A LASER VELOCITY MEASUREMENT SYSTEM
FOR HIGH-TEMPERATURE WIND TUNNELS

by George R. Grant and Ralph W. Donaldson

Ames Research Center
Moffett Field, Calif.

1. Report No. NASA TM X-1976	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle A LASER VELOCITY MEASUREMENT SYSTEM FOR HIGH-TEMPERATURE WIND TUNNELS		5. Report Date April 1970
		6. Performing Organization Code
7. Author(s) George R. Grant and Ralph W. Donaldson		8. Performing Organization Report No. A-3406
9. Performing Organization Name and Address NASA Ames Research Center Moffett Field, Calif. 94035		10. Work Unit No. 722-03-00-01-00-21
		11. Contract or Grant No.
		13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D. C. 20546		
		14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

Traditional low-velocity measurement techniques of using probes inserted into the flow are cumbersome in high-velocity, high-enthalpy gas flow facilities because the probes disturb the flow and deteriorate rapidly. A laser probe utilizing the Doppler shift of scattered laser light has been shown to be suitable for this purpose.

Velocities of 6×10^4 cm/sec (Mach 2.8) have been measured in a small cold flow nozzle made especially for this purpose. Insufficient heterodyne signal eventually limits the highest velocities that can be measured by this method, but in the present experiment the highest velocity measured was limited only by the maximum practical flow rate of our cold flow nozzle. The measurements were obtained by (1) the use of a high power argon laser, (2) the addition of finely divided TiO_2 and NH_4Cl to the stream, and (3) careful design of the detector system to assure superposition of the direct and the scattered beam at the photocathode. This superposition was accomplished by means of an image transfer system which focused the entrance aperture of the detector system on the photocathode, and had the additional advantage of allowing for the insertion of a 4880 Å filter in a parallel part of the transfer system optics. Simultaneous pitot probe measurements of stream velocity agreed well.

17. Key Words Suggested by Author(s) velocity Doppler	18. Distribution Statement Unclassified - Unlimited		
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 9	22. Price* $3.00

A LASER VELOCITY MEASUREMENT SYSTEM FOR

HIGH-TEMPERATURE WIND TUNNELS

By George R. Grant and Ralph W. Donaldson

Ames Research Center

SUMMARY

Traditional low-velocity measurement techniques of using probes inserted into the flow are cumbersome in high-velocity, high-enthalpy gas flow facilities because the probes disturb the flow and deteriorate rapidly. A laser probe utilizing the Doppler shift of scattered laser light has been shown to be suitable for this purpose.

Velocities of 6×10^4 cm/sec (Mach 2.8) have been measured in a small cold flow nozzle made especially for this purpose. Insufficient heterodyne signal eventually limits the highest velocities that can be measured by this method, but in the present experiment the highest velocity measured was limited only by the maximum practical flow rate of our cold flow nozzle. The measurements were obtained by (1) the use of a high power argon laser, (2) the addition of finely divided TiO_2 and NH_4Cl to the stream, and (3) careful design of the detector system to assure superposition of the direct and the scattered beam at the photocathode. This superposition was accomplished by means of an image transfer system which focused the entrance aperture of the detector system on the photocathode, and had the additional advantage of allowing for the insertion of a 4880 Å filter in a parallel part of the transfer system optics. Simultaneous pitot probe measurements of stream velocity agreed well.

INTRODUCTION

One of the high enthalpy test facilities at Ames Research Center requires velocity measurements of a high-density stream that may reach a temperature of 2444° C and a velocity as high as 1.2×10^5 cm/sec. Because probes inserted into such a stream disturb the flow and because the probes themselves disintegrate rapidly in the extreme environment, it was necessary to develop a velocity measuring system that would not require such probes.

