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LDV Measurements of Turbulent Flow Behavior of Droplets in a Two-Phase Coaxial Jet

Byung-Joon Rho* and Je-Ha Oh**

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Coaxial nozzles are frequently utilized for the atomization of liquids in sprays. The performance of a nozzle is generally evaluated by its atomizing characteristics, which are actually governed by the turbulence interactions of two fluids. With this point of view, this experimental study was carried out to investigate the turbulent behavior of the droplets atomized in a two-phase coaxial jet. Air and water have been used as the working fluids, and the measurements have been made by an on-line data acquisition system connected to a two-channel LDV set(DISA, 5W, Argon laser, blue : 488 nm, green : 514.5 nm). In order to generate a two-phase mixing jet, two types of coaxial nozzles(liquid column type, liquid sheet type) were used. For the investigations of the turbulent flow structure of this two-phase mixing jet, the spreading rates, mean and fluctuating components, intermittency factors and the iso-contours of joint probability densities were measured and analyzed. The results from the both types of nozzles did not show remarkable differences in mean and fluctuating velocity distributions, intermittency factors or the iso-joint probability density contours. Since the measurements were made in the fully developed turbulent mixing regions, the mean velocity distribution profiles showed good similarities and agreed well with the semi-empirical curves. The RMS values were represented as high order levels and so were the intermittency factors. The typical development trends of turbulent components of u' and v' for both types were illustrated in the iso-joint probability density contours.

Key Words: Two-Phase Coaxial Jet, Laser Doppler Velocimeter, Intermittency Factor, Joint Probability Density, Spreading Angle, Liquid Column and Sheet Type Nozzle

Nomenclature

b : half width of the mixing flow
D_{eq} : equivalent diameter of the annular area of the nozzle exit
$F(u')$: local flatness factor of u'-component
$F(u')_{cl}$: center line flatness factor of u'-component
Mr : mass ratio (air/water)
$\bar{U}$: axial mean velocity
$\bar{U}_m$: axial maximum mean velocity
u' : axial fluctuating component
v' : radial fluctuating component
X : axial distance
Y : radial distance
$\gamma(u')$: intermittency factor of u'-component
η : defined as Y/b

* Department of Precision Mechanical Engineering, Chonbuk National University, Chonju, 560-756, Republic of Korea
** Graduate Student

1. Introduction

Two-phase turbulent mixing flows are actually developed in most combustion systems such as internal combustion engines, boilers, burners, kerosene heaters, etc. Some of these flows are premixed in the mixing chamber and some of them are mixed directly in the combustion chamber. Two-phase mixing flows of air and fuel are usually effectuated in order to get uniform and complete mixtures across the whole flow cross sections. Various types of the two-phase jet, that is, a simple parallel jet, a coaxial parallel jet, a cross jet and a coaxial cross jet, can be employed for these purposes.

So far these applications have been generally adapted through experience rather than exact theoretical or experimental background. Recent investigations in this field tend to develop new sophisticated data acquisition techniques to improve the combustion systems, but it requires expert knowledge in this field to solve many problems and deal with various methods of investigation. Two-phase flows in the combustion systems continue until just before ignition, and should be studied in the fluid mechanics field. Such studies should include atomization and turbulent mixing flow characteristics.

A good atomization can be expected through a higher order turbulent momentum created in the colliding and mixing processes of a two-phase fluid turbulent jet. The turbulent cross jets generate more intense turbulent mixing flows compared to a parallel or a single jet.

Recent interest in this field is concentrated on the cross jets colliding at certain angles. Rho et al. (1990~1992) have investigated the turbulent cross jet generated by two circular contraction nozzles with a cross angle of 45 degrees. In these studies the turbulent mixing flow structures, the intermittent phenomena, and the p.d.f. characteristics were experimentally analyzed in comparison with those of a single round turbulent jet. In relation with the two-phase turbulent jet, Otani(1988) has developed a low-air-pressurized burner through an experimental study on the cross jet of fuel and air. Ohnish et al.(1988) has effectuated the experiments on the two-phase cross jet of a coaxial nozzle and they presented the results showing a better atomization than that of a single phase coaxial jet. In this study the droplets' size distributions were measured by an immersion sampling method. A photographic method was taken by Zanelli(1988) to measure the drop sizes, break-up lengths and other atomizing characteristics. In addition, similar investigations, such as Kurokawa and Toda(1988) for cooling systems, Blümcke et al.(1988) in the combustion chamber of a gas turbine, Santavicca et al. (1984) for diesel injection spray nozzles, have been performed for the improvement of the systems.

