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OPTICAL DIAGNOSTICS FOR AIR BREATHING ENGINES

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Abstract

Optical diagnostic methods for the simultaneous measurement of velocity and particle size in reacting flows relevant to studies of air breathing engines are presented. Two techniques are described: in both cases the speed is measured by Laser Doppler Velocimetry (LDV); for size and size distribution measurements the pedestal method and Phase Doppler Anemometry (PDA) can be utilized. The pedestal method was developed for measurements in flow systems based on axisymmetrical sudden expansion and confined coaxial two phase jets. The data acquisition equipment comprises three branches - one for the velocity measurements, the second for the pedestal height which is proportional to the particle size and the third for validation. The PDA technique uses the interferometric pattern created by the interaction of liquid droplets with the LDV control volume. Detecting the structure of that pattern reveals accurately the information of the droplet diameter. However, difficulties are encountered when attempting to exploit the PDA technique in confined geometries due to optical access requirements.

In the paper, both techniques, their potential, limitation and calibration methods are described.

I. Introduction

The development of modern combustion and propulsion systems, in which emphasis is put on flame stabilization and high performance, requires to optimize fuel injection processes. To achieve this aim one combines suitable computer codes with experimental information, which provides the initial conditions and serves to validate the codes. Diagnostic measurements, which allow to perform accurate, simultaneous measurements of particle sizes and velocity vectors, together with temperature and pressure measurements play, therefore, an important role in the design of new systems.

This paper describes two techniques for local, instantaneous two phase flow measurements, based on the exploitation of the Doppler effect and the use of laser light, namely the pedestal amplitude technique and the Phase Doppler Anemometry (PDA). The particular flow geometries of interest are: a) axisymmetric sudden expansion. This flow is attractive because the region of recirculation can serve as a flame holder for a dump combustor(1,2). b) Confined coaxial two phase jets which are used to study mixing phenomena in combustors of gas generator ramjets (ducted rockets). In such combustors fuel rich metallized solid propellants are burned in a primary combustion chamber. The products, which contain metal particles and are partially enriched gaseous fuels, expand through a primary nozzle into a secondary chamber where they mix and subsequently react with secondary ram air and are exhausted through a secondary nozzle(3-8).

Experimental data on fuel injection patterns during combustion and mixing processes are essential for understanding combustion efficiency and stability. Computer codes for such reacting two phase flows can be obtained by modifying existing programs(9,10). They require, however, preliminary information on the initial conditions of the fuel spray(11). Most non-intrusive techniques for local and instantaneous two-phase flow measurement are based on Laser Doppler Anemometry (LDA). In two-phase flows, both phases move in a common space. The dispersed phase consists of either: a) spray of droplets with a wide range of size distributions, where it is difficult to distinguish between the phases as the very small droplets will follow the gas flow, while larger ones exhibit different flow patterns, or b) metal or oxidized metal particles in the micron size range. When the velocity fields of the two phases overlap it is necessary to measure for each partaicle the Doppler frequency and additional information about its size, to enable phase classification. Various techniques are applied in order to evaluate the size as well as the velocity of particles. The most common are pedestal amplitude and phase Doppler anemometry. The pedestal amplitude methods(12-16) are based on the monotonic relation existing between the pedestal amplitude and the particle diameter, a characteristic of the LDA signal. This technique allows measurements of single solid or liquid particles in a range from about 0.1 to 1000 micrometers.

The Phase Doppler anemometry (PDA) was initially proposed by Durst and Zare(17) in 1975, but has been applied only recently(18-26). This method makes use of an interferometric pattern generated by spherical droplets crossing the control volume, which is defined by the two incident coherent laser beams. The shape of the pattern depends on the particle diameter and its index of refraction. The detection of the phase between signals recorded by several photomultipliers, aligned at different observation angles to the control volume, determine the droplet diameter.

II. Experimental System

The systems which were employed for developing and testing the above mentioned diagnostic techniques used an axisymmetric sudden expansion and confined coaxial two-phase jets, as shown in Figs. 1a and 1b respectively. The sudden expansion combustion chamber is provided with facilities for changing operational parameters, such as the fuel injectors (e.g. hollow cone and full cone injectors), injector location (radial or axial) fuel and air flow rates and the step height. The confined coaxial flow configuration is provided with facilities to alter the air momentum ratio between the inner and outer jets, the particle concentration and the tracer gas concentration of the inner jet. The particle (aluminum oxide) diameter has a relatively uniform size distribution with an average diameter of 20 μm. The LDV tracking particles were much smaller with an average diameter of about 5 μm. The two size ranges of the particles presented almost a bimodal size distribution. The outer cylinder of both systems was transparent (quartz and pyrex) to en-able optical access for the laser light.

The particle velocity was measured in both systems by means of an LDV system, which was coupled with data acquisition systems suitable to obtain the size measurements by the pedestal technique. The LDV system used is shown schematically in Fig. 2.

A 15 mW HeNe (632.8 nm) laser beam (Spectra Physics No. 124) is directed to an LDV modular optic unit (DISA 55X). The two emitted beams are focused via a 300 mm focal length lens. Scattered light from particles crossing the control volume is focused in the forward direction onto the photomultiplier's pinhole (0.15 mm diameter) through a 250 mm focal length lens.

Two techniques were used to evaluate the particles diameter: the pedestal technique and Phase Doppler Anemometry. In the pedestal technique droplets which cross the control volume scatter a burst of light with an oscillation frequency (the Doppler frequency) linearly related to the droplet velocity and with a pedestal amplitude linearly related to the droplet size(13) (see Fig. 3). Due to the fact that the light intensity within the control volume has a spatial distribution, the amplitude of signals detected from droplets of similar characteristics depends on their trajectory within the control volume. In its center the light intensity can be considered to be uniform and thus to provide equal reference level for all the measured droplets. Only signals of droplets which cross through the center, as recorded by an additional validation system, are accepted by the data acquisition system. Hence, an additional system, consisting of two photodetectors, aligned on the two beams (after the collecting lens), is used to detect the droplet path inside the control volume (see Fig. 4). The photodetectors are mounted on micrometric holders, which allow angular rotation and translation in three directions. An iris is mounted in front of each photodetector to provide better alignment. It is followed by a spherical microlens (1 mm diameter) and a second iris. This combination is required to increase sensitivity and to reduce the light intensity impinging upon the photodectectors.

