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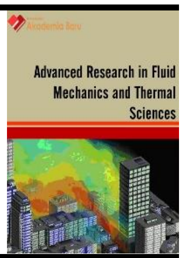

Studies on the Spray Characteristics of Pressure-Swirl Atomizers for Automatic Hand Sanitizer Application

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ABSTRACT

Automatic Hand Sanitizer (AHS) is an effective and useful tool to sanitize hands and is used widely in schools, workplace and healthcare settings. However, there are still issues that arise with spray type AHSs as it does not cover all parts of the hand, the volume of the sanitizer is not sufficient or it may miss the hands or be deflected into the air. The purpose of this work is to use numerical modelling techniques to evaluate the spray characteristics of AHS using pressure-swirl atomizer. ANSYS Fluent is used to simulate the spray produced by pressure-swirl atomizer. LISA (Linearized Instability Sheet Atomization) model is used for the primary atomization process while the TAB (Taylor Analogy Breakup) model is used for the secondary breakup of droplets. The parameters that were investigated include the spray angle and the droplet Sauter Mean Diameter (SMD). The simulation was first conducted using water as the atomization fluid to simulate water-based sanitizer spray and validated against experimental data. It was found that the simulation model developed shows good comparisons with experimental data when water was used. In addition, two scenarios were investigated with the validated CFD model: (i) increase in mass flow rate, (ii) ethyl-alcohol atomization for AHS application. Simulation results showed that the increase of flow rate does not affect water atomization but it does affect spray angle and SMD values for Ethyl-alcohol atomization. It is suggested that a higher flow rate can improve the atomization quality and spray coverage of alcohol-based sanitizer liquid for AHS application.

Keywords:
Automatic Hand Sanitiser (AHS), Computational Fluid Dynamics (CFD), Pressure-Swirl Atomizer.

1. Introduction

Hand sanitizers can be used to reduce gastrointestinal illnesses [1], to reduce absentee rates in elementary schools [2], and to reduce illnesses in university dormitories [3]. Alcohol-based sanitizers are proven to kill most bacteria, fungi, and stop some viruses. For hospitals and clinics, it is reported that the optimum alcohol concentration to kill bacteria is 70% to 95% [4,5]. Alcohol-based sanitizers

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containing at least 70% alcohol (mainly Ethyl-alcohol) can kill 99.9% of the bacteria on hands after 30 seconds of application and 99.99% to 99.999% in one minute of application. Because of this, ethyl-alcohol remain the best liquid for hand sanitizers as it is inexpensive, readily obtainable, harmless to the skin and bacteriologically potent [6].

Automatic hand sanitizer (AHS) is useful in providing a very fast, yet antiseptic and efficient method to sanitize hands so that the users have no objection repeating the use of the device [7]. However, there are still issues that arise for spray type automatic sanitizers such as it does not cover all parts of the hand or the volume of the sanitizer is not sufficient. Some manufacturers recommend using 1.1 mL per application of alcohol-based sanitizers for effective hand disinfection [8]. However, it is reported that 70% ethanol (v/v) with a recommended volume of 1.1 mL per application do not ensure complete coverage of both hands and do not achieve current ASTM efficacy standards [8]. Besides that, some of the sanitizers may miss the hands or be deflected into the air and became wasteful. Thus it is important to investigate the spray characteristics of an automatic hand sanitizer to overcome these issues.

One of the nozzle types that can be used in an automatic hand sanitizer is the pressure-swirl atomizer. Due to the nature of the complex atomization process, CFD analysis had become a very useful tool to solve the atomization process. Several authors had used CFD analysis method to simulate pressure-swirl atomizers. Fung *et al.,* [9] used CFD method to simulate spray atomization from a nasal spray device and Dikshit Kulshreshta [10] used CFD simulation for pressure-swirl atomizer used in small-scale gas turbine combustion chamber.

The most commonly used breakup model for pressure-swirl atomizer is the linear instability sheet atomization (LISA) model by Senecal *et al.,* [11]. The LISA model has been widely applied in the simulations of spray breakup in combustion engines where the application is under very high pressure [12]. However, there are not much application for small-scale low-pressure atomizer as indicated by Fung, Inthavong [9] in their publication which made the CFD simulation for small-scale low-pressure atomizer not verified. The difference of low-pressure and high-pressure atomizer can be seen by the spray shape produced which is reported by Savich, S [13] that shows high-pressure injection produces a spray with close to parabolic shape while low-pressure injection produces a spray close to conical shape.

Therefore, in this study, LISA spray model in ANSYS FLUENT is used to verify its applicability for small-scale pressure-swirl atomizer that is used in AHS. The spray produced by CFD simulation is validated against experimental results and comparison of the spray angle and the droplet Sauter Mean Diameter (SMD) was conducted. The spray angle can be used to determine the dispersion and coverage area of the resultant sprays [14]. The wider the spray angle means a smaller droplet size is produced and more space to distribute the droplets. Spray angle can be measured by forming two straight lines from the nozzle outlet orifice to cut the spray contours at a specified distance from the atomizer face [15].