Many parameters, such as mass ratios, exit diameters, injecting angles, exit shapes of the nozzle, etc., must be considered in conducting experimental studies of a two-phase coaxial jet. In this study all of the parameters except for the mass ratios have been fixed, and a parallel coaxial nozzle with the diffusing exit shape of 90 degrees was utilized.

The measurements have been made by a two-channel LDV set connected to an on-line computer analyzing system.

The purpose of this study was to investigate the turbulent flow behavior in a two-phase coaxial jet, and measurements have been intensively made on the mean and fluctuating velocities, intermittency factors and joint probability densities of turbulent components.

2. Experimental Setup and Measurements

Two types of coaxial nozzles, the liquid column type and the liquid sheet type, have been used to carry out this experimental study. As shown in Fig. 1, the liquid column type was designed to have the exit section ratio of liquid/air=0.16 and the liquid sheet type to have liquid/air=0.56. These ratios were calculated based on experiences since the recommended values for these experimental conditions were not found in any references. The exits of the nozzles were shaped as the truncated cones of 90 degrees in order that the jet flows be well diffused and mixed without exterior interruptions, and these kits were made of bronze to keep them well machined and from being rusted.

Figure 2 illustrates the schematic arrangement of the overall experimental setup consisting of(A) data acquisition and treatment part,(B) laser and optic part,(C) two-phase coaxial nozzle part,(D) liquid supply part and(E) air supply part. This LDV system(DISA, 5W, Argon) is a two-channel and a counter back scattering type with the laser beams of blue(488 nm) and green(514.5 nm).