The photodetectors will detect a constant light level except for the time when a droplet crosses the central part of the laser beams. The maximum light attentuation caused by droplets of specific dimensions will occur when they cross the central part of the two beams within the control volume (at the waist of each beam, see Fig. 5). When a particle passes through the center of the control volume, it will have a simultaneous effect on both beams and the two photodetectors will record attenuation in their signal amplitude at exactly the same time. An additional electronic circuit was built to generate a validation pulse(12), whenever the signals originating from the two photodetectors overlap. This validation pulse is used to confirm that the signal obtained originated from a particle which crossed through the center of the control volume, and therefore its pedestal amplitude is representative. The signal amplitude technique implies a monotonic one to one relation between absolute signal amplitude and droplet size. Although in some cases the response curve can be predicted, an experimentally obtained calibration curve is required due to the many parameters which must be taken into consideration, such as: laser power, sensitivity of the photomultiplier, particles' characteristics, influence of windows, etc.

As regards the data acquisition system, the electric signal generated by the photomultiplier contains information about the velocity and the size of the measured droplets. It is connected to two parallel units for frequency and amplitude measurements. The Doppler frequency is processed by a DISA frequency counter, which converts it to a linearly related analog voltage. In order to obtain the pedestal amplitude, the signal from the photomultiplier is connected to a low pass filter, which removes the Doppler frequency oscillations, revealing the pedestal amplitude of the signal. This signal is directed to a specially built peak-detector unit which detects and maintains the maximum amplitude of the signal. The measurement system features three channels: the recording of the Doppler frequency, the pedestal amplitude and the validation pulse. All three channels are connected to a multiplexed 12 bits A/D converter, interfaced to a PDP 11/84 minicomputer. Sequential sampling of the three channels is performed and data are recorded as triplets of information in the computer memory. After termination of data acquisition at a specific measurement location, a data processing program is run and used to obtain velocity histograms, which are displayed for the gas phase and for each preselected range of droplet diameters. The system is fully automated and allows to record large samples (at least 2000 data points at each location) in order to reduce statistical errors.

In the phase Doppler technique, the measurement principle is based on the following phenomena: when two coherent and monochromatic laser beams impinge upon a liquid droplet, interference fringe patterns are generated in space at different locations depending on the scattering mechanism involved. The spacing of those fringes in the forward or backward direction are inversely proportional to the diameter of the sphere. Hence by measuring the fringe spacing, the diameter of the sphere could be determined.

The spatial distribution of the light intensity of the fringes near the axis can be calculated according to the interferometry theory for two overlapping coherent light sources. Hence the fringe spacing δ is calculated for the forward direction according to (see Fig. 6a):

$$\delta = \frac{\lambda}{2\sin\phi}\left(\frac{4L}{d_p}\cdot\frac{(n-1)}{n}\right) \qquad (1)$$

and in the backward direction according to (see Fig. 6b):

$$\delta = \frac{\lambda}{2\sin\phi}\cdot\frac{4L}{d_p} \qquad (2)$$

When a drop traverses the intersection region of the two laser beams, oscillation of the light intensity will be recorded as the fringes sweep by the photodetectors apertures. Two detectors, located at close lateral distance, $\overline{\Delta Y}$, within the y-z plane) and near the optical axis $\hat{x}$ (see again Figs. 6a and 6b) will record an oscillation frequency of:

$$F = \frac{2U_{\perp}}{\lambda}\cdot\sin\phi \qquad (3)$$

The signals of the two detectors will show a phase difference θ (degrees) which is related to the lateral distance between the detector, $\overline{\Delta Y}$, and to fringe spacing, δ:

$$\theta = 360\cdot\frac{\overline{\Delta Y}}{\delta} \qquad (4)$$

Measuring θ determines δ which indicates the particle diameter, hence for the forward direction of detection

$$\theta = d_p\left[\overline{\Delta Y}\,\frac{180\cdot\sin\phi}{\lambda\ L}\cdot\frac{n}{n-1}\right] \qquad (5)$$

and for the backward direction of detection

$$\theta = d_p\left[\overline{\Delta Y}\,\frac{180\cdot\sin\phi}{\lambda\ L}\right] \qquad (6)$$

If the terms in the square brackets of Eq. (5) or (6) is adjusted, by proper selection of the operational parameters, to obtain a value of one million (when L, λ and $\overline{\Delta Y}$ are measured in meters), the phase difference between the two signals in degrees will equal the diameter of the droplets in μm. This kind of relation is convenient in studies of liquid spray combustion, where droplet diameters are in the range of $d_p < 300\ \mu m$. This condition will be achieved, for example in a forward scattering system containing a HeNe laser with kerosene fuel (n=1.35) where $2\phi=8^{\circ}$, L=0.5m and $\overline{\Delta Y}$=6.5mm. The use of such a technique has the distinct advantage over the previously mentioned methods of being sensitive to information based on changes in the time domain. Such information is independent of absolute values of light intensity and thus is not susceptible to inaccuracy due to extinction processes caused by the surroundings. Several papers were published on the description and use of the PDA technique. However, all previous works made use of off-axis light detection, i.e. detection from direction deviating by some angle (typically 30°-150°) from the optical axis. Such a configuration is more convenient due to its high fringe coherence and signal quality (high signal to noise ratio), obtained during measurements of small droplets ($d_p \leq 100\mu m$). This is the result of not being affected by the diffraction of light which is dominant for the small drops in the forward direction.

