IOP Conf. Series: Materials Science and Engineering **243** (2017) 012047 doi:10.1088/1757-899X/243/1/012047

Determine spray droplets on water sensitive paper (WSP) for low pressure deflector nozzle using image J

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Abstract. In this study, determine of spray droplets size (SMD) using water sensitive paper (WSP) at low fluid pressure with deflector nozzle or tangential flow nozzle model Delavan AL75 and New Design Nozzle with two different type of swirl (ND2.5 A1.0 & ND2.5 B1.0). These three deflected flat sprays have used at different liquid mixing ratio. These liquid mixture ratios are pure water, 10% of lime juice + 90% of water (L10W90) and 30% of lime juice + 70% of water (L30W70). WSP is used to collect the spray droplets from nozzles. The operational liquid pressure of each nozzle is 3 bar, while air operational pressures are 3 bar and 6 bar. Then, the WSP were scanned using scanner then it was analyzed using ImageJ software. ImageJ can be used for determining the diameter of droplets size on the WSP. As the results from an experiment, the AL75 nozzle recorded the lowest Sauter mean diameter which is 193.69µm at 6 bar of pressurized air while ND2.5 A1.0 recorded the highest Sauter mean diameter which is 353.61µm at 3 bar of pressurized air. Summary from the experiment shows that the higher of droplet size is because of the lower air pressure (3 Bar). Then, increasing of liquid viscosity also increase the SMD. The orifice diameter for New Design nozzle (ND-2.5) is smaller than AL75, which are 2.5mm and 2.8mm respectively. The different nozzle design also gives effect the SMD. WSP is an alternative method to determine SMD for spray droplets with the low cost if compared to Phase Doppler Anemometry (PDA).

1. Introduction

Air pollution is a major environment-related health threat to humanity and a risk factor for both acute and chronic respiratory disease. Excessive burning of fuel which is a necessity of our daily lives for cooking, driving and other industrial activities. It will be releasing a huge amount of chemical substances in the air every day and these pollute the air. Under the Clean Air Act, Environmental protection Agency-US (EPA) establishes air quality standards to protect public health, including the health of "sensitive" populations such as people with asthma, children, and older adults. EPA also sets limits to protect public welfare. Department of Environment Ministry of Natural Resources and Environment (Malaysia) has recommended air qualities guidance following air emission standards for the control of air pollution and gaseous emissions [1][2]. The commercial cooking process is one of the major sources for air pollutions. EPA has reported that 21% gas emissions from industries include the cooking process. One of the solutions is installed atomization nozzles into kitchen hood ventilation system for cooling, cleaning or filtering the grease and smoke during the cooking process. The size of droplets of spray will give effect in the ventilation system, spray performance and result of emissions.

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In this research, the main objective is to determine spray droplets using water sensitive paper. (WSP) is useful spray droplet sampling devices provided that their limitations are taken into account. This method has been used more than 40 years by Turner and Huntington at 1970. Currently, the big issue in Universiti Tun Hussein Onn Malaysia (UTHM) for spray research group is to determine spray droplet sizes which are UTHM don't have the apparatus to measure droplets size of spray such as Phase Doppler Anemometry (PDA). It is the economical method if compared with PDA and Particle Image Velocimetry (PIV). The color of WSP is yellow and change the blue color when the spray particles on this paper as shown as in Figure 1. This color transition is when to the reaction of Bromophenol Blue to a pH change from 2.8 to 4.6 and it is for spray deposition indicator. Most of the researcher using this method such as P. Jaeken, P. Lootens (2000), B. Panneton (2002), R. D. Fox, M. Salyani, J. A. Cooper (2001), M. Salyani, H. Zhu (2013), and R. D. Fox, R. C. Derksen (2003) [3]–[7]. The specification nozzle plays an important role to get a good of spray behavior such as spray angle, droplets size, etc.

