Multi-Intensity-Layer PIV application to a practical burner

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ABSTRACT
PIV applicability to a spray was investigated by comparing with PDA results and showed the good agreement of detected velocity. But some region discrepancy can be observed. The new technique ‘Multi-Intensity-Layer PIV’ which can detect velocity and droplet size at same time was proposed and applied to a spray burner for evaluation. Evaluation was done under comparison with size-classified PDA since this new technique tries to describe droplet behavior and flow structure for each droplet size classes. In the new technique Mie theory is applied and the source image was distributed into three images (layers) to distinguish following, alternative and penetration effect in a large scale turbulent structure. Layer distribution was done with using the pixel intensity on source images and each criterion was selected carefully with consideration of diameter square information. Good agreement of size-classified PDA and Multi-Intensity-Layer PIV data was observed around the central axis but very large discrepancies were also observed around r=20mm region. For the investigation of these agreement and discrepancy velocity-diameter correlation was taken into account and found that discrepancy is due to the wide ranges of velocity and diameter droplet existence and flow complexity. In these regions PIV would generate erroneous or incorrect vector because PIV technique uses spatial average in the interrogation window. With consideration of this error source in a spray measurement flow structure analysis was done with this ‘Multi-Intensity-Layer PIV’ technique Source images were distributed in three layers and three different vector maps were produced from a pair of images. By comparing these vector maps of different layers we succeeded to describe the droplet behavior and flow structure such as droplet following and penetration, hollow cone structure and shear flow region with its size dependency. And finally concluded that this technique can be useful tool to understand droplet behavior in the spray flow fields.
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1. INTRODUCTION
Improvements of fuel-air mixture in a combustor provides the higher thermal efficiency and also lower NOx and CO2 emission (Chigier 1991). To investigate the fuel-air mixture characteristics many researches and studies have been done with using various measurement techniques. Especially, in the spray flow field droplet behaviors were investigated in detail with recent highly developed laser techniques such as laser Doppler velocimetry and phase Doppler anemometry (Edwards 1990, Lefebvre 1989). In PDA application to a practical burner (Taylor 1993) we succeeded to describe the droplet behavior in detail for each droplet size classes, so call Size-classified PDA technique (Ikeda 1997a) and succeeded to demonstrate droplet penetration and following in a large scale turbulent structure. Furthermore, time series measurement (Ikeda 1997b) has been done at very high data rate to know the velocity fluctuations at each measurement points and found the periodic fluctuation of axial and radial velocity components. This periodic behavior of the droplet velocity can easily leads us to predict the existence of spatial structure of droplet distribution such as droplet cluster, branch structure, mushroom vortex and so on. In order to prove the existence of such spatial structure and also to investigate the mechanism of the structure laser sheet visualization (Buch 1996, Fessler 1995 and Nishida 1992) and Particle Image Velocimetry (PIV) (Raffel 1998, MST 1997, Keane 1997 and Grant 1994) were applied to a spray flow. The aim of our research is to know temporal and spatial mechanism of droplet behavior and its characteristics. But conventional Particle Image Velocimetry cannot describe droplet size information even though spatial distribution of velocity is available. In this research we developed a new PIV technique that we call ‘Multi-Intensity-Layer PIV’ and its evaluations has also been done. The special aspect of this research is that the evaluation of this method has been done based on
comparison with size-classified PDA results in the whole region of interest.

2. EXPERIMENTAL APPARATUS

Figure 1 shows the gun-type burner that is used for the measurement (Ikeda 1995). Hollow cone spray of 60° (0.7MPa) was produced by Danfos type nozzle that was attached on the central axis and A-type heavy oil was used. Ambient air is going through a baffle plate installed to generate reversing flow region at downstream and give the swirling force to the ambient air. Measurement apparatus is shown in Fig. 2. In this study the ‘Multi-Intensity-Layer PIV’ was applied in cold flow condition. The flow without combustion is illuminated by double pulsed Nd:YAG laser that have 532nm wavelength and planar information is captured by a 8bit 1008(H) x 1018(W) resolution Kodak ES1.0 cross correlation camera. The area of interest of this measurement is 80x80 mm from the exit of the nozzle that means one pixel of CCD chip represents 80µm in physical dimension. The camera (8bit resolution) has its highest quantum efficiency around 520 to 530 nm. Dark current of the camera was 13 of 0 to 255 grayscale and treated as background noise.

3. CONCEPT OF Multi-Intensity-Layer PIV

The method is a simple application of Mie theory (van de Hulst 1981); Mie scattering intensity from droplet is proportional to diameter squared in a certain receiving angle. Generally Mie scattering intensity of 10 to 100µm droplets is believed to be proportional at 30° receiving angle. That means the intensity distribution on CCD captured image has the droplet diameter information so that we proposed to utilize its intensity information to convert into droplet diameter information on PIV data analysis. We call this method as ‘Multi-Intensity-Layer PIV’ (Ikeda 1998 and Yamada 1998). Basic concept of this Multi-Intensity-Layer PIV is shown in Fig. 3. The light scattered from the droplets was digitized in 8bit, 0 to 255 grayscale. A pair of 8bit source images, that were illuminated with slight time difference (20µs) each other, were distributed into three different images depending on pixel intensity. We call these separated images as ‘layer’ and the source image is distributed into multiple ‘Layers’. Layer distribution criterion of 8bit image is the key feature of this technique and should carefully be done.