In practice the amount of experimental conditions, where off-axis light detection could be performed are limited. Many combustion studies and spray diagnostics are required to be performed in a confined space. Just a few examples are models of ramjet combustors, cylinders of reciprocating engines, jet engine's afterburners and models for flame stabilization by bluff bodies. In such geometries optical windows have to be installed for the incident laser beams and for the collection of scattered light. Difficulties will be encountered when side detection is performed; these will increase with the detection angle. This is due to the fact that when traversing a cross section, the size of window required for the collection of light might be too large. (A schematic illustration of the effect is shown in Fig. 7.) This geometrical limitation has led to studies, directed to find the minimal value of drop size which can be measured whenever on-axis or back-scattered light collections are performed$^{(25,26)}$.

Schematic descriptions of the experimental setups used in the forward and backward PDA are given in Figs. 8a and 8b, respectively.

III. Results

A calibration curve for the pedestal technique obtained as described in Ref. 12, is presented in Fig. 9. It shows a monotonic linear relation between droplet diameter and the pedestal signal amplitude. This is typical for large droplets (in the order of the control volume diameter). The figure also shows a relatively wide distribution around the mean. This is probably due to variation of light intensity inside the modified control volume and thus represents the limitation of the technique.

Experimental results of velocity measurements of the two phase flow systems are shown in Fig. 10. Figure 10a demonstrates the variation of the axial mean and fluctuating gas velocities with radius, at three axial positions of the sudden expansion combustor. These data were taken in single phase flow, i.e. without droplets. The recirculation zone is clearly seen in the figure, extending to slightly more than 200 mm. The velocity profile develops along the combustor chamber from a "top hat" shape at its entrance to a fully developed turbulent pipe flow profile further downstream. Part b of the figure includes droplet velocity information at a specific axial location (z=200 mm). The variation of mean and rms droplet speed with radius is demonstrated, as well as the local variation of velocity histogram with droplet diameters.

Part a of Fig. 11 demonstrates the gaseous velocity profile in the confined coaxial jets configuration. Measurements were compared to values predicted by a modified TEACH Code exhibiting the clear difference between velocities of the two jets. Figure 11b shows the radial distribution of the particle velocity; the particle diffusion is relatively low as they originate from the central jet only and their spread is not sufficient in order to fill the whole cross section. However, as regards the experimental technique, comparing parts a and b of the figure clearly demonstrates its ability to distinguish between the two phases.

For the Phase Doppler measurements it was necessary to perform a validation experiment. For this purpose two experimental setups were assembled. One for studying the minimal measurable droplet size in the forward direction and the other for the backward collection of light. Both configurations require relatively small optical access for the laser beams and light collection.

Calibrated polystyrene latex spheres, suspended in water and forced to move with a magnetic mixer, were measured within couvettes. The spheres, were measured in monodisperse groups of average (known) diameters. Spheres of different size groups were measured and the results are summarized in Fig. 12a. The correlation coefficient was calculated to be 0.995 with a slope of 0.924. The figure shows a 30 μm lower size limit. It also demonstrates higher accuracy than measurements performed with the pedestal technique however some variations were detected, probably due to variation in particle size within the groups and due to lower signal to noise ratio. The latter could be the result of the high particle concentration (i.e. several particles interfered with part of the beam before the intersection regions or with the refracted light) and due to nonlinear trajectories within the control volume.

In the backward configuration calibration measurements were also performed using the same type of polystyrene latex spheres suspended in water which were forced to move by magnetic mixers within the courvettes. Groups of different diameters were tested in order to evaluate the practical minimal size which still generate signals of sufficient quality (signal to noise ratio) required. Spheres of 60, 40 and 20 μm in diameter were measured as well as fine metal wire of 5 μm in diameter. The wire was fixed on a disc installed on a rotating dc motor and aligned perpendicular to the plane defined by the two incident laser beams. The need to use the metal wire was due to the low signal to noise ratio of the suspended spheres of 10 μm diameter or less, caused by background optical noise. The single wire, which was free of the background noise, produced signals of much better quality, and hence, was confirmed by a validated routine. Results are summarized in Fig. 12b. The figure shows very good agreement between the measured diameters and the values specified by the manufacturer.

IV. Discussion

The selection of the optimal measurement technique for a specific application is based on the two phase flow characteristics. When all particles fulfill the conditions of sphericity and smoothness, there is a clear advantage in utilizing the phase Doppler technique due to its higher accuracy in determining the particle diameter. This applies to most experimental conditions which include liquid sprays, both reacting and nonreacting. The technique can be applied to sprays with a wide size range. The lower measurable size depends on the specific geometry of the receiving optics, as affected by the experimental impositions. Collection angles of 30°-150° off-axis which are possible in a free flow on transparent confined configurations are definitely preferable. However, in confined opaque experimental systems, where the installment of optical window is limited, forwards and backwards PDA presents a possible technique. Between the two, the forward mode produces a much better signal quality but it is affected by diffraction which limits the lower measurable size to about 30 μm. This relatively high minimal value can be reduced, as discussed in Ref. 25 by incorporating the visibility technique which somehow complicates the experimental setup, but enables measurements down to about 5 μm. Back scattered light collection should be used whenever the forward option is impractical. This is due to the lower signal amplitudes and S/N level. A few examples for such conditions are two phase flow studies in turbomachines, spray combustion inside gas turbine and fuel injection in piston engines. Measurements of sizes down to 5 μm were proved to be possible, however they required high intensity of laser light (power per unit area) and rigorous signal processing. For particles having an arbitrary shape or in the presence of impurities, phase Doppler anemometry is inappropriate; in those cases the pedestal amplitude technique should be used. It also has significant advantages due to its simplicity in cases of bimodal particle size distributions. Its accuracy is lower, depending on the specific experimental conditions. The pedestal technique can determine the size of particles over a large dynamic range, however it has a higher size limit which is determined by the diameter of the laser beam waist at the control volume. The lower particle size limit can be of the order of 0.1 μm; the limiting factor is the signal to noise ratio obtained at the photomultiplier. It should be noted that whenever the technique is applied, calibration curves must be obtained for each experimental condition since extrapolation of calibration curves cannot be performed automatically.