This study is a focus to find the droplet size of water spray by using deflected nozzle. The mixture of water and organic lime water will be used for this experiment. It can be stated that the liquid ratio mixing, type of deflected nozzle and pressurized air can give an important role to reduce the hood from clogging. Through this experiment, it will give more understanding about the spray behavior after applying different parameters especially droplets sizes. Organic lime juice will be used in this experiment because it can reduce the cohesion of oil particles by breaking their bond strength. The scope of study, is the used nozzle are AL75 (atomizer), New Design of atomizer (ND2.5 A1.0) and New Design of atomizer (ND2.5 B1.0), the liquid used 100% of water (water), 10% of organic lime juice mixed with 90% of water (L10W90) and 30% of organic lime juice mixed with 70% of water (L30W70), the size of test rig is in range 60cm x 70cm x 90cm, analysis the WSP using ImageJ software, the pressurized liquid is 3 bar, while pressurized of air is 3 bar and 6 bar, and the experiment at atmospheric pressure (Patm= 1.01325 bar) and ambient temperature (T=28°C).

Semião [6]essentially use Sauter mean Diameter (SMD) as one of the methods to calculate the droplet sizes with available correlations for pressure-jet and pre-filming airblast atomizers. Rosin-Rammler and Nukiyama-Tanasawa use this function plus have modified some functions such as the upper-limit, log-normal and chi-squared functions [6]. Introducing the definition of SMD:

$$SMD = \frac{\int_0^\infty D^3\, dN}{\int_0^\infty D^2\, dN} \tag{1}$$

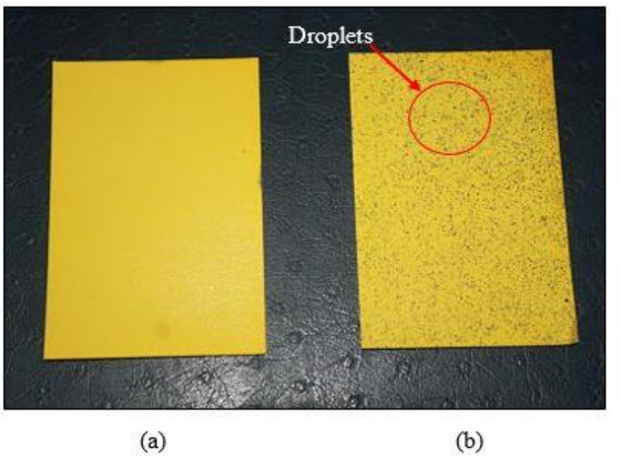

Figure 1. Water sensitive paper (a) before exposure and (b) after exposure to the spray

The sprays tested in this study were used by WSP. SMD correlation is an important parameter to identify the type of atomizers. According to N. Ashgriz (2011), AL75 and ND-2.5 are deflector nozzles with the tangential flow in category flat fan nozzle for cooling and cleaning process [9]. Base on the both designs, the type of nozzles is air assist atomizer because they need air to produces atomization with the internal mixing chamber. According to Kurt A. Estes and I. Mudawar (1995) and J. Kim (2007) [10]-[11], SMD correlation for cooling and cleaning process define as (Correlation A):

$$SMD = d_{32} = d_o \left[3.67 \left(We_{do}^{1/2} Re_{do} \right)^{-0.259} \right] \quad (2)$$

AL75 and ND-2.5 nozzles also have swirl in the nozzle assembly. According to Kennedy (1985), SMD correlation for pressure swirl define as below(Correlation B)[9]:

$$SMD = d_{32} = 10^{-3}\sigma \left(6.11 + 32000 \frac{\dot{m}_L}{\Delta P_L^{0.5}} - 6.973 \times 10^{-3} \Delta P_L^{0.5} + 1.89 \times 10^{-6} \Delta P_L \right) \quad (3)$$

Correlation A and B will be comparable to determine the type of atomizer between nozzle AL75 and ND-2.5.

