Journal of Applied Sciences

ISSN 1812-5654

Journal of Applied Sciences 11 (11): 1966-1972, 2011
ISSN 1812-5654 / DOI: 10.3923/jas.2011.1966.1972

Droplet Size Measurement for Liquid Spray using Digital Image Analysis Technique

[1]N. Lad, [2]A. Aroussi and [1,3]M.F. Muhamad Said
[1]Department of Engineering, Thermal and Fluid Engineering, University of Leicester, UK
[2]Department of Mechanical Engineering, Universiti Teknologi PETRONAS, Tronoh, 31750, Malaysia
[3]Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, Malaysia

Abstract: The developed Digital Image Analysis (DIA) system has been examined in terms of its capability to characterise the high speed, fine droplet at downstream of a spray atomiser. The architecture and working principle of the DIA system were explained. This system has employed a high intensity pulsed laser as a light source and a digital camera to capture the droplet images. The DIA technique has been implemented in extracting the valuable information of spray droplet from the images. Image processing algorithms were applied in the development of the software and they were described in this paper. In order to evaluate the repeatability of the DIA system, the measurement of droplet size was repeated several times. The deviation result has confirmed that the DIA system has a good repeatability on sizing the drops. The available methods to characterize the droplet spray were briefly explained. The DIA system was used to investigate the effect of a circular cylinder on the drop size of an atomizer at downstream of the spray flow. The cylinder was introduced at 250 mm downstream of the nozzle exit. The measured mean drop size for 'with cylinder' and 'no cylinder' were at 9.2 and 8.1 µm, respectively. It was observed that due to the coalescence of the drops after it passed through the cylinder, the mean drop size were found to be slightly larger when the circular cylinder is introduced.

Key words: Droplet sizing, image analysis technique, shadow sizing, image processing

INTRODUCTION

A lot of industrial applications have to deal with problems that involve two-phase flow with particles or droplets as a secondary fluid. The requirement to produce sprays with the desired droplets size distribution is the primary quantities of interest in evaluating the performance of two-phase flow systems such as fuel atomisers, metered dose inhalers, agricultural sprays and paint sprayers. The significance of obtaining the droplet size was described in the following examples which are on agriculture and fuel spray applications.

In the agricultural sprays application, especially in irrigation, certain ranges of nozzle types that produce small droplets including sprinklers are used (Sudheer and Panda, 2000). The nozzles have a capability to generate droplets diameter up to a millimetre at very high flow rates so that water can be used uniformly and efficiently. If a large number of small droplets are produced, significant water loss due to drift and evaporation can occur. In order to maintain the spray size distribution while operating at lower line pressure, the design of the nozzles has to be optimized. This may give higher savings in terms of energy where the irrigation is widely used in the agriculture application.

Most of the work in the characterisation of fuel sprays have been performed on cold or non-burning sprays and on the burning of individual droplets (Fujisawa *et al*., 2003). These data are useful in correlating the performance of nozzle type and fuel flow parameters with the combustion performance. Generally, the process of the fuel spray combustion depends on the fuel type, droplet size distribution, ambient gas composition, temperature and pressure. These parameters may affect the heat, mass and momentum transfer, and the chemical reactions. Data on the droplet size at various regions in the spray flame, droplet flight angle, velocity and the gas phase velocity would be useful.

In order to measure the droplet size for the desire application, an appropriate technique has to be applied. There are several difficulties in obtaining accurate droplet size due to the spray behaviour in the various of applications (Lefebvre, 1989). These include the higher concentration of drops in a spray, the high and changing velocity of the drops, the wide range of drop sizes and the changes of drop size with time through evaporation and coalescence processes.

A wide variety of measurement techniques have been employed in determining the droplet size in two-phase flow systems. The most popular technique is Phase

Corresponding Author: N. Lad, Department of Engineering, Thermal and Fluid Engineering, University of Leicester, UK

Doppler Anemometry (PDA). It was considered as the most accurate method for spray characterisation investigation. However, the PDA system has some limitations. It requires an accurate alignment, higher capital cost and inability to accurately determine non-spherical droplets (Kashdan *et al*., 2007). There is also another method used by different researchers to determine the droplet size which is digital image processing technique. They found that the accuracy of this technique for the spray characterisation study is comparable with well known devices such as the PDA (Blaisot and Yon, 2005; Kashdan *et al*., 2003). Furthermore, the interest in digital image processing techniques for spray characterisation is increasing due to the recent improvement of image resolution, sensitivity of imaging systems and cost reduction. Therefore, this paper describes the principle of Digital Image Analysis (DIA) technique and also the components involve in the development of the DIA system. Also, the capability of the DIA system is examined to determine the fine sizes and fast moving droplets of spray atomiser.

