Mansoura Engineering Journal, (MEJ), Vol. 14, No.1, June 1989

A DOPPLER-MEI COMBINATION TECHNIQUE FOR SIMULTANEOUS MEASUREMENTS OF SIZE AND VELOCITY DISTRIBUTIONS OF SPRAY DROPLETS

تقنية الدمج بين تأثير دوبلر وتأثير مي لليزر للقياس المتزامن لتوزيعات الحجم والسرعة لقطرات رشة السائل

El-Emam, S. H. * and Mizutani, Y. **

* Department of Mechanical Power Engineering, Mansoura University.

** Department of Mechanical Engineering, Osaka University, Japan.

خلاصة – في هذا البحث تم التوصل الى تطوير طريقة بصرية ذات مرونة كافية للقياس المتزامن لتوزيعات الحجم والسرعة لقطرات رشات السوائل . وتعتمد هذه الطريقة على تقنية الدمج بين تأثير دوبلر وتأثير مي لشعاع الليزر . Laser Doppler - Mei Combination Technique
في هذا البحث كان التركيز موجها للتوصل الى طريقة لتصحيح الاخطاء التي تحدث بصورة حتمية في قياسات التوزيع العددي والحجمي لقطرات رشات السوائل باستخدام منظومات الليزر البصرية . أيضا ، تم استحداث تقنية تعتمد على التحليل الاحصائي للقياسات لاستنتاج علاقة متبادلة بين قياسات حجم وسرعة القطرات . استخدمت الطريقة المبتكرة في قياس التوزيع العددي والحجمي والسرعة لقطرات رشة سائل محقون داخل أنبوب شفاف بواسطة مرذاذ يعمل بالترددات الفوق سمعية . أيضا أجريت قياسات مناظرة للتوزيع العددي والحجمي للقطرات باستخدام تقنية أكسيد المغنسيوم . وتشير نتائج المقارنة الى وجود اتفاق واضح في نتائج قياسات التوزيع العددي والحجمي للقطرات ذات أقطار في حدود من ١٥ ـ ٨٠ ميكرون . وتتميز التقنية البصرية المذكورة بالمرونة في الأداء وإمكانية القياس المتزامن للسرعة والتوزيع العددي والحجمي للقطرات بدون إدخال مجسات تؤثر على مجال القياس . وقد أوضحت نتائج القياس إتساع مدى توزيع سرعات قطرات رشة السائل .

ABSTRACT

An easy and flexible optical method for simultaneous measurements of sizes and velocities of spray droplets has been developed. The method is based on the Doppler-Mei combination technique. Emphasis is focussed on the establishment of a correction procedure of the errors which inevitably occur in measuring results of droplet size distributions using laser beam optical systems. Also a statistical data reduction technique to derive the correlation between size and velocity of spray droplets has been developed.

The method has been applied for measurements of velocity and size distributions of droplets of a confined spray injected from an ultrasonic atomizer. Also counterpart measurements of droplet size distribution have been carried out using the magnisium oxide method. Experimental results show that droplet size distribution obtained by this method are in fair agreement with those obtained by the magnesium oxide method in diameter range between 15 and 80μm. It was also found that velocities of droplets are distributed over a wide range regardless of their sizes.

1. INTRODUCTION

Simultaneous measurements of the size, velocity and concentration of spray droplets constitute an important step for obtaining more and detailed information about the flow characteristics for optimizing the processes in a wide variety of operational facilities. Also, it is desired that these measurements be obtained locally with fine discrimination but without disturbing the two-phase flow-field. Optical methods consisting of imaging and laser light scatter have been applied with varying degree of success. The relative success of a method is largely dependent upon the measuring environment, drop size distribution and number density and other physical concepts of the test apparatus. Instrument limitations are dependent upon the physical concepts incorporated into the measurement device and how the concepts are affected by the interaction with the surrounding spray, fluid dynamics and temperature fields.

The double flash, direct photography technique [1] and the double pulse, in-line holography technique [2] are suited for observation of the size distribution, population density and velocity vectors of droplets in large volumes of the flow field. By these techniques, however, it is difficult to process data automatically due to the difference in effective focal depth between droplets of different sizes [3].

During the last few years a number of different methods for measuring size and velocity of spray droplets by means of laser-Doppler-techniques have been developed. Drop sizing interferometry is used in conjunction with laser Doppler anemometry. Real time, in situ, simultaneous size and velocity measurements of a droplet are made using crossed-beam interferometry. The principles and practice of laser Doppler anemometry are described in the book by Durst et al [4].

Interferometric techniques for particle sizing based upon light scattering have been developed using the concepts of visibility [5&6], peak amplitude [7] and angle ratioing [8&9]. Simultaneous measurements of size and velocity distributions of spray droplets have been obtained using laser Doppler-visibility technique [10&11], phase-Doppler technique [12-14] and Doppler-Mei combination technique [15-17]. These techniques show locally fine discrimination and are suited to statistical data processing requirements.

