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Application of a Two-Dimensional Laser Doppler Velocimetry System in an Undergraduate Fluid Mechanics Course

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An experiment has been designed and built for an undergraduate fluid mechanics course, which uses a laser Doppler velocimeter (LDV) to measure velocities in a cylindrical stirred tank. The experiment involves the measurement of radial, tangential and axial velocities as a function of distance from the impeller shaft and as a function of rotational speed of agitator. The range of agitation velocity is between 25 and 125 r.p.m. FIND (flow information description) software is used to analyze the signal produced by the LDV. The experiment also allows the students to estimate turbulent intensities and energy dissipation within the stirred tank. The LDV system uses an 8 W argon laser, which is used for its inherent advantages, namely non-invasive measurement, direct velocity measurement, high-frequency response and very small measuring volume.

EDUCATIONAL SUMMARY

1. The paper describes new training tools or laboratory concepts/instrumentation/experiments in a fluid mechanics laboratory.
2. The paper describes new equipment useful in experimental fluid mechanics courses.
3. Jenior level students are involved in the use of the equipment.
4. The introduction of laser doppler anemometry in an undergraduate fluid mechanics course is a novel approach.
5. The material presented to be incorporated in engineering teaching by integrating the experiment with the course.
6. No additonal text is required.
7. The concepts presented have been tested in the classroom, though it is too early to conclude anything definitely about the success of this approach.

INTRODUCTION

LASER DOPPLER velocimetry (LDV) is the measurement of fluid velocity by detecting the Doppler frequency shift of laser light that has been scattered by small particles moving with the fluid. The technique was originally discussed in a pioneering paper by Cummins *et al.* [1] in which they measured the Brownian motion of an aqueous suspension of micro-sized particles by observing the spectrum of the scattered light. In these measurements the quantity of interest was the broadening of the laser light spectrum due to the random particle motion. However, they also observed a net shift in the frequency of the light, an effect that they attributed to small convection currents that generated mean velocities in their water cell. Hence, almost, inadvertently, they performed the first measurements of fluid velocity by LDV. Shortly thereafter, Yeh and Cummins [2] carried out an experiment intended expressly to demonstrate the measurement of fluid velocities.

The LDV concept rapidly attracted the attention of numerous experimental fluid dynamicists, and within a few years various research groups had communicated the results of successful LDV measurements of laminar water flow in square ducts [3,4], laminar water flow in round ducts [5], laminar gas flow [6,7], turbulent water flow in pipes [8], and wind-tunnel turbulence [9].

The following advantages of LDV indicate the potential capabilities. The technique is non-intrusive, so it can be used in flows that are hostile to material probes or that will be altered by the presence of a material probe. The technique does not depend on the thermophysical properties of the fluid, in contrast to thermal probes or chemical probes. LDV allows the unambiguous measurement of one or more components of the velocity vector, independent of the fluctuation intensity. The technique offers reasonably good spatial resolution, and it is capable of tracking very high-frequency fluctuations of the flow velocity. In addition to all of this, the achievable accuracies are impressive; Goldstein and Kried [4] reported 0.1% absolute accuracy for measurements of flow development in a square duct.

This paper describes the incorporation of a two-dimensional LDV system in an undergraduate fluid mechanics course. An experiment has been designed which uses the LDV system to measure velocities in a cylinder equipped with an agitator. The following sections will describe the experiment in detail.

LASER DOPPLER VELOCIMETER

A two-dimensional LDV system purchased from TSI Corporation (St Paul, MN) is used in this experiment, a schematic of which is shown in Fig. 1. A very high power, 8 W, argon-ion laser is employed. The laser is optimized for excellent performance in backscatter mode and maintains very good spatial resolution in on-axis operation. The following is a list of LDV equipment in the fluid mechanic laboratory: argon-ion laser, mirror sets, beam collimater, beam splitters, frequency shifter, color separator, Bragg cells and frequency shift system, photomultiplier systems, signal processors, and a computer.

