows follows a period of inactivity. During the 1960's, considerable research was conducted on supersonic and hypersonic flows. Much of the research was directed at understanding the problem of re-entry. Test facilities such as supersonic/hypersonic wind tunnels, shock tunnels, and shock tubes were established. The diagnostic instrumentation in these facilities provided limited data. The instrumentation included pressure transducers, heat-transfer gages, schlieren and interferometry, and gas-sampling probes. The data were sufficient to help understand the flow phenomena. With the advent of computer and laser technologies, the activities in the area of computational fluid dynamics (CFD) and sophisticated instrumentation were accelerated. The design and analysis of re-entry-type vehicles have become increasingly dependent upon numerical schemes for predicting the flowfield.[1] The adequacy of CFD as the sole design tool for aerodynamic vehicles in the foreseeable future is doubtful.[2] CFD produces more detailed aerodynamic information faster than previously possible, particularly on simple configurations such as an airfoil section, a fuselage, or even a complete wing. However, reliable modeling of complex complete configurations including vortex interactions, boundary-layer transition, and chemistry are not yet available. Even the detailed physics of the flow near the leading or trailing edge of a wing is very difficult, if not impossible, to compute within the required accuracy. Experimental aerodynamics, therefore, remain an important component in the design of future transport aircraft. This is even more true in terms of development of the propulsion system.

To examine the applicability of various diagnostic techniques, it is necessary to establish the measurement requirements in terms of the parameters and the measurement environments. This in turn requires the examination of the available or proposed design facilities. Figure 1 shows the performance envelope of some existing ground test facilities.[3] Also shown is the performance profile for a proposed entry research vehicle (ERV). The research vehicle is proposed for investigation of basic flowfield phenomena for high-altitude/hypervelocity flights. Nonintrusive measurement techniques are also needed in support of candidate flight experiments.

Examination of the performance envelope of existing flow facilities (e.g., Fig. 1) will help determine the required dynamic range of the instrumentation employed in these facilities.[4] It is also generally agreed that the environments associated with supersonic and hypersonic test facilities are harsh both inside and outside the test facility. Inside, the measurement environment is characterized by high temperatures, high velocities, and high noise levels. Outside, it is characterized by high noise and vibration levels and by varying temperature and pressure fields, which can adversely affect the alignment and overall performance. For application of optical techniques, this requires that all optical components be mounted independent of

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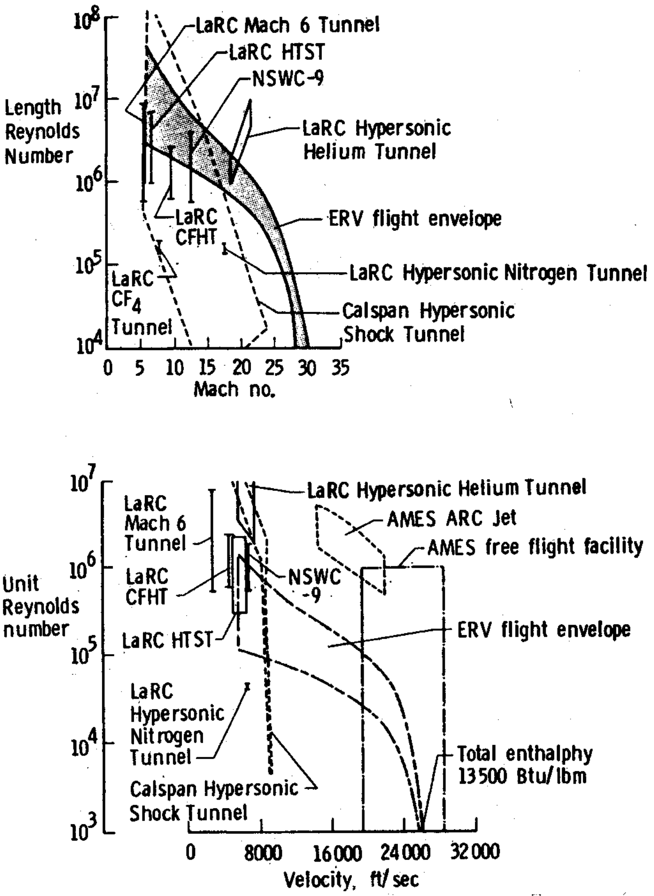

Fig. 1 Unit Reynolds number, Mach number, and velocity range of test facilities.[3]

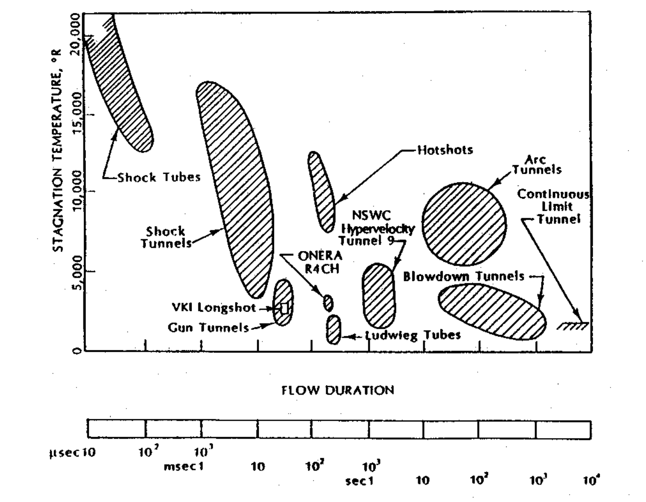

Fig. 2 Stagnation-temperature/flow-duration map of ground-test facilities.[5]

the test chamber and acoustically isolated from other equipment. Moreover, as system alignment is critical, it will be necessary to rigidly couple detection components to the light source and the transmitting optics. Entry and exit of the laser signal and detected light through the walls require special windows and ports, depending on the process being used. Windows must be located where no condensation will occur. Entry and exit windows must be as normal as possible to the light direction to reduce aberrations.

A more important criterion regarding the measurement requirement is the duration of the flow. Figure 2 shows the flow duration map of some of the ground test facilities.[5] Here, the type of instrumentation, frequency response, and measurement durations are all directed by the test facilities.