Chigier and his coworkers [16] have developed a single-particle-counting, forward scattering laser-Doppler velocimeter technique for application to burning and nonburning sprays. This is a kind of Doppler-Mei combination technique. They determined the sizes and velocities of spray droplets simultaneously for droplet diameters larger than the fringe spacing in the measurement control volume. The technique is an interesting and useful one. However, some difficulties are still left unsolved, i.e.:

1. The control volume is confined to the intersection of the field by a vertical slit. Since the control volume is surrounded by sharp boundaries, the droplets partially penetrating the volume should be considered in addition to the intensity distribution of the incident beams.
2. Some kinds of atomizers make sprays having size distributions that are not well represented by an algebraic function like the Rosin-Rammler distribution function.
3. The forward-scattered light-intensity lobe has characteristics more complex than the component at another angle [13].

The aim of the present investigation is to develope an easier and more flexible technique for determining the sizes and velocities of spray droplets simultaneously. Emphasis is placed on the establishment of a correction procedure for size distribution which is applicable to any size distribution type as well as the development of a statistical data-reduction technique to drive the correlation between size and velocity of spray droplets.

2. OPTICAL SYSTEM AND CONTROL VOLUME

The optical system is composed of a laser Doppler velocimeter system of dual-beam forward-scatter type and an additional subsystem to detect the light scattered in the direction perpendicular to the laser beam as shown in Fig. 1. The beam from a 15 mW He-Ne laser is split into two parallel beams by a beam splitter BS, then focused by a lens L_1 at the objective point. The laser generated beam has a wave-length of 632.8nm and a beam diameter of 1.0mm. The splited beams cross each other at an angle 2γ of 11.11°, composing a Doppler signal control volume as shown in Fig. 2. The

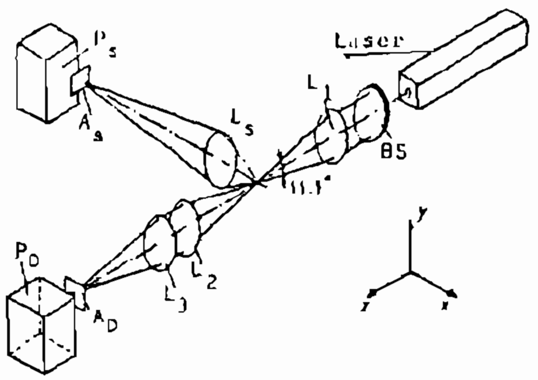
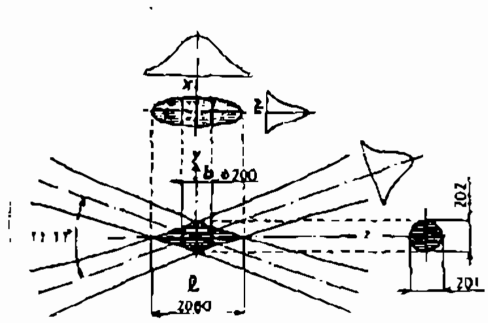


Fig. 1 Optical system.



(Dimensions in μm)

Fig. 2 Control Systems.

waist diameter (D), and the length of control volume (ℓ) are 0.2mm and 2.08mm respectively, and the fringe spacings are about 3.3um.

The light scattered forward by a droplet located in this control volume is collected by lenses L_2 and L_3 and detected by a photomultiplier apparatus P_D through an aperture A_D. Meanwhile, the light scattered at 90° is collected by a lens L_s and detected by a photomultiplier apparatus P_s through an aperture A_s. Since the view field of the photomultiplier P_s is of 200 μm diameter at the objective point, the control volume for the Mei scattering subsystem is the part of the Doppler signal control volume penetrated by view cylinder of 200μm diameter.

The Doppler signal of forward scattered light detected by the photomultiplier P_D, from which the pedestals have been removed by a high-pass filter, is converted into velocity signal in proportion to the Doppler frequency f_D by a frequency tracker. Meanwhile, the Mei signal of 90° scattered light detected by the photomultiplier P_s is averaged over more than one cycle by a low-pass filter and amplified by a preamplifier.

The Doppler signal and Mei signal are converted into digital signals and read alternately by a signal microprocessor (Model 1980B counter type) and stored in its memory. Since the laser beams have radially a Gaussian distribution in intensity, the Mei signal shows a peak every instant a droplet passes through the horizontal plane involving the center of the control volume. Meanwhile, the velocity signal holds the last value until the next droplet enters the control volume. After a series of read-in cycles, the signal microprocessor picks up every peak value in the Mei signal stored and the corresponding value in velocity signal in a pair.

Each pair of size and velocity data is classified into groups and accumulated in the histogram area of memory of the signal microprocessor. Then the next series of read-in cycles is started. This signal-processing cycle is continued until the number of sampled pairs reached the preset value of about $2x10^4$. A threshold level is set up for the Mei signal just above the noise level, and the peaks below this level are omitted to avoid the confusion of noise with signals.