2. Methodology

The main objective of this study is to measure a droplets size by using three type of deflected nozzle with different ratio of liquid. The type of liquids are water, L10W90) and (L30W70). M. F. Sies, N. Asmuin (2017) had studied liquid properties such as density, viscosity, surface tension .etc [12]. The design of the deflector nozzles as shown as in Figure 2. Figure 2(a) is a front view of deflector nozzle AL75 with area mixing chamber 13.3 mm^2 and Figure 2 (b) is shown a front view new design deflector nozzle (ND-2.5) with swirl A1.0 (80 ^{O}) and B1.0 (80 ^{O}), while the area mixing chamber is 64.95 mm^2.

The pressurized air and liquid are fed through at (i) and (ii). Then the mixed of two phase flow (liquid and air) at mixing chamber. The experiment was conducted with water, L10W90, and L30W70 at 28oC as a test liquid. Figure 3is a side view of both deflector nozzle and the impingement surface. The function of surface impingement nozzle is a stream of liquid to impinge on a surface caused by a sheet of liquid that breaks up into droplets. Figure below shows a complete schematic diagram of the experimental setup and location (10 points) of WSP at the test rig for this research in Figure . The fluid flow control system is consists of the water pump and compressor to supply liquid and air at a certain pressure. Besides that, two flow meter and pressure gauge were mounted with 6mm air tube to monitor both liquid and air pressure. Air and liquid pressure will combine in the AL75, ND2.5 A1.0, and ND2.5 B1.0 deflector nozzles to produce the spray.

shows that the initial condition for experiment setup. From the previous study, the suitable liquid pressure for both deflector nozzle is 3 bar for produce full spray development with air pressure 3 bar and 6 bar.

After the WSP has been sprayed, the droplet size on the WSP needs to measure by using the image J software. It cannot be simply measured because of the tiny droplet size. Then, the WSP analyzed using ImageJ to measure size distribution, a number of spots per unit area, area mean diameter, an area covered by spots and covered area by enlarging the images of spots at different radial–distances from the individual spots [7].The detailed procedure using ImageJ software can refer at website http://www.smalldropsprays.info/stepbystepmethods/ImageJ-software.Unfortunately, the overlap of droplets from spray occur because of the high air pressure. The dense of droplets and unsuitable spots on the WSP image must be eliminated for easy to analyze and get the good result. The spot for shape features must be eliminated on WSP image. Therefore, researchers can eliminate non-circular spots manually [13].

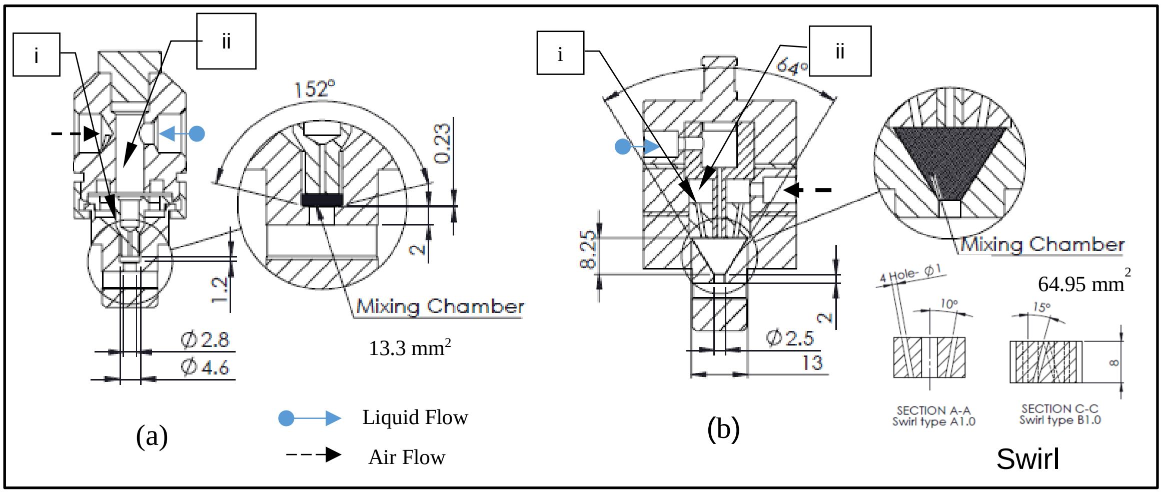

Figure 2. Deflector nozzles with different sizes (a) AL75 (b) ND-2.5 with swirl A1.0 & B1.0