The SMD, on the other hand is obtained by calculating the diameter of a drop whose surface to volume ratio is the same as of the entire spray and is widely used in various applications [16]. The value of SMD can be used as an indicator to determine the atomization quality [15]. Besides that, this study also focuses on the “breakup length” of the spray as it is one of the key spatial scales of the continuous liquid jet past the nozzle exit. The breakup length is important because it defines the spatial extent of the primary atomization region. The measurement of the breakup length is therefore crucial in spray studies, because it is essential for the physics of atomization, the performance of atomizers [17,18],and for the evaluation of computational models for atomization [19,20].

The simulation was first conducted using water for validation and validated model is used to conduct ethyl-alcohol atomization. Furthermore, the CFD results will provide insight into the AHS device design in order to improve the sanitizers coating of hands during hand sanitization.

2. Methodology
2.1 Experimental Method

The mechanism of the atomizer tested allow liquid to be fed to the atomizer partly through a central cylindrical port which gives a pure axial type entry and partly through side inlet slots which provides swirl to the liquid. The geometry for the atomizer used in this study is shown in Figure 1.

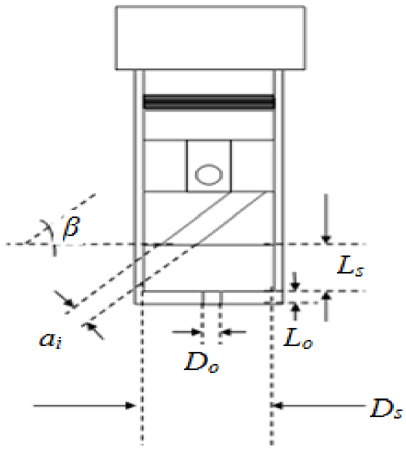

Fig. 1. Geometry of a pressure-swirl atomizer

The important dimension is the diameter of the nozzle exit orifice, D_O = 1 mm, the swirl chamber diameter, D_S = 4 mm, length of the nozzle orifice, L_O = 1 mm, the area of the tangential inlet, a_i = 0.93mm×0.5mm, the tangential inlet length, L_P = 1.5 mm, length of the swirl chamber L_S = 3mm, the tangential inlet angle, β = 25°.

The experimental set-up includes a water supply tank, a centrifugal pump, a submersible pump, feed lines fitted with flow control valves and strainer, a pressure gauge and a flow meter. The atomizer is mounted downward on a vertical plane so that the water spray is injected directly into a collecting basin at the ambient condition. The images of the resultant sprays produced were captured by a complementary metal-oxide-semiconductor (CMOS) sensor camera with 16.2 million pixels resolutions. The speed light was set to a maximum value which results in an exposure of 26µs. Shadowgraph technique was applied in acquiring the resultant sprays images. Acquired images were processed via image processing software for further analysis. The line diagram of the experimental setup is shown in Figure 2.