3. CAUSES OF ERROS AND CORRECTION OF SIZE DISTRIBUTION DATA

According to Lorenz-Mei theory [9], a droplet illuminated by an incident beam having a uniform intensity, I_1, scatteres light in the perpendicular direction, the intensity I_s, of which observed at a fixed distance is represented by the following relation:

$$I_s = f(\alpha) \cdot I_1 \cdot d^2 = k \cdot d^2 \quad \ldots\ldots (1)$$

where α is the size parameter defined as $\pi d/\lambda$, d is the droplet diameter and λ is the wave length.

Since, in the present case, two laser beams having a Gaussian distribution of intensity, the center line intensities I_o, and the waist diameter (b), as shown in Fig. 2, are crossing at a small angle 2γ with each other, the intensity distribution in the Doppler control volume is represented by the following equation [10]:

$$I_1 = 2I_o\,[\cosh(\gamma yz/b^2) + \cos(2\gamma Ky - g)]$$

$$\times \exp[-2(x^2 + y^2 + \gamma^2 z^2) / b^2] \quad \ldots\ldots (2)$$

where K is the magnitude of the vectors of incident beams and g is a function that account for relative phase difference between them. Therefore, the intensity $\overline{I_1}$, averaged over fringes, is represented by:

$$\overline{I_1} = 2I_o \exp[-2(x^2 + y^2 + \gamma^2 z^2) / b^2] \times \cosh(\gamma yz/b^2) \quad \ldots\ldots (3)$$

The intensity $\overline{I_{1p}}$, in the z, x plane is given by the next relation:

$$\overline{I_{1p}} = 2I_o \exp[-2(x^2 + \gamma^2 z^2) / b^2] \quad \ldots\ldots (4)$$

Hodkinson and Greenleaves [18] have developed a technique for calculating the intensity of light scattered by a transparent spherical particle on the basis of classical diffraction and of geometrical scattering by external reflection and transmission. Applying this technique to the present situation $f(\alpha)$ in Eq. (1) is approximately represented by the following relation:

$$f(\alpha) = c\,(e + 0.1013 / \alpha) \quad \ldots\ldots (5)$$

where c is a constant and e is calculated from the reflactive index (m) using the next relation:

$$e = \frac{1}{8\pi}\left[\frac{1 - \sqrt{2}(m^2 - 0.5)^{1/2}}{1 + \sqrt{2}(m^2 - 0.5)^{1/2}}\right]^2 + \frac{1}{8\pi}\left[\frac{m^2 - \sqrt{2}(m^2 - 0.5)^{1/2}}{m^2 + \sqrt{2}(m^2 - 0.5)^{1/2}}\right]^2 \quad \ldots\ldots (6)$$

Since the present optical system deviated from the standard Lorenz-Mei theory, errors may occur for the following reasons:

1. Two droplets or more, which enter the Mei control volume simultaneously, are misinterpreted as one larger droplet.
2. A droplet, a part of which is outside the control volume, is misinterpreted as a smaller one.
3. Since the laser beams have radially a Gaussian distribution in intensity, the intensity of scattered light depends on the location of the droplet center.
4. A larger droplet can contact the Mei control volume for a larger distance, so that the effective control volume depends on its size. Therefore, the population density calculated on the basis of the Mei control volume should be corrected for droplet size.

The errors resulting from reason (1) are diminished by reducing the control volume. On the other hand, the errors resulting from reasons (2)-(4) are diminished by enlarging the control volume.

3.1. Errors Resulting from Reason (1)

The probability P_n that n droplets exist in a volume V simultaneously is represented by the relation

$$P_n = e^{-m} \cdot m^n / n! \quad \ldots\ldots\ldots\ldots (7)$$

where $m = N.V$ and N is the average population density of droplets. The P_n-values calculated for the present Mei control volume ($\sim 6\times10^{-3}$ mm^3, see Fig. 2) are shown in Fig. 3. Note that the velocity signal is meaningless for n $\geq$2. It may be noted from Fig. 3 that $P_2 << P_1$ for $N << 10^2/\text{mm}^3$, where P_1 and P_2 are the P_n-values for n=1 and 2, respectively. Since coexistence of two droplets or more can be easily recognized from the shape of the corresponding peak in Mei signal (twin or multiple peak), such data are simply omitted automatically.

3.2. Errors Resulted from Reasons (2)-(4)

Since these errors are nither recognized nor evaluated from the Mei signal, the location must be made theoretically. The following assumptions are made to that purpose:

1. Droplets have a uniform probability of passage through any part of the z,x plane regardless of their sizes or velocities.
2. The mean peak intensity $\overline{I}_{sp}$ of light scattered by a droplet can be estimated by substituting the $\overline{I}_{ip}$-value at the droplet center for I_i in Eq. (1), whether or not the center is located within the waist diameter , (b) control volume (droplet A or C in Fig. 4). If however, the droplet passes partially through the view field of the photomultiplier P_s (droplet B in Fig. 4), the $\overline{I}_{sp}$-value is reduced by the fraction r of droplet projection area seen by P_s at the instant the center passes through the z,x plane.