Spray characterization methods: According to Lefebvre (1989), the ideal techniques of drop size that can be used as a guide line in developing a new spray characterisation device should have certain features. They include non-intrusive methods, wide drop size range, capable of measuring both spatial and temporal distributions, able to perform means of sampling and counting. However, it is quite impossible for a single device to have all of these criteria. Often the application dictates the dominant features desired. Therefore, it is important to highlight the capabilities and limitations of the developed techniques.

Figure 1 shows the methods used to characterise the liquid sprays. It can be categorised as intrusive and non-intrusive. The intrusive methods also called sampling techniques use probes or other instruments to collect samples from the measurement location. However, in certain conditions, the probes may disturb the flow field and affect the flow behaviour. In these methods, several characteristic samples of particles are collected and analysed using mechanical sampling devices. Under this intrusive method, it include the collection of drops on slides, collection of drops in cells, molten wax techniques, drop freezing techniques, cascade impactors, charged wire and hot wire techniques. These and other conventional methods are described in detail by previous researchers (Lefebvre, 1989; Allen, 1997; Rhodes, 1998). Nowadays, due to the rapid development of modern technology such as powerful computers, lasers, cameras and automation systems, the methods involved in spray characterisation have changed significantly. Those conventional methods have gradually been replaced by non-intrusive methods which are based on light-matter interaction.

Non-intrusive methods do not interfere with the flow systems. The fact that the flow is not disturbed, allows the application of these methods in high speed flows with shocks or in boundary layers close to walls. Non-intrusive instruments are invariably optical techniques designed to measure the flow field. The examples are laser diffraction, Particle Tracking Velocimetry (PTV) (Hatem, 1997), Phase Doppler Anemometry (PDA) (Crowe *et al*., 1997) and Particle Image Velocimetry (PIV) (Raffel *et al*., 2007). This non-intrusive can be classified into two categories, which are imaging and non-imaging methods. Imaging methods include photography and holography (Thompson, 1984). Usually, images are two-dimensional, such as a photograph or screen display. They may be captured by optical devices such as cameras, mirrors, lenses, telescopes or microscopes. Non-imaging methods can be divided into two groups and they are ensemble and single particle counting (Crowe *et al*., 1997). Ensemble methods or also known as multiple particle counting are those that measure a large number of particles simultaneously, while the single particle counting are those that count and size individual particle one at a time.

Application of the DIA technique: In this study, the DIA technique has been developed for the automated determination of the properties of droplets such as its size. It requires 8-bit digital shadow images of the two-phase flow under investigation. Analysis of the images is performed through automated processing algorithm. The DIA technique has been applied to obtain the droplet size downstream of the spray nozzle. A circular cylinder, which is an intrusive obstacle, has been introduced in the spray flow regime. The interaction of fluid flow with a circular cylinder is an area of great interest due to its fundamental importance. For example, it represents a generic configuration for studying vortex dynamics, the drag and lift variation due to wake unsteadiness and its relevance in technical applications. Spray flows provide irregularity in the upstream approach and causes varying effects downstream of an obstacle. With these effects it is important to note that measuring obstacles placed within these flows such endoscopes may not see a true depiction of the flow properties. This study looks at the effects of droplet size caused by the intrusive obstacle using DIA techniques.

Experimental setup: The DIA technique is based on the extraction of information from the digital images. In order to acquire these images, several components or equipments have been utilised. The following sub-topics

