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LASER DOPPLER VELOCIMETRY FOR CONTINUOUS FLOW SOLAR-PUMPED IODINE LASER SYSTEM

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ABSTRACT

A laser Doppler velocimetry (LDV) system, developed by IRD, was employed to measure the flow velocity profile of iodide vapor inside laser tubes of 36 mm ID and 20 mm ID. The LDV, which was operated in the forward scatter mode used a low-power (15 mW) He-Ne laser beam. Velocity ranges from 1 m/s up to 17 m/s was measured to within one percent accuracy. The flow velocity profile across the laser tube was measured and the intensity of turbulence was determined. The flow of iodide inside the laser tube demonstrated a mixture of both turbulence and laminar. The flow meter used for the laser system previously was calibrated with the LDV and found to be in good agreement.

INTRODUCTION

The LDV techniques are successfully applied to flow velocity measurements in aerodynamic tests[1–5]. Frequency shifts in the light reflected from a moving object is the basis of the measurement. In practice the impurity particles or the particles entering in the gaseous flow serve as moving objects. The impurities act as scattering centers and their mean velocity, if the particles are small enough, is the same as the velocity of the gaseous flow and is given by the mean Doppler shift f_D of the received signal. This technique requires no need of calibration or knowledge of other flow parameters such as pressure and temperature and gives a reading which is linear with the velocity of particles in gases or liquids. By scanning along the flow field, simultaneous measurement of turbulence is also possible with high accuracy.

The purpose of this report is to describe the results of LDV tests performed for the determination of the flow characteristics inside the laser tube of the cw solar-simulator-pumped iodine laser. The results also provided the calibration of the flow meter used in the system. The technique, optics, procedures, and results are described in this report

Laser Doppler Velocimeter Technique

Details of the application of this technique for the laser system will be reported separately. The following is a brief description of the technique: in a LDV arrangement, two beams of equal irradiance are focused by a lens into the gaseous flow whose velocity is to be measured (see figure 1). The region where the beams cross becomes the measurement region. If the two incident beams are coherent, then their intersection will result in the formation of a set of interference fringes in the plane of the beams at the crossing point. The fringes will be parallel to the bisector of the beams, that is, normal to direction of the component of flow being measured. The fringe pattern is a combination of alternating light and dark regions of equal separation (figure 1). The fringe separation d is given by

$$d = \frac{\lambda}{2 \sin (\theta/2)},$$

where λ is the wavelength of the laser light and θ is the angle between the optical axis of the intersecting beams.

A particle in the moving flow and passing through the fringes will scatter light with a sinusoidal intensity variation with time. The rate of intensity variation is a function of the fringe separation

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and of the particle velocity in the direction normal to the fringes. The particle velocity is given by $v = df$, where f is the frequency of the photodetector output signal; f is the same as Doppler frequency f_D, so that

$$v = d\, f_D = \frac{\lambda f_D}{2 \sin\,(\theta/2)}.$$

Optical System

A typical dual-beam optical LDV system, used to measure the axial component of the iodide flow velocity inside the laser tube, is shown in figure 2. Light from a low-power (15 mW) He-Ne laser with TEM_{00} mode of operation and a wavelength of 632.8 nm passes through a beam splitter prism which gives two parallel beams of equal intensity with 50 mm separation. A transmitter lens, L_1, with a focal length of 47.62 cm was used to focus the beams to a spot size (measurement region) of 0.20 mm in diameter by 3 mm long. The light scattered by particles in the measurement region is collected by a F 1:2 lens, L_2, and is imaged on a high-gain, low-noise photomultiplier tube (PMT) with an S-20 wavelength response by a 10 × (0.25 numerical aperture) microscope objective lens, L_3.

Flowing Iodine Laser System

The experimental set up for the cw iodine laser system with continuous iodide flow is shown in figure 3. The flow of iodide vapor was longitudinal inside the laser tube and was necessary for the removal of quenching products formed as the results of photodissociation in the pumping region. The iodide n-C_3F_7I was in a liquid state at room temperature and had a vapor pressure of 350 torr. The flow was maintained by a pressure differential between the heated evaporator containing the liquid iodide and the liquid-nitrogen-cooled condenser. To obtain sufficient flow rate of iodide, the evaporator was immersed in a tub of heated water and stirred with a magnetic stirrer. The temperature of water was kept constant at 40°C to provide an initial vapor pressure of about one atmosphere. Prior to filling with lasant, the laser tube, the evaporator, and the condenser were evacuated by a diffusion pump having a liquid nitrogen trap.

To monitor the flow rate of iodide, a mass flow meter was connected between the evaporator and the laser tube. The flow rate was controlled by the valve in the line between the flow-meter and the evaporator. The averaged flow velocity could then be calculated from the pressure measured at both ends of the laser tube and the mass flow rate using the relation

$$v = 0.127 \frac{F}{Ap},$$

where F is the mass flow rate in SCCM (standard cubic centimeter per minute), A is the laser tube cross section in cm^2, p is the pressure of iodide in torr, and v the velocity in m/s. The numerical constant (0.127) is the result of unit conversion. When the valve opening was left static, the flow rate of the iodide vapor was a linear function of the pressures at the ends of the laser tube. This indicated that the flow velocity of the iodide molecules in the laser tube remained constant for different flow rates. Therefore, the flow velocity was varied by controlling another valve located downstream between the laser tube and the condenser.

Two different sizes, 36 mm and 20 mm (ID), and 0.9 m long, suprasil quartz laser tubes were used in these experiments. Stainless steel tubes were used in the flow line between the laser tube ends and the evaporator and the condenser. The length and ID of each tube were 0.9 m and 12.7 mm, respectively. These stainless steel tubes were connected with the laser tube at an angle of about 45° with respect to the flow axis. This arrangement was used to achieve a straight flow along the axis.

Test Procedure

A preliminary test indicated that the photodissociation products such as I_2 provided insufficient scattering for the detector system and an introduction of foreign particulates became necessary. A small flask with a valve was used to inject fine particles of aluminum oxide (Al_2O_3) in the flow of iodide. The size of the Al_2O_3 particle was about 0.6 μm. The flask with Al_2O_3 was vacuum dried and evacuated down to 10^{-3} torr by a mechanical pump. It then was connected with the iodine laser system to inject the Al_2O_3 particles perpendicular to the flow of iodide. Prior to the particle injection the iodide flow was brought to the desired pressure by adjusting the valves in the flow line. Iodide pressures of 5 torr and 10 torr were used in these tests. The velocity range was from 1 m/s to 17 m/s. When the desired pressure was established and the data were recorded, the Al_2O_3 particles were injected into the flow by opening the valve to the flask. At the same time the laser velocimeter was adjusted to measure the axial velocity component along the centerline of the measurement region, as shown in figure 2.

Measurements and Results

A. The mass flow meter calibration. The iodide mass flow meter in the system, which was used for the estimate of the average flow velocity, was calibrated with the LDV. This measurement was performed for both sizes of the laser tubes. A comparison of the velocities (V_m) measured with the LDV and velocities (V_c) calculated from the mass flow meter parameters, shown in figures 4 and 5, indicates good agreement. The values of the parameters of n-C_3F_7I gas flow for these tests are given in tables 1 and 2.