In the dual-beam arrangement, two equal intensity beams are focused in the same point in the flow field by the focusing lens. The region where the two beams cross becomes the measurement region. When a particle (present in the flow) goes through the measurement region, light is scattered from each beam. The 'mixing' or the heterodyning of the scattered light from the two beams provides the shift frequency. In a dual-beam mode shifting one of the two beams can be thought of as causing a 'moving fringe' system. A stationary particle in the measuring volume will then give an output frequency to the photodetector of f_s. If the velocity increases in the direction of the fringe movement, the frequency will decrease, and vice versa. An important characteristic of the frequency shifting is the influence on the number of Doppler cycles generated by one particle. With the 'fringes' moving past a stationary particle one gets a continuous signal or an 'infinite' number of cycles. At the other extreme, a particle moving in the same direction as the 'fringes' and at the same effective velocity will give no Doppler signal at all. Therefore, with frequency shifting and flow reversals the number of Doppler cycles generated by a single particle can range from zero to infinity.

The dual-beam method of measuring velocity can be easily explained by a 'fringe model'. In the region where beams cross, the wavefronts are quasiplanar. The intersection of the two beams will result in the interference of these wavefronts, creating a fringe pattern in the plane of the beams and at the crossing point. The fringes are parallel to the bisector of the beams. A particle going through these dark and light patterns will scatter light whose intensity will vary. Intensity across the laser beam follows a Dared distribution. If d_f is the distance between the fringes and t is the time for a particle to go from one fringe to another (time between successive peak), then velocity component, V, normal to the fringe is: $V = d_f/t =$ (frequency)(d_f). The velocity component that is measured is always normal to the bisector of the beams and hence is independent of the positioning of the scattered light setup.

EXPERIMENTAL FACILITY

The experimental setup consists of a cylinder, fabricated from a Plexiglas block, supported on a

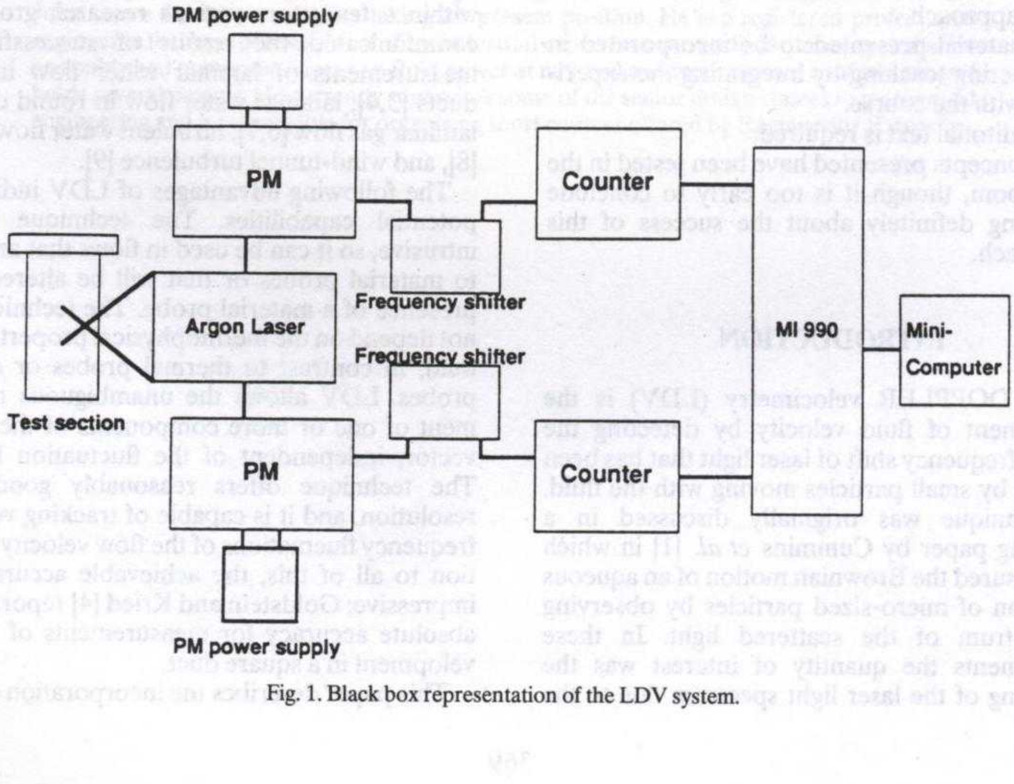

Fig. 1. Black box representation of the LDV system.