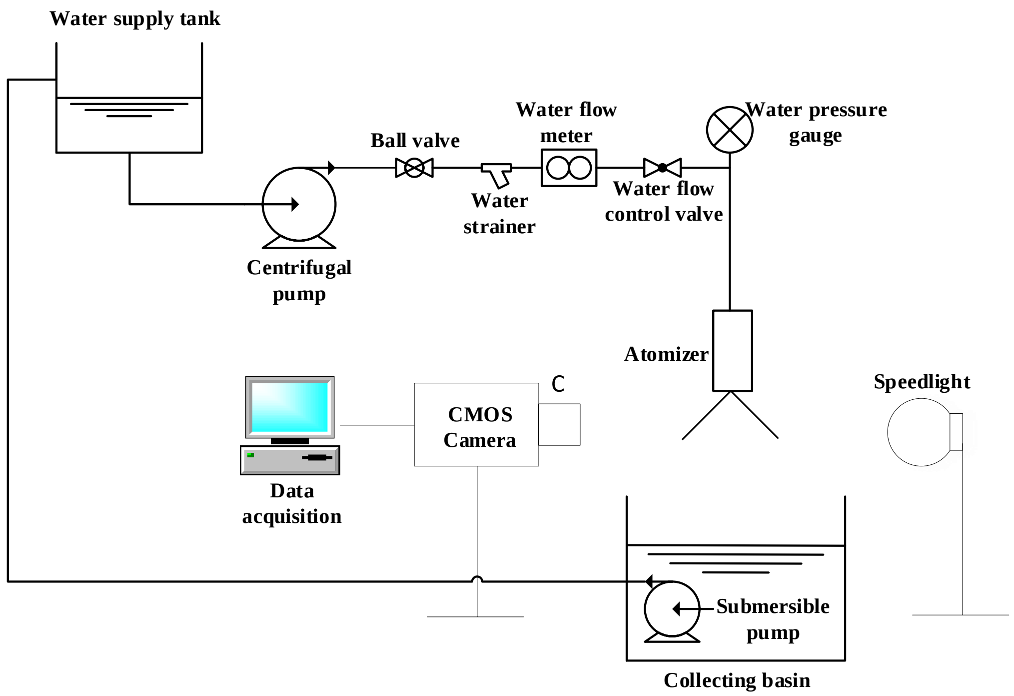

Fig. 2. Line diagram of experimental set-up

2.2 Simulation Method
2.2.1 Numerical method

A 3-Dimensional (3D) computational domain to simulate the spray atomization was a cylinder having the dimension of 0.2m diameter and 0.2m in depth. The dimension for the pressure-swirl atomizer used for the simulation follows the dimension for the pressure-swirl atomizer as shown in Figure 1.

The mesh consisted of 553,363 elements of tetrahedral cells. Figure 3 shows the mesh configuration used in this simulation. The commercial CFD code, ANSYS Fluent v14 was used to simulate the sprays produced by using a pressure-swirl atomizer. The dimensions used in the simulations are obtained from the theoretical relations developed and were verified experimentally to successfully produce swirl motion spray for pressure-swirl atomizer [9,10].

The fluids used for modelling are liquid water which is the fluid flowing through the tangential inlets and injecting at the nozzle exit orifice, and the air is used as the continuous phase, which is filled in the external domain initially before the injection occurs. The properties for the fluid used is shown in Table 1. For all cases, the fluids air and water are taken at room temperature and atmospheric pressure. Inlet boundary condition is selected as mass flow inlet. The nozzle walls have been given the wall boundary condition with specified shear and default values of roughness constant and other constants. The outlet is defined as pressure outlet, as the flow is exiting into the domain where air at atmospheric conditions is filled initially. The flow rate of the sanitizer liquid is calculated based on the estimation of 1.5 mL to 8.5mL per application using AHS sprays. The flow rate is varied to investigate the effects of flow rate on the spray characteristics. The details on the boundary condition and models used in this study are summarized in Table 2.

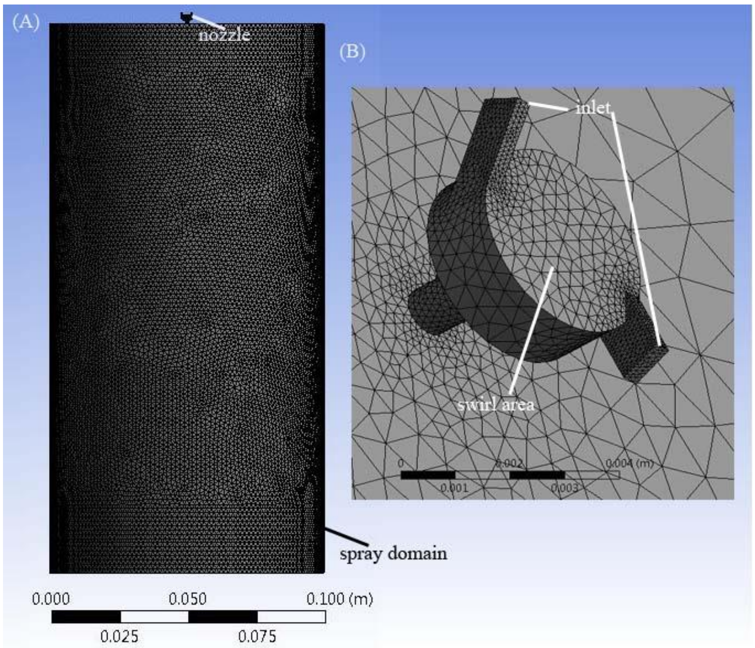

Fig. 3. Mesh configuration for nozzle and spray domain

Table 1
Fluid Properties

Properties	Air	Water	Ethyl-alcohol
Density (kg/m^3)	1.225	998.2	790
Specific heat, Cp (J/(kg· K))	1006	4182	2470
Viscosity (kg/(m· s))	1.789×10^{-4}	0.0010	0.0012
Vaporization Temperature (K)	-	284	271
Droplet Surface Tension (n/m)	-	0.0719	0.0223

Table 2
Boundary Conditions and Models Used

Models/ Properties	Type
Viscous Model	Realizable k-epsilon with standard wall function.
Species Model	Species Transport with Diffusion Energy Source
Mixture Material	Ethyl-alcohol-air
Discrete Phase Model	Interaction with Continuous Phase with unsteady Particle Tracking Particle time step size: 0.0001s Tracking Parameters: dynamic-drag law Spray Models: Breakup with TAB breakup model
Injection Properties	Injection Type: Pressure-swirl atomizer Particle Type: Droplet Material: water liquid and ethyl-alcohol liquid Evaporating species: H_2O and C_2H_5OH Number of particle stream: 100 Temperature: 293K Start time: 0 s Stop time: 100s Velocity Magnitude: 48.892 m/s
Flow Rate (l/min)	0.1, 0.2, 0.3, 0.4, 0.5