In spray research \(D_{10}, D_{50}\) and \(D_{98}\) (SMD) is popular but hard to explain the droplet behavior. Penetration of droplet was caused by its mass and velocity. It is not enough to identify the droplet size in order to discuss the air-fuel mixture characteristics. We did size-classified PDA in the spray and demonstrate typical droplet behavior.
dependency on the size range. These results allow us to understand the typical spray behavior in a certain droplet diameter range. For understanding of air-fuel mixture formation, the key parameter is small droplet group, which may follow the turbulent flow so as to have quick evaporation, and large droplet diameter group that cannot follow and penetrate the shear flow region. Then evaporate in far down stream that is the reason why spray droplet cannot be burn in a small region. This Multi-Intensity-Layer PIV is to measure these typical spray behaviors, not detail droplet diameter. Furthermore, the instantaneous spatial spray structure can be measured in 2-dimensional plane.

In our flow field droplet diameter distribution is from nearly 0µm up to 80µm so that we assume that the intensity from nearly 0µm droplets equals 0 in 8bit grayscale and 80µm droplets to 255. Our previous research tells that less than 30µm droplet follows the large scale turbulent structure while more than 50µm droplet penetrates. So we tried to detect the droplet behavior of the size of 0 to 30µm, 30 to 50µm and more than 50µm. We define that the intensity from nearly 0µm droplet is 14 and the intensity of 80µm is 255. Based upon Mie theory, 0² equals to 14/255 intensity and 80² equals to 255/255 intensity. The intensity of 30µm and 50µm were calculated by simple linear interpolation. The intensity of source images were finally distributed into three layers, layer1 (14-47/255), layer2 (48-73/255) and layer3 (74-255/255) based on Mie theory that tells ‘Mie scattering intensity is proportional to its diameter squared’. The concept of layer distribution is shown in Fig. 3. The intensity of 0 to 13 of 255 was treated as background noise and dark current noise of the CCD camera.

![Fig. 3 Concept of Multi-Intensity-Layer PIV](image-url)
A pair of source image was distributed into three image pairs and vector calculations were done so that from a pair of source images three vector maps can be produced separately. Data analyzing procedure was shown in Fig. 4.

**Conventional PIV**

![Conventional PIV Diagram](image)

**Multi-Intensity Layer PIV**

![Multi-Intensity Layer PIV Diagram](image)

4. RESULTS AND DISCUSSION

4-1. Applicability of conventional PIV to a practical burner

At the beginning investigation on the applicability of PIV was done in a spray. PIV evaluation was done comparing with PDA data. Figure 5 shows the comparison of the mean axial and radial velocity component (SMD velocity) with PIV velocity components from the average of 500 vector maps in cold flow measurement. Based on our purpose, that is to investigate the mechanism of recirculation region, PDA/PIV comparison was done on x=8mm and 20mm since the axial length of the recirculation region is 30mm and the flow structure inside of this region should be observed in detail. On the figure velocity component acquired by PIV briefly agreed with PDA results and the fact shows that PIV can demonstrate the flow structure with certain accuracy and PIV can applicable to our spray flow to understand the fundamental flow structures. Some discrepancies could also be found around r=-20mm and 20mm axis.

However, PIV cannot demonstrate the instantaneous spatial velocity distribution of different droplet sizes and droplet behavior can hardly be discussed without droplet size information, which is the reason we are developing the ‘Multi-Intensity-Layer PIV’.
4-2. Evaluation of Multi-Intensity-Layer PIV