V. Conclusions

Two methods for measuring velocity and particle size in combustion systems have been discussed: the pedestal technique and phase Doppler anemometry. After describing in detail the experimental apparatus and reporting on results obtained with both methods, they are compared and it is concluded that the PDA technique should be preferred for spherical particles having a diameter larger than a few micrometers, since it gives more accurate results of the measured sphere diameter. If, however, the particles are irregular in shape or their size is smaller than a few micrometers (down to about 0.1 μm) or if they display a bimodal size distribution, then the pedestal technique should be used with appropriate calibration.

VI. References

1. Drewry, J.E., "Fluid Dynamic Characterization of Sudden-Expansion Ramjet Combustor Flowfields", AIAA Journal, 16, pp. 313-319, 1978.

2. Yang, B.T. and Yu, H.M., "The Flowfield in a Suddenly Enlarged Combustion Chamber", AIAA J. 21, pp. 92-97, 1983.

3. Schadow, K.C., "Boron Combustion Characteristics in Ducted Rockets", Combustion Science and Technology, 5, pp. 107-117, 1972.

4. Schadow, K.C., "The Influence of Combustion Parameters on the Combustion of Particle Laden Fuels in Ducted Flows", AIAA Paper 73-177, January 1973.

5. Schadow, K.C., "Study of Gas Phase Reactions in Particle Laden, Ducted Flows", AIAA Journal, 11, No. 7, pp. 1042-1044, 1973.

6. Schadow, K.C., "Fuel-Rich, Particle Laden Plume Combustion", AIAA Paper 75-245, January 1975.

7. Zetterström, K.A., Sjöblom, B., Jarnmo, A., "Solid Ducted Rocket Engine Combustor Tests", 6th International Symposium on Air Breathing Engines, Symposium Papers, AIAA, New York, pp. 9-16, June 1983.

8. Choudhury, P.R., "Characteristics of a Side Dump Gas Generator Ramjet", AIAA Paper 82-1258, June 1982.

9. Chen, L. and Tao Chung-Shan, C.C., "Study on the Side Inlet Dump Combustor of Solid Ducted Rocket with Reacting Flow", AIAA Paper 84-1378.

10. Sturgess, G.J., Syed, S.A. and McManus, K.R., "Calculation of a Hollow Cone Liquid Spray in a Uniform Airstream", J. Propulsion and Power, 1, pp. 360-369, 1985.

11. Tambour, Y., "A Lagrangian Sectional Approach for Simulating Droplet Size Distribution of Vaporizing Fuel Spray in Turbulent Jet", Combustion and Flame, 60, pp. 15-28, 1985.

12. Albagli, D., Laredo, D., Levy, Y., Timnat, Y.M., "Two Phase Flow Diagnostics in Propulsion Systems", 11th ICIASF, Stanford, August 26-28, 1985.

13. Levy, Y. and Timnat, Y.M., "Two Phase Flow Measurements Using a Modified Laser Doppler Anemometry System", Single and Multiphase Flows in an Electromagnetic Field. Energy, Metallurgical, and Solar Applications (Branover, Lykoudis and Mond eds.) Progress in Astronautics and Aeronautics, 100, AIAA, New York, 1985.

14. Mizutani, Y., Kodama, H. and Miyasaka, K., "Doppler Mie Combination Technique for Determination of Size Velocity Correlation of Spray Droplets", Combustion and Flame, 44, pp. 85-95, 1982.

15. Yule, A.J., Chigier, N.A., Atakan, S. and Ungut, A., "Particle Size and Velocity Measurements by Laser Anemometry", AIAA Paper No. 77-214, 1977.

16. Yule, A.J., Ereaut, P.R. and Ungut, A., "Droplet Sizes and Velocities in Vaporizing Sprays", Combustion and Flame, 54, pp. 15-22, 1983.

17. Durst, F. and Zare, M., "Laser Doppler Measurements in Two Phase Flows", SFB 80/TM/63, Univ. of Karlsruhe, 1975.

18. Bachalo, W.D. and Houser, M.J., "Development of the Phase/Doppler Spray Analyser for Liquid Drop Size and Velocity Characterization", AIAA Paper No. 1199, 1984.

19. Bachalo, W.D. and Houser, M.J., "Phase/Doppler Spray Analyser for Simultaneous Measurements of Drop Size and Velocity Distributions", Optical Engineering, 25, p. 5, 1984.

20. Bachalo, W.D. and Houser, M.J., "Spray Drop Size and Velocity Measurements Using the Phase/Doppler Particle Analyser", ICLASS-85, Imperial College, London, 1985.

21. Bauckhage, K. and Floegel, H.H., "Simultaneous Measurements of Droplet Size and Velocity in Nozzle Spray", 2nd Int. Symp. on Application of Laser Anemometry of Fluid Mechanics, Lisbon, 1984.

22. Bauckhage, K., "Simultaneous Measurements of Velocity and Size of Drops in Free Flow Fluid Sprays", ICLASS-85, Imperial College, London, 1985.

23. Gouesbet, G., Grenan, G. and Klein, R., "Simultaneous Optical Measurement of Velocity and Size of Individual Particles", 2nd Int. Symp. on Application of Laser Doppler Anemometry to Fluid Mechanics, Lisbon, 1984.

24. Levy, Y., "The Phase Doppler Anemometry Technique for Measurement of Size and Velocity of Individual Drops in Combustion Systems", Collection of Papers, 28th Israel Annual Conference on Aviation and Astronautics, pp. 220-223, 1986.

25. Levy, Y., "On Axis Phase Doppler Anemometry for Spray Diagnostics", TAE Report No. 615, Aeronautical Engineering, Technion, Haifa, Israel.

26. Levy, Y., "Back Scattered Phase Doppler Anemometry (PDA) for Spray Diagnostics", 4th Int. Symp. on the Application of Laser Anemometry to Fluid Mechanics, Lisbon, July 1988.