B. The flow velocity profile across the laser tube. For the 36-mm ID laser tube, this measurement was done in one site only because of the limitation in access. The measurement region was located at a distance L (about 0.7 m) from the inlet of iodide vapor into the laser tube, so that the ratio of the length of this distance to the laser tube diameter (L/D) was about 20. However, this ratio could be varied for the 20-mm ID laser tube by locating the experimental set up detached from the laser pumping hardware. The ratios (L/D) ranged from 4.5 to 35.

The average flow velocity of n-C_3F_7I was kept constant throughout the profile measurement by maintaining the flow rate and pressure of the iodide constant. The average velocity and pressure of the iodide in the 36-mm ID tube were (10.8 + 0.1) m/s and (5 + 0.1) torr, respectively, and those in the 20-mm ID tube were (16.5 + 0.2) m/s and (9.7 + 0.2) torr, respectively. Two kinds of Al_2O_3 particles, coated and uncoated, were used with the 36-mm ID laser tube. Two tests were performed with each kind of Al_2O_3. There was no obvious difference in the measured data for the kinds of Al_2O_3. Therefore, later tests were performed with only uncoated Al_2O_3 particles. Eleven data points were taken by the LDV along the diameter of 36-mm ID laser tube. The data were taken in steps of 0.3 cm. Figure 6 shows the measured data for the mean velocity profile, and figure 7 shows the turbulence intensity profile.

The number of data points for the 20-mm ID laser tube was 7 with a distance step of 0.25 cm. Figures 8 and 9 show the mean velocity profiles and figures 10 and 11 show the turbulence intensities.

The turbulence intensity near the wall of the laser tube was 4 times higher than that at the axis of the tube. There was no flow and consequently no turbulence intensity could be measured near (1 mm) the wall. In general the onset of turbulence is often abrupt and can be determined approximately by the Reynolds number,

$$R_e = \frac{2\bar{v}r\rho}{\eta}$$

where $\bar{v}$ is the average velocity, r is the laser tube radius, and ρ and η are the density and viscosity of the medium, respectively. Reynolds numbers calculated from the above equation for 5 torr and 10 torr pressures of n-C_3F_7I and the velocity range from 1 m/s up to 17 m/s are shown in tables 3 and 4 for the 36-mm ID and 20-mm ID laser tubes, respectively. Flow is laminar if R_e has a value less than 2000 but is turbulent if R_e exceeds 2000.

Comparing with data from Table 3, we find that for $p = 5$ torr and $v > 10$ m/s, the flow in the 36-mm ID tube is expected to fall in a turbulent regime. However, the measurements for the $p = 5$ torr and $v = 10$ m/s (figure 7) indicate that the main flow had only <10% turbulence, indicating the flow was still laminar.

C. Profile variation along the axial distance. The velocity profile changes from the parabola in the up-stream side of the laser tube where the ratio L/D was less than 15 (see figure 8). Also the turbulence intensity increases for the lower value of L/D (see figure 10). The velocity profile demonstrated closely a parabola when the ratio of L/D was 20 and over (see figure 9), i.e. the flow is less turbulent in the down-stream side of the laser tube (see figure 11) and becomes laminar as expected.

CONCLUSION

The flow field measurements have been performed on continuous pipe flow of iodide vapor in the cw solar-simulator-pumped iodine laser system using a low-power (15 mW) laser Doppler velocimeter developed by IRD. These measurements were obtained for laser tubes of two different diameters in the absence of laser action. The mass flow meter was calibrated with the LDV to obtain true flow velocity values and error limits. The velocities calculated from iodide flow parameters such as mass flow rate, flow pressure, and tube diameter agreed to within 4 percent with the velocities measured by LDV. The flow velocity profiles across the laser tube diameter were also obtained and the intensities of turbulence were measured. The nature of the iodide flow inside the laser tube was found to be a mixture of both turbulent and laminar flow but became progressively laminar toward down stream.

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SYMBOLS

A	Laser tube cross section, cm^2
d	Fringe separation, cm
D	Diameter of the laser tube, cm
f_D	Doppler frequency, Hz
F	Flow meter
L	Distance of the measurement site from the inlet of flow, cm
L_1	First lens
L_2	Second lens
L_3	Third lens
LN_2	Liquid nitrogen
M_1	Back mirror with maximum reflectivity
M_2	Output mirror with 85% reflectivity
p	Pressure, torr
P_i	Inlet pressure gage
P_o	Outlet pressure gage
r	Radius of laser tube, cm
R_e	Reynolds number
SCCM	Mass flow rate in standard cubic centimeter per minute
v	Flow velocity, m/s
$\bar{v}$	Average velocity, m/s
V_c	Calculated mean flow velocity, m/s
V_m	Measured mean flow velocity, m/s
η	Viscosity, g/cm.s
θ	Angle between the optical axis of intersecting beams in radian
λ	Wavelength of the laser light, nm
ρ	Density, g/cm^3

Table 1. Data for flow system calibration using a 36 mm ID laser tube and n-C_3F_7I.

Flow-meter reading	Flow rate SCCM	Pressure torr	Calculated mean velocity, m/s	Measured mean velocity, m/s	V_m/V_c
30 000	5400	7.5	9.0	10.8	1.20
28 500	5130	7.5	8.5	9.7	1.14
17 000	3060	7.5	5.1	5.2	1.02
3 000	540	7.5	.9	1.2	1.33
7 000	1260	4.0	3.9	4.6	1.18
13 000	2340	5.0	5.8	6.6	1.14
22 000	3960	6.0	8.2	8.9	1.08
25 000	4500	6.2	9.1	10.0	1.10
32 000	5760	7.8	9.2	10.4	1.13

Table 2. Data for flow system calibration using a 20 mm ID laser tube and n-C_3F_7I.

Flow-meter reading	Flow rate SCCM	Pressure torr	Calculated mean velocity, m/s	Measured mean velocity, m/s	V_m/V_c
22 200	3996	11.1	14.6	15.9	1.09
19 200	3456	11.1	12.6	13.9	1.10
13 500	2430	11.1	8.9	9.5	1.07
12 000	2160	11.2	7.8	8.7	1.11
11 100	1998	11.2	7.2	8.0	1.11
9 700	1746	11.1	6.4	7.1	1.10
7 200	1296	11.1	4.7	5.4	1.14
4 200	756	13.0	2.3	2.9	1.26

Table 3. Calculated Reynolds number for 36 mm ID of laser tube.

$P = 5$ torr		$P = 10$ torr	
V, m/s	R_c	V, m/s	R_c
1	217.24	1	434.48
2	434.48	2	868.97
3	651.72	3	1303.45
4	868.97	4	1737.93
5	1086.21	5	2172.41
6	1303.45	6	2606.90
7	1520.69	7	3041.38
8	1737.93	8	3475.86
9	1955.17	9	3910.34
10	2172.41	10	4344.83
11	2389.66	11	4779.31
12	2606.90	12	5213.79

Table 4. Calculated Reynolds number for 20 mm ID of laser tube.