2.2.2 Governing equations (primary breakup model)

This study uses the LISA (Linearized Instability Sheet Atomization) model to simulate the effects of primary breakup in pressure-swirl atomizers as described in detail by other researchers [10,11,21]. (Figure 4) Pressure-swirl atomizers are known to have high atomization efficiencies. The fluid inside pressure-swirl atomizers is set into a rotational motion and the resulting centrifugal forces lead to a formation of a thin liquid film along the injector walls, surrounding an air core at the centre of the injector. Outside the injection nozzle, the tangential motion of the fuel is transformed into a radial component forming a liquid sheet. This sheet is subject to aerodynamic instabilities that cause it to break up into ligaments. Figure 1 shows the primary atomization process.

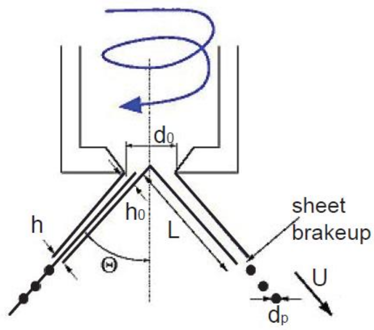

Fig. 4. Pressure-Swirl Atomizer [21]

The swirling liquid comes out of exit orifice of diameter d_0 with the liquid film of thickness h_0 at an angle ϑ. Liquid sheet gets disintegrated into ligaments and further into droplets. The process can be expressed by Eq. (1).

$$m = \pi\rho_P u\dot{h}_0(d_0 - h_0) \tag{1}$$

where $\dot{m}$ is the mass flow rate through the injector, ρ_p is the particle density, and d_0 is the injector exit diameter.

The total velocity, U, is assumed to be related to the injector pressure by the following relation

$$U = k_V\sqrt{\frac{2\Delta p}{\rho_P}} \tag{2}$$

and

$$k_V = max\left[0.7, \frac{4\dot{m}}{\pi {d_0}^2 \rho_P cos\theta}\right]\sqrt{\frac{\rho_P}{2\Delta p}} \tag{3}$$

where ΔP is the pressure difference across the injector and k_v is the discharge coefficient. The computed film thickness, h_0, will be equal to half the injector nozzle diameter if the discharge coefficient, k_v, is larger than 0.7 [21].

Assuming that the value of ΔP (injection pressure difference) is known, the total injection velocity can be computed from equation of U. The axial film velocity component, u, is then derived from

$$u = U\cos\theta \tag{4}$$

where θ is the spray angle, which is assumed to be known. At this point, the thickness, h_0, and axial velocity component of the liquid film are known at the injector exit. The tangential component of velocity ($w = U \sin \vartheta$) is assumed to be equal to the radial velocity component of the liquid sheet downstream of the nozzle exit. The axial component of velocity is assumed to remain constant.

The model used in this study is the Taylor Analogy Breakup (TAB) model, which is responsible for the breakup of parent droplets formed by LISA model. There is five distinct breakup regime determined by the Weber number of parent droplets. The details are available in the report by Pilch and Erdman (1987) [22]. The model equations of TAB model can also be found in ANSYS theory guide [21].

3. Results and Discussions

3.1 Mesh Independence Study

To establish the accuracy of the CFD solution, and to keep the computational costs low, the mesh convergence study was performed by developing three different meshes: coarse, medium, and fine mesh. The mesh convergence study was conducted to determine how the mesh quality affects the spray angle and SMD results obtained from the CFD simulation. The number of mesh and the simulation time for the three mesh size used in simulating water atomization at 0.1 l/min is shown in Table 3. It is very clear that CFD simulation time is highly dependent on the number of mesh considered. From this result, the medium mesh was selected to save the computational cost since the difference between the medium and fine mesh is small.

Table 3
Spray angle and SMD results using coarse, medium and fine mesh

Mesh Type	Number of Mesh	Spray Angle	SMD
Coarse	48048	27.876	4.70E-06
Medium	106270	24.559	4.65E-05
Fine	234793	24.216	8.29E-05

3.2 Verification of Swirl Generation in the Pressure- Swirl Atomizer

For pressure-swirl atomizer, the swirl motion is imparted to the flowing liquid in the upstream region of the liquid orifice. It is done by passing the liquid through tangential orifices. The swirling motion makes the liquid to confine with the walls of the swirl chamber and creates an air-core in the spray axis region. Filmy liquid flow with aircore is seen inside the fuel orifice. At the orifice exit, the swirling liquid diverges (due to centrifugal force) out in the form of a thin liquid film. The liquid film disintegrates via hydrodynamic instability mechanisms and produces fine droplets [10].