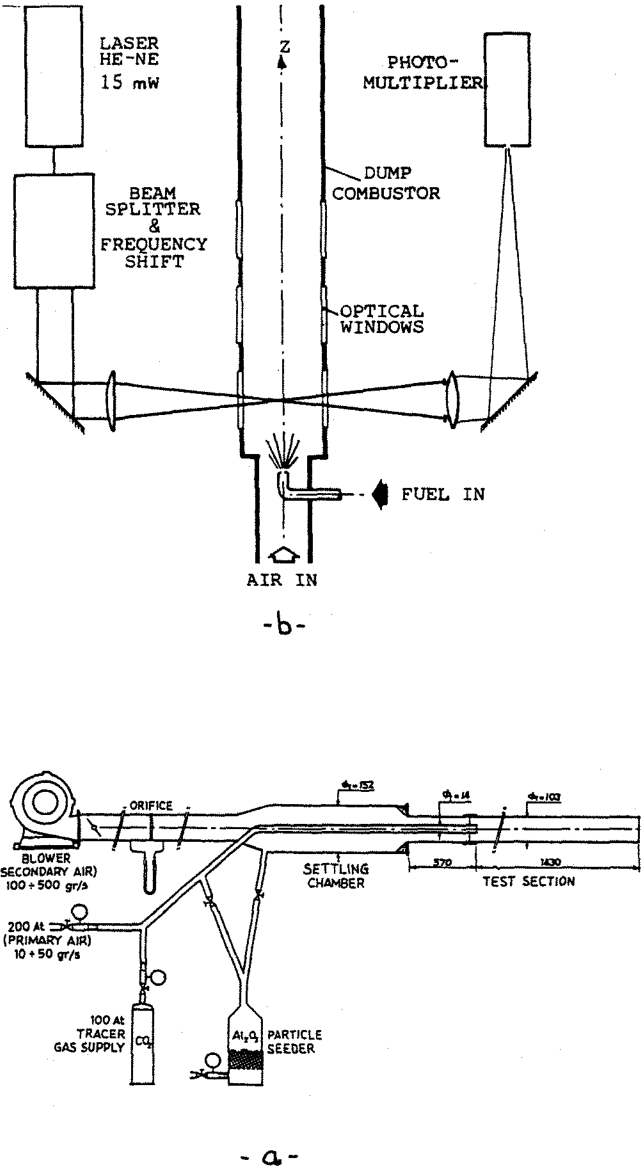


Fig. 1. The flow system
a) sudden expansion combustor
b) confined coaxial two phase jets.

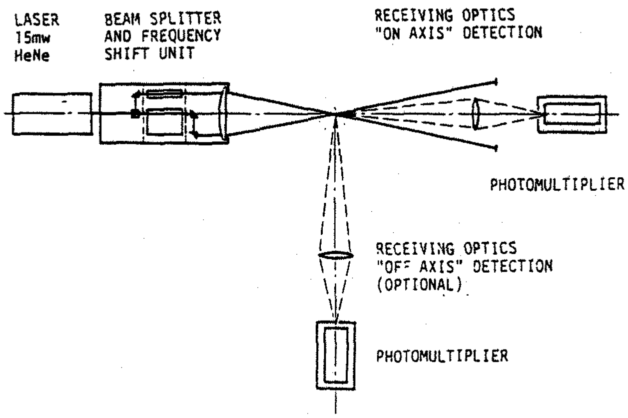


Fig. 2. LDA optics package for the pedestal technique in the sudden expansion (dump) combustor.

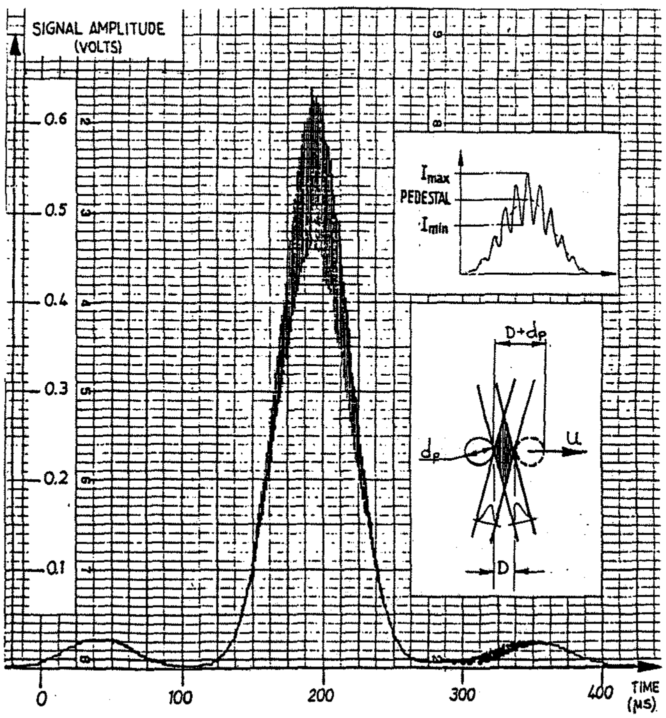


Fig. 3. The burst generated by a droplet crossing the control volume.

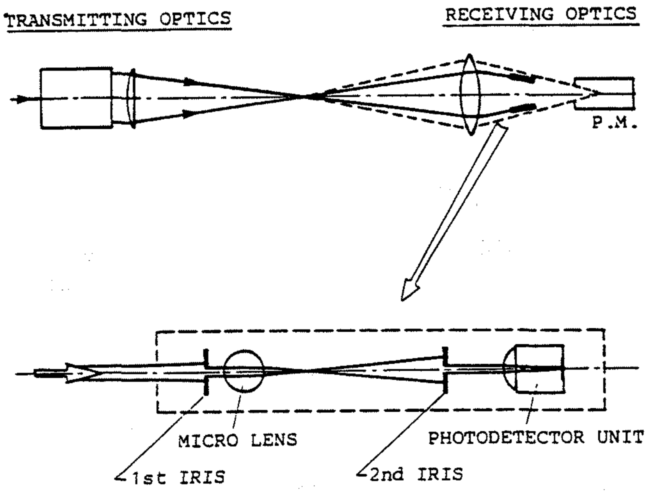


Fig. 4. The modified receiving optics.