$P = 5$ torr		$P = 10$ torr	
V, m/s	R_c	V, m/s	R_c
1	120.69	1	241.38
2	241.38	2	482.76
3	362.07	3	724.14
4	482.76	4	965.52
5	606.45	5	1206.90
6	724.14	6	1448.28
7	844.83	7	1689.66
8	965.52	8	1931.03
9	1086.20	9	2172.40
10	1206.90	10	2413.80
11	1327.59	11	2655.17
12	1448.28	12	2896.55
13	1568.96	13	3137.93
14	1689.66	14	3379.31
15	1810.34	15	3620.69
16	1931.03	16	3862.07
17	2051.72	17	4103.45

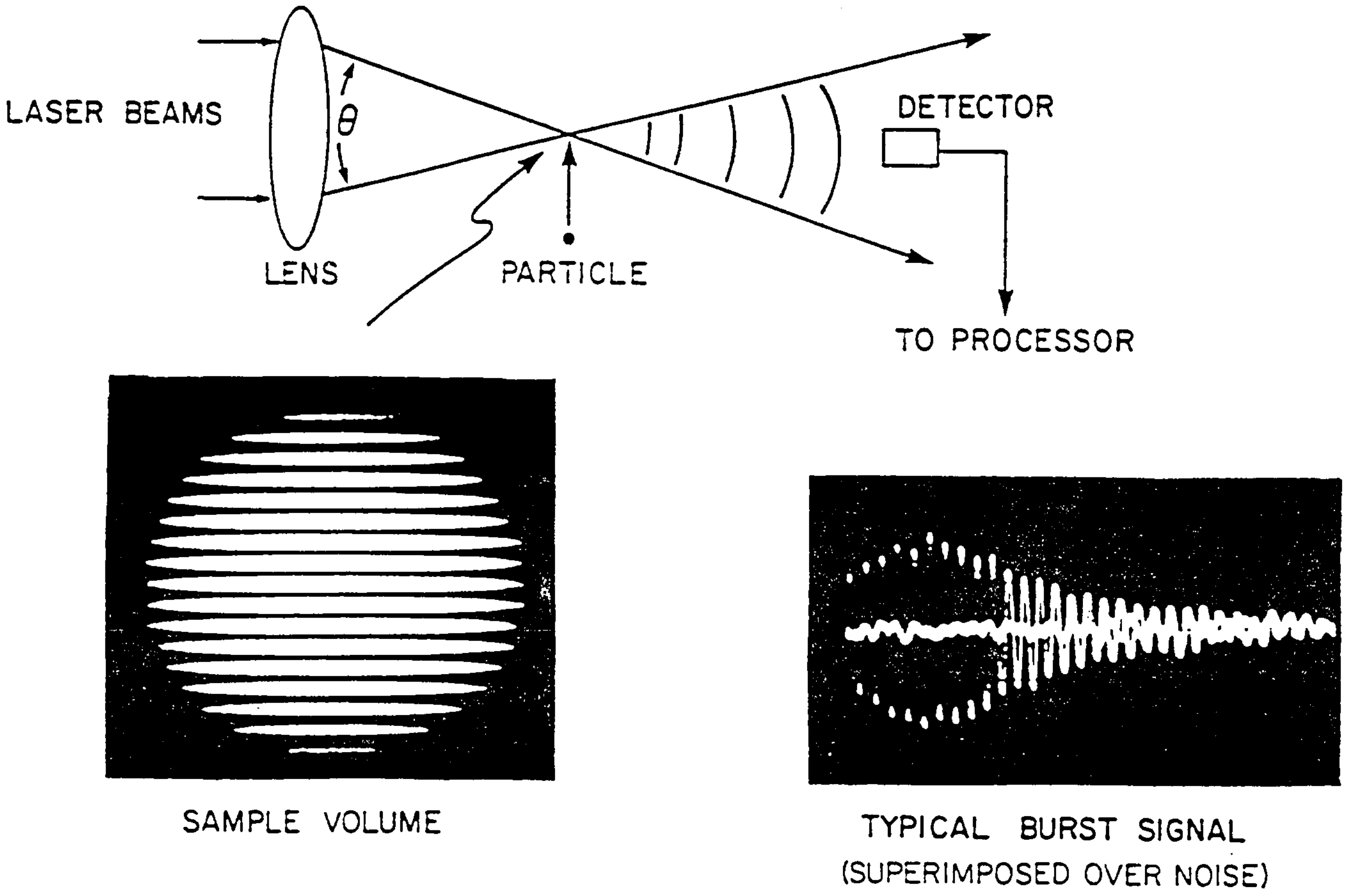

Figure 1. Laser Doppler velocimeter technique.

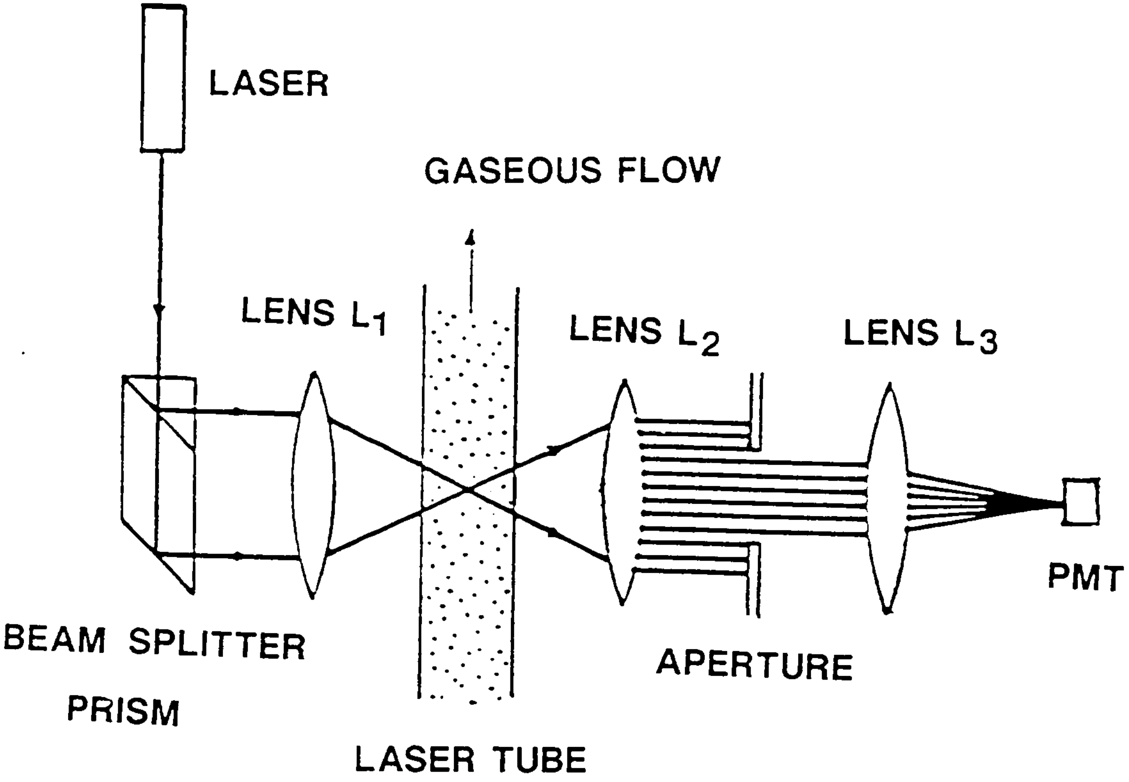

Figure 2. Diagram of the laser velocimeter system.