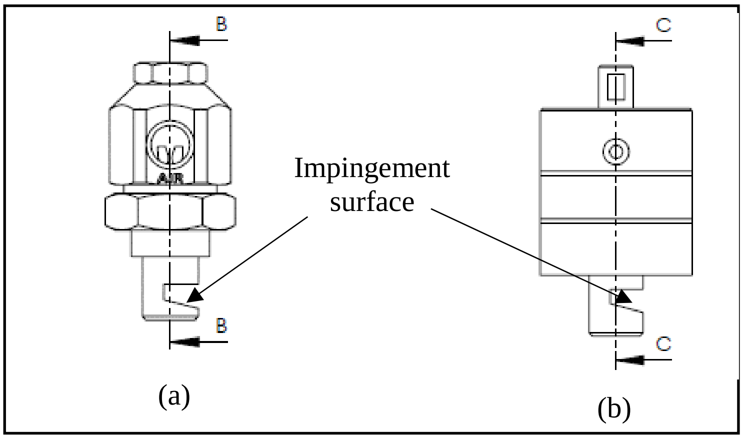

Figure 3. Side view of Deflector Nozzle (a) AL75 (b) ND-2.5

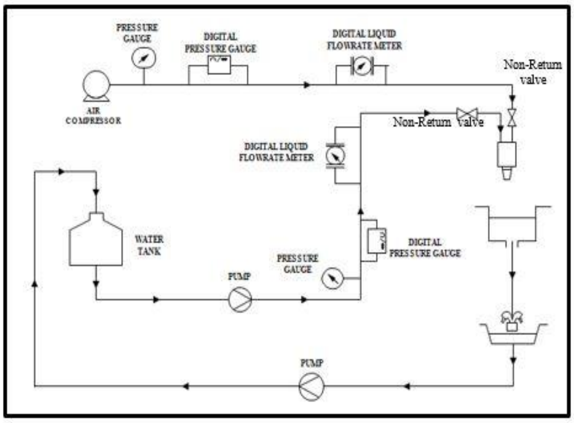

Figure 4. A schematic diagram of spray test rig

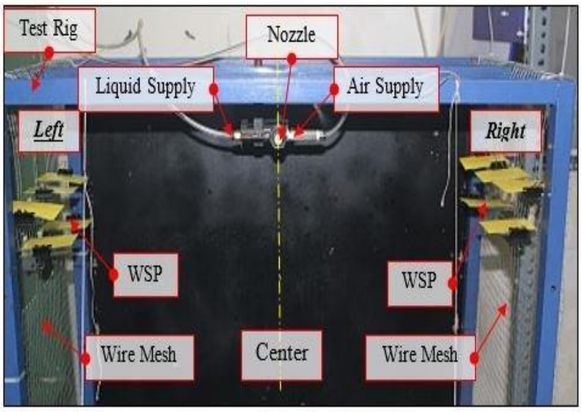

Figure 5. Water sensitive paper experiment setup

Table 1. Initial condition for experiments setup.

Exp. ID	**Nozzle**	**Liquid**	**P $_{Liquid}$ (bar)**	$Q_L\ (L/min)$	**P $_{Air}$ (bar)**	$Q_A\ (L/min)$
A	AL75	Water	3	0.140	3	40
B	AL75	L10W90	3	0.130	3	40
C	AL75	L30W70	3	0.123	3	40
D	AL75	Water	3	0.128	6	60
E	AL75	L10W90	3	0.110	6	60
F	AL75	L30W70	3	0.097	6	60
G	ND2.5-A1.0	Water	3	0.460	3	25
H	ND2.5-A1.0	L10W90	3	0.420	3	25
I	ND2.5-A1.0	L30W70	3	0.400	3	25
J	ND2.5-A1.0	Water	3	0.330	6	40
K	ND2.5-A1.0	L10W90	3	0.320	6	40
L	ND2.5-A1.0	L30W70	3	0.300	6	40
M	ND2.5-B1.0	Water	3	0.440	3	25
N	ND2.5-B1.0	L10W90	3	0.400	3	25
O	ND2.5-B1.0	L30W70	3	0.330	3	25
P	ND2.5-B1.0	Water	3	0.300	6	40
Q	ND2.5-B1.0	L10W90	3	0.230	6	40
R	ND2.5-B1.0	L30W70	3	0.200	6	40

