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MEASUREMENT OF DROPLET VELOCITY DISTRIBUTION FROM A FIRE SPRINKLER

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Abstract. *Fire sprinklers are widely used across the world. Their contribution to fire protection is well known. Thus, it is useful to know the spray characteristics of a fire sprinkler in order to estimate its performance and efficiency. The two major characteristics of a spray are droplet size and velocity. In this paper, a simple technique is presented to measure the droplet velocity from a fire sprinkler spray. This technique provides a distribution of velocities over a range.*

1 INTRODUCTION

Water as the oldest fire suppression agent still play an important role in fire suppression. Although more new fire suppression agents have been developed, sprinkler systems are still the most common fixed fire suppression system [1]. Its excellent performance is proved by many studies [2]-[4]. Its high heat capacity (4.2 J/g.K) and high latent heat of vaporisation (2442 J/g) are very helpful in terms of absorbing energy. In addition, when it evaporates to steam, its volume can expands 1700 times, diluting oxygen and fuel vapors. Therefore, it is important to estimate how far the droplets can penetrate the fire until it evaporate. It cools down the air if the droplets evaporate above the fire and it has a suppression effect on the fire if the droplets reach the fire surface or near it. Whether the droplets reach the fire or not depends on their size and velocity, and the size of the fire as well. Thus it is important to know the droplet velocity and size.

The effectiveness of a fire sprinkler is proved by statistics. Installing a fire sprinkler system can significantly reduce life loss and property loss. Statistics from NFPA [5] suggests that the death rate per 1,000 fires was 82% lower with wet pipe sprinklers during the period between 2007 and 2011. The property loss reduction varies from 0% to 75% due to water damage problem. Although fire sprinklers have an excellent fire suppression effect, sometimes it fails to suppress the fire. According to NFPA [5], water did not reach the fire (44%) and insufficient water was released (30%) are the two major reasons for most cases of sprinkler ineffectiveness in non-confined fires. Therefore the spray characteristics of fire sprinklers have to be studied and measured in order to predict its performance during a fire.

Furthermore, attempts of computer modelling have been made to simulate a fire suppression [9]-[12]. Droplet size and velocity are required as input parameters. Thus it is necessary to measure the velocity and size of droplets from a sprinkler.

During the past decades, techniques have been developed to measure the droplet size and velocity from a fire sprinkler [6]-[8]. In this paper another technique is presented to measure the droplet velocity. The advantage of this technique is that it is time-independent and it has a low requirement on equipment.

2 EXISTING TECHNIQUES

Sheppard [6] utilised a sophisticated laser sheet particle image velocimetry (PIV) system to measure the droplet velocity in a region. In PIV a sheet of high-intensity laser light is positioned within the flow field while a video camera is placed perpendicular to the laser sheet. By comparing a pair of images which are taken at a certain time interval, the velocity for any droplet could be determined if the same droplet can be identified in both images. However it is highly impossible for his technique to extinguish individual droplets due to the arbitral spray pattern and similarity between each droplets (all the droplets are small dots in his image). Therefore Sheppard [6] decided to apply Fourier-based cross-correlation method to obtain statistical average of the displacement of many droplets in the same region of the imaged velocity field.

The other method to measure the droplet velocity is the particle tracking velocimetry and imaging (PTVI) technique, applied by Putorti [7] and Everest & Atreya [8]. Two consecutive laser pulses of different wavelengths are emitted. Due to the wavelength difference, the dyed water appears in two different colours. One photograph which has an exposure time equivalent to the sum of the two pulses is taken, so that it is a combination of two images resulted by the two pulses. The images show the location change of the same droplet due to the time interval of the laser pulses. Each droplet is distinguished by its size since very clear images of the droplets are obtained. Because of the colour difference, the droplet velocity can be measured by measuring the distance between the centres of a pair of droplets.