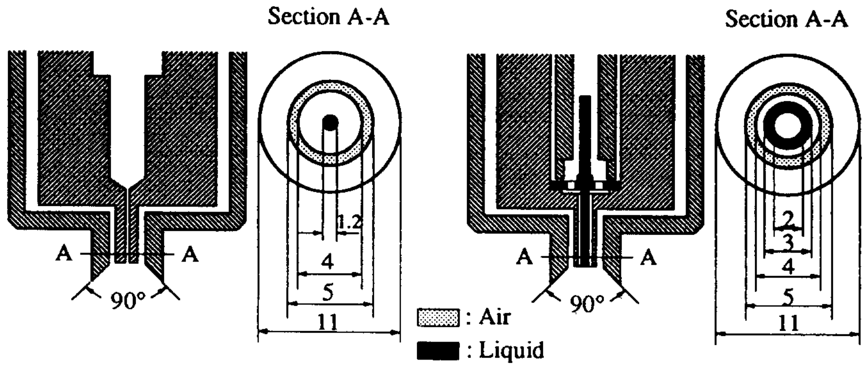


Fig. 1 Details of coaxial nozzles

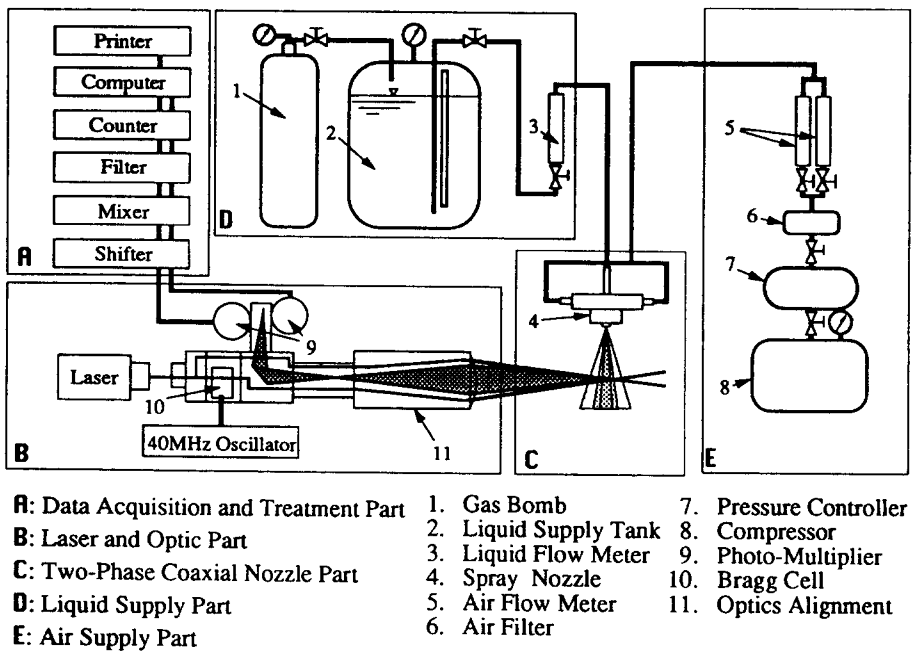


Fig. 2 Schematic arrangement of the experimental system

The data have been acquired and treated by part A consisting of a shifter, a mixer, a filter, a counter, and a computer system. The acquired signals were shifted and transferred to a filter through a shifter and a mixer. These signals were classified by a comparator set in a counter to detect the accurate and required Doppler signals. The frequencies of the detected Doppler signals were converted to numerical values by a mean velocity counter, and the digitalized frequencies were transferred to a buffer interface and analyzed by an on-line computer system. The sampling number of 3000 droplets was treated within a maximum of 120 seconds.

A liquid supply tank pressurized by a gas bomb of 392 kPa was used for uniform and steady jet flows and the flow rates have been minutely controlled by a ball valve. Air was supplied by a compressor(1.47 MPa) and the flow rates were controlled by two air flow meters and a pressure controller was set up to stabilize the pulsating flows. Since the air is apt to be contaminated by the impurities in the tanks such as oil and dust, an air filter was fixed before the air flow meters.

As a coordinates system, the axial and radial directions were defined as X and Y respectively, and the data acquisitions of velocity components have been effectuated in the regions of $X/D_{eq}=100\sim133$ and the half widths of the jets were measured in the wide ranges of $X/D_{eq}=67\sim167$. At each position, the mean and fluctuating velocities, the intermittency factors and the probability densities were measured in the radial direction.

3. Results and Discussions

3.1 Mean velocity distributions

In general, the diffusion angle of the mean flow in a single free jet is known as 5~7 degrees. In order to observe the diffusing characteristics of this two-phase coaxial jet, the half widths of the jet were measured along the center line. The half widths of the jet at each axial position have been decided to be the positions in which the half maximum velocities occurred. Due to the fluctuations and the entrainments of the surrounding air, the boundaries of the turbulent free jet can hardly be exactly measured, and so in this experiment, the half widths of the jet were measured to examine the diffusion rate. The results are presented in Fig. 3.

As shown in the figure, the half widths increase linearly with almost the same diffusion rate for both the liquid column and sheet type nozzles, and the spreading angle is calculated as 4.8 degrees from the mean gradient of diffusion rates. This value seems to be relatively small since the diffusion rate of the droplets in a two-phase

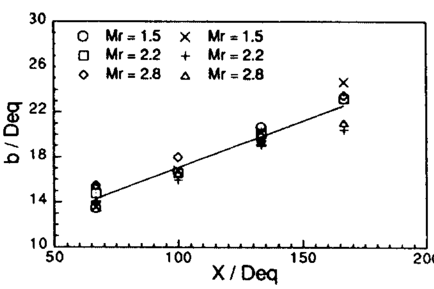


Fig. 3 Variations of half widths(○, □, ◇ ; column type, ×, +, △ ; sheet type)

mixing flow is usually smaller than that of a single air free jet. This phenomenon could be explained by the fact that differences exist in gravities, accelerations and turbulent fluctuations of the fluid particles between an air free jet and a two-phase coaxial jet. However, the gradients are remarkably constant despite some scatter in the far downstream region($X/D_{eq}>150$), and the empirical equation gives

$$b/D_{eq}=0.083X/D_{eq}+8.75 \quad (1)$$

In a single phase jet, Görtler(1957) derived an equation for mean velocity distribution by defining a constant experimentally,

$$\frac{\bar{U}}{\bar{U}_m}=1-\tanh^2(0.881\eta) \quad (2)$$

and Gauss suggested an equation for a cloche-shaped symmetric curve ;

$$\frac{\bar{U}}{\bar{U}_m}=\exp(-0.693\eta^2),\ (with\ \eta=Y/b) \quad (3)$$

These two equations are available for a fully developed turbulent flow region, and the data obtained in these measurements have been compared with these semi-empirical curves.