Recently, Scanner printer can scan the WSP image to the Jpeg format (Joint Photographic Experts Group). The WSP had scanned to collect droplet sizes data include the spray distributions, the total of droplet number, droplet area, spray deposit amount and spray coverage percentage from ImageJ software [14]. After that, all data can transfer to MS excel to determine the droplets size using equation (1), equation (4), equation (5) and equation (6).

Next, there is an equation used to turn the spot to the actual droplet diameter. The equation is:

$$d = 0.95{d_s}^{0.910} \tag{4}$$

Where,

$$d_s = \sqrt{\frac{4A}{\pi}} \tag{5}$$

A = the spots area

The final equation to calculate actual drop diameter is:

$$d = 1.06\ A^{0.455} \tag{6}$$

By selecting the area of interest, ImageJ will process the image and calculate the droplet size as shown as in Figure 6 (a). Generate the result by analyzing the area of the interest as shown as in Figure 6 (b). Compare the experiment data with Correlation A using equation (2) and correlation B using equation (3).

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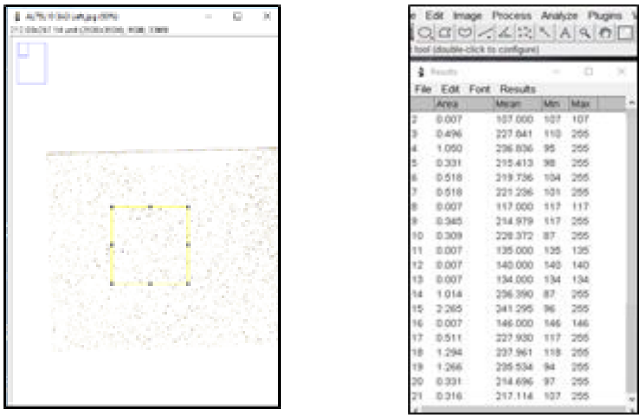

(a) (b)

Figure 6. (a) An Example area of interest was drawn on the WSP (b) Result generated from ImageJ

3. Results and discussions

The SMD result for liquid pressure 3 bar and air pressure 3 bar and 6 bar using deflector nozzle type AL75, ND2.5 A1.0, and ND2.5 B1.0 as shown as in Figure 7. Figure 7 also shows that the SMD correlation for experiment data value. SMD Correlation A is higher than SMD Correlation B because of the different design and nozzle applied. Correlation A is for air assist nozzle, while Correlation B is for pressure swirl nozzle. The result can be seen that SMD is influenced by the different ratio of liquid, liquid properties and different type of spray nozzle. L30W70 shows that the highest value of SMD. The SMD value for ND2.5 A1.0 at 3 bar of pressurized air is 353.61µm and 6 bar is 342.20µm. The ND2.5 B1.0 spray nozzle was recorded 318.82µm for 3 bar and 306.63µm for 6 bar. At the AL75 spray nozzle, 3 bar air pressurized is 222µm and 6 bar is 220µm.