3 METHODS

The technique presented in this paper avoids the use of a laser, since laser is expensive and has restrictions when using it. The aim of this project is to provide an alternative method which is simpler and easier to operate. To get a slice of the spray, walls were built around the sprinkler to physically block the water. On one of the walls, a slot was created to allow a slice of the spray passing through. Then a video camera was utilised to record the spray for images analysing. Unlike PTVI, the camera utilised was not good enough to get clear images of droplets. Instead, streaks of the droplets were recorded with a suitable shutter speed. The movement of a droplet was captured in a form of a straight streak. The length of this travel distance was measured after image processing. The traveling time was known as shutter speed. Therefore the velocity of each droplet was able to be calculated.

4 EXPERIMENT SETUP

The success of the experiment depends on the identification the droplets. Thus obtaining clear images of streaks is critical. In order to obtain good quality images, water was dyed to eliminate the transparency effect, distinguishing the droplets from the background. Figure 1(a) and 1(b) show the original image and binary image after image processing.

Figure 1(a): Original image

Figure 1(b): Binary image

Since water was dyed, a concern of changing properties was raised. The surface tension and density difference was tested. Dyed water and regular water were put into two identical test tubes to check that if there was a significant different in terms of surface tension, which can affect the formation of droplets. They formed curves with same depth. Thus surface tension was not significantly affected. The density of the water was also checked by measuring the weight of the same bottle containing dyed water first and then swapped into regular water. The difference was 0.5 g corresponding to a 0.5 ml difference in volume and 0.5% in percentage. It was ignored by considering the accuracy error from filling the same bottle with same amount of water.

The fundamental difference between the technique presented in this paper and the previous techniques is that spray is physically blocked rather than cut by a laser sheet. The setup is illustrated in Figure 2. A closed water system was built for this experiment so that the dyed water was collected and pumped up again.

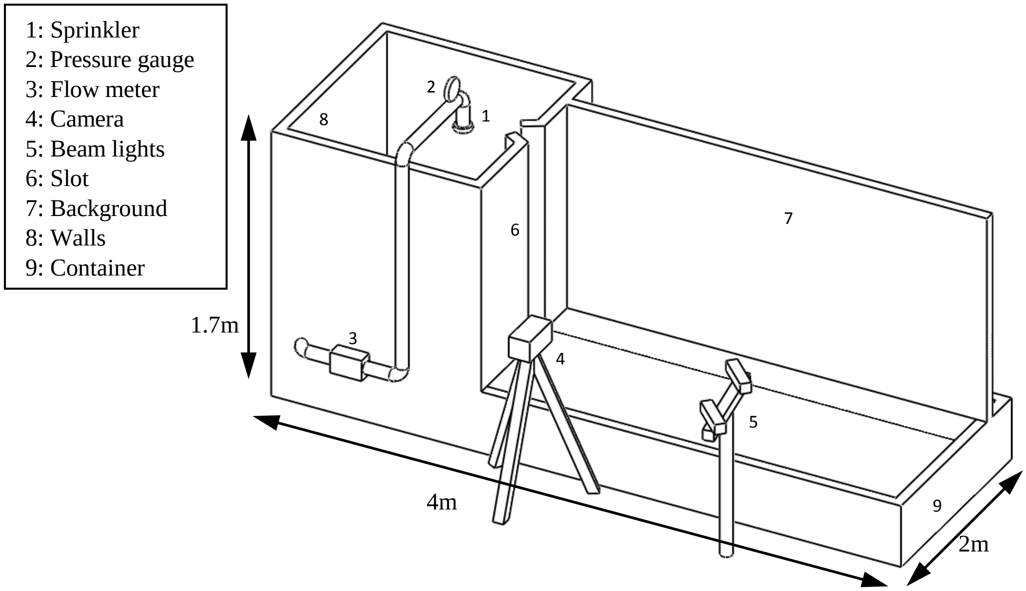

Figure 2: Setup

The walls were 2m (length) by 1.7m (height) each and one of them had a slot in the middle. The slot size is shown in Figure 3. The reason to bend the edge of the slot is to block the splash water back, reducing the effect on the spray coming out of the slot.