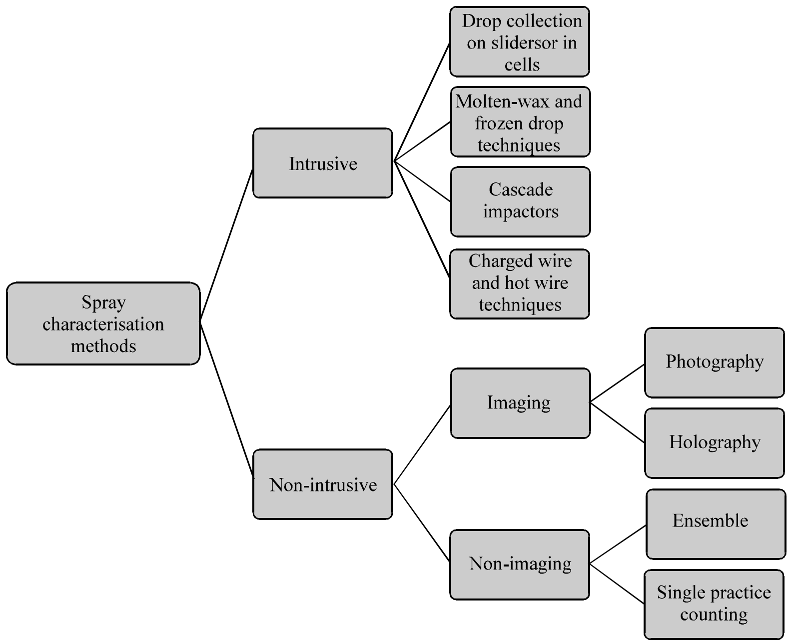

Fig. 1: An overview of spray characterisation methods

describe the function of each component and also explain about the DIA system setup.

Components of the DIA system: There was three main components used in the development of DIA system and they included a laser, a digital camera and a computer (Fig. 2). All these components were integrated to make the whole systems work. Besides that, a software program was developed using LabView codes in order to perform automated image processing and analysis tasks.

In the development of DIA system (Fig. 2), the pulsed laser was used as a light source for the digital camera. A proper amount of light was necessary so that a good quality of drops images can be achieved. The maximum output of the laser was around 200 mJ and it produced a pulsed beam with a 532 nm in wavelength. A pulsed beam was critical for fast moving droplets and desirable even for slow moving fluid. The laser beam was converted to a laser cone using a concave lens, and then it was diffused by a diffuser. The laser system has produced a trigger signal and it occurred at about 2 μsec before the laser pulsed. This trigger signal was used to synchronise the detection of the digital camera. The output of the signal is +5V TTL and is a positive edge.

Digital camera was used to capture shadow images of the droplets which were back-lighted by the diffused light. The DIA technique was applied to process and analyse the images to determine droplet size distribution in real-time using custom developed software. A FireWire type camera was selected as part of the DIA system development. It equipped with IEEE1394-b connectors to allow high image transfer speed. This monochrome camera has a resolution up to 1280×960 pixels. It also has an ability to receive an external triggering signal for synchronization with the pulsed laser.

The purpose of DIA system was to characterise small particles or droplets in the range of micron sizes. Thus, it was important to have a higher magnification of image. Therefore, a 200 mm micro-lens equipped with a spacer or bellow were used in this study. As a result, field of view (FOV) of the image with a resolution of 1280×960 pixels was at 1.82 mm×1.36 mm. The optical configuration of this current setup has produced a magnification factor of 2.6 and having a 250 mm working distance.

The DIA system was equipped with a computer for controlling the laser and the camera. The developed software was installed in this computer and used as a platform for synchronisation between the pulsed laser and the camera. A monitor of the computer was used to display on-line results. These results were obtained from the developed software where the software automatically processed and analysed the acquired images and plotted them into graphs.

Working principle of the DIA system: In this experiment, the DIA system was applied to perform an on-line characterisation of spray droplets. A schematic diagram of the system setup was depicted in Fig. 2. A computer

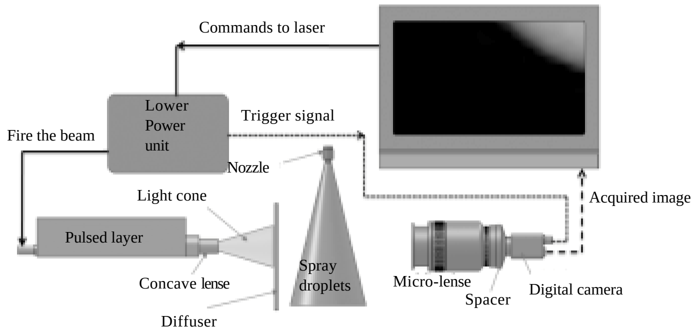

Fig. 2: Setup of the DIA system

was used to send commands to the laser to fire the beam at required light intensity. The commands were written using Hyperterminal windows program and sent to a laser power supply via serial RS-232 cable. Once the commands were entered, the pulsed beam was fired from the laser unit and converted to laser cone by a concave lens. The repetition rate and duration of this pulsed were about 0.5 Hz and 5 µsec, respectively. The droplets were back-lighted with a light source and the camera acquired the shadow image of the drops in a sequence of frames.