Figure 4 illustrates the axial mean velocity

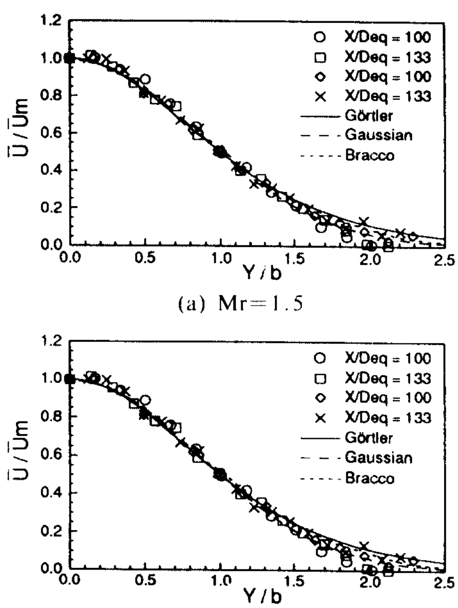


Fig. 4 Axial mean velocity distributions(○, □ ; column type, ◇, × ; sheet type)

distributions measured in the radial direction for $Mr=1.5$ and 2.2. As shown in the figures, the non-dimensional distributions for both the liquid column and sheet types had good similarities and agreed well with the existing curves and the experimental data for a single liquid jet obtained by Bracco et al.(1984).

The radial mean velocities for both cases of $Mr=1.5$ and 2.2 have been measured. The results showed relatively small values compared with the axial mean velocities. Since the measurements were made in the region of far downstream($X/D_{eq}=100\sim133$, $300\sim400$ mm from the nozzle exit) the turbulent mixing flow at this position could not be expected to be stable due to strong fluctuations. The entrainments of the flow towards the higher velocity side are generally known and proved in the previous experimental investigations. In this two-phase coaxial jet, the diameters of the atomized droplets varied from 10 μm to 200 μm. Hence the entrainments of the small and light droplets towards the higher air flow-stream(towards the central axis) could apparently be observed by PIV system at the core region of the jet. The relatively large and heavy droplets seemed to flow towards their own direction with slight spreading angles. These overall flow patterns in the flow field could easily be visualized taking advantage of the light sheet of an image analyzing system.

The radial mean velocity should theoretically be zero on the central axis, but it could hardly obtain the exact values on the right position due to strong fluctuations and the displacements of the center point of flow cross sections. While it could certainly be accepted through this investigation that the negative flows of the radial mean components developed in the core region, these results were not presented in this paper for it required some verifications through trials and errors.

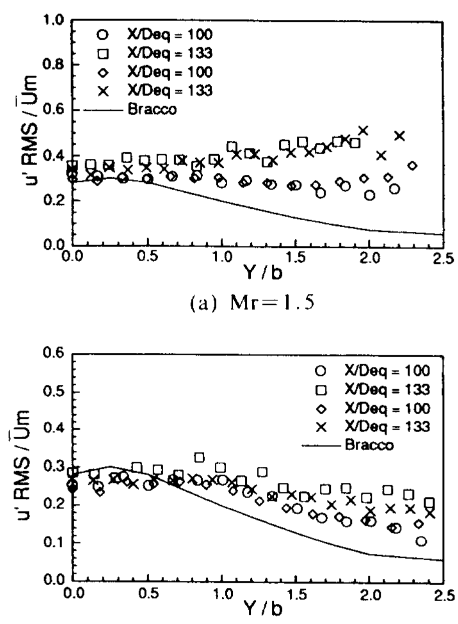
3.2 Intensity of turbulence distributions

In general, the turbulent components develop strongly in the regions of half maximum mean velocity in a single phase turbulent free jet. This phenomenon is visibly shown in the initial and transient mixing regions but it disappears in the fully developed turbulent mixing flow ones. In this region the highest intensity of turbulence is observed in the central part of the flow and it decreases gradually with the lateral distance.