Based on the above-mentioned concept source images used for conventional PIV were distinguished into three images (layers) and cross-correlation was executed between temporally successive two images (layers). At each layer conditions 500 vector maps were averaged for statistical evaluation. Axial and radial velocity component of axial distance x=8mm and 20mm is shown in Fig. 6. On each figure the velocity component around the central axis (r=0) at each layer show good agreement with size-classified PDA results both in axial and radial velocity component and the layer of higher intensity has the larger axial velocity component both on x=8mm and 20mm level. At the recirculation region of left hand side (r=–40 to –14) largest droplets more than 50 µm has the biggest magnitude of negative component at axial distance x=8mm. This behavior can also be observed in Multi-Intensity-Layer PIV data (Layer 3), that is, in this recirculating flow region layer 3 axial velocity components has the higher magnitude of negative velocity component than the other two layers. On the other hand the location of r=0mm axial velocity component of the highest intensity (Layer 3) is the largest of all the three layers and shows good agreement with the droplet of more than 50µm on axial component. Axial component of middle intensity (Layer 2) shows some agreement with 30-50 µm droplets and lowest one (Layer 1) with 20-30 µm droplets around the central axis (r=0). But at the location around r=–20mm and 20mm there are very high velocity gradient on axial component and big discrepancies can be observed both on x=8mm and 20mm. Around this high velocity gradient region both axial and radial velocity components of all the layers were always smaller than the PDA velocity. Thus, Multi-Intensity-Layer PIV can provide good agreement in a certain location but discrepancies still remains on the other location at the same time. Here we conclude that most of all the discrepancies between size-classified PDA and Multi-Intensity-Layer PIV occurred around the axis r=–20mm and 20mm.
At our comparison of conventional PIV with PDA on Fig. 5 in the previous section, discrepancies are also observed but not such big like the ones of the size-classified PDA and Multi-Intensity-Layer PIV comparison. The difference between these two comparisons is that there is no droplet size information included in the former one. If the droplet size information was put into PDA and PIV data such big difference of the velocity came out in the certain limited measurement points and interrogation windows. This fact leads us to view the velocity-diameter correlation at each location where the discrepancy is high. In order to investigate the cause of this discrepancy velocity-diameter distribution diagram acquired by PDA was shown in Fig. 7. At the location of \((x,r)=(8,20), (20,-20)\) and \((20,20)\) there are wider distribution of velocity and diameter than the other location observed. At these locations the velocity-diameter correlation seems to have bimodal peak. Additionally, there was no linear correlation between diameter and velocity (e.g. larger droplet has bigger velocity). The bimodal peak means in these locations at least two dominating flow exists and the flow structure would be so much complicated while the other point has only one. The possible reason for the discrepancy of the Multi-Intensity-Layer PIV velocities against size-classified PDA would be such that there are many kind of magnitude of velocity detected on the interrogation window so that all the detected velocities were spatially averaged.

**Fig. 6 Size-classified PDA and Multi-Intensity-Layer PIV comparison**
4-3. Multi-Intensity-Layer PIV application to a burner

With considering above mentioning error source, vector maps were shown in Fig. 8. On the axial velocity component there are two recirculation regions observed just downstream of the burner throat. The recirculation region was generated due to the existence of baffle plate. The size of recirculation region is always fluctuating in time and space but this vector information was 500 vector maps averaged so that we can deal with these data as the averaged flow structures.

On the vector maps of Layer 1 and 3 strong penetrations of the droplets, that is, hollow cone structure was observed. Layer 3 seems to have much more strong penetrating velocity than that of Layer 1 and on Layer 1 vector map large scale structure can be observed on the area of r=10 to 30mm, x=0 to 20mm region but on Layer 3 map this structure does not exist or corrupted. In order to discuss the difference between these two layers quantitatively axial and radial component of velocity and vorticity were shown in Fig. 9.
Fig. 8 Multi-Intensity-Layer PIV vector map at Layer 1 and Layer 3

Fig. 9 Velocity components and vorticity at Layer 1 and Layer 3
About the recirculating region the size can be defined by the height (x-direction) and the width (r-direction) of the white colored region on axial velocity distribution on Fig. 10. The heights of the recirculating region on Layer 1 are 22mm (left) and 30mm (right) but on Layer 3 20mm (left) and 20mm (right). Recirculating region was shortening on Layer 3. Around the central axis (r=0mm) large velocity of the droplet can be observed. The height of the red colored region (u=13 to 17 m/s) was 35mm on Layer 1 and approximately 45mm on Layer 3. The possible reasons for this are the initial velocities of droplets are faster and the size is larger than that of Layer 1. Larger droplet can travel faster because of its strong momentum and hardly be evaporated so that large droplet can travels at constant size and velocity to the main flow region (x=40mm) and then starts to be evaporated. The small droplets would readily be affected by surrounding air and easily be evaporated so that the small droplet cannot travel at constant size and velocity. Layer 3 has stronger radial velocity than Layer 2. Our PDA results indicated that the hollow cone structure is mainly being consisted of larger droplet so that larger droplet can have strong radial velocity. From these results Layer 3 represents the droplet behavior of larger droplets while Layer 1 is for small ones. On the vorticity map Layer 3 has much wider area where the vorticity is strong than Layer 1 due to the strong shear between bigger droplet and smaller ones. Thus, by distinguishing the layers flow characteristics and droplet behavior of different droplet size could be demonstrated.

5. CONCLUSIONS

On this study the applicability of conventional Particle Image Velocimetry to a spray was investigated and newly developed ‘Multi-Intensity-Layer PIV’ was evaluated with size-classified PDA and applied to a practical burner. Our conclusions are as follows:

- Conventional PIV was applied to a burner and succeeded to describe the brief flow structure and found that PIV is applicable to the spray flows.
- Wide range of velocity and diameter droplets in the interrogation window decrease the detectability of correct velocity.
- In this burner the flow structure is very complicated around r=20mm region so that discrepancy between PDA and PIV became bigger.
- Layer 1 represents 20-30µm droplet velocity and Layer 3 showed good agreement with the velocity of bigger than 50 µm droplets on the central axis.
- Succeeded to describe flow structure and droplet behavior with ‘Multi-Intensity-Layer PIV’ technique.

REFERENCES