laboratory bench with a three-way motion mechanism. The medial fluid is water. The cylinder is mounted on a magnetostirrer which supplies the necessary energy for the impeller inside the vessel to rotate the fluid in the system. It is necessary to minimize laser beam dispersion through index of refraction matching. The index experiment involves standard laser beam alignment to maintain high signal to noise ratio as well as standard calibration experiments to determine accurately the position of the sample volume within the cylinder.

All of the velocity information (axial, radial and tangential) is collected, using the two-dimensional FIND software, on an IBM PC compatible through a TSI interface card. The FIND software calculates velocity, mean velocity standard deviation, turbulence, third moment, skewness coefficient, fourth moment, flatness coefficient, Reynolds stresses and correlation coefficient.

The experiment is carried out at impeller rotational speed of 25, 50, 75, 100 and 125 r.p.m. The measurements are made at four different axial locations: one below the impeller, one above the impeller, and the other two in between.

The procedure for this experiment is described in the Appendix. The students are required to report components of velocity, turbulent intensity and Reynolds stress data as a function of position for different rotational speed. Tangenial, radial, axial velocities and their turbulent intensities are investigated for two rotational speeds (40 and 60 r.p.m., respectively) at a fixed height of 5 cm from the bottom of the reactor, which is the height of the impeller. This height was chosen because the circulation zone can easily be detected at that level. Measurements can also be made at some other vertical location in order to map the complete flow velocity in the r–z plane.

RESULTS AND DISCUSSION

Students should have learned the fundamentals of Doppler effects and LDV at the conclusion of this experiment. They will learn how a two-dimensional LDV system works, and will learn the theoretical knowledge of calculating velocity and turbulent intensity from signals generated by frequency shift of scattered light. They are asked to plot components of velocity as a function of rotational speed of the agitator. Figure 2 shows a typical axial velocity profile normalized with respect to speed of blade tip at 40 r.p.m. Axial velocity profiles are very similar for two rotational speeds. An interesting point for students to note from the profile is a weak circulation loop within the reactor.

Students are also asked to determine turbulent intensities in all three components. They should be able to discuss the results of measurement, and recommend how to improve mixing in these stirred tanks.

CONCLUSION

A fluid mechanics experiment which employs a two-dimensional LDV has been designed and built.

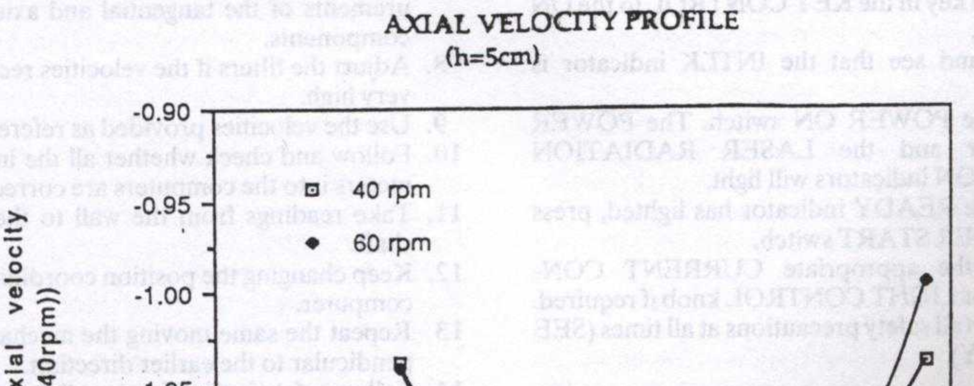

Fig. 2. Axial velocity as a function of radius at two different speeds.