At about 2 µs before the laser pulsed, a trigger signal was produced from the laser power supply unit. This signal was then triggered the camera to acquire a raw image of the drops. The resolution of acquired image was at 1280×960 pixels. The working distance between the drops and a focal lens was about 250 mm. The image was then directly transferred from the camera to a memory of computer via IEEE-1394b FireWire cable for instant processing. The image was processed and analysed using the developed software in order to obtain the droplet size distribution and the mean size.

Digital image processing and analysis: The DIA technique was applied to extract valuable information from an image. Once the raw image was received by the software, it was processed to enhance its appearance and then analysed to extract the desired information such as a number of pixels occupied by a single droplet. The developed software was produced using a LabView platform. The flowchart of the algorithms was outlined in Fig. 3. After image acquisition, the first processing stage was image enhancement. It was the process by which to improve an image so that it looks subjectively better (Petrou and Bosdogianni, 1999). In this study, the approach is to enhance the image by changing the brightness, contrast and gamma values. The filter function also applied to compute backgrounds in order to correct the light drifts.

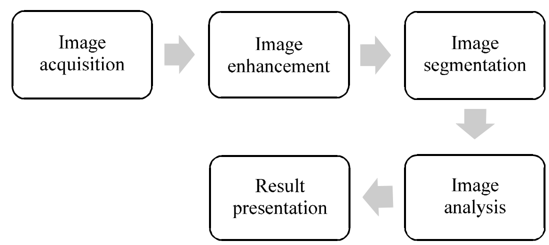

Fig. 3: Algorithms of the developed software

The second stage of image processing was image segmentation. It extracted the outlines of different regions in the image such as to divide the image into regions which are made up of pixels. In this case, thresholding was used to separate the drops from the background. In order to obtain the area of a single drop, the number of pixels that represent a single dark object was calculated. This algorithm also determined the number of drops per image. The algorithm of result presentation was created to calculate the droplets diameter based on the area of the drops and display a real-time plot of their size distribution. In this case, the calculation of droplet size was based on equivalent diameter Eq. 1:

$$D_p = 2\sqrt{\frac{A_p}{\pi}} \quad (1)$$

where, D_p was the equivalent diameter of the drop and A_p was the area of the drop. This developed software has identified every drop in the image and maintained a list of data that contains information regarding each of the drops.

Spray generator: As mentioned earlier, this study is to examine the capability of DIA system in measuring fine sizes and fast moving of spray atomiser droplets. The experimental setup of spray atomiser was illustrated in

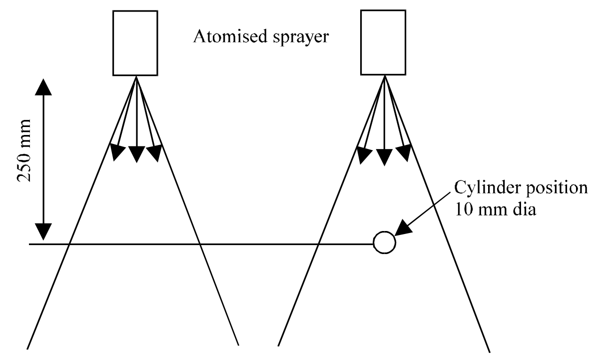

Fig. 4: Schematic of spray generator experimental setup; no cylinder (left) and with cylinder (right)

Fig. 4. The cylinder was introduced at 250 mm downstream of the nozzle exit. The drops size was measured at 10 mm downstream of the cylinder. Another measurement was performed at the same location but without the cylinder. The intrusiveness of a circular cylinder (which simulates an endoscope) within a spray is quantified by the following setup: A liquid-air blast atomiser continuously discharges within a test section of air at atmospheric pressure, with and without a circular cylinder placed at 250 mm downstream of the nozzle.

The agent used in this study is water that was supplied to the flow field of the atomiser. The supplied air pressure was 344.7 kPa or 50 psi and a specified flow rate of 0.0045 kg sec^{-1}. For these experiments, the incoming air (supplied from a 7 L min^{-1} compressor) was directly connected to the spray gun via a regulator valve. This atomiser was produced a 30° solid cone of spray droplets.