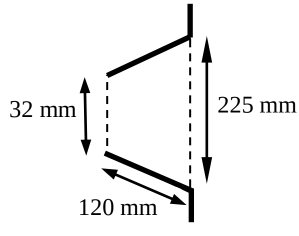

Figure 3: 32mm angled slot

The background board was 2m by 1.5m with 100mm grids on it. These 100mm girds were used as reference for calibrating the pixel size during the image processing. When filming the droplets, the background board was covered by a black textile to provide a better contrast to highlight the droplets and cover the grids at the same time.

The video camera used for this experiment was Panasonic HDC-TM 900. It had a resolution of 1080 pixel and a frame rate of 50 frames per second.

The fire sprinkler utilised is VK302. It is a pendent sprinkler with K-factor of 5.6. The sprinkler was orientated parallel to the slot so that the arms were not in the way. Two pressures were tested, 37 kPa and 88 kPa with a corresponding flow rate of 48 L/m and 76 L/m.

Due to the need for a fast shutter speed, extra lighting devices were required to provide sufficient light. For this experiment, LED white beam lights were applied, because it was found that beam lights provided a better result than scatter lights since it is more condensed.

5 IMAGE PROCESSING

Images were processed in a way that all the streaks can be identified and their length can be measured. First of all the images had to be transformed into binary form for identification purpose. In order to do this, the images were first transformed into grey images and then into binary. The threshold level, which is the required input for changing grey images into binary image, was automatically calculated for each image. During the process, as an addition step the background was subtracted away so that only droplets were kept in binary images. In the next step, all the streaks were identified, so that they can be plotted in Matlab. By plotting the streaks in Matlab, the coordinates for each end of the streaks were able to be read off the graph and recorded. The final step was calculating the length of each streak, and hence working out the velocity for each droplet. Everything was calculated in pixel so far, the calibration of pixel length was required in order to provide a velocity in m/s. An image of the grid board was taken and transformed through the same steps as shown in Figure 4, resulting a Matlab plot from which coordinates of the corners of each grid were obtained. Using these coordinates, the length of each 100mm grid in pixel was determined, hence the length for each pixel was calculated.

Because the grid was created on the background board not on the spray plane, similar triangle rule was applied to find the actual pixel length. To measure the distance between the camera, the spray plane and the background board, a ruler was placed between the board and the camera, while the spray made a water pool on the rule. The distance between the water pool and the board was determined by using the value in the middle of the water pool. This measurement was only done once by assuming the distance between the spray and the board did not change with respect to variation of water pressure. Since the camera was moved around to capture different regions of the spray the distance between the camera and the board was measured several times. Knowing the distance between the camera and the board, and the distance between the spray and the board, the actual length of 100mm grids represented in the spray plane was calculated. The ratio was calculated to be 97%. The actual pixel length was only 3% less than it calculated directly from the background board. The difference is small enough to be neglected.