Figure 5 shows the comparisons between the present data and those of Bracco et al.(1984). The solid line represents Bracco's data obtained from his Diesel-type sprays.

The local values of u'-components of droplets measured along the radial axis have been normalized by the maximum values of u-mean for each axial position respectively. Since the local maximum values of u-mean on the central axis are decided depending upon the mass ratio, and higher values of u-mean could be expected from the higher mass ratio, as shown in Fig. 5, the intensities of turbulence for $Mr=1.5$ show higher levels across the whole cross sections than the case of $Mr=2.2$.

It can be considered that the better atomization is generally expected in the higher mass ratio flow than in the lower one, however, the higher intensity of turbulence can be usually obtained in the latter case because the larger particles flow with



(a) Mr=1.5

(b) Mr=2.2

Fig. 5 Distributions of intensity of turbulence for u'-component(symbols as in Fig. 4) relatively lower mean velocity and higher fluctuating velocity component compared with the case of smaller particle's flow.

The u'-components of droplets measured in this experiment showed high intensity levels compared with the results of Bracco et al.(1984). The distributions of the intensity of turbulence at each axial measuring position, for $Mr=1.5$, show almost the same levels across the cross sections.

These two figures illustrate that the intensity levels for both types of nozzle measured at the same measuring position do not have a remarkable difference. Some scattered phenomena are found in the outer region of the jet for $Mr=1.5$ but these are distinctively reduced in the case of $Mr=2.2$.

Radial components of v'-RMS are presented in Fig. 6. The intensity levels for both cases of $Mr=1.5$, 2.2 are comparatively lower than those of u'-RMS. This signifies that the axial components develop much more strongly and govern the two-phase mixing structures. The non-dimensional distribution profiles of v'-RMS have a good similarity and show a similar trend to Bracco's result across the whole cross sections.

3.3 Intermittency factors

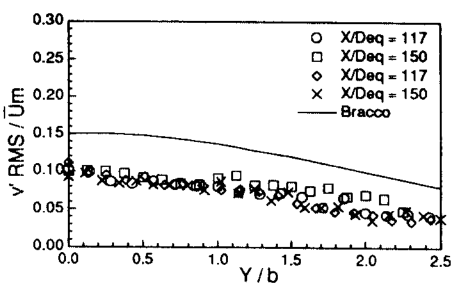
In order to observe the developing characteristics of fluctuating components at a position during a certain time-interval, the flatness factor is usually employed as an evaluation parameter, and defined as

$$F(u')=\frac{\overline{u'^4}}{(\overline{u'^2})^2} \tag{4}$$

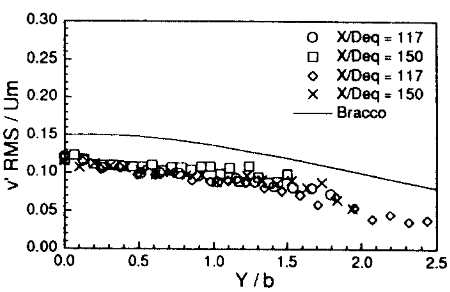
In a turbulent flow region, if there is a position in which the turbulent component develops axisymetrically with time, a cloche-shaped curve(Gaussian curve) can be obtained with a value of $F(u')=3$. This value can be approximately obtained on the center line of an axisymmetric turbulent jet. The flatness factors on the center line are taken as a parameter for non-dimensional analysis as in the following Eq. (5).