RESULTS AND DISCUSSION

In this study, the effect of the circular cylinder on the drop size of an atomiser at downstream of the flow was investigated. Measurement of drop size was carried-out using DIA technique. A shadow method was applied to obtain drops images. In this method, the drops were back-lighted with a light source and a camera acquired the shadow image of the drops (Fig. 2). A short light flash produced by a laser was used to freeze the drops motion so that the camera can captured clear drops image. The images were then processed and analysed using DIA technique to obtain the drop size distribution, mean size and its shape.

Image calibration: In principle, the DIA system used images to determine the drop size. Therefore, a calibration against known size or dimension was critical to the validity of the results. Calibration image was used to assess the absolute accuracy of the system where a known dimension image was used to transform a pixel coordinate to real-world coordinate through scaling in the x and y (horizontal and vertical) directions.

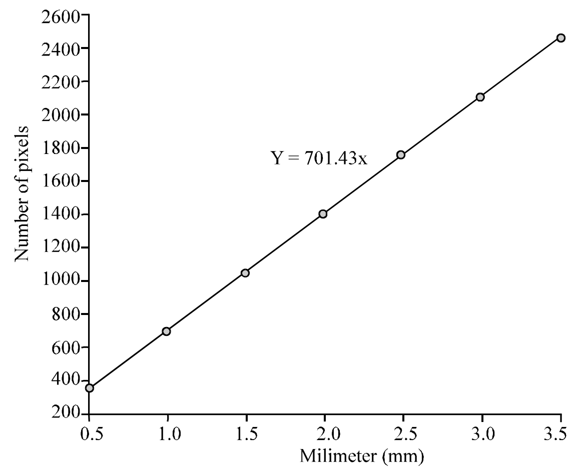

Fig. 5: Image Calibration plot

In this experiment, static image were used for the calibration. The camera was positioned over a known dimension of graph paper which was placed on a flat surface. An image was taken for calibration purpose. Then the image was translated from pixels to micron unit. Figure 5 depicts the calibration plot of the image. It shows that 1 mm of distant equal to 702 pixels. Therefore, it can be concluded that one pixel of image was equal to 0.00142 mm or 1.42 μm.

Drop size analysis: Figure 6 shows a raw shadow image taken at the measurement location. This image was cropped from original image and it has 324×324 μm of FOV. It illustrates that the drops were not overlap due to the lower concentration of the drops at downstream of the nozzle. Also, there were some blurred drops images depicted and this was due to the out of focus. In order to determine an accurate drop size distribution, only focus image drops were selected during the image segmentation process. Therefore, Fig. 7 depicts the number of drop on processed image is lower than the acquired image.

The acquired raw image was enhanced and segmented to produce the processed image (Fig. 7). Image enhancement was applied to improve the image by changing the brightness and the contrast as well as applying the filter function so that it looked subjectively better. After the image was enhanced, it was then segmented to separate the particles from the background