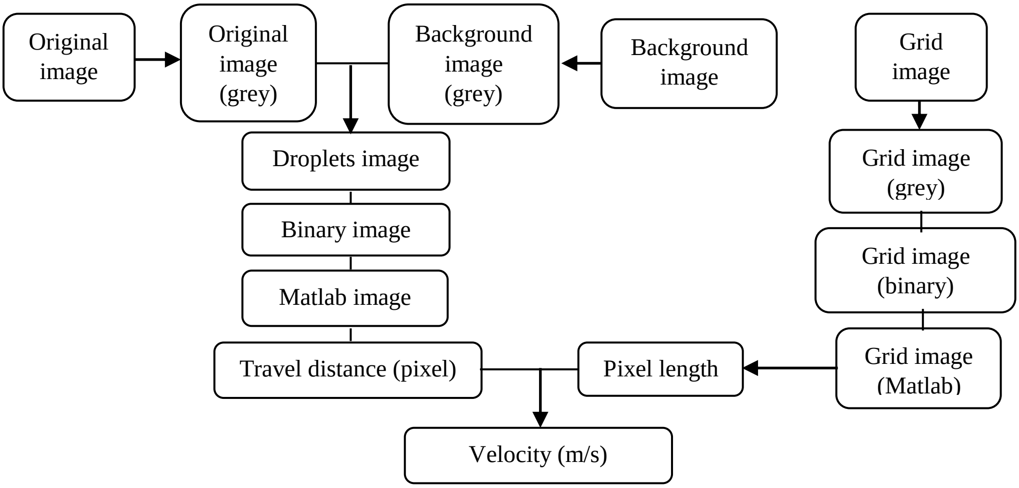

Figure 4: Flow chart for image processing

6 RESULTS AND DISCUSSION

Four regions were selected for recording the spray with two different water pressure, 37 kPa and 88 kPa. Each region is labeled in letters in Figure 5 to show the relative location between them, but it does not mean the recorded region was exact a 100mm square. The upper left corner of the square A was 900mm away from the sprinkler in horizontal direction and 760mm lower in vertical direction.

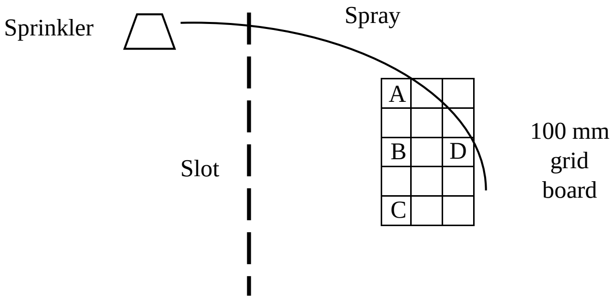

Figure 5: Regions recorded

The effects of shutter speed, magnification, water pressure and location are illustrated in Figure 6 – 10. The first vertical axis is normalised frequency and the second axis is cumulative distribution function (CDF). Because the streak lengths were read from plots, a reading error of one pixel for each end is applied. The pixel length was calculated in a range between 0.11 mm/pixel and 0.19 mm/pixel for the experiments shown in Figure 6 – 10. Thus two pixels reading error corresponds to 0.5 m/s of uncertainty. By considering other uncertainties like losing dark ends from image processing, one streak length is the sum of the droplet travel distance and twice its diameter, and streaks have a thickness resulting an error on choosing the ends, the final results are rounded up to nearest integer. All the experiment results show a most frequent velocity of 4 m/s ± 1 m/s.

The shutter speed has an impact on the length of the streaks. Longer time provides longer streaks. As shown in Figure 6, the effect of shutter speed is insignificant.

Unlike shutter speed, different magnifications provide different results in terms of maximum velocity. With larger magnification, a larger maximum velocity was measured. However, theoretically magnification should not have any impact on the results since it varies in ratio. The possible reason is due to the different focus planes between the experiments since the focus planes were selected to maximise the number of clear droplets recorded. The larger maximum velocity might come from the outer part of the spray which might be affected by the slot. Thus more experiences shall be planned to find it out.

The water pressure effect is obtained by comparing Figure 9 and 10 (b). Due to the large magnification, Figure 10 (a) has a maximum velocity as large as 87 m/s. However as shown in Figure 10 (b), 99% of the velocities are less than 35 m/s, which is the same for Figure 7. Consider the most frequent velocity, they have similar results. Although the experiment with 88 kPa at location B has a higher distribution for 3 m/s, it is in the uncertainty of 1 m/s.

The location impact is shown in Figure 8 – 10. They all follow the same pattern. Due to the accuracy of the experiments, no significant difference is observed.

The overall most frequent velocity is 4 m/s (12% - 20% of all droplets). 80% of the droplets have a velocity less than 12 m/s, and 90% of the droplets have a velocity less than 18 m/s. Although a few measured velocities are larger than 35 m/s, 99% of the droplets are less than 35 m/s.