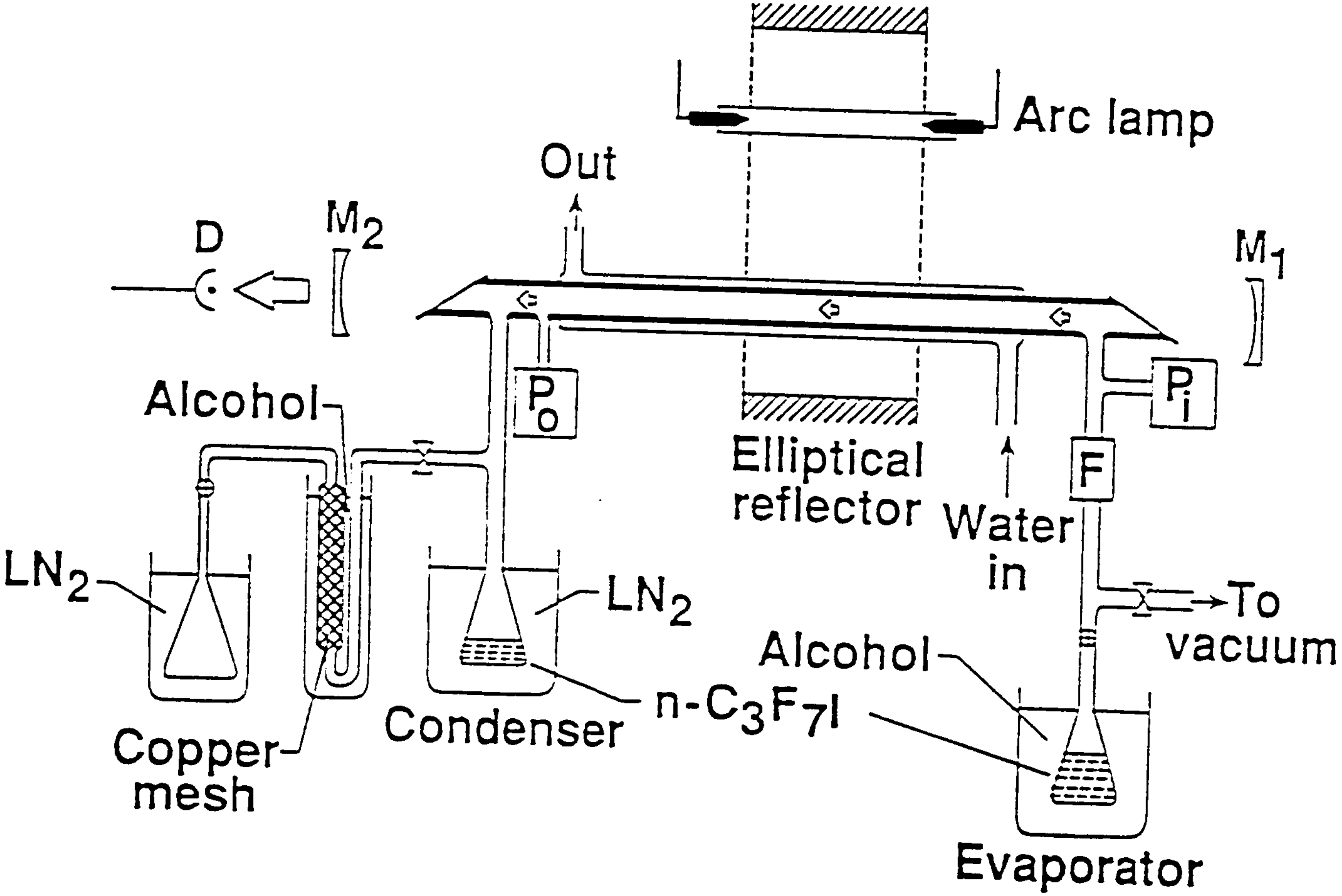

Figure 3. Diagram of the continuous flow solar-pumped iodine laser system.

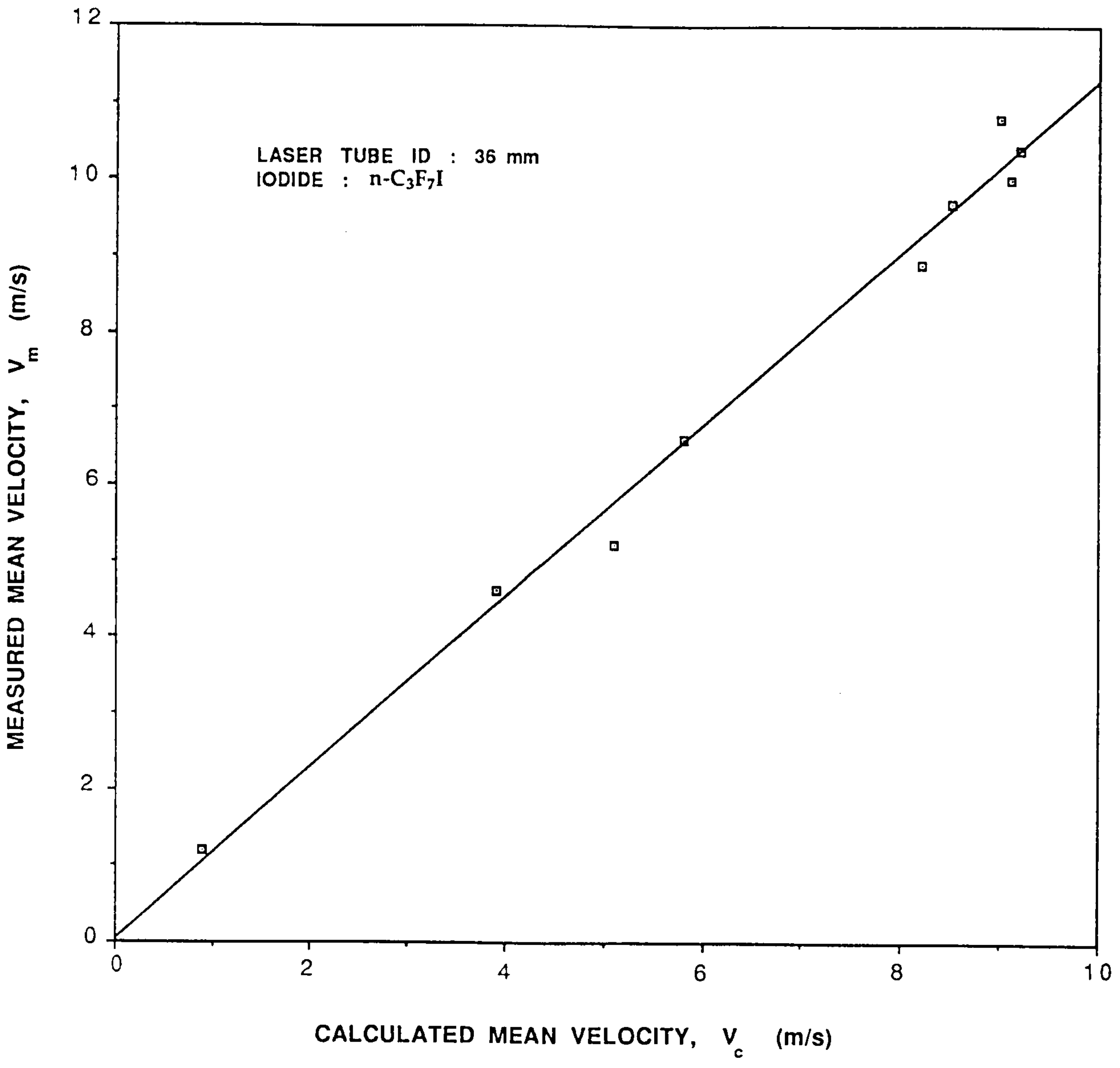

Figure 4. Measured mean velocity versus calculated mean velocity for calibration of the flow meter using 36 mm ID laser tube.