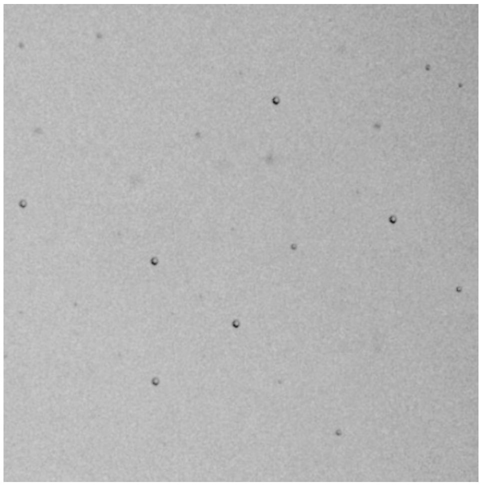

Fig. 6: Actual raw image

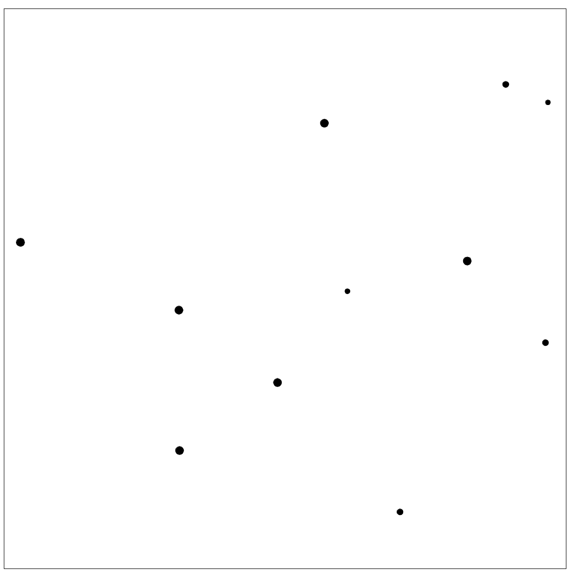

Fig. 7: Processed image

by applying a threshold function. Then, the particle analysis function was applied to the image to calculate the number of pixels on each region and converted them to equivalent diameter. This function determined the number of drops per image. In this software, algorithms were designed to plot the size distribution and calculate for the mean value. These results were based on the equivalent diameter of each drop for the entire images.

The measured drop size distribution shows that the size ranges were from 3 to 18 μm (Fig. 8). This was true for both cases which are with and without circular cylinder. A total of 11500 drops for each case were detected in introduces in the flow regime, the drop size distribution depicts increasing size of bigger drops and reducing smaller size. The dominant size is about 8.7 μm compared

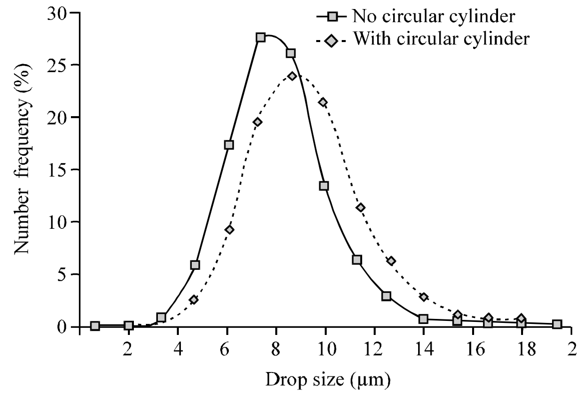

Fig. 8: Drop size distribution (number frequency)

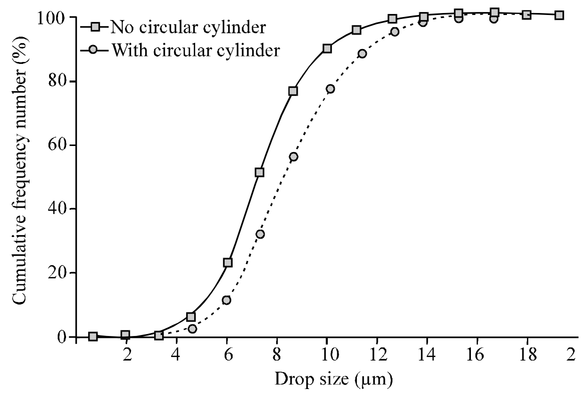

Fig. 9: Drop size distribution (cumulative number frequency)

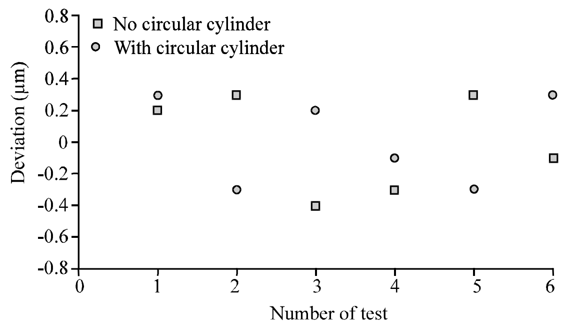

Fig. 10: Deviation data of drop sizing

to 7.2 μm without the cylinder. Cumulative frequency of size distribution recorded that 100% of the droplet were below than 17.0 μm for the flow with the cylinder, while 15.5 μm without the cylinder (Fig. 9).

In this study, the measurement of each case has been repeated for about 6 times to investigate the repeatability of the DIA system. For each test, at least 100 images have been acquired and analysed. In average, about 22 droplets were detected on each image.