The procedure for correcting the size distribution under the above assumption is as follows. The relation between the mean peak intensity $\overline{I}_{sp}$ of scattered light and the mean intensity $\overline{I}_{ip}$ of incident light at droplet center in the z,x plane is written as follows:

$$\overline{I}_{sp} = r\ \overline{f(\alpha)}\ \overline{I}_{ip} \cdot d^2 = r\ \overline{k}_p\ d^2 \quad \ldots\ldots\ldots\ldots (8)$$

where $\overline{f(\alpha)}$ is the $f(\alpha)$-value averaged over the span of variation of and r is the fraction of droplet projection area.

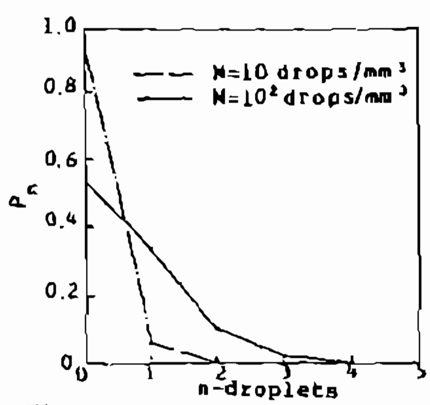


Fig. 3 Probability of coexistence of n-droplets in the Mei control volume.

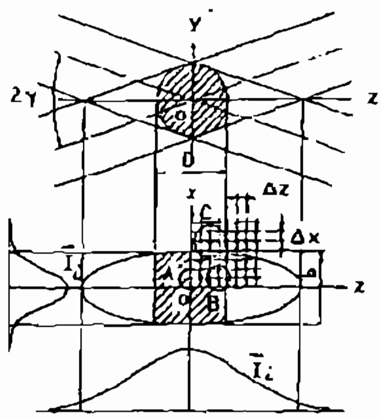


Fig. 4 Grid configuration for correction procedure.

The average $\overline{K}_s$-value at the origin has been determined so that the size distribution corrected in the manner described here reaches best agreement with the counterpart data obtained by the magnesium-oxide method. As a result, $\overline{K}_s$-value of $1.3\times10^{-3}\mu A/\mu m^2$ has been obtained for the used kerosine injected spray as the intensity $\overline{I}_{sp}$, of the scattered light is represented by the output current of the photomultoplier P_m.

Then grids of z and x intervals are placed on a quarter of z, x plane as shown in Fig. 4, and $\overline{I}_{1p}$-values are calculated at each grid point using Eq. (4). The apparent diameter d of a droplet whose real diameter is d_r is calculated at each grid point from the relation:

$$d^2 = \overline{I}_{sp} / [\overline{f(\alpha)} \cdot \overline{I}_{1o}] \quad \ldots\ldots \quad (9)$$

where $\overline{I}_{1o}$ is the $\overline{I}_{1p}$-value at the origin. Notice that $d=d_r$ only at the origin.

Relative probabilities of $P_t(d)/P_t(d_r)$, $P_i(d)/P_t(d_r)$ and $P_o(d)/P_t(d_r)$ are estimated following the above procedure. $P_t(d)$ denotes the probability that a droplet, whose real diameter is d_r has an apparent diameter d, which is divided into two parts, $P_i(d)$ and $P_o(d)$. $P_i(d)$ for droplets whose center is located within the Mei control volume, while $P_o(d)$ for droplets whose center is outside the Mei control volume. This procedure is repeated increasing the d_r-value by Δd_r. A typical example of the result is shown in Fig. 5.

Assuming that the real diameter of any droplet does not exceed the maximum observed diameter d_{max}, the diameter range between d_{min} and d_{max} is divided into m groupos, where d_{min} is the minimum apparent diameter observable. Using the curves of normalized probability densities as shown in Fig. 5, the number $(\Delta n_{m,i})_t$ of droplets whose apparent diameter belongs to the ith group (i=1,2,....m) whereas its real diameter belongs to the m-th group is subtracted from the number $\Delta_o n_i$ of droplets whose apparent diameter belongs to the ith group and the number $(\Delta n_{m,i})_i$ of droplets whose center is located within the Mei control volume is added to the number $\Delta_o n_m$ of droplets whose apparent diameter belongs to the m-th group. Here:

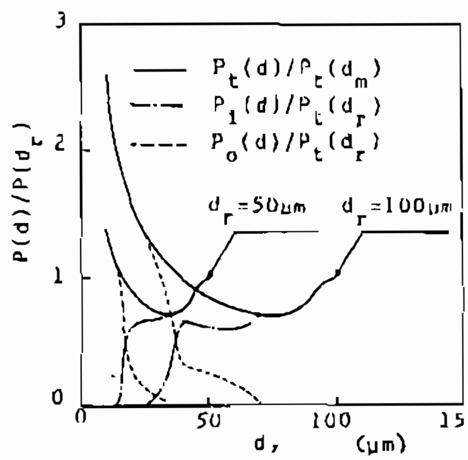


Fig. 5 Normilized probability densities of underestimation of droplet size.