It is of interest to note that the limitations of the ground-based facilities for accurate simulation of the environment of the re-entry vehicles have been widely recognized and alternative approaches have been proposed.[3] The Shuttle-launched ERV definition study[6] has identified flight experiments that include basic flowfield phenomena for high-altitude/hypervelocity flights. The study has also shown that the development of nonintrusive measurement techniques is required to support the candidate flight experiments.

In the present paper, some of the diagnostic techniques applicable for studies of high-speed flows are presented. Measurement requirements and the relevant limitations are discussed, and the merit of each technique is established. The range of Mach numbers considered here is from transonic to hypersonic ($M > 6$) velocities.

Measurement topics considered here are velocity and density (or index of refraction). The importance of other parameters such as temperature, pressure, species concentration, wall shear stress, are recognized[7] but are excluded from our discussions here. Measurement techniques that are specifically reviewed include laser Doppler velocimetry, laser transit anemometry, laser Dopper spectrometry, laser-induced fluorescence, coherent Raman spectroscopy for measurement of gas velocity, and laser holography and holographic tomography for measurement of flow density (index of refraction).

Diagnostic Techniques

Velocity

Measurement of mean velocity and possibly higher-order fluctuating terms constitute possibly the most important measurement requirements for detailed investigation of flow phenomena. Mapping of the velocity field may be achieved through planar measurement of the (two-dimensional) velocity field or through the measurement of velocity at a number of points (either simultaneously for transient events or consecutively for steady flows). Here a number of nonintrusive laser velocimeter techniques are discussed. Discussions are limited to optical Doppler-based techniques. They are generally divided into two groups: those measuring the Doppler shift of light-scattering particles assumed to be traveling with the flow, and those that directly measure the Doppler shift related to the collective molecular motion. The first group includes classical laser Doppler anemometry, laser transit anemometry, and laser Doppler spectroscopy. The second group includes the measurement of instantaneous velocity based on laser-induced fluorescence (LIF) and coherent Raman spectroscopy.

Particle-Based Velocimetry Techniques

Laser Doppler Anemometry

Laser Doppler anemometry (LDA) traditionally includes dual-beam (real-fringe) and reference-beam laser anemometry. Dual-beam anemometry produces a sample volume by crossing two focused laser beams at the measurement location, forming a well-defined set of interference fringes. When a particle in the flow transits these fringes, the scattered light beam is modulated by a frequency that is proportional to velocity. Detailed descriptions of the technique are given in Refs. 8 and 9.

The reference beam laser anemometry is based on interference of the light scattered from the seed particles and a reference beam on the surface of the detector. Use of multiple scattering centers is preferred in this case. Because of its inferior signal-to-noise, this technique has not been used in high-speed flow measurements. A complete discussion is given in Ref. 8.

During the 1970's, laser Doppler anemometry was successfully applied to supersonic flows.[10-12] The applicability of LDA in hypersonic flows was also investigated.[13-17] A two-

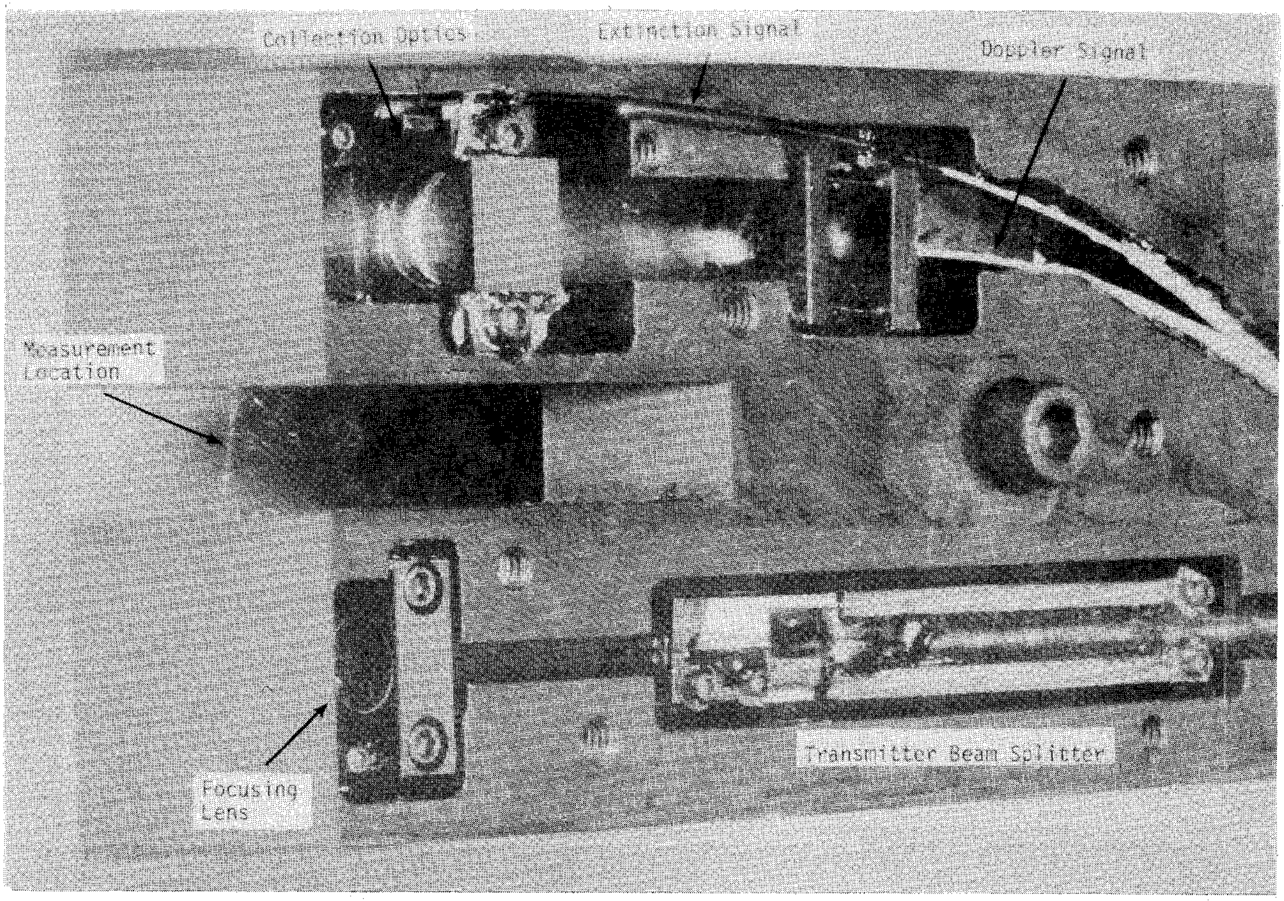

Fig. 3 Miniature LDV probe for shock tube.