Taking advantage of the Eq. (4), the intermittency factor is given by

$$\gamma(u')=\frac{F(u')}{F(u')_{cl}} \tag{5}$$

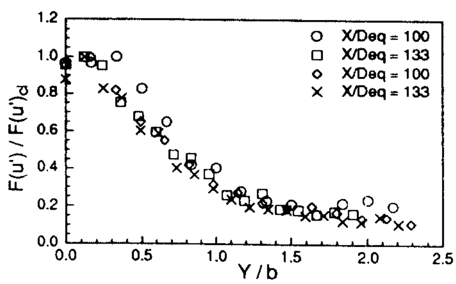


(a) Mr=1.5

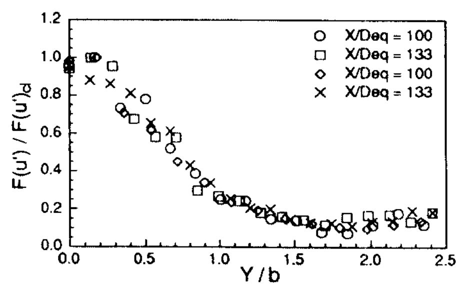


(b) Mr=2.2

Fig. 6 Distributions of intensity of turbulence for v'-component(symbols as in Fig. 4)



(a)= (a) Mr=1.5



(b) Mr=2.2

Fig. 7 Distributions of intermittency factors(symbols as in Fig. 4)

The intermittency factors are presented in Fig. 7. For each mass ratio, the distribution profiles have a good agreement independent of jet types. Wygnanski and Fiedler[12] observed in the plane half-jet $\gamma(u')\cong 1$ at the "half value" point of the mixing region. But this value is not comparable with the results of a complex turbulent jet, moreover for a two-phase mixing turbulent jet the intermittency factors are obeyed by the characteristics produced by jet conditions.

In these figures, the intermittency value $\gamma(u')\cong 1$ is obtained in the central regions of $Y/b\leq 0.25$ and it decreases along the radial axis.

This shows that the two-phase coaxial jet has a comparatively more narrow developing turbulence region than single phase round jet, and intermittency factors of turbulence are higher at the outer boundaries. Velocity distributions of the two-phase jet are similar to the single phase jet, while intermittency distributions are very different from that of single phase jet. This is related to the concentration. In this study, concentration of