$$(\Delta n_{m,i})_t = \Delta_o n_m \cdot P_t(d_i) / P_t(d_m) \quad \ldots\ldots \quad (10)$$

$$(\Delta n_{m,i})_i = \Delta_o n_m \cdot P_i(d_i) / P_t(d_m) \quad \ldots\ldots \quad (11)$$

The number $\Delta_1 n_i$ of droplets belonging to every size group is as follows after a series of such correction has been excuted:

$$\Delta_1 n_i = \Delta_o n_i - (\Delta n_{m,i})_t, \quad (i \leq m-1), \quad \ldots\ldots \quad (12)$$

$$\Delta_1 n_m = \Delta_o n_m + \sum_{i=1}^{m-1} (\Delta n_{m,i})_i \quad \ldots\ldots \quad (13)$$

Note that $\Delta_1 n_m$ represents the number of droplets whose real diameters belong to the m-th group.

The same procedure followed for the mth group can be followed for the (m-1)-th group, and the number $\Delta_2 n_{m-1}$ of droplets whose real diameters belong to the (m-1)-th group is obtained. By repeating the procedure for the remainder down to the second group, the numbers $\Delta_1 n_m$, $\Delta_2 n_{m-1}$, ..., $\Delta_{m-1} n_2$, and $\Delta_{m-1} n_1$ of droplets whose real diameters belong to the respective groups are obtained.

One of the advantages of this correction procedure is that the threshold level for the Mei signal has only slight influence on the size distribution resulting from the correction procedure, especially in the larger size range. Since if a large droplet makes a small peak in the Mei signal, then the droplet center is located outside the Mei control volume and should simply be omitted. Therefore, the noise level has an effect mainly on the minimum detectable droplet diameter.

4. DATA CORRECTION AND MANAGEMENT

Since the data obtained by the signal processing system are pairs of apparent diameter and velocity, erroneous correlation data will result unless corrections are made However. pairs of real diameter and velocity cannot be derived directly from the data, and this correction must be done statistically as follows;

Droplets are classified into velocity groups, the size distribution for each velocity group is corrected by the method described in Section 3.2. If for each velocity group and specific size the probability density for that size is selected from the corrected size distribution curve, the probability density distribution curve of velocity is obtained for the size. This procedure is repeated for each of the size group. The correction coefficient between diameter and velocities also obtained since the probability density for any pair of diameter and velocity is known by the above method

A microcomputer utilizing a 8080 microprocessor is used for the data handling and reduction. The flow chart of the calculation program is shown in Fig. 6. The system produces histograms of the droplet size and velocity as the data is accumulated.

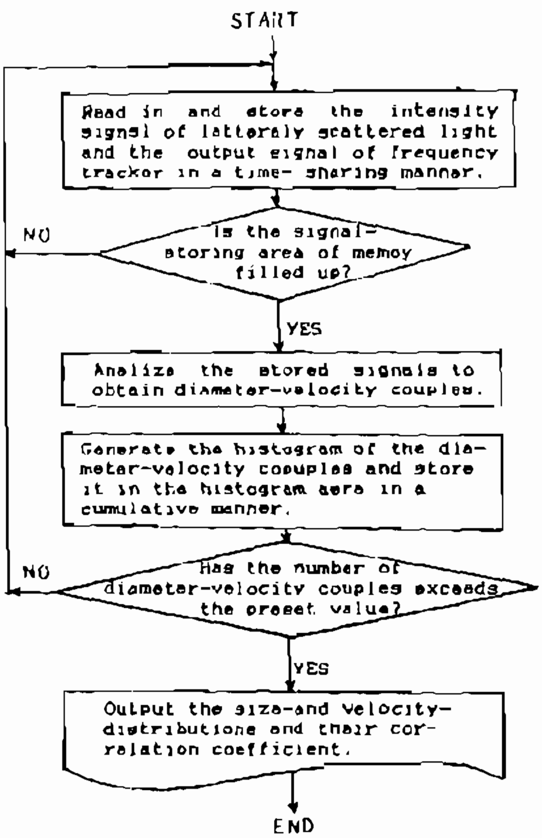


Fig. 6 Flow chart of the calculation program.

Sample time and number of samples are recorded. When a preset number of samples have been measured, the tabulated results can be printed or stored on floppy disks. Two floppy disk units are provided, one for software storage and the other for data.

5. APPLICATION AND RESULTS

5.1. Experimental Apparatus

The present described technique has been applied for simultenous measurements of size and velocity distribution of droplets of a kerosine spray atomized by an ultrasonic atomizer. A schematic diagram of the experimental apparatus is shown in Fig. 7. Kerosine to be atomized is fed to the atomizer from the reservoir through a calibrated transfer pump 2. The transfer capacity of the pump has been adjusted at 10 cm^3/min. The electric power to derive the atomizer is fed from the ultrasonic oscillator through the impedance transformer while the frequency and the power supplied are measured by the electronic counter and high frequency wattmeter , respectively. (For more details of ultrasonic atomization, see Refs. (19) and (20)). The resonance frequency of the used atomizer f_o=70 kHz. Spray is injected downward through a transpartent duct of a square cross-section area of 280mm×280mm. A plate of wire gauze (10 mesh) is placed around the atomizer to ensure a relatively flat distribution of the entrainment air at the entrance section of the injection duct.