component velocimeter was used in Ref. 13 to survey a 5-mm-thick boundary layer developed on a flat plate in the Mach 6 High Reynolds Number Wind Tunnel. In Ref. 15, local velocity measurement of gas flows for velocities from 100 to 10,000 m/s is described. Special-purpose laser velocimeters have been designed and used in extremely demanding environments. Use of fiber optics and laser diodes has made it possible for the velocimeter to become minaturized and used in more inaccessible environments. Figure 3 shows as example of a single-component laser velocimeter designed and built for application in a shock tube.[18] It uses a single-mode fiber optics beam splitter, selfoc lens collimators, and miniature focusing and collection lenses. It had no moving or adjustable parts and performed without any difficulties inside a shock tube for over 100 runs.

Laser Transit Anemometry

Laser transit anemometry (LTA) is based on the generation of two or more spatial markers at the measurement point. The time of transit of the scatter centers through the markers defines the instantaneous velocity.[19] LTA, which is usually applied in a backscatter mode, is self-contained, does not require coherence (and, therefore, was more tolerant to phase distortions along its optical paths), and can cope with smaller particles for equivalent laser power. Its superiority close to walls and surfaces has been established.

Laser Doppler Spectrometry

Laser Doppler spectrometry is more promising for gas velocity measurements in high-speed flows. The technique was pioneered by Smeets and George[20-22] for the measurement of velocity in highly transient and short-duration flows. It, however, may also be applied to nontransient flows. The basic arrangement of the system is illustrated in Fig. 4. Monochromatic laser light is transmitted by a multimode optical fiber and is concentrated at the measuring point. Doppler-shifted

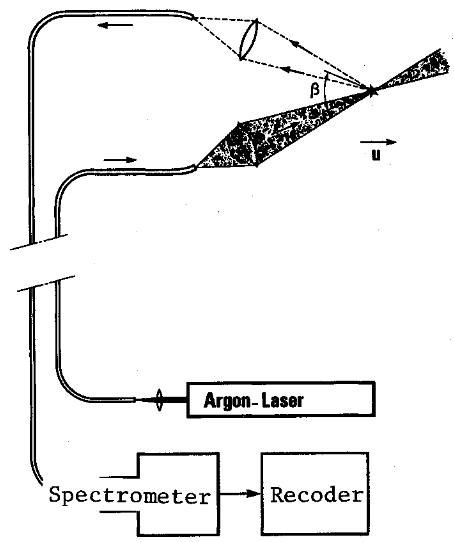

Fig. 4 Laser Doppler spectrometer.[20]

light scattered by the tracer particles at this point is collected and transmitted to the spectrometer using a second optical fiber. The Doppler shift in terms of the relative wavelength change $d\lambda/\lambda$ depends on the velocity component u of the particles in the direction of the bisector between illumination and observation directions and on the angle β between these directions:

$$\frac{d\lambda}{\lambda} = 2\frac{u}{c}\cos\left(\frac{\beta}{2}\right) \tag{1}$$

where c is the speed of light.

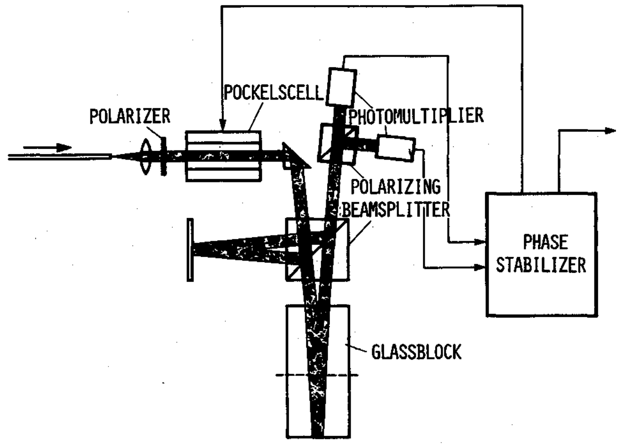

Fig. 5 Principle of interference spectrometer.[20]

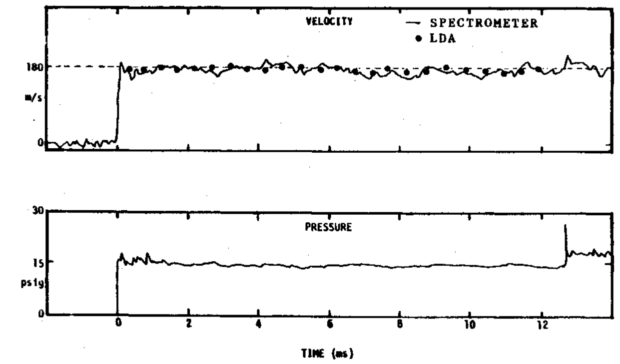

Fig. 6 Comparison of velocity measured by dual-beam and Doppler spectroscopy.

The principle of the interference spectrometer developed for detecting the wavelength change is depicted in Fig. 5. The scattered light leaving the light fiber is first collimated with an objective lens. After having been linearly polarized, it passes through a Pockels cell and then enters a Michelson interferometer. The incoming light beam (having a 45-deg polarization direction) is divided in a polarizing beam-splitter cube into two components of equal intensity that are linearly polarized in the directions parallel and normal to the plane of the Michelson interferometer. By means of a glass block or another optical system placed in one of its two legs, an optical path difference between the two components of the interferometer is generated. After recombination, the two overlapping beams pass through a second polarizing beam-splitter cube with axis at 45 deg with respect to the first beam splitter. In this way, the two beams leaving the second beam splitter show complementary interference. The interferometer is first adjusted to infinite fringe spacing so that the illuminated spots on the photodetectors show no more fringes.

Changes in the velocity of light-scattering particles produce Doppler shift on the collected light. This in turn results in finite-fringe formation at the photocathodes. With the use of a Pockels cell and a stabilizing feedback system, the relative phase of the incoming light is changed so as to maintain the quadrature conditions between the two detectors. It can be shown that the voltage feedback of the Pockels cell is linearly proportional to the change in the velocity of the scattering centers.