Several solutions to this problem have been suggested in the literature. The use of Doppler-shifted laser light to measure stream velocity was described, for example, by Yeh and Cummings (ref. 1) and was first applied to relatively low-velocity liquid streams. Forman et al. (ref. 2) extended the basic technique to gas flows, measuring velocities up to 3×10^5 cm/sec. More recently, Huffaker (ref. 3) of Marshall Space Flight Center has published details of a three-dimensional system for measuring jet turbulence. In practice, such a technique does not measure the gas stream velocity directly, but rather the velocity of small, particulate scattering centers entrained in the

gas. The work done by most researchers has required the addition of material to the stream. In the Ames facility, for which the instrument based on this principle and described in this report was designed, the particulate matter is already present as the product of the decrepitation of the brick in the storage heater of the test facility during heat cycling. This natural dust may provide sufficient scattering to permit accurate velocity measurement.

SCATTERING MECHANISM

As yet, there is little data available on the size of dust particles expected from the storage heater brick of the test facility. The characteristics of the wind tunnel will dictate the particle size required to guarantee that a particle is traveling at some reasonable percentage of stream velocity when it reaches the test section.

The particles entrained in the flow are accelerated by viscous drag. In laminar flow the forces required to accelerate the material can be equated to the drag force given by Stokes' law. (In practical situations the drag is always greater than that given by Stokes' law.) The accelerating force F, is given by

$$F = m \frac{dV}{dt} \tag{1}$$

and the drag force, D, is

$$D = 3\pi\mu V d \tag{2}$$

m   mass of the particle

$\frac{dv}{dt}$ acceleration of the particle

μ viscosity of the gas

d   diameter of the particle

V   velocity difference between the flowing gas and the particle

The forces D and F are equated to obtain the time, t, to achieve velocity, V,

$$t = \frac{m}{3\pi\mu d} \frac{dV}{V} \tag{3}$$

The time for a particle to reach 90 percent of stream velocity, V_1, is:

$$t_{90\%} = \frac{m}{3\pi\mu d} \int_{V_1}^{0.1V_1} \frac{dV}{V} \quad \text{or} \quad t_{90\%} = 0.244 \frac{m}{\mu d}$$

In the test facility of interest the gas velocity is about 1.2×10^5 cm/sec and the available accelerating distance is 30 cm. The time of acceleration is, therefore, about 500 microseconds. A typical value for the gaseous viscosity is 300 micropoise, so that the largest mass for a particle accelerated to

2

90 percent of the free-stream velocity in this distance is related to its diameter by $m = 0.6 \times 10^{-6}$ d. Assuming spherical particles of TiO_2 with a density of four we can solve for the particle diameter, $d = 5.3 \times 10^{-4}$ cm. That is, particles of TiO_2 less than 5μ in diameter will be accelerated to 90 percent of stream velocity in 30 cm. Particles of 0.5μ would reach at least 99 percent of the stream velocity in the same distance.

If the particles are small compared to the wavelength, λ, of the laser light (i.e., submicron sizes), the scattering will occur in accordance with Rayleigh scattering theory; that is, the scattering cross section, σ, will be described by the formula:

$$\sigma = \frac{8\pi}{3} \left(\frac{2\pi}{\lambda} \right)^4 |a|^2 \qquad (4)$$

where a is the polarizability (ref. 3).

The scattering particles may not be small compared to the wavelength of the incident radiation, and the more general Mie description of the scattering phenomenon is required for the wider range of particle sizes that may be present (ref. 4). This theory states that when the conductivity and dielectric constant of particles are small (when the conductivity and dielectric constant are large, most of the incident light is reflected or absorbed), the scattered intensity pattern predominates to the front of the very small scatterer with reference to the direction of the incident radiation. As the radius of the particle increases (only spherical particles being considered), more of the energy is scattered in the forward direction until essentially all the energy is scattered in the forward direction. As the radius is further increased, the forward intensity goes through a series of maxima and minima until the radius becomes very large and most of the incident energy is reflected or absorbed. Fortunately for the velocity measuring system, collecting forward-scattered light is convenient from the standpoint of optical system design.

OPTICAL SYSTEM DESIGN

The design of the optics is governed by the constraints imposed by the heterodyne detection process employed. Several analyses have been published of heterodyne detection of light with a suitable detector (refs. 1, 2). The only detector considered for this instrument was the photomultiplier tube since there is no other broadband detector with as high a sensitivity to light of the wavelengths under consideration. The high sensitivity is required because of the small signal expected, and the broadband characteristic is required because of the wide range of frequencies to be measured.