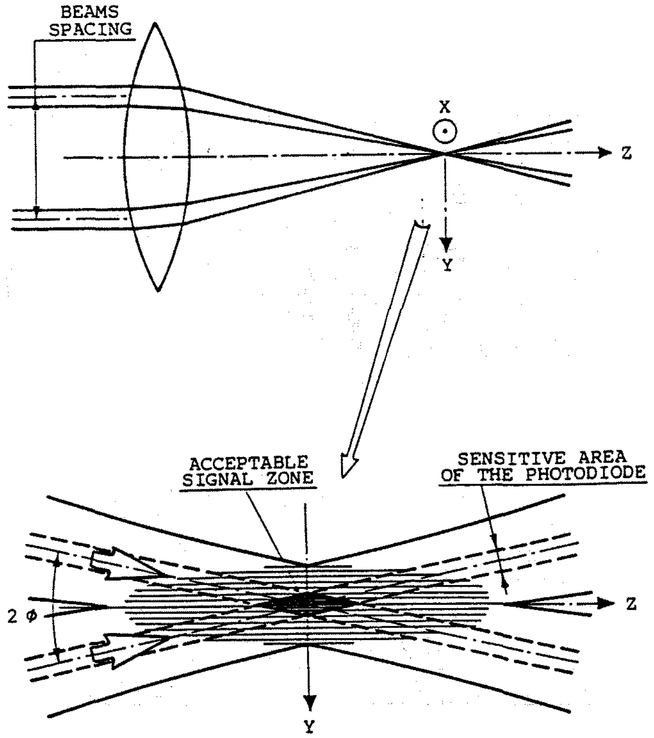


Fig. 5. Schematic of the "modified" control volume.

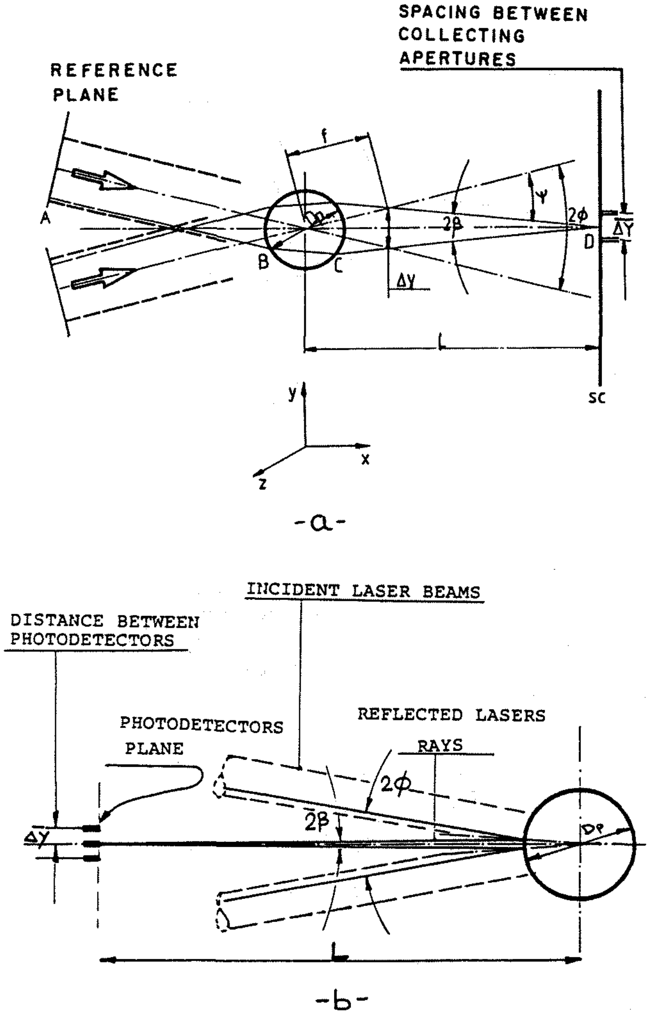


Fig. 6. Schematics of laser light trajectories in the PDA techniques:
a) forward direction
b) backward direction.

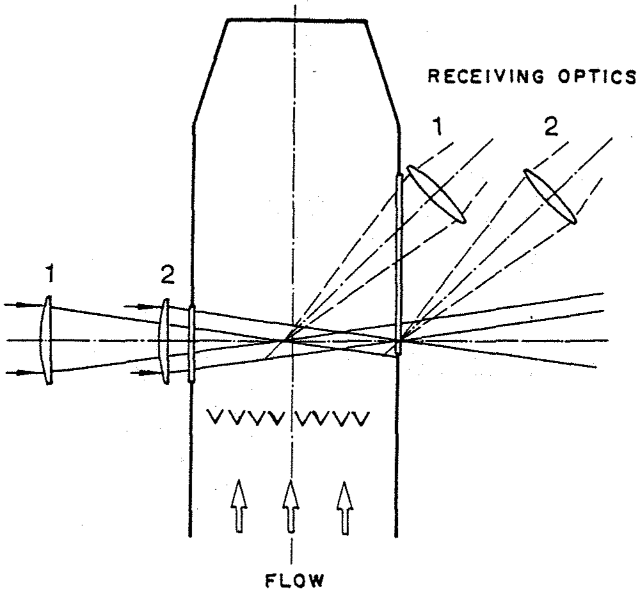


Fig. 7. The effect of off axis light detection on the size of the optical window required.