The sensitivity of the velocimeter is a function of the optical path difference between the two components. The spectrometer is capable of detecting a wavelength shift of $d\lambda/\lambda = 10^{-10}$, which is the stability limit of an Ar^+ laser with etalon. This is equivalent to a velocity resolution of a few cm/s. The technique is extremely useful in the measurement of high-speed and short-duration flows. Unlike standard laser velocimetery techniques, the spectrometry technique does not require additional signal processing.

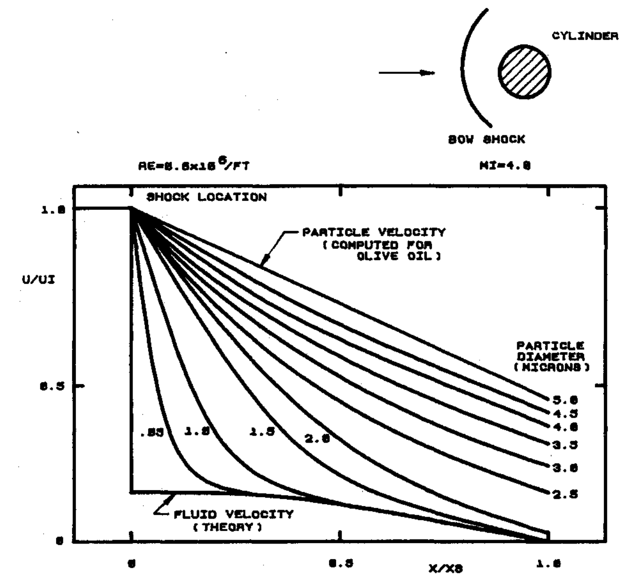

Fig. 7 Particle relational distance behind a shock wave.[29]

The interference spectrometer is able to continuously monitor the change in the velocity. Figure 6 shows the velocity of submicron incense particles measured at the TRW 17-in. shock tube.[18] The trace of the pressure-time history of the flow is also included for comparison.

Seed Particle Considerations

Issues in the design of a laser velocimeter for high-speed flows include signal-to-noise ratio (SNR), optical access, test facility environment, and errors associated with particle lag. Recent progress in signal processing techniques[23,24] have made it possible to process Doppler signals with extremely low SNR. This in turn permits the use of smaller seed particles. In general, the subject of proper seeding of the flow has been acknowledged as one of the most critical problem areas in particle-based laser velocimetry.[25-27] Fundamental to all applications of this type of velocimetry is the assumption that the flow can be characterized by the motions of the scatter centers that either naturally reside in the flow or are introduced into it artificially. The problem is considered of sufficient importance that entire conferences have been devoted to the subject.[28] The consequences of particle dynamic effects on the velocity measurements can be summarized as follows:

1) Interpretation of velocity measurements requires the capability of analytically examining particle dynamics effects.

2) Broad particle-size distributions produce artificial turbulence and should be avoided.

3) Correction for mean-flow particle lag may be feasible for monodisperse seed particles.

The errors associated with the particle lag and the maximum acceptable particle size are determined by the flow acceleration and the level of turbulence. As an extreme, Fig. 7 shows the response of particles to a shock wave as a function of particle diameter,[29] showing that even particles as small as 0.5 μ have a finite relaxation time.

Hypersonic-flow velocities at ground-based facilities are usually achieved through large reduction of pressure at the tunnel exit. This, in turn, results in extremely low densities. It has been generally agreed that, due to the problems associated with particle lag, particle-based instrumentation may not be used in high-speed, low-density flows. It is of interest to evaluate an order-of-magnitude estimate of the errors associated with the use of particle-based velocimeters. A test case of an analytically designed highly diverging hypersonic nozzle[30] is considered. The nozzle contour and the estimates of the density, freestream velocity, and the pressure along the axis of the

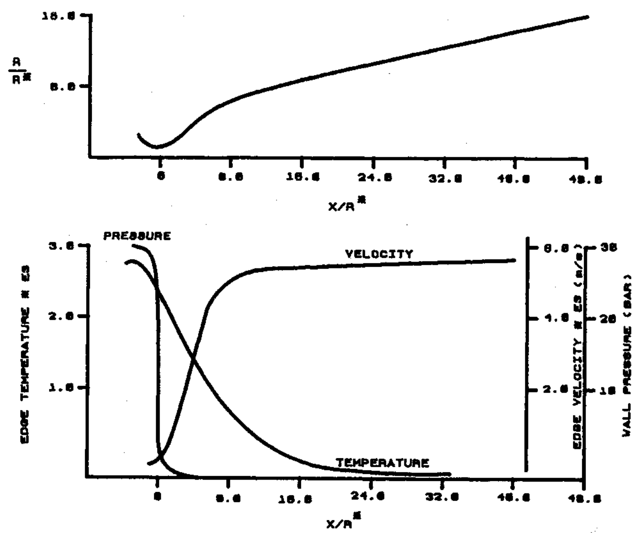

Fig. 8 Designed parameter of a shock-free hypersonic nozzle.[30]

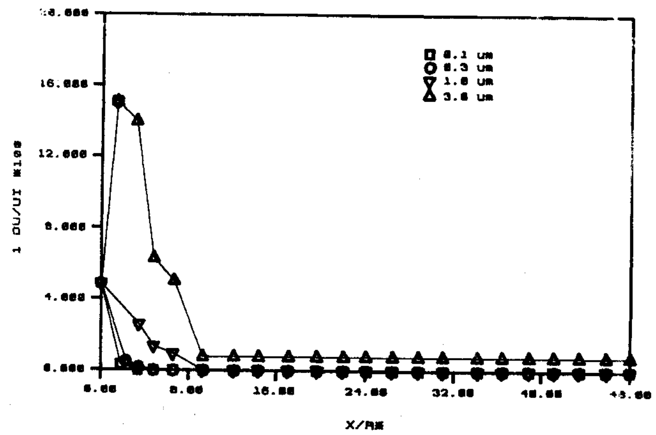

Fig. 9 Particle lag vs particle diameter.