The experiment is used in an undergraduate fluid mechanics course in the Mechanical Engineering Department at Northeastern University. The experiment consists of measuring radial, tangential and axial velocities in a cylindrical stirred tank. Measurements are done at different locations, and various impeller rotational speeds. The students use Flow Information Description (FIND) software, developed by TSI Inc. to calculate velocity, turbulence intensity and Reynolds stress.

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APPENDIX: PROCEDURE

Start up

1. Open the water supply line to laser and adjust the pressure to 25 p.s.i.g.
2. Put the main power on.
3. Check to be sure the LINE and the FUSE indicators are lighted.
4. Turn the key in the KEY CONTROL to the ON position.
5. Check and see that the INTLK indicator is lighted.
6. Press the POWER ON switch. The POWER indicator and the LASER RADIATION EMISSION indicators will light.
7. After the READY indicator has lighted, press the LASER START switch.
8. Adjust the appropriate CURRENT CONTROL or LIGHT CONTROL knob if required.
9. Maintain all safety precautions at all times (SEE SAFETY).

Procedure

1. Position the stirred tank at the center of the moving mechanism.
2. Turn on the laser beams and focus the intersection point of all rays at the shaft of the impeller.
3. Move the x–y–z mechanism in one direction (away from the laser mount) using the lever below the lab bench and count the number of revolutions for the intersection point of rays to go from shaft to the wall.
4. Turn off the laser.
5. Ensure all safety precautions.
6. Wear the safety glasses (which will obscure all laser wavelengths), and by counting the number of revolutions position the PORI (point of ray intersection) at the wall and start the data acquisition.
7. Turn on the PC and start the TSI FIND software and check for optimum velocity measurements of the tangential and axial velocity components.
8. Adjust the filters if the velocities recorded are very high.
9. Use the velocities provided as reference.
10. Follow and check whether all the input parameters into the computers are correct.
11. Take readings from the wall to the impeller shaft.
12. Keep changing the position coordinated in the computer.
13 Repeat the same moving the mechanism perpendicular to the earlier direction.
14. Follow safety instructions at all times.
15. Repeat the same for different rotational speeds.

Shut down

1. Turn off laser, shut off the attentuator.
2. Shut off power to laser.
3. Shut off main power.
4. Shut off water supply to the laser.
5. Remove all protective equipment.

Data analysis

For each rotational speed:

1. Present velocity vs. position data.
2. Present turbulent intensity data vs position.

Professor Mohamad Metghalchi has been involved with combustion research since 1975. As a graduate student at Massachusetts Institute of Technology, he was in charge of design and construction of a spherical combustion bomb to study the properties of laminar flames. He measured laminar flame velocity of fuel/air mixtures at different conditions. His work at MIT was funded by the Department of Transportation, General Motors and the Army Research Office. Professor Metghalchi joined the Department of Mechanical Engineering at Northeastern University in 1979; he has been involved in research in the area of thermal science both in experimental and theoretical research. He was primarily responsible for setting up a two-dimensional laser Doppler anemometry system to be used in the undergraduate fluid mechanics laboratory and biotechnology research. He has been awarded grants from the NSF, the DoE and the biotechnology industry to carry on his research. He has published articles in *Combustion and Flame*, *International Journal of Heat and Mass Transfer* and *International Symposium on Combustion,* and has many presentations in ASME winter annual meetings. Professor Metghalchi is currently Associate Chairman of the Mechanical Engineering Department at Northeastern University.

Bhaskaran Natarajan was born in Lucknow, India. He has a MS degree in chemical engineering from Northeastern University in Boston, MA and has a B.Tech. in chemical engineering from the Indian Institute of Technology in Kanpur, India. Areas of research interests include fluid mechanics, reaction kinetics, modeling and cell culture. He is currently working as a research engineer for Brown and Williamson Tobacco Corporation in Louisville, KY. His current responsibilities include quality management, training and process improvement. He is interested in painting, music, public speaking and essay writing.