The second highest of SMD value is L10W90. For nozzle ND2.5 A1.0, 3 bar of air pressurized recorded 332.44µm and 6 bar is 314.09µm. At spray nozzle ND2.5 B1.0, 299.89µm is for 3 bar followed by 6 bar which is 293.48µm. For AL75, the value of SMD at 3 bar and 6 bar is 209.17 µm and 203.68µm respectively. The lowest value of SMD is water where for ND2.5 A1.0 are 312.87µm at 3 bar and 309.29µm at 6 bar. The SMD for spray nozzle ND2.5 B1.0 is 290.78µm and 288.81µm at 3 bar and 6 bar respectively. For spray nozzle AL75, the value of SMD at 3 bar is 193.69µm and 6 bar is 191.41µm. SMD value for AL75 is lower than ND-2.5 because the area of mixing chamber for AL75 smallest than ND-2.5.

The different of fluid flow rate is generally the different results of SMD. L30W70 the highest SMD value because of higher viscosity if compared with other liquid. From the observation during the experiment, L3070 was produced more droplets. The viscosity of liquid give effects of spray pattern formation and droplets size. The liquid viscosity higher than water viscosity will give higher SMD value for same liquid and air pressure. These results support the idea by Anisa et al. (2010), that different ratio of liquid will give a different viscosity. SMD value for L30W70 is the highest values for both pressurized air, which is 3 bar and 6 bar followed by L10W90. The lowest value of SMD is pure water. By increasing the air operating pressure, the SMD also increases [15].

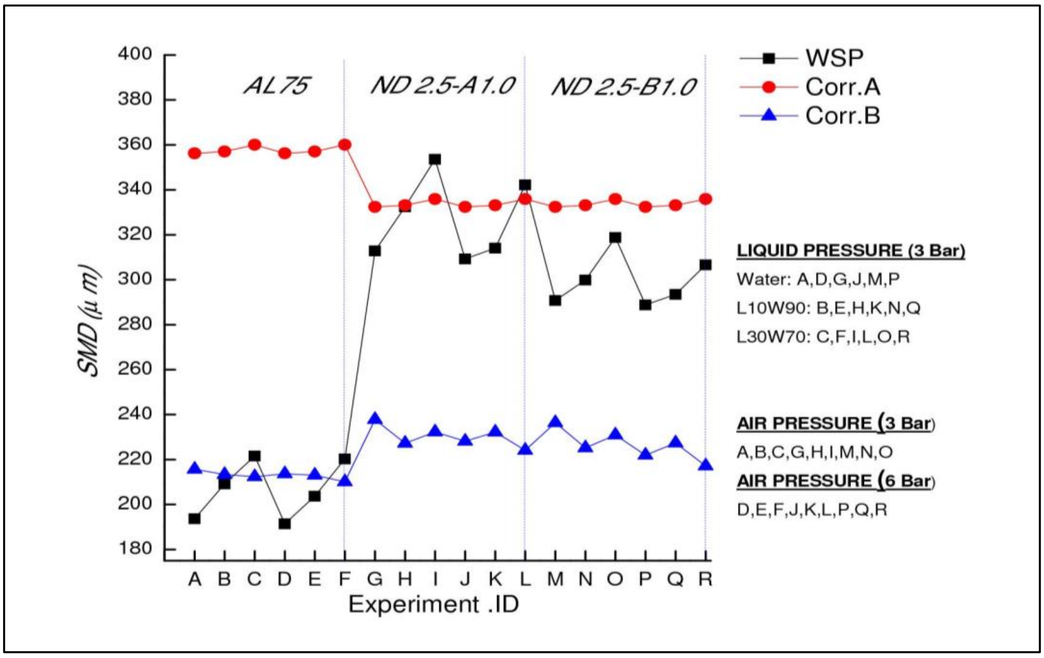

Figure 7. Relative of SMD experiment (WSP) and SMD correlation.