Figure 5 shows the streamlines at the inlet indicating the swirling motion of the flow in the swirl chamber. The swirling motion helps in creating the air core at the centre spray axis due to the centrifugal motion of the liquid in the swirl chamber, and by confining the liquid at the walls of the swirl chamber. The path lines at the inlet and wall of the pressure-swirl nozzle clearly depict the swirling motion of the liquid and the creation of the central air core at the central axis of the atomizer [23]. This result shows a similar streamlines pattern with the work published by Arun, S. and P. Rakesh which confirms that the swirling motion is established inside the pressure-swirl atomizer [23].

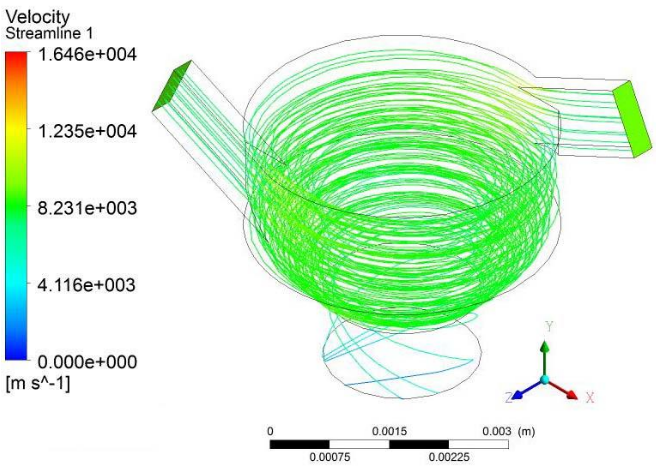

Fig. 5. Sample of water flow streamline in nozzle

3.3 Comparison of Spray Pattern, Spray Angle and Sauter Mean Diameter (SMD) between CFD and Experimental Results

Experimental procedures have been carried out to investigate the effect of flow rate on the spray angle and particles Sauter Mean Diameter (SMD). The samples of images obtained from sprays formed by a pressure-swirl atomizer are presented in Figure 6. From this figure, it can be observed that the spray angle does not change significantly between the different flowrate tested but the spray break up length as labelled L_{bu} in Figure 6 is observed to increase with the increase of flow rate. To promote a well-distributed spray, a short breakup length and wide spray angle were desirable characteristics of the spray [24]. A longer spray breakup length means the spatial extent of the primary atomization region is longer which takes a longer time to break up into droplets and a more narrow dispersion which will cause a relatively smaller spray angle at the nozzle exit. This might be the reason why there is no noticeable difference in spray angle even though the increase in the flow rate is known to increase spray angle values [25]. The images from Figure 6 is then analyzed to obtain the spray angle and Sauter Mean Diameter for CFD simulation validation as shown in Figure 8. A sample of spray angle analysis for the experiment result using ImageJ software is as shown in Figure 7.

Figure 8 shows CFD results of water particles residence time produced by the pressure-swirl water atomization. From Figure 8, spray pattern for flow rate 0.1 l/min shows that the spray distance or spray penetration is smaller and stopping at the middle of the simulation spray domain while producing droplets at the top of the simulated area. Other flow rate tested shows that the spray reaches the outlet boundary set during the simulation. Besides that, the spray pattern produced using CFD simulation shows a similar pattern for flow rate 0.2 l/min to 0.5 l/min compared to experimental results which shows a difference on the spray break-up length. The spray break-up length is not captured in these results as it is not possible to measure these values using particle residence time results. The image from Figure 8 is then analyzed for CFD and experimental result comparison of spray angle is as shown in Figure 10. A sample of spray angle analysis for the CFD result using ImageJ software is as shown in Figure 9.

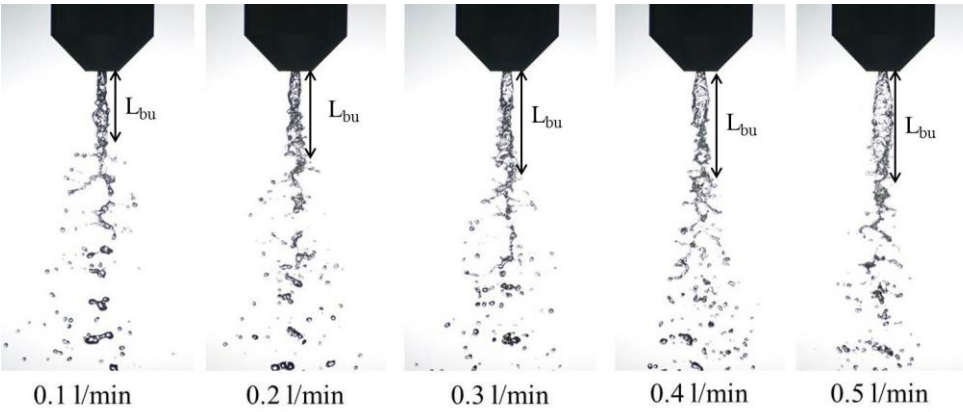

Fig. 6. Samples of photograph taken for mass flow rate 0.1 l/min, 0.2 l/min, 0.3 l/min, 0.4 l/min and 0.5 l/min