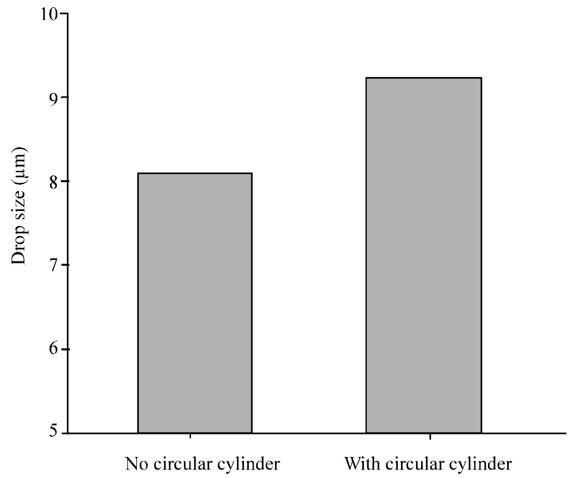

Fig. 11: Mean Drop Size

Figure 10 depicts the deviation data at different tests cases. Deviation is the different between average drop sizes on each test with the mean drop size. The result shows that all the tests produce less difference compared to each other. It was recorded that the deviation for both cases were below than 0.4 μm. It means that the DIA system has a good repeatability in sizing the droplet. The standard deviation for no cylinder case and with cylinder case was at 0.31 and 0.29 μm, respectively.

Calculation of mean droplet size was carried out based on the measured average sizing from each test (Fig. 11). The mean size of 8.1 μm was recorded when no circular cylinder was placed in the flow regime. It was found that the mean size was increased to 9.2 μm when the cylinder was introduced to the spray flow. This size increment was believed due to the coalescence of the drops after they pass around the circular cylinder.

CONCLUSIONS

This study has presented the operational principle and evaluation of the DIA system which was based on the digital imaging analysis technique. The DIA system was tested in measuring the droplet size distribution and mean size at downstream of the spray flow regime. Image enhancement and image segmentation were applied to eliminate the drops which were not in focus. These were important to obtain accurate droplet size. The DIA system has a good repeatability on sizing the drops. This can be confirmed through the deviation result found in this study. Using the DIA system, it was observed that due to the coalescence of the drops after it passed through the cylinder, the mean drop size were found to be slightly larger when the circular cylinder was introduced. The capability of DIA system has been examined by successfully measured the fine sizes and fast moving droplets spray. At this current DIA system setup, it is only capable of measuring the drops that in the range of microns. Optical configurations of the system such as focal lens, working distance and bellow have to be changed in order to measure larger drops size.

REFERENCES

Allen, T., 1997. Particle Size Measurement. Chapman and Hall, New York.

Blaisot, J.B. and J. Yon, 2005. Droplet size and morphology characterization for dense sprays by image processing: Application to the diesel spray. Exp. Fluids, 39: 977-994.

Crowe, C.T., J.D. Schwarzkopf, M. Sommerfeld and Y. Tsuji, 1997. Multiphase Flows with Droplets and Particles. CRC Press, United States.

Fujisawa, N., A. Hosokawa and S. Tomimatsu, 2003. Simultaneous measurement of droplet size and velocity field by an interferometric imaging technique in spray combustion. Measur. Sci. Technol., 14: 1341-1349.

Hatem, A.B., 1997. Software Development for Particle Tracking Velocimetry. University of Nottingham, United Kingdom.

Kashdan, J.T., J.S. Shrimpton and A. Whybrew, 2003. Two-phase flow characterization by automated digital image analysis. Part 1: Fundamental principles and calibration of the technique. Particle Particle Syst. Characterization, 20: 387-397.

Kashdan, J.T., J.S. Shrimpton and A. Whybrew, 2007. A digital image analysis technique for quantitative characterisation of high-speed sprays. Optics Lasers Eng., 45: 106-115.

Lefebvre, A.H., 1989. Atomization and Sprays. CRC Press, New York.

Petrou, M. and P. Bosdogianni, 1999. Image Processing: The Fundamentals. John Wiley and Sons Inc., New Jersey.

Raffel, M., C.E. Willert, S.T. Wereley and J. Kompenhans, 2007. Particle Image Velocimetry: A Practical Guide. 2nd Edn., Springer, Berlin, Germany.

Rhodes, M., 1998. Introduction to Particle Technology. John Wiley and Sons Inc., New Jersey.

Sudheer, K.P. and R.K. Panda, 2000. Digital image processing for determining drop sizes from irrigation spray nozzles. Agric. Water Manage., 45: 159-167.

Thompson, B.J., 1984. Droplet Characteristics with Conventional and Holographic Imaging Techniques. In: Liquid particle size measurement techniques, Tishkoff, J.M., R.D. Ingebo and J.B. Kennedy (Eds.). American Society for Testing and Material, Philadelphia.