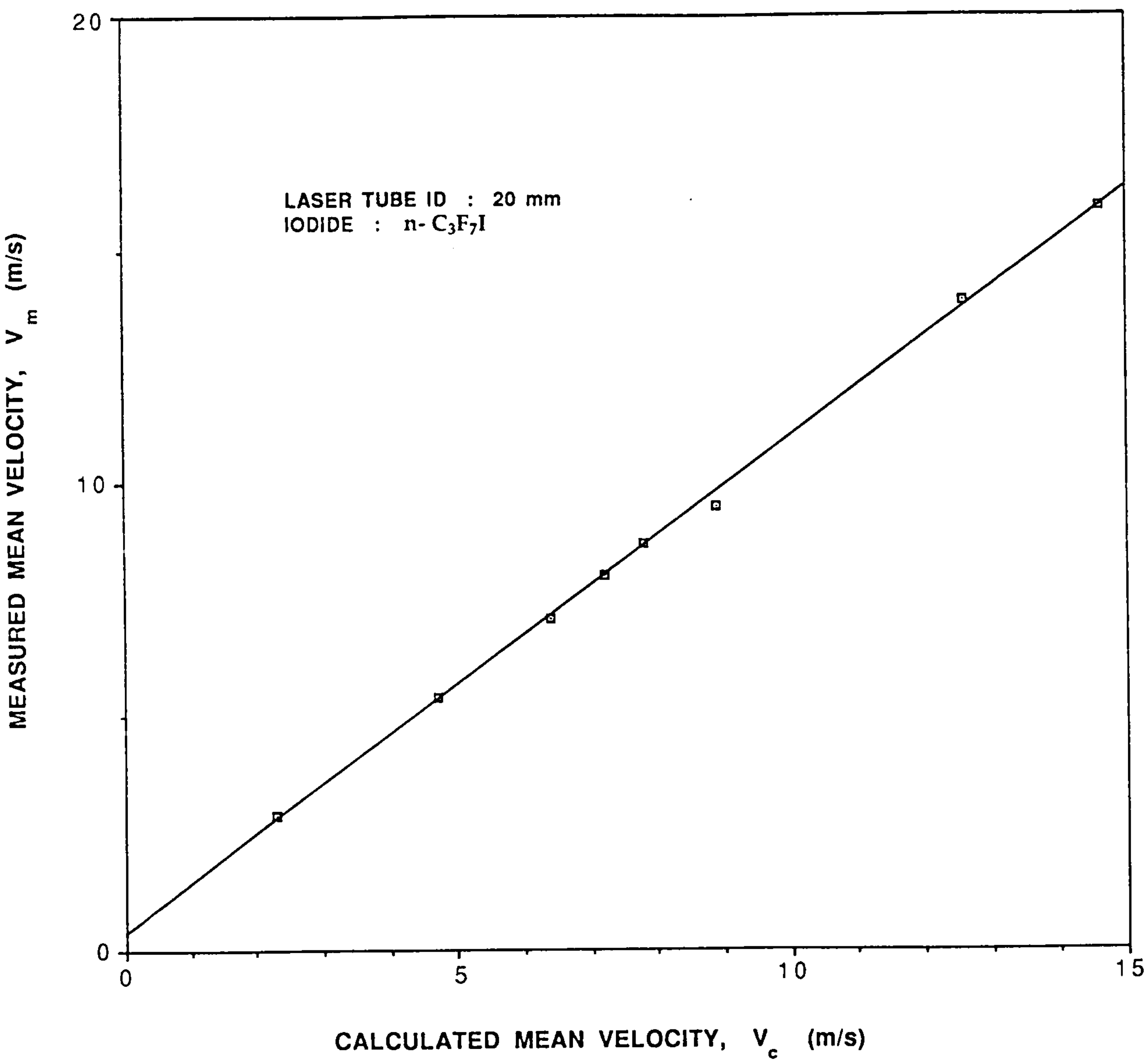

Figure 5. Measured mean velocity versus caculated mean velocity for calibration of the flow meter using 20 mm ID laser tube.