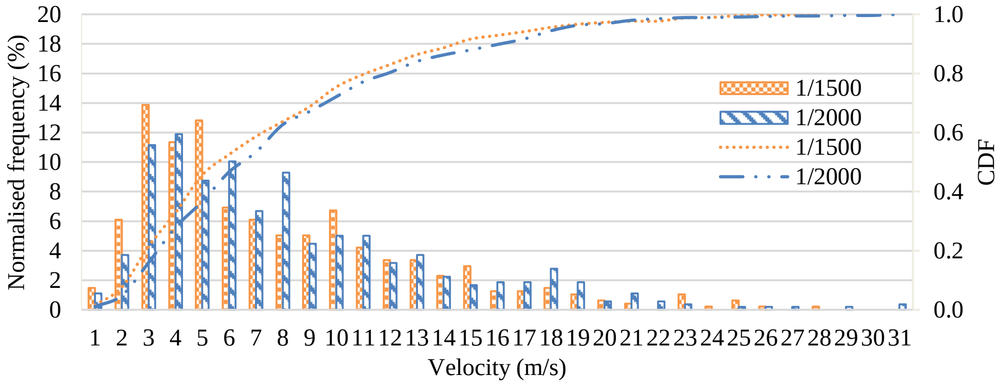

Figure 6: Droplet velocity distribution at position C with 3x magnification (37 kPa)

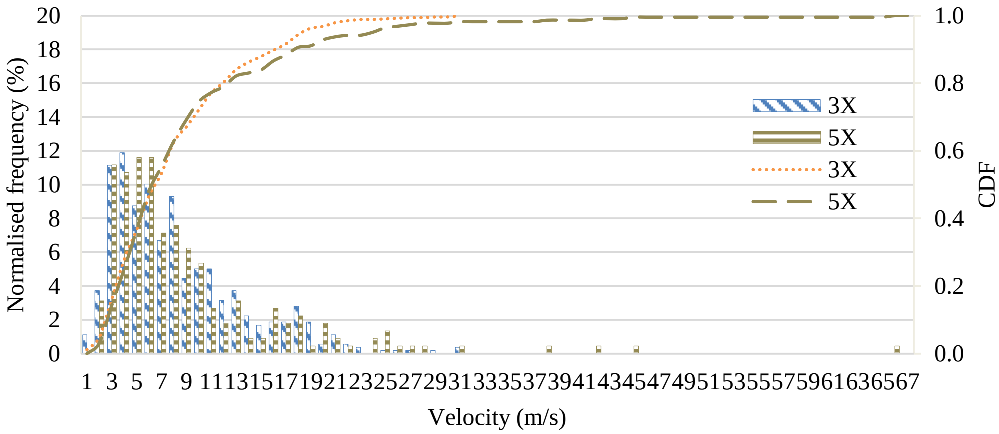

Figure 7: Droplet velocity distribution at position C with 1/2000 shutter speed (37 kPa)

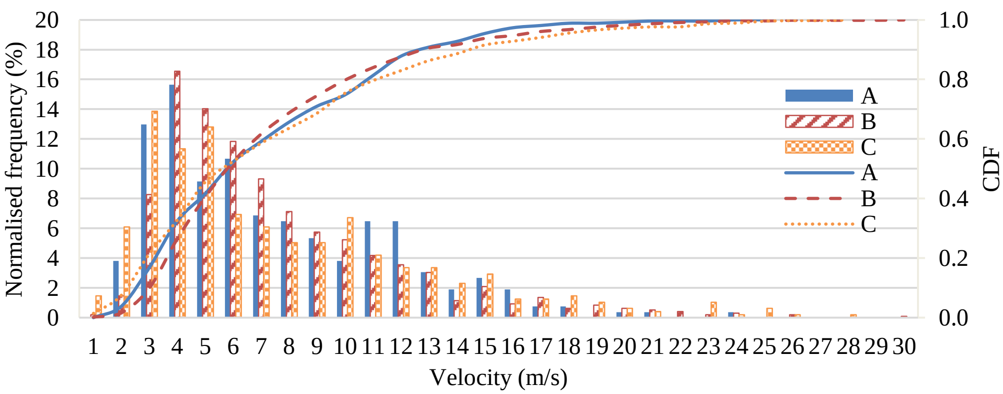

Figure 8: Droplet velocity distribution with 1/1500 shutter speed and 3x magnification (37 kPa)