The figure also shows the diagramatic arrangement of the optical system components An accurate traverser is used to define the location of the objective control volume with the use of light smoke to trace laser beam inside the transparent injection duct.

For the sake of the technique calibration as well as to compare obtained measuring results, counterpart measurements of drop size distribution has been measured by the magnesium oxide method using the sampling device shown in Fig. 8.

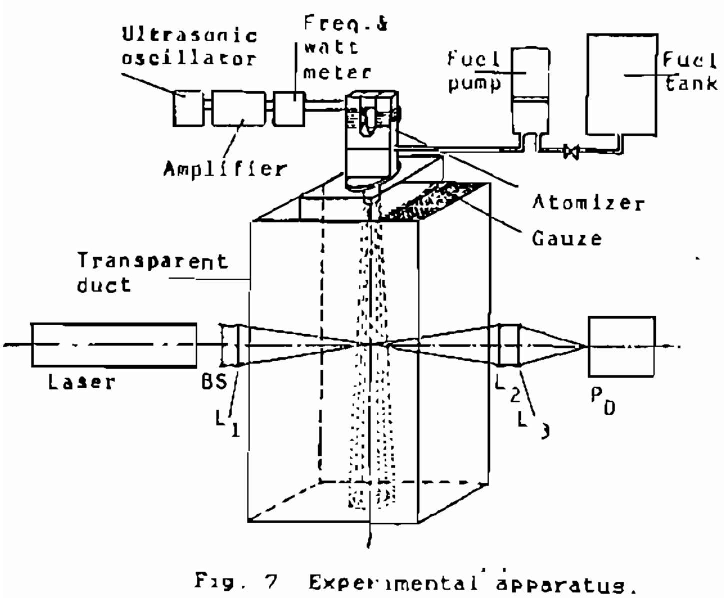


Fig. 7 Experimental apparatus.

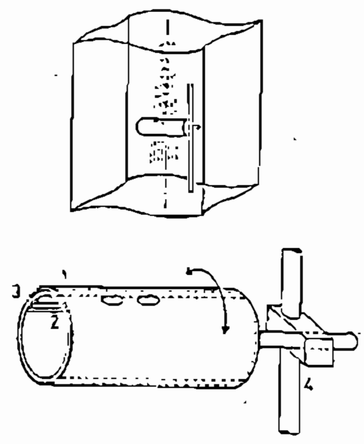


Fig. 8 Droplet sampling device.

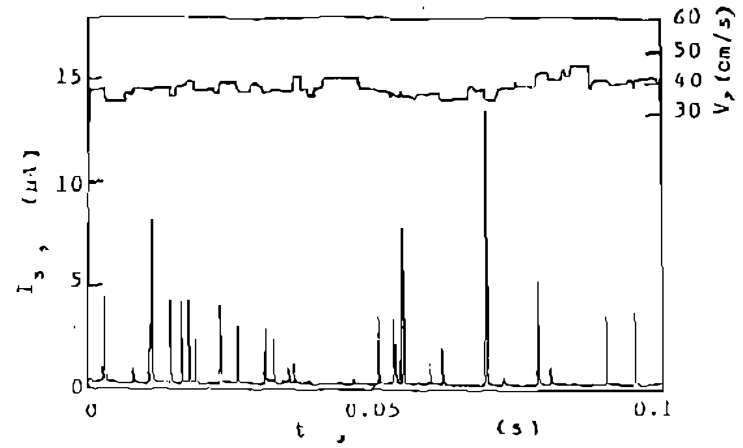


Fig. 9 Velocity and Mei signals.

5.2. Results and Discussions

A typical example of the velocity signal and Mei signal for a sample control volume located on the axis of the spray at 100mm below the tip of the atomizer is shown in Fig. 9. The figure shows that a few twin peaks are observed in the Mei signal, which corresponding to the condition that two droplets enter the Mei control volume simultaneously.

Results of measured size distributions at two different axial distances from the atomizer tip plane on the axis of the spray are shown in Fig 10. The number of droplets sampled is 2×10^4 for the optical method and 500 for the magnesium oxide method. Agreement between results of the optical method with the counterpart obtained by the magnesium oxide method is shown in the figure