Table 2. SMD and percentage error between experiment (WSP), Correlation A and Correlation B

Exp. ID	Nozzle	Liquid	WSP	Correlation A		Correlation B	
			SMD(μm)	SMD(μm)	% error	SMD(μm)	% error
A	AL75	Water	193.69	356.26	84%	215.68	11%
B	AL75	L10W90	209.17	357.04	71%	213.38	2%
C	AL75	L30W70	221.56	360.03	62%	212.35	4%
D	AL75	Water	191.41	356.26	86%	213.63	12%
E	AL75	L10W90	203.68	357.04	75%	213.07	5%
F	AL75	L30W70	220.3	360.03	63%	210.10	5%
				Average	**74%**	**Average**	**6%**
G	ND2.5-A1.0	Water	312.87	332.40	6%	237.79	24%
H	ND2.5-A1.0	L10W90	332.44	333.13	0%	227.27	32%
I	ND2.5-A1.0	L30W70	353.61	335.93	5%	232.28	34%
J	ND2.5-A1.0	Water	309.29	332.40	7%	228.18	26%
K	ND2.5-A1.0	L10W90	314.09	333.13	6%	232.21	26%
L	ND2.5-A1.0	L30W70	342.2	335.93	2%	224.08	35%
				Average	**4%**	**Average**	**29%**
M	ND2.5-B1.0	Water	290.78	332.40	14%	236.41	19%
N	ND2.5-B1.0	L10W90	299.89	333.13	11%	225.21	25%
O	ND2.5-B1.0	L30W70	318.82	335.93	5%	230.90	28%
P	ND2.5-B1.0	Water	288.81	332.40	15%	221.94	23%
Q	ND2.5-B1.0	L10W90	293.48	333.13	14%	227.37	23%
R	ND2.5-B1.0	L30W70	306.63	335.93	10%	217.19	29%
				Average	**11%**	**Average**	**24%**

On this study, it shows that the higher of droplet size is because of the lower of liquid pressure and low pressurized air in 3 bar. It was explained that the air pressure 3 bar is the higher value of SMD than air pressure 6 bar. The air operational pressure increase will increase spray velocity and air can distribute to mixing chamber area [8]. The different between ND2.5 A1.0 and ND2.5 B1.0 is the swirl angle. For ND2.5 A1.0, the angle is 80°, while for ND2.5 B1.0 is 75°. Therefore, it can be said that bigger angle of swirl gives a high SMD value. Next, the difference between New Design nozzle and the AL75 nozzle is their orifice diameter. The orifice diameter for New Design nozzle is smaller than AL75, which is 2.5 mm and 2.8 mm respectively. These results agree with Santangelo's (2010) and L. Broniarz-press (2008) findings that the SMD is decreasing with increasing of orifice diameter [16][17].

Table 2 shows that the SMD value and percentage error between experiment, correlation A and correlation B. Correlation A are acceptable for ND-2.5 because the average of percentage error is smaller than AL75. Percentage error is 4% for ND-2.5-A1.0 and 11% for ND-2.5-B1.0. Nozzle AL75 has a 74% error after applied correlation A, but the smallest error is 6% after validated with correlation B. That means AL75 is the trend and predicted SMD with correlation B.

4. Conclusion

The present work has been focused on determining droplet size diameter using low cost operational using WSP technique. The different nozzle design, operational pressure, and liquid properties give the effect of droplets sizes (SMD). The increase of viscosity will increase the droplet size and decreasing droplet size is by increasing the operating pressure. Decrease area of mixing chamber and increase of orifice diameter contribute decreasing of SMD value. From the results, most of the droplets size can be categorized as medium sprays and coarse sprays because the range of droplets diameter for medium sprays is in between 90μm to 300μm. These deflector nozzles suitable for cleaning and cooling industrial process.

Nomenclature

SMD (d_{32})	Sauter mean diameter	σ	Liquid surface tension (N/m)
D	Diameter of droplet (m)	m_L	Liquid mass flow rate(kg/s)
d_o	Orifice diameter (m)	d_s	Spot diameter (mm)
We_{do}	Weber number at orifice diameter	ΔP_L	Differential of liquid pressure (Pa)
Re_{do}	Reynold number at orifice diameter	A	The spots area (mm^2)

Acknowledgements

The authors are indebted to Universiti Tun Hussein Malaysia (UTHM), Halton Manufacturing Sdn. Bhd, and Delavan Spray Technologies under the auspices of who's this work was carried out (Grant KTP No. 1440).

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