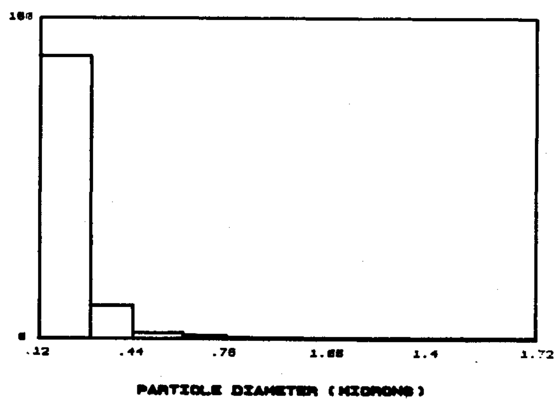

Fig. 10 Incense smoke particle diameter distribution.[31]

nozzle are given in Fig. 8. It is assumed that the contour design of the nozzle is such that the flow will continuously accelerate to hypersonic speeds.

Single spherical particles with an initial velocity slip of 5% are released at the throat of the nozzle. The motion of the particles is described by the Stokes drag law. The purpose of this exercise was to evaluate the level of error expected in the mean velocity of the centerline flow. Four particle sizes were assumed. The results of the calculated particle velocity lag for different particle sizes are given in Fig. 9. The results show that the errors for submicron particles for measurement of the freestream velocities in the presence of large-velocity gradients

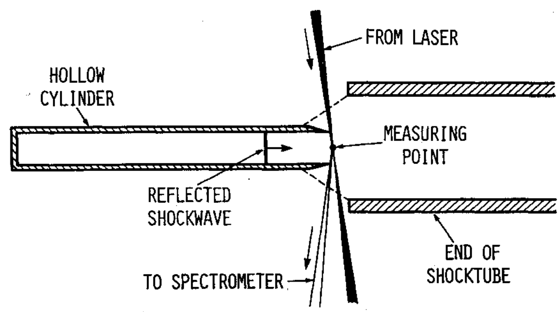

Fig. 11 Schematic particle response to a normal shock wave.[34]

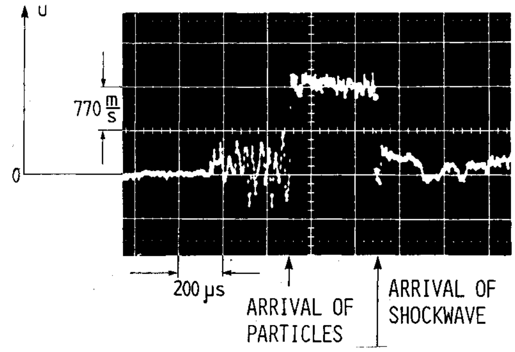

Fig. 12 Submicron particle response to a normal shock wave.[34]

without shock waves are within a few percent, and thus may be acceptable.

Production of submicron seed particles is not a trivial matter. A number of techniques have been proposed for the production of seed particles. Figure 10 shows the particle-size distribution generated from an incense cone[31] with 90% of the particles being in the 0.1–0.45-m-diam range. The authors measured 99% of the step change in the velocity within 1 mm of the shock front.

Liu et al.[32] developed a condensation aerosol generator for producing aerosols with median diameter of less than 0.1 μm. The applicability of this technique in hypersonic flows will depend on the injection schemes and the rate of evaporation of the droplets in the hot section of the flow.

Recently, Smeets and Mathieu[33,34] generated soot particles by means of pyrolysis of hydrocarbon gas within a shock tube. They found that by mixing 1% of acetylene in the driven gas (N_2) of the shock tube, they could produce sufficiently high particle number densities, with the median size of the particles well below 0.2 m. Figure 11 shows the setup of an experiment reported in Ref. 33 where the response of the particles to a reflected shock from a closed-end tube was examined. The velocity trace is shown in Fig. 12, where the arrival of the shock wave is recorded with a response time of well below $20 \mu s$. The above seeding technique is most appropriate for velocimeters whose signals are not degraded with the presence of multiple particles in the flow, such as reference-beam velocimeter and velocity interferometry.

Spectroscopic Velocity Techniques

Atomic and molecular spectroscopy provide a powerful tool for hypersonic-flow velocity measurements. Spectroscopic methods refer to a class of techniques that directly extract the velocity by observing the Doppler shift in either the absorption line frequency or the fluorescence emission, or by tagging the flowfield with agent species and measuring their scattering spectra upon interaction with a laser source. Therefore, spectroscopic methods alleviate the slip velocity ambiguity associated with traditional particle-scattering methods.

Agent species may be either species naturally existing in the fluid flow or trace species seeded to the flow. In wind-tunnel applications, the dominant species are molecular oxygen and nitrogen. Nitrogen transitions are in the very low ultraviolet region of the spectrum, which renders nitrogen unamenable to excitation using existing laser sources. Molecular nitrogen, however, provides a tool for species-independent techniques such as coherent Raman spectroscopy. Oxygen has a number of interesting spectroscopic features that make it acquiescent to laser excitation. The dominant absorption bands of O_2 are the Schumann-Runge system of transitions. Under atmospheric conditions, the Schumann-Runge band system has continuum transition in the range of 130–175 nm and discrete transitions from 175–250 nm.[35] Additional spectroscopic data on O_2 molecules can be found in the literatures.[36,37] The discrete transitions range of O_2 is within the range of operation of ArF excimer lasers. The vibrational-rotational frequencies are too close to each other, and would require a very narrow laser linewidth[38] to selectively excite these lines. Commercially available ArF lasers have a wide linewidth, which would result in large errors in the velocity.

Alkali species such as sodium are preferred by spectroscopists as agent species, since their energy levels are far separated in the spectrum,[39] which does not impose restrictive requirements on the linewidth of the excitation laser. Second, alkali species absorb and fluoresce in the visible range, which is the efficient range of the excitation source and the detectors. The corrosive nature of alkalis, compounded by their great appetite to react chemically with other species such as H_2O, hindered their utilization in aerodynamic measurements in wind tunnels.

Iodine, which has a resonant transition at 514.5 nm, has been used as a trace species in many applications.[40–42] Iodine has the same advantages as the alkalis and, moreover, it can be excited using an Ar^+ laser, which reduces the equipment cost tremendously. However, iodine is very toxic and has a very low saturation pressure, which limits its application to high-density flows.