It is necessary to relate the frequency from the detector output to the actual stream velocity. Two inputs are necessary for this task; the relationship between stream velocity and particle velocity, which has already been discussed, and the relationship between the frequency and the particle velocity which is

$$F_D = \frac{2V}{\lambda} \sin \frac{\theta}{2} \sin \left(\alpha - \frac{\theta}{2} \right)$$
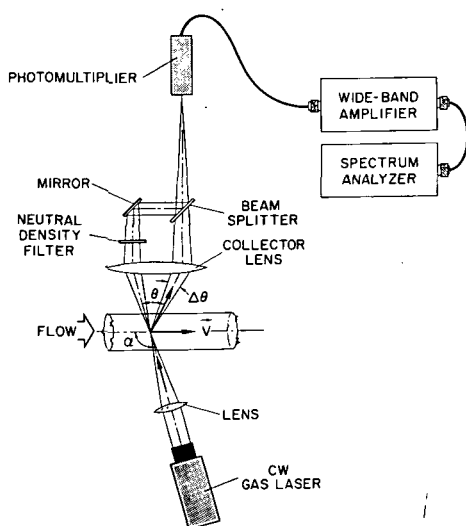
3

Figure 1.- Experimental arrangement for laser
Doppler flowmeter measurements.

where V is the velocity of the scattering particles, α is the angle between the irradiating light λ and the particle velocity, and θ is the scattering angle with respect to the angle of incidence. The flow is assumed to be nonturbulent. The angles α and θ are shown in figure 1.

Though it would be desirable to use collecting optics with a small F number in order to gather as much light as possible, it should be noted that for higher values of V, θ must be kept small in order to keep F_D within the bandwidth of the detector and data processing system. With this system it follows that Δθ (see fig. 1) must be small, and since each scattering angle represents a different frequency, a small Δθ gives a small frequency spread.

The adverse effect of the large F number collection optics may be counteracted by using a higher powered light source. An argon ion laser is used in these experiments. For several reasons, the argon ion laser will produce more signal output from the detector than the more commonly used HeNe laser. While commercially available HeNe lasers have rated outputs up to about 50 mW, the argon ion lasers may now be obtained with outputs up to 5 W. The power ratio of 100 will appear as a direct increase in output at the detector. The laser that was employed produced a power of ∼ 2 W at 4880 Å, giving 40 times more power. A second advantage of the argon ion laser over the HeNe laser is that photocathodes are more sensitive to the argon wavelengths than to longer HeNe wavelengths. It is difficult to quantify the exact degree of improvement expected since the photocathode response may vary over a rather wide range, depending on unpredictable differences in the composition of the photosensitive surface. A third improvement concerns the influence of the wavelength of incident light on the amplitude of the forward scattered light. If the scatterers are very small (i.e., Rayleigh scattering), the improvement will be very pronounced because of the $(1/\lambda)^4$ term. For larger particles, the effect is not nearly so apparent, but Mie theory still predicts a strong short wavelength dependence for the forward scattered intensity.

EXPERIMENTAL PROCEDURE

A parametric investigation was first undertaken to compare the sensitivities and outputs of available photodetectors for wavelengths and power levels from argon ion and HeNe lasers. Table 1 is a presentation of the results. The calculated column was based upon the published output of

TABLE 1.- COMPARISON BETWEEN HeNe AND Ar LASERS FOR SCATTERING EXPERIMENT

	Calculated	Measured
50 mW HeNe with S-11 Detector	1	1
50 mW HeNe with S-20 Detector	40	
1 W Argon with S-11 Detector	1000	1500
1 W Argon with S-20 Detector	2000	

the lasers, the published spectral response of the photocathode materials and the fourth power dependence of the scattering upon frequency. The results were normalized to the 50 mW HeNe laser source and an S-11 photocathode detector. The calculations show a gain of approximately 1000 in going from 50 mW HeNe laser source with an S-11 detector to a 1 W argon ion laser source with the same S-11 photocathode. An additional gain can be obtained by using an S-20 photocathode.