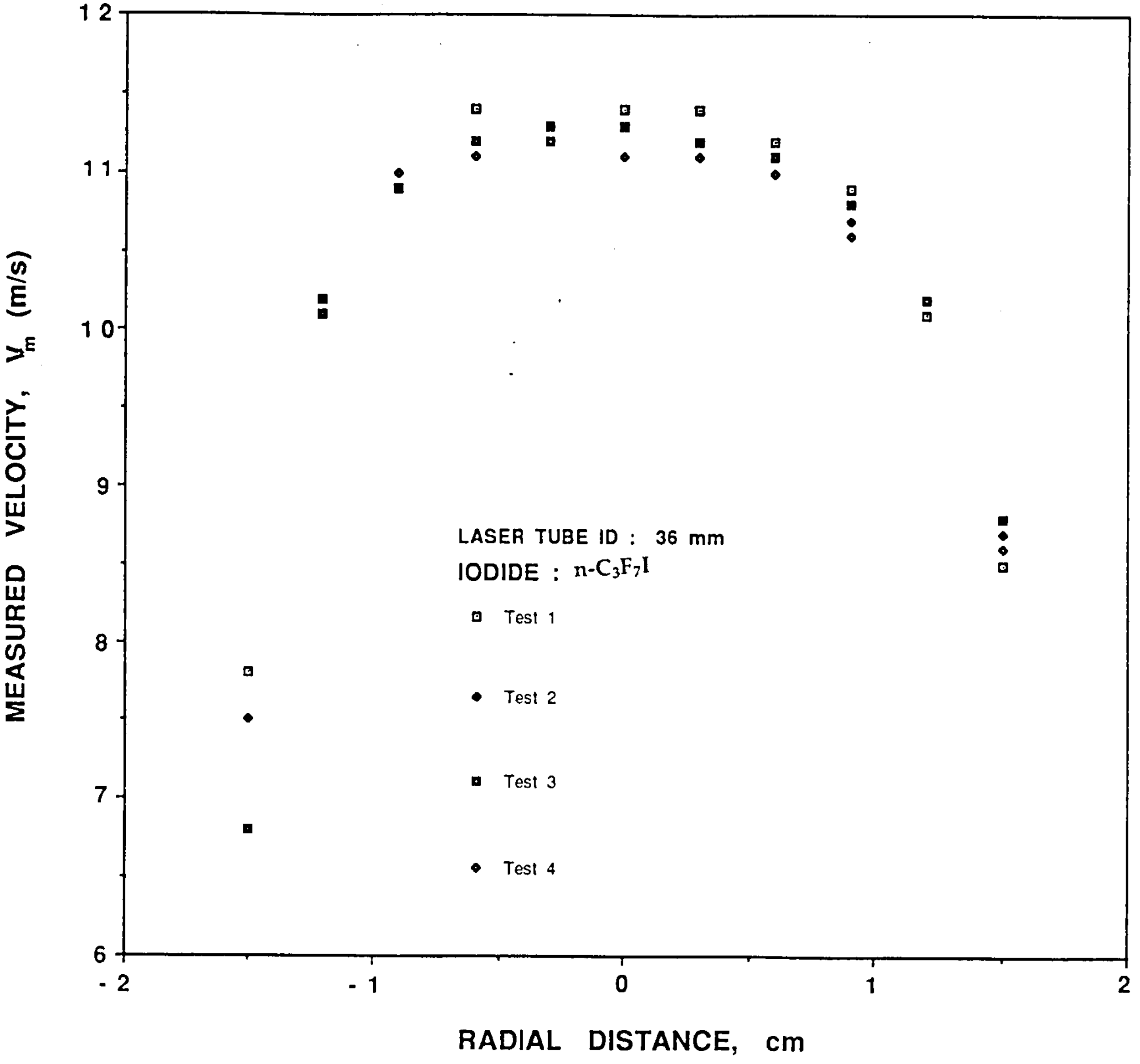

Figure 6. Measured mean velocity profile across a diameter of 36 mm ID laser tube as a function of radial distance.

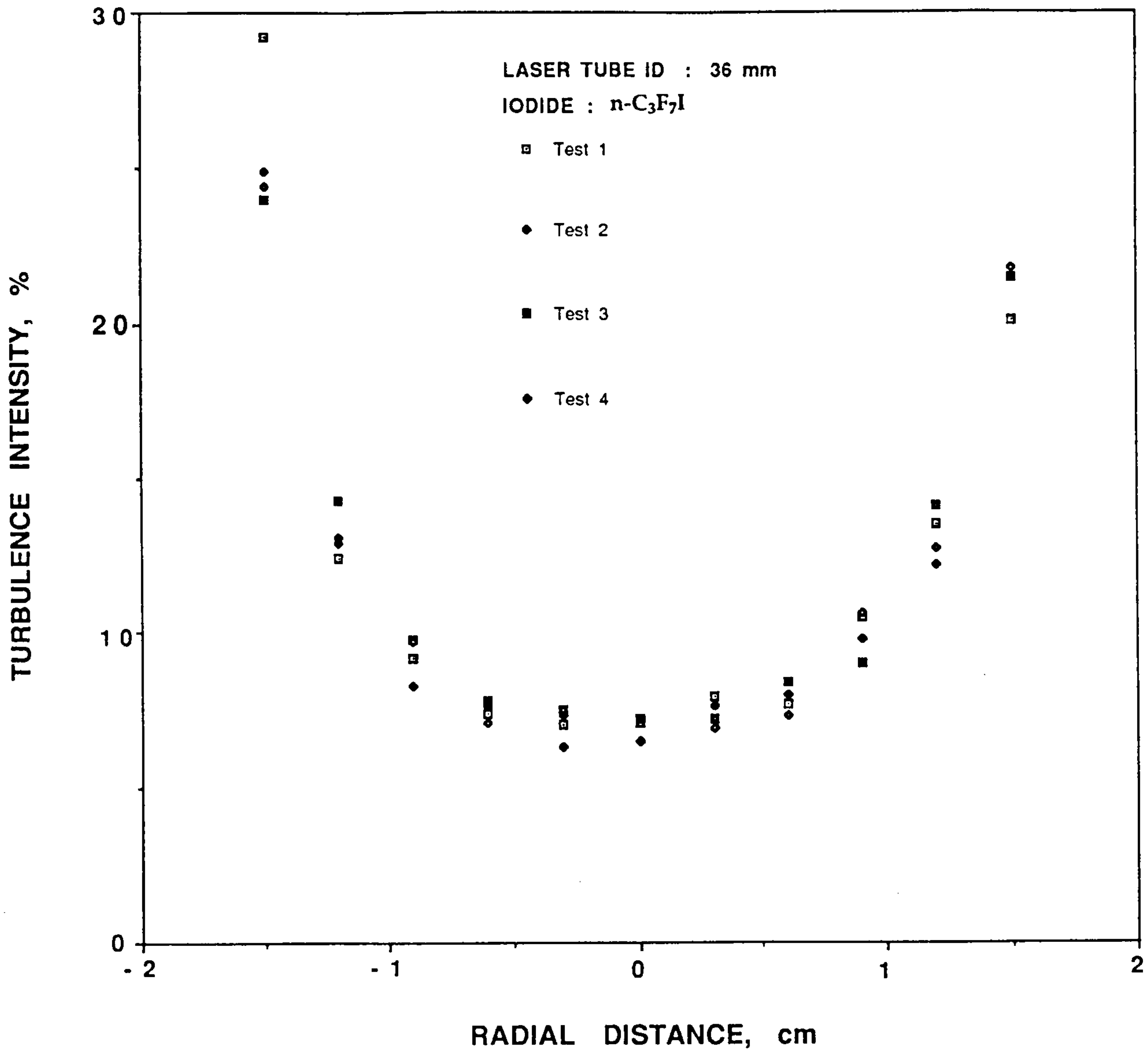

Figure 7. Measured turbulence intensity profile across a diameter of 36 mm ID laser tube as a function of radial distance.