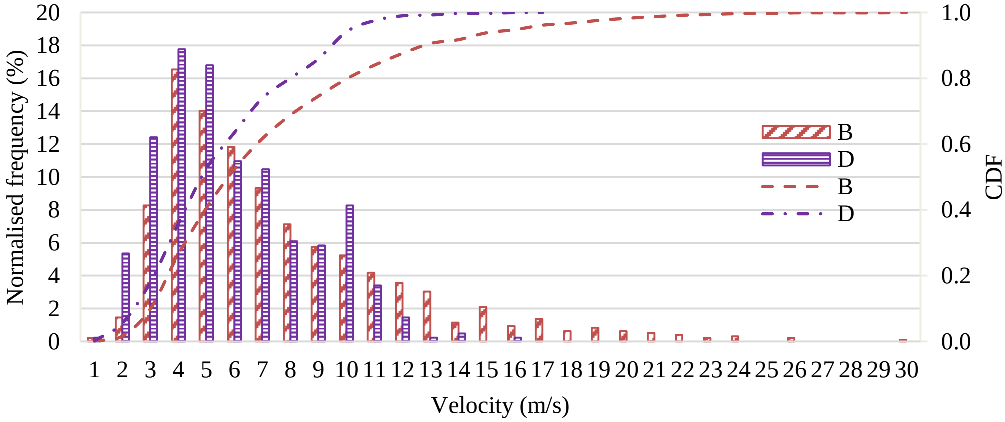

Figure 9: Droplet velocity distribution with 1/1500 shutter speed and 3x magnification (37 kPa)

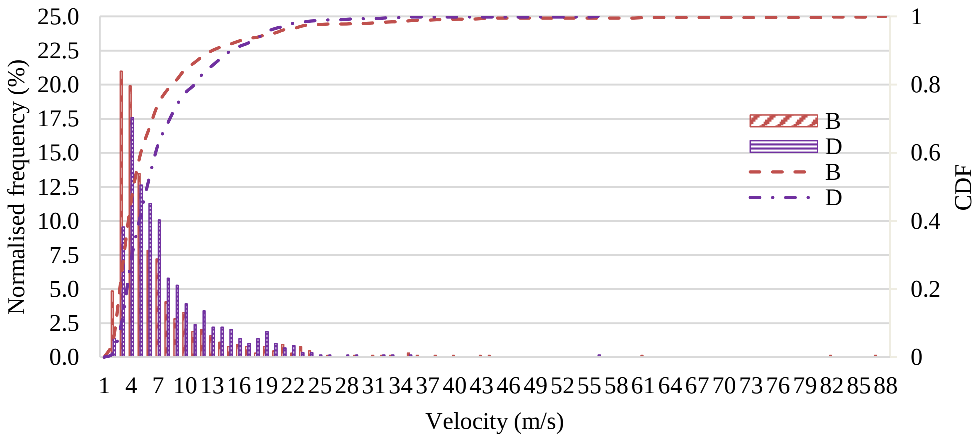

Figure 10 (a): Droplet velocity distribution with 1/2000 shutter speed and 6x magnification (88 kPa)