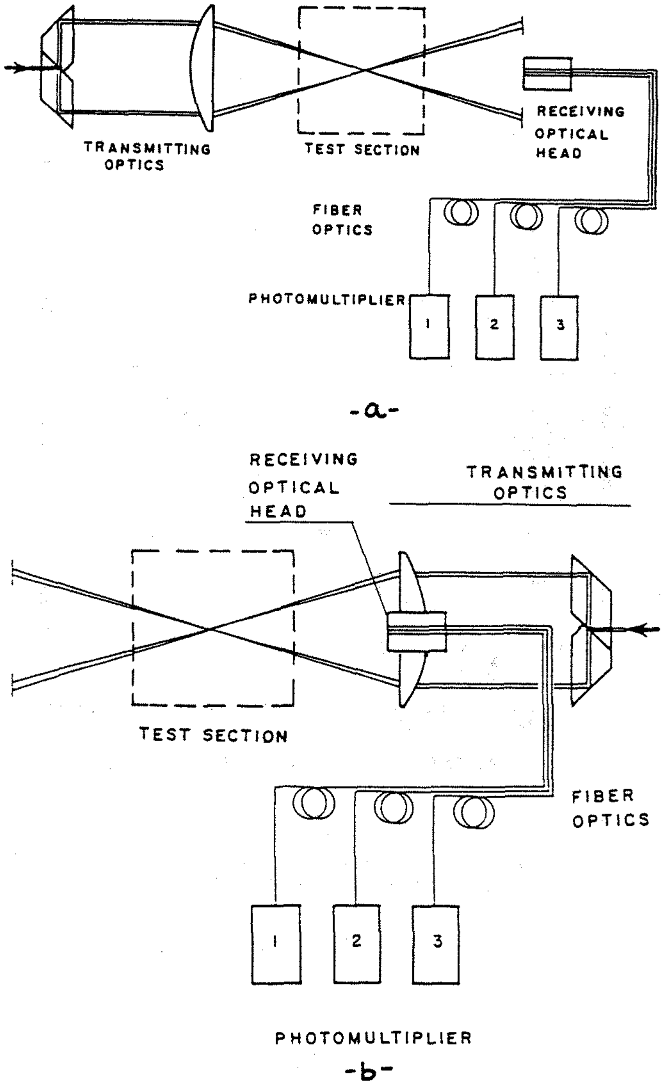


Fig. 8. Schematic description of the experimental setup for:
a) forward scattering PDA
b) backward scattering PDA.

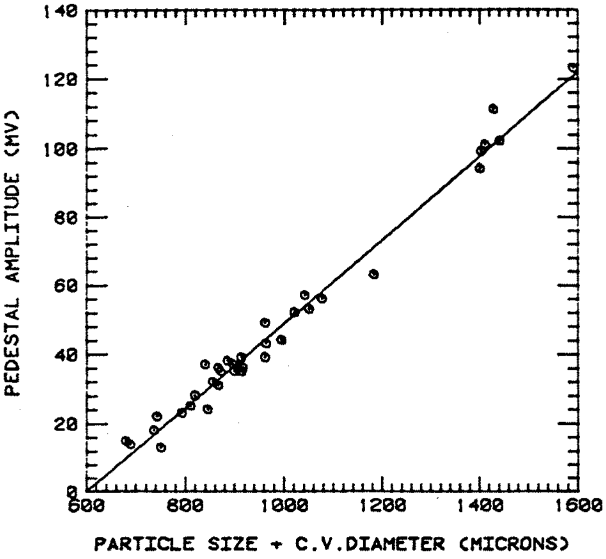


Fig. 9. Calibration curve for the pedestal technique.