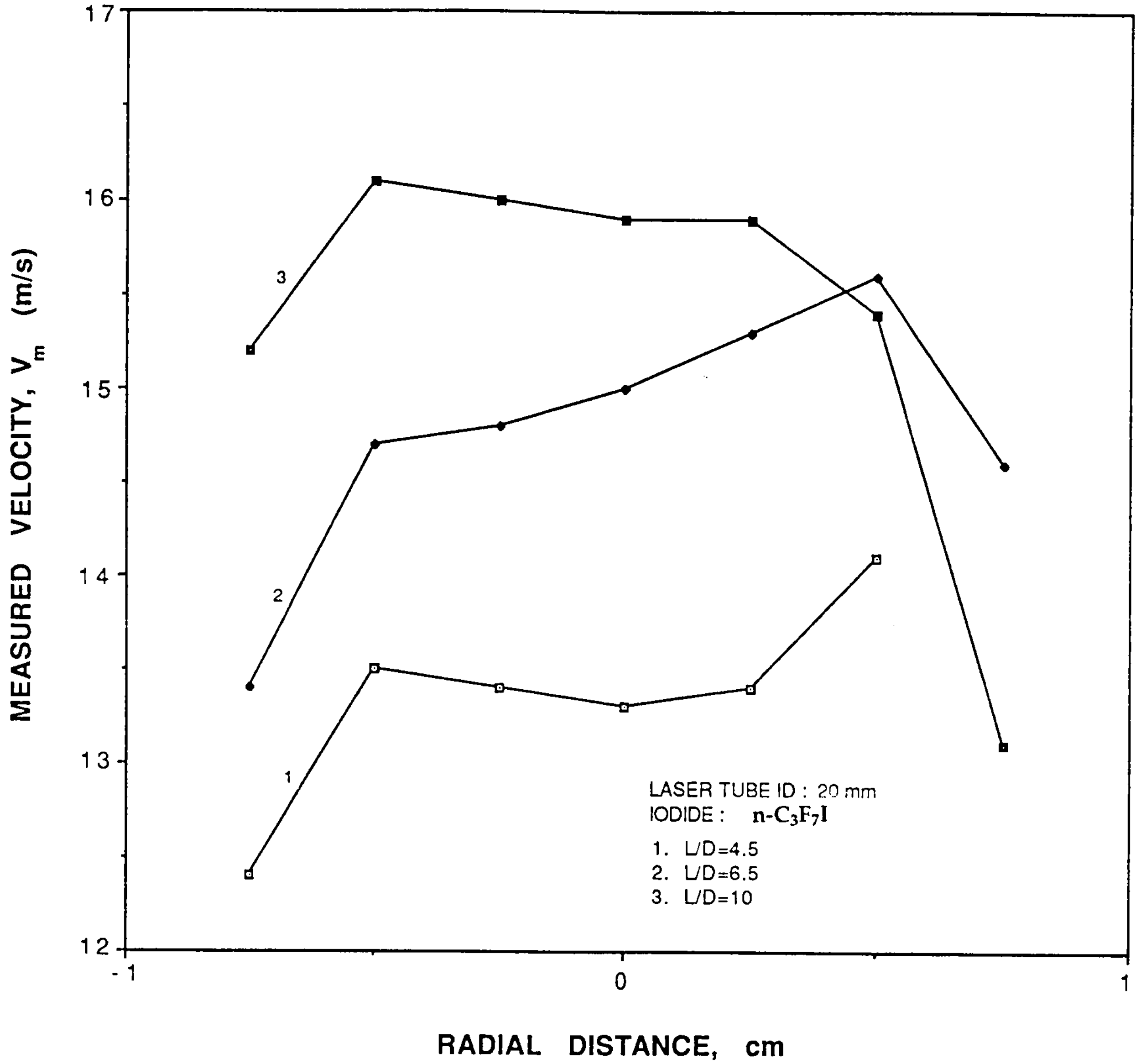

Figure 8. Measured mean velocity profile across the 20 mm ID laser tube as a function of the radial distance.

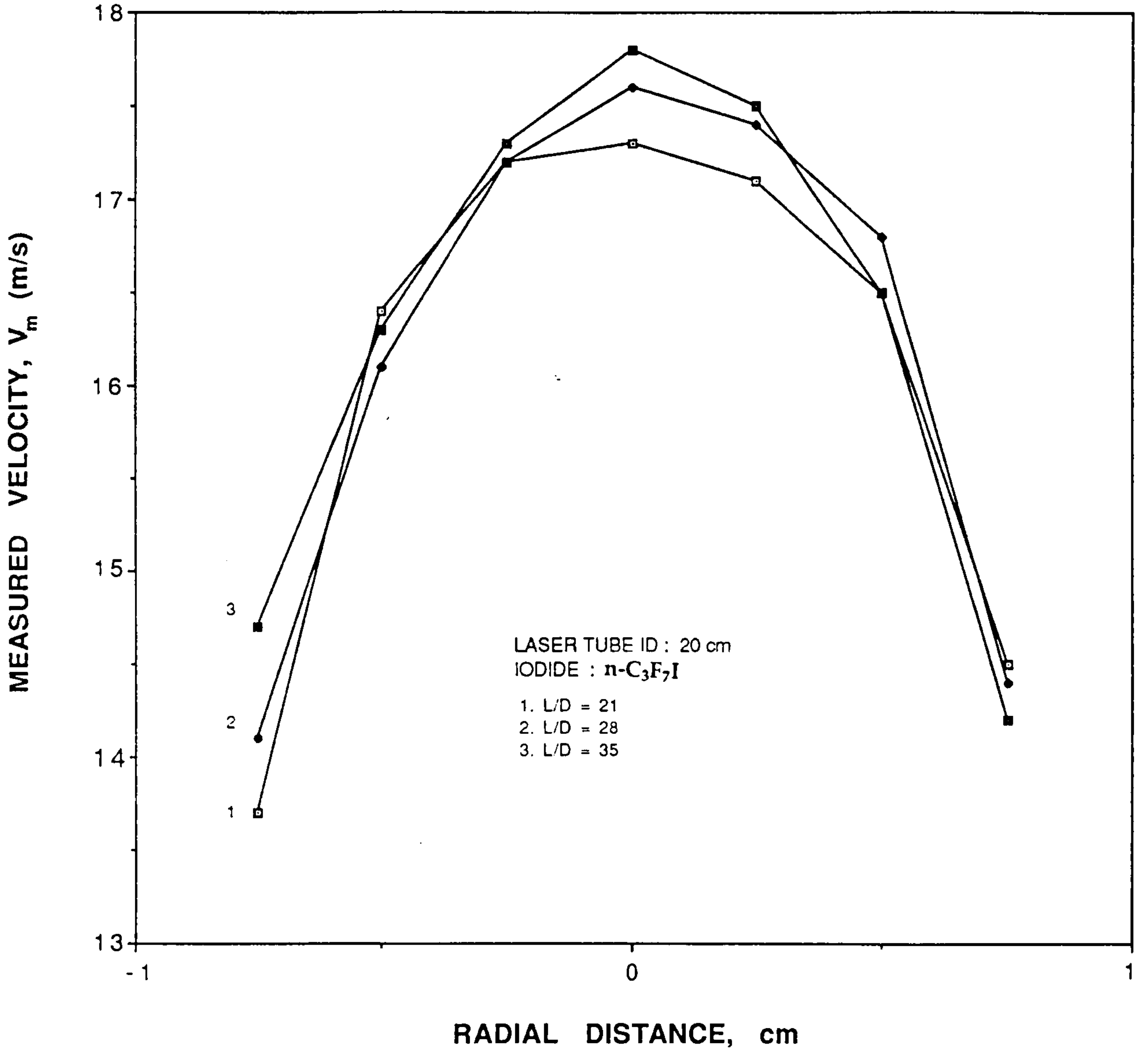

Figure 9. Measured mean velocity profile across the 20 mm ID laser tube as a function of the radial distance.