In the experimental setup an S-11 photocathode was used for observing the amount of scattering from a known amount of material injected into the laser beam. The photomultiplier view was restricted so that only a small known volume of the laser scattering medium was observed. Exactly the same physical setup was used with a HeNe and subsequently with an argon ion laser. The HeNe laser produced a 50 mW output beam and the argon ion laser produced 1 W single mode. Again, the data were normalized to the 50 mW HeNe laser with an S-11 photocathode detector.

The observed signal ratio between the argon ion and the HeNe lasers approximates 1500, whereas the calculated ratio was 1000. This can indicate that the S-11 photocathode may not have conformed to the published data.
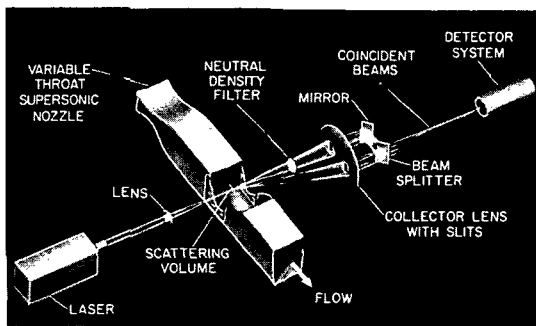

Figure 2.- Schematic drawing of Doppler velocity system.

Since the particle density in the test stream was unknown, the more powerful argon ion laser was selected initially in order to increase the scattered light signal. The optical system used is shown in figure 2. The laser was focused at a point in the stream and a portion of the scattered light was collected and focused onto a photomultiplier. The direct laser beam was focused at the same spot on the photomultiplier where it heterodyned with the scattered beam and produced a signal that was amplified by the photomultiplier. The output could be observed with a wide-band spectrum analyzer. Neutral density filters were required to reduce the intensity of the reference beam, and mirrors were used to direct the light beams onto the photomultiplier.

As stated before, the divergence angle for the incident and scattered light must be kept very small in order to keep the Doppler frequency within the bandwidth of the electronics equipment and the photomultiplier tube. The angle presently used is about 3°. This small angle has made it necessary to use one large collimation lens (7-inch Aero Ektar), which has been masked off to give two slits on the face of the lens. Besides making it possible to have a small collection angle for the light, the single collection lens reduces alinement problems. The mask, which fits over the Aero Ektar collection lens, has two slits about 9 mm apart and 1 mm wide by 25 mm long. Of course, the reference and signal light beams must still be colinear and focused on the face of the photomultiplier tube. The path length of the reference beam was approximately 9 mm longer than that of the scattered beam, but at the F numbers involved, this was not important.

Focusing and superimposing these two beams on the photocathode of an S-20 photomultiplier required special care since the photocathode is vacuum deposited onto the inside of the photomultiplier and window and is extremely transparent. The image transfer system shown in figure 3 optically places the plane of the photocathode at the aperture H. Both lenses have a 25 mm focal length and are arranged so that the 4880 Å filter is illuminated normal to its surface. With this system a sharp image on the face of the aperturing plate is transferred onto the best possible position on the photocathode.
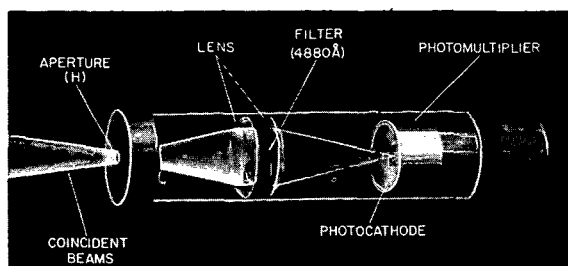

Figure 3.- Schematic drawing of detector system.

The small aperture effectively limits the amount of inherent room light entering the detector, and the bandpass interference filter further limits the light getting to the photomultiplier tube to a narrow wavelength band about 4880 Å. The use of this detector system considerably simplified the alinement procedure.