Laser-Induced Fluorescence

Velocity measurements using resonant Doppler absorption were first pioneered by Miles.[43] Later, schemes using laser-induced fluorescence for velocity measurements were developed and used for supersonic and subsonic flow measurements by McDaniel et al.[44]

Measurement of the Doppler-shifted absorption line is the basis for velocity measurements using laser-induced fluorescence. The Doppler shift of an absorption line Δv_D is proportional to the velocity component u in the direction of laser beam propagation such that

$$\frac{\Delta v_D}{v_0} = \frac{u}{c} \tag{2}$$

where v_0 is the center of the laser frequency. There are two schemes to measure the velocity using laser-induced fluorescence: 1) narrow-band excitation scan of the absorption line and broadband fluorescence detection, and 2) narrow-band wing excitation with counterpropagating beams and broadband fluorescence detection.

The former scheme uses a tunable narrow-band laser beam to scan a resonant transition of the agent species. The resulting broadband fluorescence signal is then detected. The Doppler shift is determined by comparing the center of the fluorescence signals of moving molecules to that of molecules in a stationary cell.[44,45] The velocity is then obtained from Eq. (2). This scheme can measure velocity with an accuracy as little as 5 m/s, depending on the energy levels of the agent species. It requires tuning the laser beam over the entire absorption line, which prohibits the use of this method in unsteady flows. This technique also requires the acquisition of a large number of data frames and therefore a large buffer space for storage.

The latter scheme[46] fixes a narrow-band laser at the frequency of the wing of the absorption line near the point of maximum slope, where the line shape is approximately linear

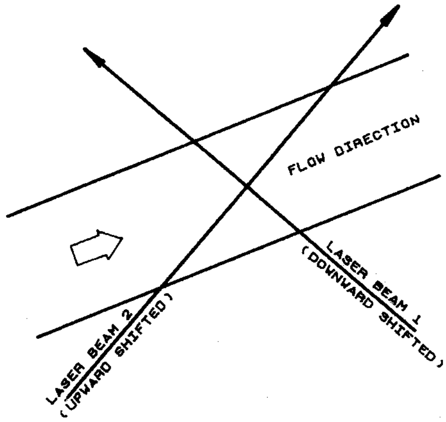

Fig. 13 Illustration of counterbeam propagation configuration.

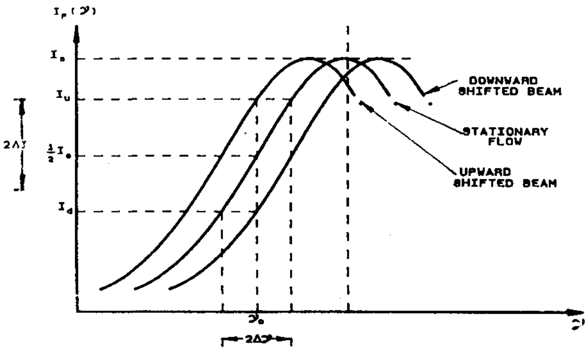

Fig. 14 Schematic of fluorescence intensity vs frequency.[46]

for small Doppler shifts. The fluorescence intensity I_F is proportional to the amount of absorption. At high speed, the Doppler shift causes the center of the absorption line to shift away from the laser frequency, resulting in a change in fluorescence intensity. In this case, the frequency shift [Eq. (2)] can be expressed in terms of the difference in fluorescence I_F and the slope of the line shape function $g(v)$ such that

$$u = \frac{c}{v_0} \cdot \frac{\Delta I_F}{I_0} \left(\frac{g(v)}{v} \bigg|_{v_0} \right) \tag{3}$$

where I_0 is the fluorescence at the center of the line. However, if the flow is monitored with two beams in such a way that one beam is upward Doppler-shifted and the other downward-shifted as schematically illustrated in Fig. 13, both the difference and center fluorescence intensity I_0 are easily determined using Eq. (4) and as shown in Fig. 14.

$$u = \frac{c}{v_0} \cdot \frac{I_u - I_d}{I_u + I_d}\, g(v) \left(\frac{g(v)}{v} \bigg|_{v_0} \right)^{-1} \tag{4}$$

This technique requires two successive laser pulses to measure one velocity component. This scheme is capable of determining the mean velocity particularly in high-speed situations. The accuracy range is similar to the former scheme.

In order to measure the velocity vector in a two-dimensional flow, two additional beams are required.[47] This method requires four successive laser shots and subsequent measurements of the fluorescence signal. Present development in detector technology does not allow signal recording in less than 50 ms, and therefore hinders the ability of performing two-dimensional velocity measurements in highly turbulent or transient flows.

Coherent Raman Spectroscopy

Coherent Raman spectroscopy was first proposed by She et al.[48] as a nonintrusive method to measure the velocity in high-speed flows. Coherent Raman includes coherent anti-Stokes Raman spectroscopy (CARS),[49] inverse Raman spectroscopy (IRS),[50] and stimulated Raman gain spectroscopy (SRGS).[51] Similar to laser-induced fluorescence, coherent Raman spectroscopy measures the velocity from the Doppler shift of the spectrum of the scattered signal. It is preferable to use molecules with a large Raman cross section as the agent species such as methane or freon. Nitrogen molecules can also be used as the agent species but with lower signal-to-noise ratio. Coherent Raman techniques are developed to measure the velocity, albeit their orders of magnitude complexity over ordinary Raman, because coherent Raman have scattering cross sections several orders of magnitude higher than spontaneous Raman and, therefore, higher signal-to-noise ratios. The ability to use nitrogen molecules that exist in abundance in wind tunnels as the agent species renders coherent Raman spectroscopy attractive for velocity measurements in wind tunnels. The complexity of the optical system combined with the requirement of more than one laser hindered the development of coherent Raman spectroscopy.

The CW CARS technique[49] has been used to measure supersonic velocities of 1010 m/s with a velocity resolution of 34 m/s, using methane as the agent species.

Inverse Raman spectroscopy[52] has been used to measure a velocity of 471 m/s with 5% uncertainty using nitrogen molecules as the agent species. Most recently, results[53] in the Mach number range 2.5-4.7 were reported using nitrogen molecules as agent species.