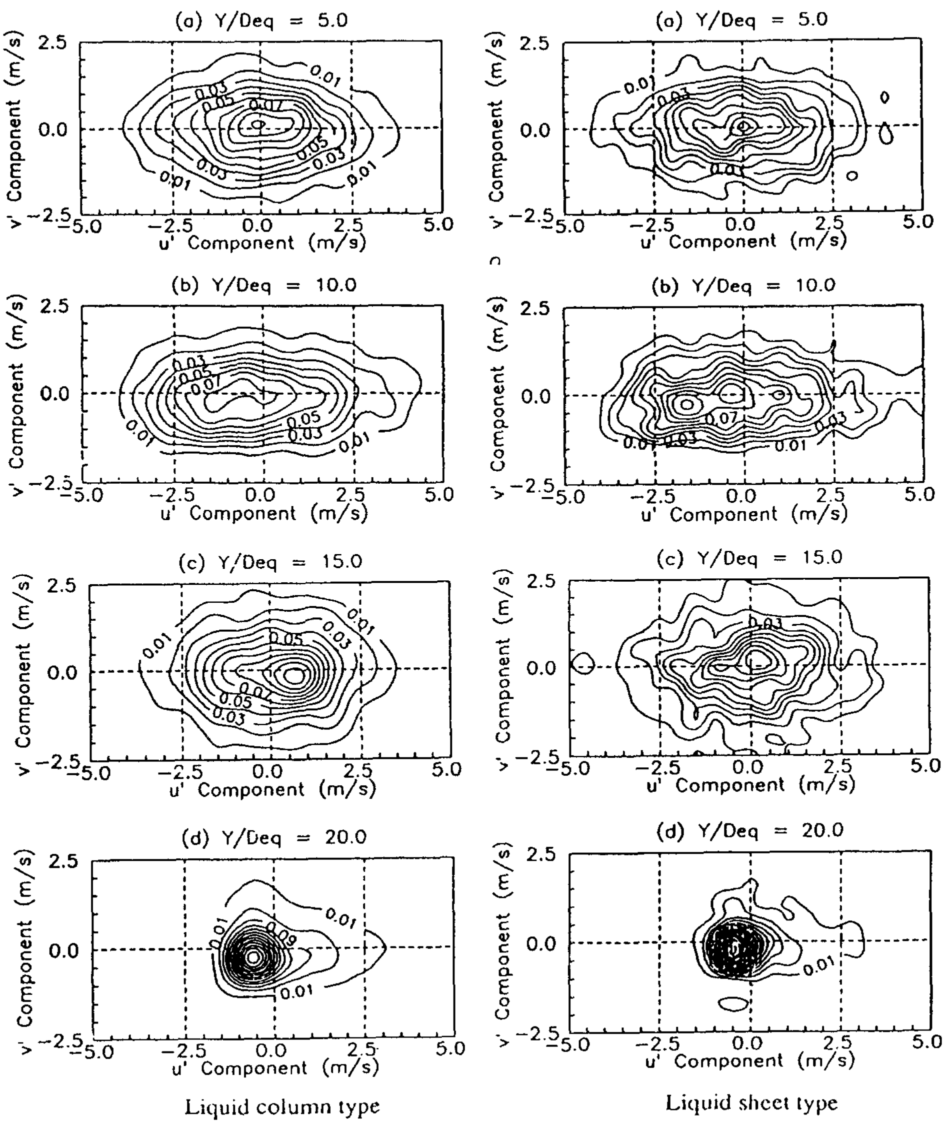


Fig. 8 Iso-contours of joint probability densities($X/D_{eq}=100$)

droplets effects on th intermittency of turbulence due to measuring the droplet velocity of dispersed phase. In the similar mean velocity distribution, if $\gamma(u')$ is small, the number of droplets using at fluid velocity measurement is relatively small. Consequently, we can predict that the concentration of droplets is low, at the outer region of the sprays.

3.4 Probability densities

A statistical analysis was conducted to investigate the characteristics of turbulent components of u' and v'. The iso-contours of joint probability densities allow the analysis of the order of relative magnitudes for each component, the fluctuating densities, and the variations of joint structures with respect to positions.(Fig. 8)

Since the flow structure in this experiment can be considered an axisymmetric one, several figures are presented in this paper to give some discussions. These results were obtained at the axial measuring position of $X/D_{eq}=100$. The developments of two components u' and v' are shown significantly different. In case of the column type, the fluctuating magnitude of u'-component is twice of v'-component near the center line($X/D_{eq}=5.0$), and it makes more differences at $X/D_{eq}=10.0$.

But this phenomenon begins to disappear after this position, and the magnitude of fluctuations remarkably decreases. The joint mixing structure of two turbulent components for both types could be considered as a steady state and the variations of fluctuating magnitudes and the structures show a similar trend.

The uncertainties of the data presented in this paper should be considered because some errors might have occurred in measurements. Taking advantage of the equations suggested by Moffat(1982, 1985) and Kline(1985), the uncertainties occurred in measurement of velocity components by LDV system can be estimated to be 1.6%. In addition, other uncertainties could also be revealed in controlling the mass flow rates of water and air, that is, 3.3% for water flow rates and 1.4% for air flow rates. Consequently, through the entire procedure of measurements the maximum uncertainty would be below 4%.

4. Concluding Remarks

This paper presented some results of turbulent flow behavior of droplets in a two-phase coaxial jet. Most of the coaxial nozzles are usually utilized for the atomizations in various spray systems or combustors. The atomizing characteristics seem to be governed by turbulence levels. From this point of view, this study was carried out to investigate the characteristics of velocity components as a first experimental step. And it is recommended that the atomizing characteristics should be studied combined with the turbulence intensities.

Through experimental investigations some results can be summarized as follows.

The spreading rates of the mixing flow half widths increase linearly with an X-axis and represent the same order of gradients independent of the nozzle types.

The axial mean velocity profiles have good similarities and agree well with the semi-empirical curves.

The intensities of turbulence of u'-components are relatively high compared with the data of Bracco but those of v'-components show significantly low levels. The RMS values for both types illustrate almost the same magnitudes with respect to mass ratios and positions.

The intermittency value $\gamma(u')\cong 1$ is obtained in the vicinity of the central axis and it decrease along the radial direction.

The iso-contours of joint probability densities for both types represent the classical forms, and the variations of fluctuating magnitudes and the structures show similar trends.

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