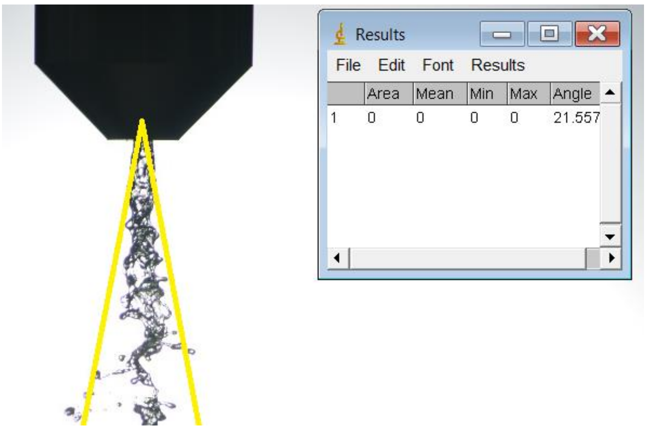

Fig. 7. Example of spray angle selection for experiment result using ImageJ Software

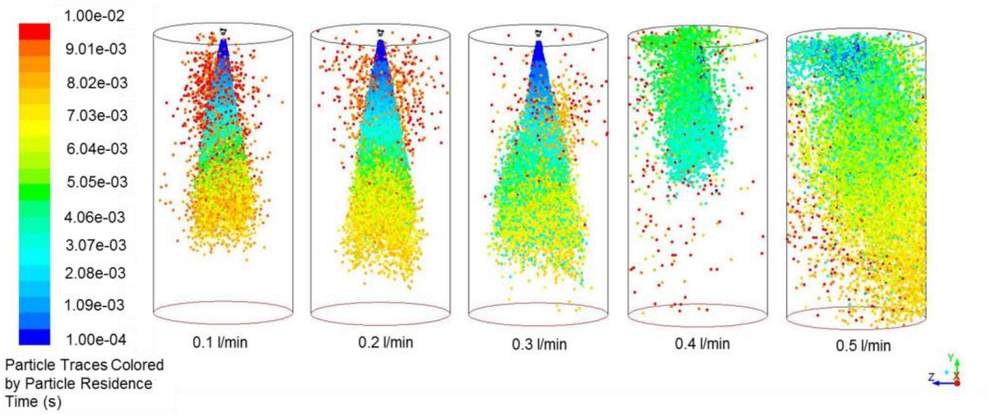

Fig. 8. CFD results of particle residence time (s) for water atomization

Figure 10 shows the variation of spray angle with water flow rate. The CFD and experimental results are matching with each other and it is clearly indicated in Figure 10. From Figure 10, the spray angle is not affected by flow rate as the spray angle value remains almost constant for both CFD and experimental result. Even though it is reported that flow rate increase spray angle values [19], it is not the case when using water as the spray angle remains constant through the flow rates tested. As mentioned in section 3.3, this might be contributed by the longer break-up length produced and thus affecting the spray angle making it narrower at the spray nozzle. This result also shows that if the sanitizer liquid used in the AHS is water-based, increasing the flow rate does not improve the sanitizer spray coverage.