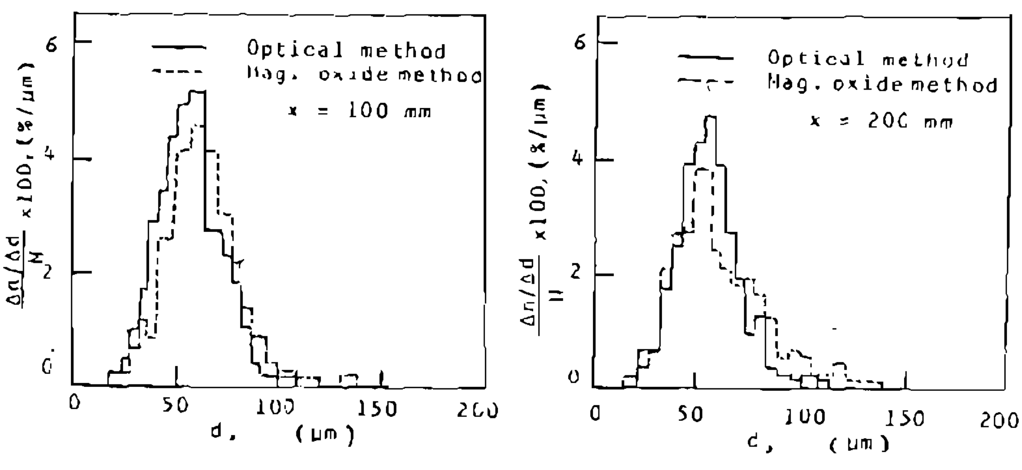


Fig. 10 Size distribution of droplets.

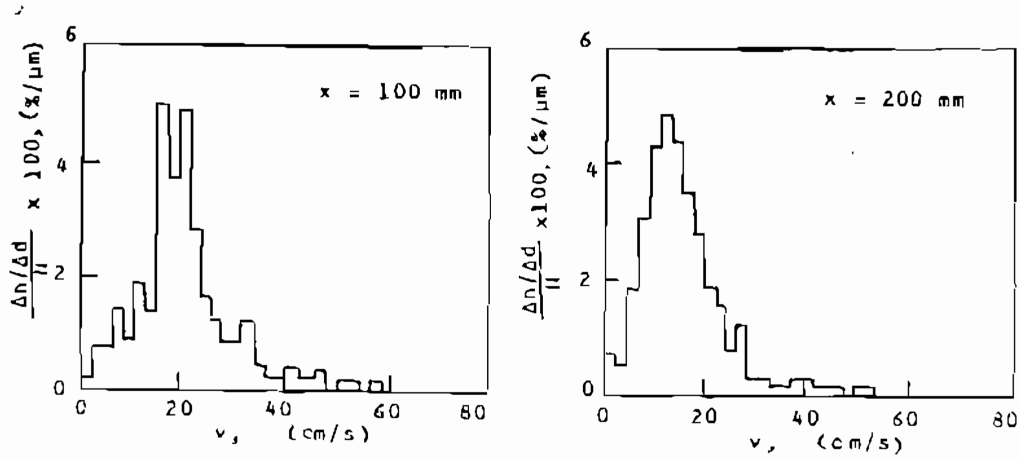


Fig. 11 Histograms of velocity distribution.

The probability densities for droplets of small sizes are higher in optical method results rather than those of the magnesium oxide method, although the maximum diameters coincide. This is probably because the collection efficiency on a magnesium oxide coated glass slide is low for minute droplets.

Measured velocity distributions at two different axial distances from the atomizer tip plane are shown in Fig. 11. Velocity distributions for droplets of various sizes at an axial distance of 100 mm from the atomizer tip plane are shown in Fig. 12. It can be noted that the shape of the velocity distribution does not change greatly with droplet size. Also velocities of droplets are distributed over a wide range regardless of their sizes.

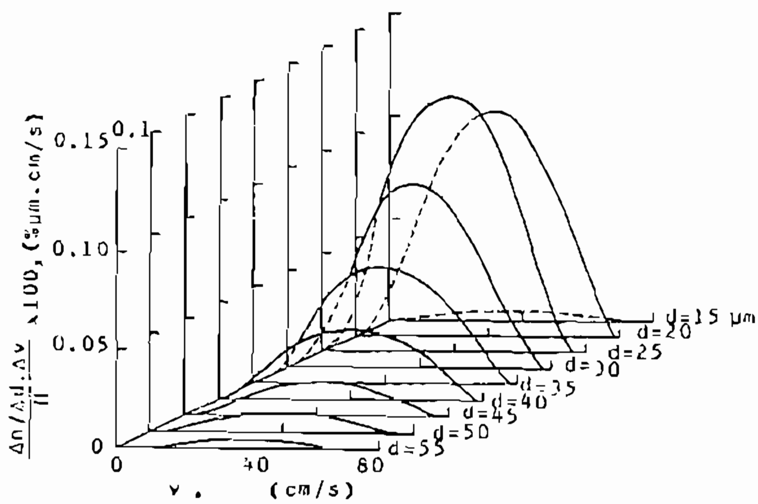


Fig. 12 Velocity distributions for droplets of various sizes.