Coherent Raman spectroscopy has the added advantage that it can measure the temperature and pressure simultaneously

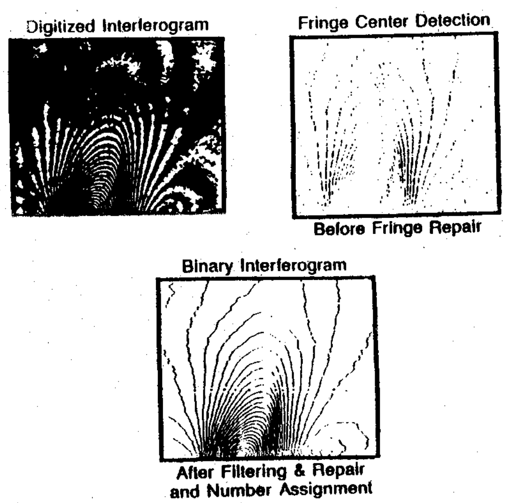

Fig. 15 Digitized interferograms.[60]

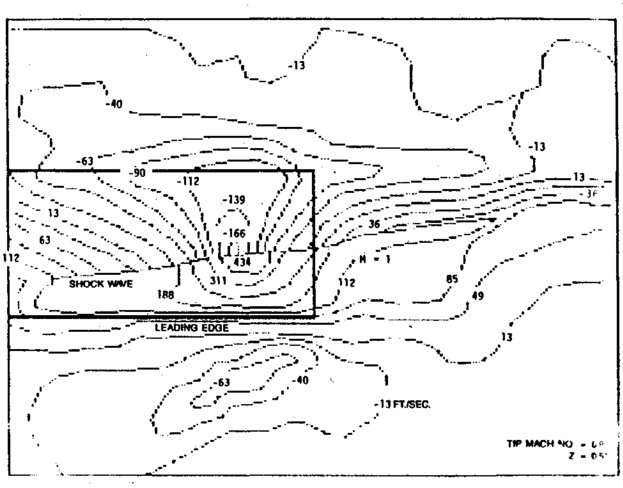

Fig. 16 Reconstructed velocity contours.

with the velocity measurements. However, the high uncertainty (10% for temperature, pressure, and velocity), the low signal-to-noise ratio, and the broadened signal spectrum limit its application to a very specific family of flow conditions.

Time of Flight Techniques

A number of spectroscopic methods extract the velocity from the time of flight of trace molecules between two well-defined points in space. Oxygen tagging, photthermal and photacoustic techniques fall within this category. Photthermal A_1, A_2 and phot acoustic A_3, A_4 techniques are suitable for acoustically quiet flows that render their application to high-speed flow very limited.

Oxygen tagging as method involves vibrationally pumping O_2 molecule at a fixed point in space using a short-pulse Reiner excitation. The long lifetime of vibrationally excited oxygen assures that the excited O_2 molecules remain excited while they move downstream. The passage of vibrationally ragged O_2 molecules is then detected via the time of flight.

Density (Index of Refration)

Holographic Interferometry. Interferometry is the metrology of phase by interfering known waves with unknown waves and quantifying the resulting interference pattern. Holographic interferometry allows the storage of two waves separated in time to be superimposed in reconstruction.[54-56] The two waves can be stored on a single hologram (double-pulse holographic interferometry) or on two separate plates (dual-plate holographic interferometry). The techniques have proven to be especially suitable for compressible aerodynamics. They have been applied to study numerous flows, including those around two-dimensional transonic airfoils[57] and transonic rotor flows.[58] In Ref. 58, the density profile within the boundary layer developed over a smooth flat plate in a Mach 3 tunnel is compared with those developed over a rough boundary layer.

Probably the most severe obstacle in the widespread use of holographic interferometry has been the methodology for extracting the data from the hologram in a timely fashion. Holography makes possible the recording of more data than can normally be used. During the past few years, great strides have been made toward solving the problem of automated data reduction.[59] An integrated system was recently developed for digitization of holographic fringe patterns. Routines have been developed for fringe center detection, fringe repair, and fringe numbering.[60] Sample of results are shown in Fig. 15.

Holographic interferometry has been successfully applied for study of three-dimensional flows around rotating blades.[61] Here, multiple-angle projections of the three-dimensional phase object were obtained.[62] The multiple images were used as input to a tomographic algorithm, based on the algebraic reconstruction technique (ART).[63] Figure 16 shows the reconstructed velocity contours and the position of the shock wave over the rotating blade.[64]

Recently, holographic measurements in a hypersonic flow have been obtained in the Lockheed Rye Canyon facility.[65] The facility was operated at stagnation pressure of about 500 psia at Mach 8. A recent modification of the flow visualization system incorporated holographic capability with the objective of developing a quantitative flowfield diagnostic. Initially, the flow over a NASP-like configuration at an angle of attack of 3 deg was studied. The resulting holographic interferograms, shown in Fig. 17, revealed that, in contrast to the higher density flows (such as those of Fig. 15), the hypersonic flowfield was optically weak. The shock waves only resulted in fractional fringe shifts. This was both due to the low density of the flow and the relatively short optical path lengths. It is apparent that the data reduction techniques based on fringe detection and fringe tracking would not provide adequate accuracy.

To increase the sensitivity of the recorded data, a phase-shifting interferometry (PSI) method was used in a conventional double-plate holographic reconstruction system. The method achieved fractional fringe-shift capability. The phase-

Table 1 Summary of velocity techniques

Technique	Parameters Measured	Turbulence level	SNR limit	Accuracy	Measured velocity range
Real fringe (LDV)	u_i, u_j		− 10 dB	0.1–10%	1000 m/s
	u_i', u_j', u_iu_j	30% and higher	0–10 dB	1% and up	
Laser Transit Anemometry	u_i, u_j		10 dB	0.1 to 10%	1200 m/s[66]
	u_i', u_j', u_iu_j	15%	10 dB	3 to 15%	
Doppler Spectrometry	u_i, u_i'	15%	20 dB	2%	1700 m/s
Laser Induced Fluorescence	u_i, u_i'	Experimental	20 dB	10%	500 m/s using Iodine[47]
					Mach 11 using Sodium[45]
Inverse Raman	u_i, u_i'	Have not been Demonstrated	20 dB	10%	Mach 4.6[51]
CARS	u_i, u_i'	Experimental	20 dB	Not Established	1000 m/sec[49]