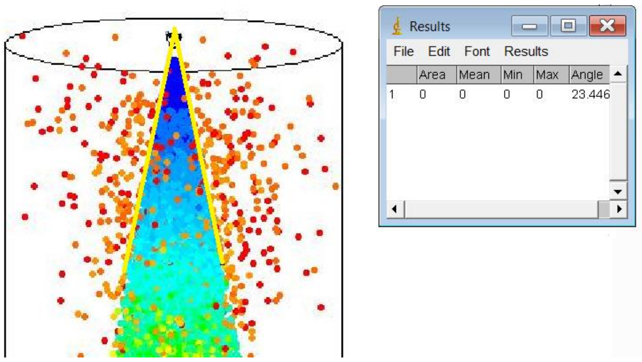

Fig. 9. Example of spray angle selection for CFD result using ImageJ Software

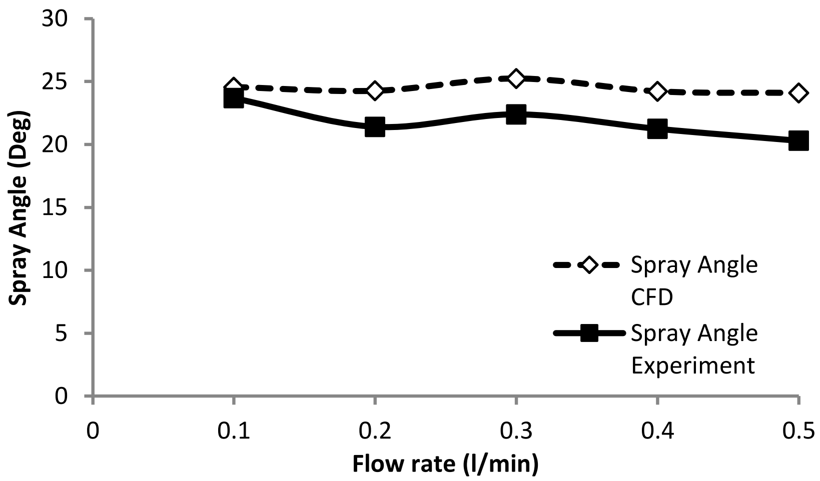

Fig. 10. CFD and experimental results of spray angle for water atomization according to flow rate

3.4 Atomization of Ethyl-Alcohol for Sanitizer Application

The validated simulation model used in the previous section is then used to simulate Ethyl-alcohol atomization to represent alcohol-based sanitizer in an AHS. CFD results of Ethyl-alcohol particle residence time is shown in Figure 11. From Figure 11, the results show that the spray pattern differs with the increase of flow rate. Flow rate between 0.1 l/min to 0.3 l/min shows that the spray length or the spray penetration and spray angle increase with increasing flow rate. A higher flow rate at 0.4 l/min and 0.5 l/min decrease spray length or the spray penetration, increase spray angle and produces more droplets around the simulation area compared to atomization at a lower flow rate (0.1 l/min to 0.3 l/min). Results of this simulation are analyzed to calculate the value of spray angle and SMD for ethyl-alcohol atomization as shown in Figure 12 and Figure 13. To calculate the spray angle for 0.4 l/min and 0.5 l/min results which shows dispersion of the spray, the value of particle traces colored by particle residence time for values bigger than 5.00 E-03(s) is first omitted to obtain a clear spray angle. The SMD results is obtained numerically using ANSYS FLUENT and the details is explained in details elsewhere [12,26].

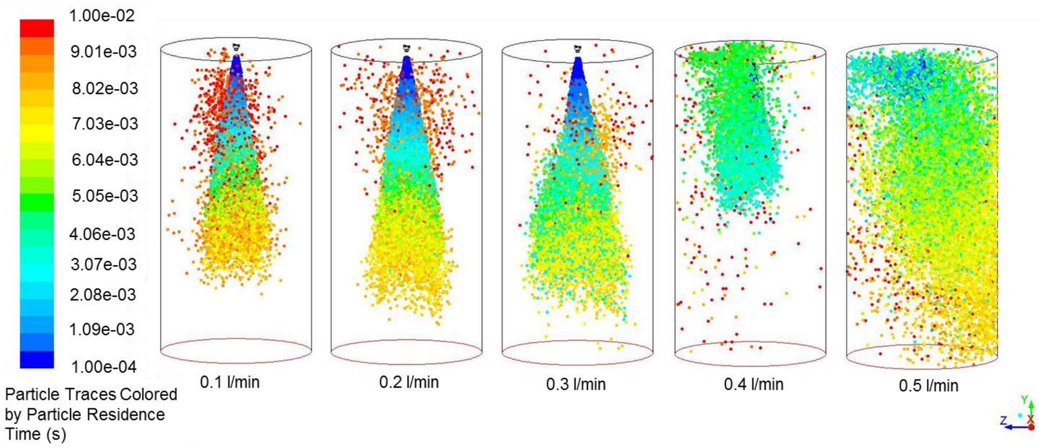

Fig. 11. CFD results of particle residence time (s) for Ethyl-alcohol atomization

To investigate further the effects of different atomization liquid properties on spray angle and SMD, the spray angle and SMD value are plotted in accordance to the liquid flow rate as shown in Figure 12 and Figure 13. As it can be observed in Figure 12, an increase in flow rate increases the spray angle when Ethyl-alcohol is used for atomization while water atomization shows constant values of spray angle. This shows that atomizations for liquids such as water that have higher surface tension and vaporisation temperature is not as affected to the increase in flow rate compared to liquids that have lower surface tension and vaporisation temperature values such as Ethyl-alcohol. From this result, it can be concluded that increasing flow rate can be used to improve the AHS sanitizer liquid coverage depending on the characteristic of the liquid such as liquid surface tension, vaporisation temperature and viscosity.