6. CONCLUSIONS

An easy and flexible method for simultaneous measurements of sizes and velocities of spray droplets has been developed. The method is based on the Doppler-Mei combination technique. Emphasis is placed on the establishment of a cerrection procedure for size distribution as well as the development of a statistical data-reduction technique to derive the correlation between size and velocity of spray droplets. The technique has been applied on a kerosine spray injected from an ultrasonic atomizer. Based on the results of the experimental observation and measurements, the following conclusions are offered:

1. The Doppler-Mei combination technique is a powerfull diagonistic tool for measurements of spray droplets. This technique enables us to obtain the distribution of size and velocity as well as their mutual correlation of spray droplets.
2. The droplet size range applicable in this work is 15~80µm. The velocity range depends on the sampling speed of the signal processing system used
3. The lower limit of size range can be lowered further by replacing Eq.(1) by more regrous one, as well as replacing the Ne-He laser with an Ar-ion laser which shows a high power in the short wave range. The upper limit of the size range (one third of the waist diameter of the laser beams) can be expanded to some extent by replacing the assumptions used in the correction procedure with more regrous ones.
4. An enlarged control volume increses the probabilty that two droplets or more enter the volume simultaneously. The best strategy against this difficulty may be to use incident beams of uniform intensity.

ACKNOLEDGEMENT

The authors wish to thank Dr. K. Nakabe and Mr. B. Fujihata of the Combustion Lab., Osaka University, for their cooperation in the excecution of the experiment. One of the authors (Dr. El-Emam), should acknowledge gratefully the Department of Mechanical Engineering, Osaka University, for providing him the opportunity for carring out this work.

REFERENCES

1. Mellor, R., Chigier, N. A. and Beer, J. M., in Combustion and Heat Transfer in Gas Turbine Systems, (E. R. Noster, Ed.), Pergamon Press, Oxford, (1971), 291-304.
2. Schafer, M., Schegk, C. D. and Umhauer, H., Local Measurement of Particle Concentration, Size and Velocity in the Sheet of a Flat Spray Nozzle with Double Pulse Holography, Proc., 3rd ICLASS-85 Vol. 2, London, (1985), V11C/1-11.
3. El-Emam, S. H., A Photographing Method for Measurements of Spray Droplets Immediately after Formation, Bull. of Mansoura Eng. Journal (MEJ), Vol. 11, No. 1, (1986), M62-M71.
4. Durst, F., Melling, A. and Whitelaw, J. H., Principles and Practice of Laser Anemometry, Academic Press, New York, (1976).
5. Van de Hulst, H. C., Light Scattering by Small Particles, Dover, New York, (1981).
6. Farmer, W. M., Visibility of Large Spheres Observed with a Laser Velocimeter: A Simple Model, Applied Optics, Vol. 19, No. 21, (1980), 3660-3667.
7. Ungut, A., Yule, A. J., Chigier, N. A. and Atakan, S., Particle Size and Velocity Measurements by Laser Anemometry, Journal of Energy, Vol. 1, (1977), 220-228.

8. Hirlman, E. D., Laser-Based Single Particle Counter for In Situ Particulate Diagnostics. Optical Engineering, Vol. 19, No. 6, (1980), 854-860.
9. Chigier, N., Drop Size and Velocity Instrumentation. Prog. Energy Combust. Sci., Vol. 19, (1983), 155-177.
10. Farmer, W. A., Sample Space for Particle Size and Velocity Measuring Interferometers. Applied Optics, Vol. 15, (1976), 1984-1989.
11. Roberds, D. W., Brasier, C. W. and Bomar, B. W., Use a Particle Sizing interferometer to Study Water Droplet Size Distribution, Optical Engineering, Vol. 18 No. 3, (1979), 677-784.
12. Bachalo, W. D., Hess, C. F. and Hartwell, C. A., An Instrument for Spray Droplet Size and Velocity Measurements. Trans. ASME. Vol. 102 Oct. (1980), 798-806.
13. Durst, F. and Umhauer, H., In the Accuracy of Flow Measurements by Laser Doppler Methods. Proc. LDA-Symp., Copenhagen, (1976), 430-456.
14. Baukhage, K., Simultaneous Measurements of Velocity end Size of Drops in Free-Flow Fluid Spray, Proc. 3rd ICLASS-85, Vol. 2, London, (1985), VC/3/1-11.
15. Bachalo, W. D. and Houser, M. J., Phase/Doppler Spray Analyzer for Simultaneous Measurements of Drop Size and Velocity Distributions, Optical Engineering, ol. 23, No. 5, (1984), 583-590.
16. Chigier, N. A., Ungut, A. and Yule, A. J., Particle Size and Velocity Measurements in Flames by Laser Anemometery, Proc.17 th Symp. (Int.) on Combust., Combustion Institute, Pittesburgh, (1979), 315-324.
17. Les, S.L. and Durst, F., On the Motion of Particles in Turbulent Duct Flows, Int. J. of Multiphase Flow, Vol. 8, No. 2, (1982), 125-146.
18. Hodkinson, J. R. and Greenleaves, I., Particle Sizing by means of the forward Scattering Lobe, J. Opt. Soc. America, Vol. 53, No. 5, (1963), 577-588.
19. Mizutani, Y., Uga, Y. and Nishimoto, T., An Investigation on Ultrasonic Atomization, Bull. JSME, Vol. 15, (1972), 620-627.
20. Bending, L., New Developments of Ultrasonic Atomization Atomizers, Proc. of ICLASS-88, Sendai-Japan, (1988), 133-138.