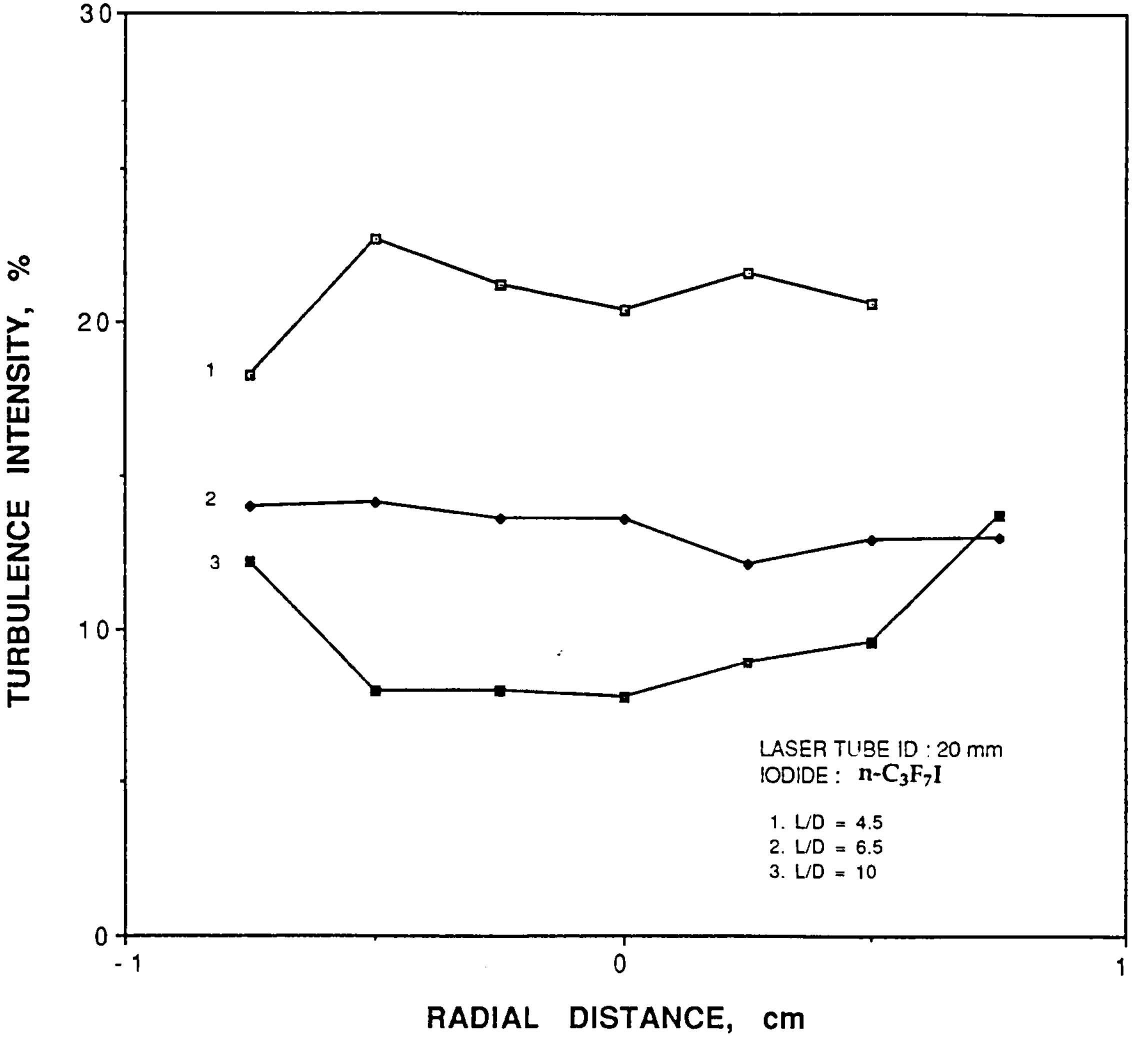

Figure 10. Measured turbulence intensity profile across the 20 mm ID laser tube as a function of the radial distance.

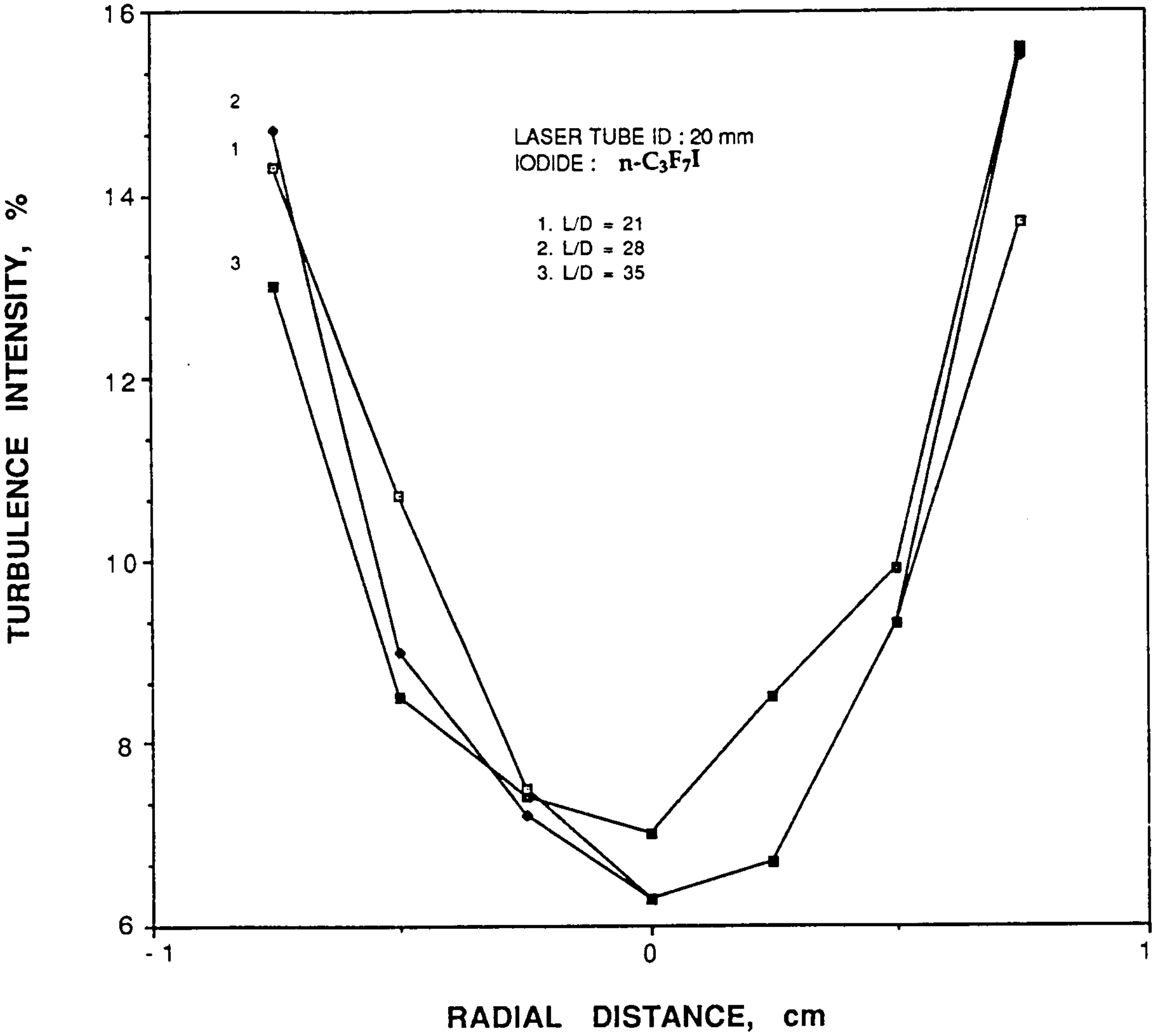

Figure 11. Measured turbulence intensity profile across the 20 mm ID laser tube as a function of radial distance.

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16. Abstract

A laser Doppler velocimetry (LDV) system, developed by Instrument Research Division, NASA Langley Research Center, was employed to measure the flow velocity profile of iodide inside the laser tubes of 36-mm and 20-mm ID. The LDV, which was operated in forward scatter mode, used a low power (15 mW) He-Ne laser beam. A velocity range from 1 m/s up to 17 m/s was measured with less than one percent accuracy. The flow velocity profile across the laser tube was measured and the intensity of turbulence was determined. The flow of iodide inside the laser tube demonstrated to be laminar in general with approximately 10% turbulent component in the main flow on the axis. The mass flow meter previously used for monitoring the laser system was calibrated with the LDV and found to be in good agreement.

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