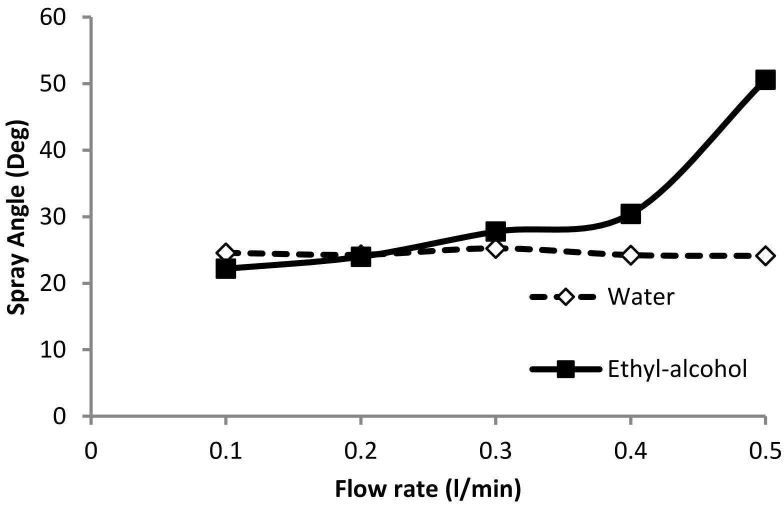

Fig. 12. Spray angle for water and Ethyl-alcohol atomization according to flow rate

Figure 13 shows the comparison between water and Ethyl-alcohol atomization. Results in Figure 13 shows that Ethyl-alcohol atomization produces smaller SMD values compared to water atomization. The smaller SMD value for Ethyl-alcohol is contributed by the lower value of surface tension of Ethyl-alcohol compared to water. The decrease in SMD value means improvements in the pressure-swirl nozzle spray quality which results in faster droplet evaporation [27]. This result is also supported by Kang *et al.,* [28], which have reported that the increase of liquid viscosity and surface tension suppress the breakup and atomization of the conical liquid film and thus decrease the atomization quality.

Furthermore, it is noted that the values of SMD for ethyl-alcohol show a non-monotonic trend with the flow rate. The SMD initially increases, reaching a maximum at a flowrate of 0.2 l/min and de-creases for a higher liquid flow rate. This shows a higher flow rate increase can reduce Ethyl-alcohol SMD value. Based on this result, a high flow rate can be used to improve the atomization quality when using Ethyl-alcohol as the sanitizer liquid for AHS.

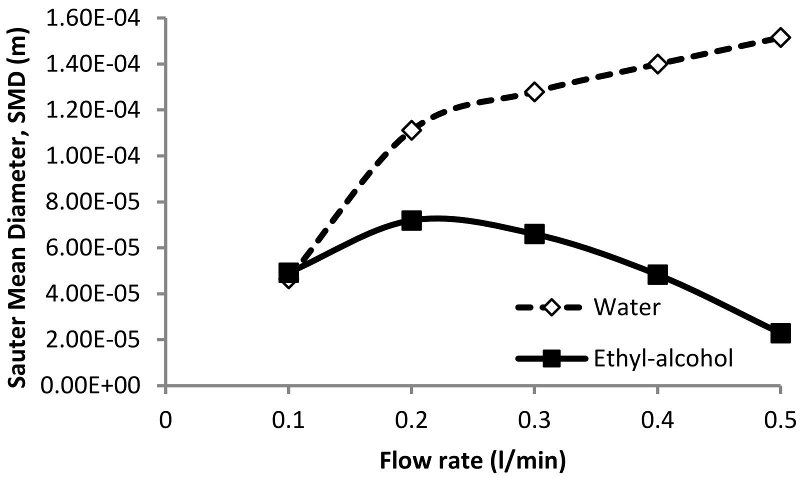

Fig. 13. SMD for water and Ethyl-alcohol atomization according to flow rate

4. Conclusions

The spray modelling from pressure-swirl atomizer is done with CFD code Fluent using the Lagrangian approach. Experiments have been performed using water as the atomization to represent water-based sanitizer liquid at flow rates 0.1 l/min to 0.5 l/min. CFD numerical simulation was also conducted using the same nozzle parameters as the experiment conducted and the results were validated. The validated CFD simulation model is then used to model Ethyl-alcohol atomization to represent alcohol-based sanitizer liquid for application in AHS.
Following conclusions have been drawn from the analysis of the CFD and experimental results

- CFD results of spray angle for water atomization show a similar pattern and a good agreement to experimental results.
- Ethyl-alcohol atomization spray angle and SMD values are influenced by the increase of flow rates tested, while water atomization is not. This might be attributed to the different surface tension value between Ethyl-alcohol and water.
- The decrease in SMD value when using Ethyl-alcohol indicated that an increase in flow rate improved the quality of atomization. Higher flow rate increases liquid swirling strength, increase air core diameter which decreases the liquid film thickness in the swirl chamber and the discharge orifice.

Besides that, for AHS application, a higher flow rate is suggested to improve the atomization quality and spray coverage of alcohol-based sanitizer liquid. Other parameters such as the nozzle orifice diameter, pressure, chamber length etc. should also be investigated to improve atomization quality and spray coverage.

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