The velocity measuring system was evaluated by using it to measure the stream velocity in a small variable-throat, cold-flow tunnel to which scattering centers had been added. A conventional pitot tube measuring probe was used to measure the total pressure. Static pressure and reservoir temperature and pressure were measured simultaneously. Charts of compressible flow were used to determine the velocity in the test section at the point of measurement. When the system is used in the high temperature test facility for which it was designed, the scattering centers will be of a refractory material. In the test nozzle used in the cold flow tests and described above, experiments with oil smoke, burning wet paper, and micron sized ZrO_2 were conducted before TiO_2 was used. Besides giving the best results, TiO_2 is a refractory material. The TiO_2 was made by combining the vapor of $TiCl_4$ directly with the vapor of NH_4OH. It is possible to produce hydrochloric acid as one of the reaction products, but an excess of NH_4OH should neutralize the HCl. Air saturated with ammonia vapor was bubbled through titanium tetrachloride. The air stream emerging from the titanium tetrachloride vessel was densely filled

with a mixture of very fine, white titanium dioxide particles and ammonium chloride smoke. This mixture was added to the stream in a plenum chamber located just ahead of the nozzle.
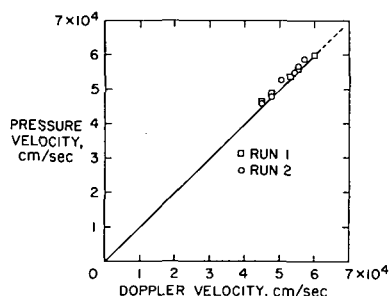

Figure 4.- Comparison of pressure velocity and Doppler velocity.

A series of tests were run on this small tunnel using both the argon ion laser Doppler shift system and a pitot tube apparatus to obtain velocity measurements. Figure 4 shows the correlation between the two measurement techniques. The line drawn on the graph is at 45°. The 2 - 3 percent difference between the measurements is well within the probable errors attributable to either system. The maximum velocity attained was limited only by the cold flow nozzle characteristics of the test apparatus rather than by the measurement technique.

CONCLUDING REMARKS

A Doppler heterodyning velocity measuring apparatus has been constructed and tested at velocities exceeding 6×10^4 cm/sec. The use of a high power argon ion laser reduces the amount of scattering material required to obtain good heterodyne signals, and the incorporation of an image transfer system simplifies the alinement procedure.

Ames Research Center
    National Aeronautics and Space Administration
        Moffett Field, Calif., 94035, Sept. 10, 1969

REFERENCES

1. Yeh, Y.; and Cummins, H. Z.: Localized Fluid Flow Measurments With an He-Ne Laser Spectrometer. Appl. Phys. Ltrs., vol. 4, 1964, p. 176.

2. Foreman, J. W., Jr.; George, E. W.; and Lewis, R. D.: Measurement of Localized Flow Velocities in Gases With a Laser Doppler Flowmeter. Appl. Phys. Ltrs., vol. 7, Aug. 15, 1965, pp. 77-78.

3. Huffaker, R. M.; Fuller, C. E.; and Lawrence, T. R.: Application of Laser Doppler Velocity Instrumentation to the Measurement of Jet Turbulence. SAE Paper 690266.

4. Stone, J. M.: Radiation and Optics. McGraw-Hill Book Company, New York, 1963.

5. Born, Max; and Wolf, E.: Principles of Optics, 3rd ed., Pergamon Press, 1966.

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

— NATIONAL AERONAUTICS AND SPACE ACT OF 1958

NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

TECHNICAL REPORTS: Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

TECHNICAL NOTES: Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

TECHNICAL MEMORANDUMS: Information receiving limited distribution because of preliminary data, security classification, or other reasons.

CONTRACTOR REPORTS: Scientific and technical information generated under a NASA contract or grant and considered an important contribution to existing knowledge.

TECHNICAL TRANSLATIONS: Information published in a foreign language considered to merit NASA distribution in English.

SPECIAL PUBLICATIONS: Information derived from or of value to NASA activities. Publications include conference proceedings, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

TECHNOLOGY UTILIZATION PUBLICATIONS: Information on technology used by NASA that may be of particular interest in commercial and other non-aerospace applications. Publications include Tech Briefs, Technology Utilization Reports and Notes, and Technology Surveys.

Details on the availability of these publications may be obtained from:

SCIENTIFIC AND TECHNICAL INFORMATION DIVISION

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Washington, D.C. 20546