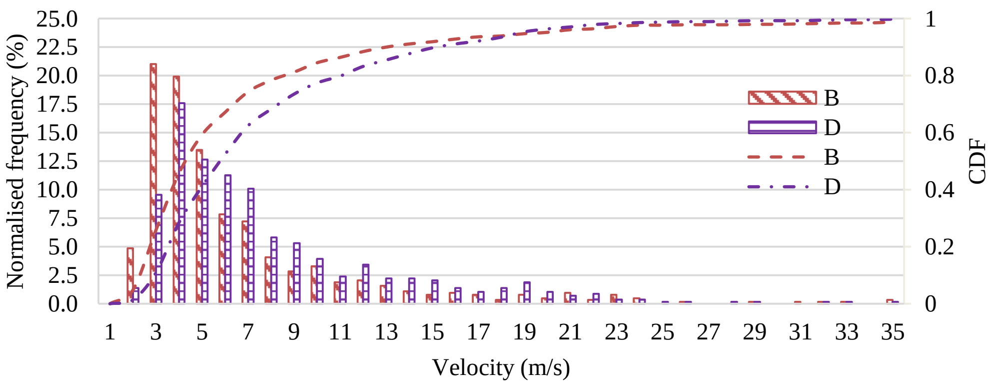

Figure 10 (b): Zoom in Figure 10 (a) with velocity less than 35 m/s

7 COMPARE TO PREVIOUS EXPERIMENTS

Technique presented in this report is an alternative mean for measuring droplets velocity. The aim is to find another measuring technique which is cheaper and simpler to operate. Because no clear images of droplets are required, the requirement for the camera is very low. Any commercial camera can achieve a shutter speed around 1/2000. Since there is no need for comparison between a pair of images, frame rate is not important either. Another advantage is that the technique presented here is time independent. All the existing techniques mentioned before require a pair of images to determine the velocity of a droplet. The time between each shot is critical for them. On the other hand, the technique presented in this report records the motion of a droplet in a single image with a variable shutter speed.

Sheppard [6] got a velocity range of 0 to 12m/s. Any vectors larger than 18m/s were eliminated by him. Due to the natural of PIV, the velocity he obtained is an average value. What Sheppard did is applying Fourier-based cross-correlation to find the average location shift between a pair of images. For a pendent fire sprinkler with a orifice diameter of 13mm and a water pressure of 59 kPa, he obtained a velocity range between 2 m/s and 6 m/s with respect to different elevation angles. 70 % of them are between 4 m/s and 6 m/s. To make a comparison the percentage for the velocity range between 3 m/s and 7 m/s is calculated to be 50% - 70%. Even though the range is larger than Sheppard's, the percentage is still on the low side. The percentage for the same range is 40%. The results obtained from this paper have a wider distribution. Furthermore, 20% of the velocities from this paper are larger than 12 m/s and 10% of the velocities are larger than 18 m/s. Therefore, the results from this paper have a wider velocity distribution but a similar most frequent velocity compared to Sheppard's results.

Putorti [7] got a velocity range of 1m/s to 35m/s. Comparing to the results from this paper, although the maximum velocity observed is larger than 35 m/s, 99% of the velocities are less than 35 m/s.

Overall the results from this paper have similarity with previous works.

8 FUTURE WORK

A video camera with faster shutter speed and frame rate or a better still camera can be utilised for measuring the size range of the droplets. Since Putorti [7] had proved that the velocity has a relationship with size, it is reasonable to say the most frequent velocity corresponds to the most frequent size.

Due to time issue, many variables are not tested from this work. For example, the slot size and its bending angle are not varied to optimise the performance. The probability to have performance effect with lights on the top of the flow is not tested. In this way, the lights can be parallel to the spray and very close to the measurement area without leaving a bright spot on the background. What it is hoped to achieve is to reduce the reflection problem by having the light parallel to the spray. Another idea about reducing the reflection effect is using a colour light which has the same colour as the dyed water.

It is well known that the arms on the sprinklers have significant effect on the spray, thus, azimuthal angle shall be changed as a variable. Also, more tests with different sprinklers shall be carried out.

The maximum velocity shall be checked by running more experiments with different focus planes too.

9 CONCLUSION

A K-factor of 5.6 fire sprinkler was tested with two water pressures (37 kPa and 88 kPa). The results show a most frequent velocity of 4 m/s (12% - 20%). 90% of the droplets have a velocity less than 18 m/s, and 50% – 70% of the droplet velocities are in the range between 3 m/s and 7 m/s.

The technique presented in this paper successfully measured the droplet velocity in a cheap and simple way. The advantages of the experiment includes time independent, low requirement on equipment, and determining droplet velocities with single image.

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