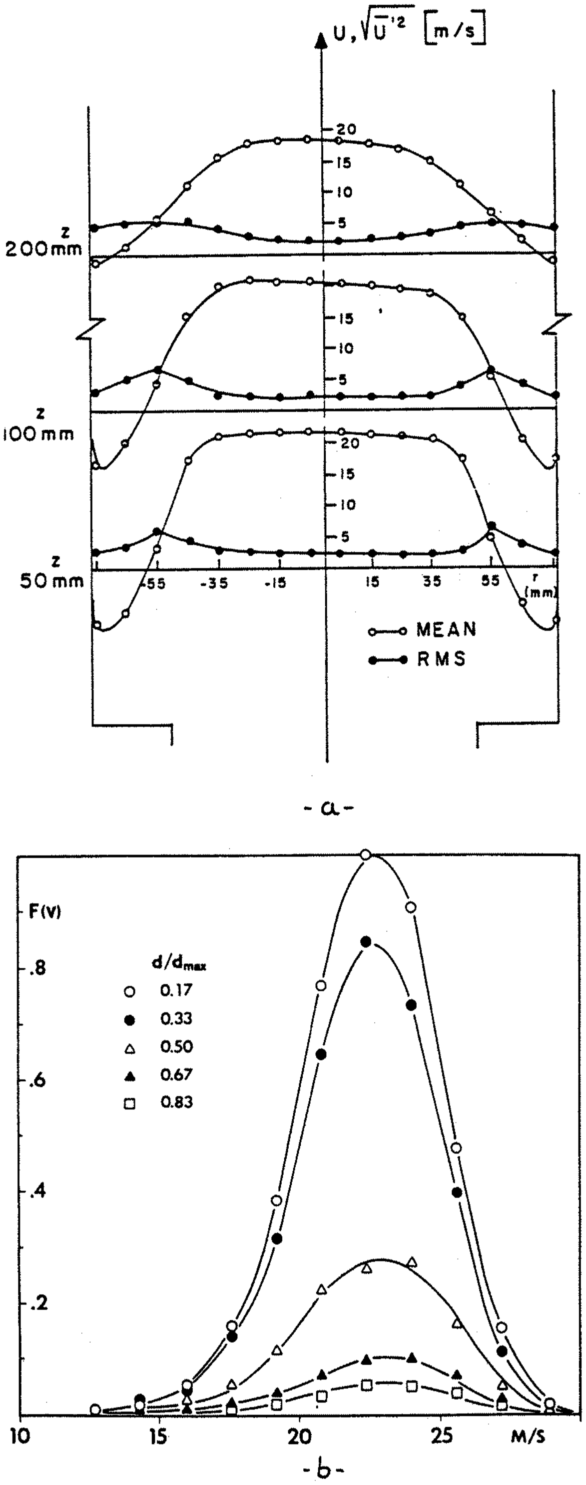
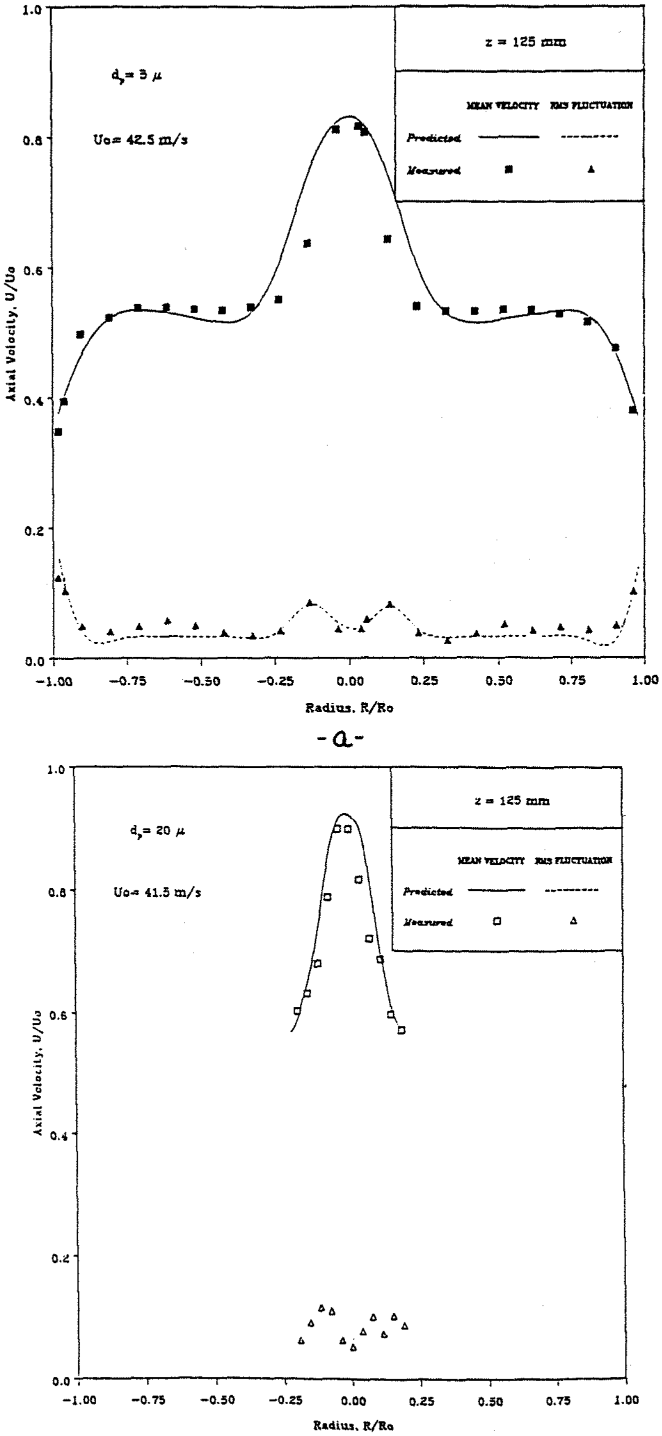


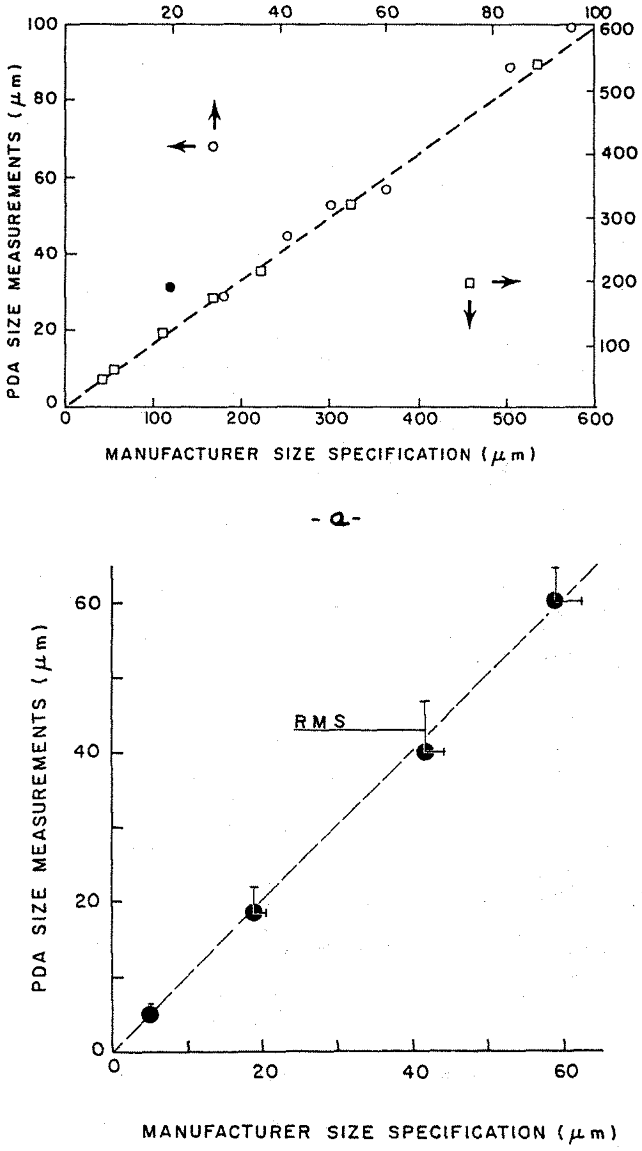
Fig. 10. Velocity measurements in the sudden expansion combustor:
a) gas phase
b) droplets.



-a-

-b-

Fig. 11. Velocity profiles in the confined coaxial jets configuration:
a) gas phase
b) particles velocity.



-a-

-b-

Fig. 12. Calibration curve for the PDA technique:
a) forward scattered light collection
b) backward scattered light collection.