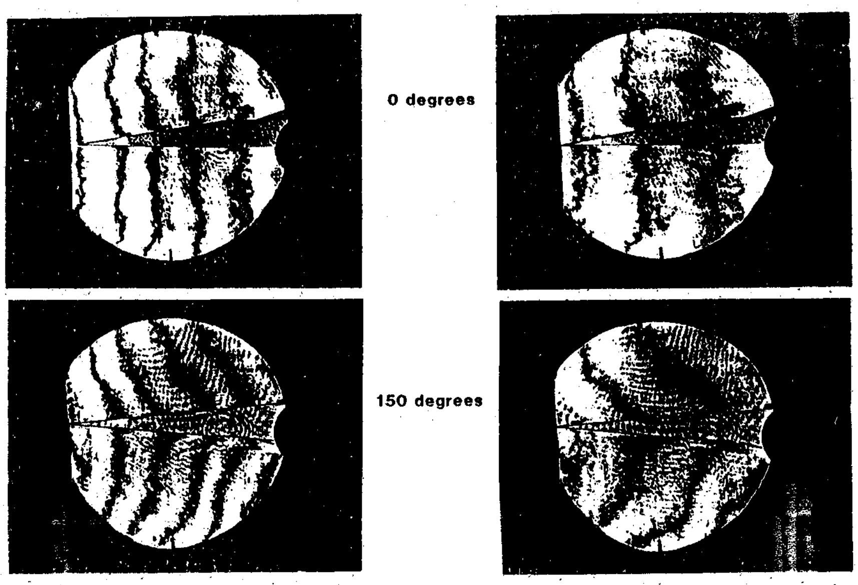

Fig. 17 Holographic interferograms of flow over an axisymmetric body at 3-deg angle of attack at Mach 8.[65]

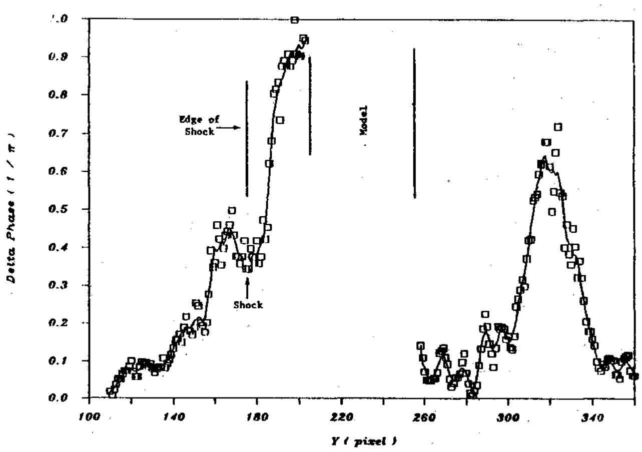

Fig. 18 Phase profile obtained from phase-shifted interferograms.[65]

shifted interferogram intensity distribution was detected with a CCD camera, and the standard PSI equations were used to relate three detected intensities (i.e., one for each phase shift) to the associated phase. The PSI data reduction resulted in a phase profile clearly depicting the shock wave as shown in Fig. 18. Development of quantitative measurement techniques for gas density with the implementation of Abel inversion schemes for axisymmetric flows and tomography for three-dimensional flows are in progress.

Summary

Diagnostic tools for the measurement of velocity, density (index of refraction), and detection of boundary-layer transition in high-speed flows have been reviewed.

Two families of techniques are suitable for hypersonic-flow velocity measurements: particle scattering and molecular scattering. Particle-scattering techniques, which include real fringe laser Doppler velocimetry, laser transit anemometry, and

Table 1 (cont.)

Technique	Frequency response Hz	Spacial resolution	Cost	Status	Concerns in Hypersonic Flows
Real fringe (LDV)	10^4	100 μm	Medium	Well Developed	Seeding, Flow density
	10^2				
Laser Transit Anemometry	Steady State	100 μm	Medium	Well Developed	Seeding, Flow density
Doppler Spectrometry	10^6	100 μm	Medium	Used in Shock Tubes	Seeding, Flow Density SNR
Laser Induced Fluorescence	10^5	100 μm	High	Demonstrated under Laboratory Conditions	Agent Species, SNR
Inverse Raman	Steady State	Few cm	High	Demonstrated in Wind Tunnels	SNR, Complexity
CARS	Steady State	Few cm	High	Demonstrated under Laboratory Conditions	SNR, Complexity

Doppler spectrometry, are well developed, and velocity measurements in supersonic and hypersonic flow regimes have been demonstrated. However, particle-scattering techniques share the same concerns and difficulties when applied to hypersonic wind tunnels: the requirement of seeding the flow, and the ambiguity due to particle lag in accelerated or decelerated flows. The question of particle lag has been addressed, and it is concluded that the measurement uncertainties are small when the particles used are less than 0.3 m in shock-free expansion flows.

The uncertainty of the fluctuating components of the velocity within the boaundary layer will depend on the density of the flow and the frequency-response of the particles.

Molecular techniques that encompass laser-induced fluorescence (LIF), inverse Raman scattering (IRS), and coherent anti-Stokes Raman scattering (CARS) are being developed. These techniques have the potential of yielding more accurate results than particle-based techniques. However, several practical aspects hinder their application to hypersonic flow measurements. LIF of alkalis, which is more accurate than LIF of O_2, requires seeding the wind tunnel with highly corrosive materials such as sodium. Seed molecules condense under the low pressure and temperature conditions characteristic to hypersonic wind tunnels. LIF of O_2 is still under investigation, and preliminary analysis shows that the velocity error is about 500 m/s. IRS and CARS measure the velocity from the spectrum of the coherent Raman scattered signal and, therefore, pressure broadening due to a shock wave can result in large errors. Velocity measurement using IRS is on-axis and, hence, the spatial resolution is poor. IRS and CARS, however, have the advantage of yielding the temperature and pressure simultaneously with the velocity, giving a unified approach to the flowfield.

Table 1 is a summary of velocity measurement techniques. The table shows the demonstrated velocity range, accuracy, SNR, and other relevant parameters of techniques.

Techniques for detecting boundary-layer transition included flow visualization, thin film, optical and holographic interferometry, and infrared imagery. The low density associated with hypersonic flow precludes the application of optical and holographic interferometry to three-dimensional models. Boundary-layer transition over two-dimensional models can be detected with optical interferometry if the optical path length is adequately long. Hypersonic wind-tunnel conditions hinder the application of infrared imagery and limits it to high subsonic flows. Flow visualization and thin-film techniques have many practical problems when applied to hypersonic conditions; however, they can be overcome with proper engineering designs.

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