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DESIGN, DEVELOPMENT AND PERFORMANCE EVALUATION OF NEW SWIRL EFFERVESCENT INJECTOR

Z. A. Ghaffar, S. Kasolang*, A. H. A. Hamid, C. S. Ow, N. R. Nik Roselina

Faculty of Mechanical Engineering, Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia

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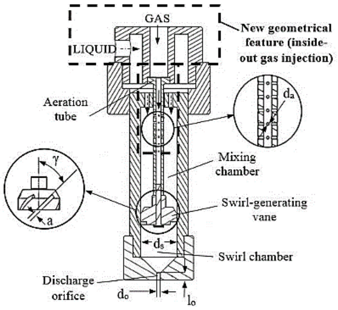
*Corresponding author
salmiahk@salam.uitm.edu.my

Graphical abstract



Abstract

The swirl effervescent injector has more desirable characteristics because it allows a system to run on low injection pressure and yet is still able to achieve an efficient atomization. In previous studies on other types of injectors, spray breakup length was reported as one of the important spray characteristics since a shorter spray breakup length tend to provide an earlier atomization. However, intensive studies on spray characteristics of the swirl effervescent injector are scarce. This paper is intended to describe the geometrical design procedures and performance assessments of a newly developed swirl effervescent injector. In designing the injector, a similitude technique was deployed to find the best design attributes among 4 existing injectors. The desired attributes were incorporated into the development of the injector. The swirl chamber was made from Perspex to permit visualization of the internal flow. A test rig was built to evaluate the injector's performance. Water was used as the working fluid and nitrogen gas as the atomizing agent. The spray breakup characteristics were observed at different GLR and recorded using high-speed shadowgraph technique. For the analyses of the video recordings and the conversion into image sequences, ImageJ and specific software have been deployed. It was found that the introduction of the swirl-generating vane prior to the discharge orifice has assisted in shortening the spray breakup length at any amount of GLR.

Keywords: Swirl effervescent injector, injector fabrication, spray breakup, shadowgraph

Abstrak

Penyuntik pusaran berbuih mempunyai ciri-ciri yang dikehendaki kerana ia membenarkan sesuatu sistem untuk beroperasi pada tekanan suntikan yang rendah tetapi masih mampu untuk mencapai pengabusan yang berkesan. Panjang penceraian semburan merupakan salah satu ciri-ciri penting semburan kerana penceraian semburan yang pendek menyediakan pengabusan yang lebih awal. Walaubagaimanapun, kajian intensif terhadap ciri-ciri semburan penyuntik pusaran berbuih sukar ditemui. Kertas ini bertujuan untuk menerangkan tatacara rekaan geometri dan penilaian prestasi penyuntik pusaran berbuih yang baru dihasilkan. Dalam mereka bentuk penyuntik tersebut, teknik similitud digunakan untuk mencari ciri-ciri terbaik rekaan antara 4 penyuntik sedia ada. Ciri-ciri rekaan yang dikehendaki digabungkan dalam menghasilkan penyuntik tersebut. Kebuk pusaran diperbuat daripada Perspeks untuk membolehkan pemvisualan aliran dalam. Satu rig ujian telah dibina untuk menilai prestasi penyuntik. Air digunakan sebagai bendalir kerja dan gas nitrogen sebagai ejen pengabusan. Ciri-ciri penceraian semburan telah diperhatikan pada GLR yang berbeza dan direkod menggunakan teknik *shadowgraph* berkelajuan tinggi. Untuk menganalisa rakaman video dan penukaran kepada urutan imej, ImageJ dan perisian tertentu telah digunakan. Didapati pengenalan ram penjana pusaran sebelum orifis nyahcas telah membantu memendekkan panjang penceraian semburan pada sebarang jumlah GLR.

Kata kunci: Penyuntik pusaran berbuih, fabrikasi penyuntik, penceraian semburan, *shadowgraph*

1.0 INTRODUCTION

Swirl effervescent injector is one of the injector which potentially applied in various machines and instruments due to the low injection pressure required to achieve good atomization and wideness of spray angle. The mechanism of this type of injector comprises the combination of mechanisms of two types of injectors which are swirl injector and effervescent injector. Particularly, in swirl effervescent injector, gas bubbles are injected into the mixing chamber through the aeration hole (component of effervescent injector) which produces a gas-liquid mixture in the chamber. The gas-liquid mixture passes through the swirl-generating vane (component of swirl injector) before exiting the injector through the discharge orifice. The resultant spray is a hollow cone type.

Spray breakup length is an important spray characteristic since a shorter spray breakup length provides an earlier atomization. Ghaffar *et al*. [1] stated that for a shorter combustion chamber, it is critical to have a shorter breakup length. Recent studies on effervescent atomization spray breakup length was conducted by Gadgil and Raghunandan [2]. They observed that the spray breakup length was mainly affected by airflow rate, jet diameter and mixture velocity. They classified the spray structures into three regimes: discrete bubble explosion, continuous bubbles explosions and annular conical spray. Hamid and Atan [3] conducted a study on the behaviour of breakup length in jet-swirl injector and concluded that a higher injection pressure leads to a shorter breakup length. Hussein *et al*. [4] found that in jet-swirl injector, the largest discharge orifice diameter produced the longest breakup length. Spray breakup is also influenced by the internal flow conditions inside the mixing chamber. The size of gas bubbles formed in the mixing chamber affects the formation of the spray structure as reported by Gadgil and Raghunandan [2] and Jagannathan *et al*. [5].

One of the methods in visualizing the spray breakup is using high-speed shadowgraph technique. This technique involves image acquisition of the resultant spray using a high-speed video camera. With the camera capability of recording thousands of images per second and high shutter speed, the movements of the high-speed droplets could be visualized in a slow motion. The term shadowgraph refers to the method of illumination by directing a continuous light source to the camera lens aperture. The camera captures the shadow of the sprays produced by the atomizer. The advantages of shadowgraph technique in spray characterization as mentioned by Ow [6] include providing size distribution, cheap instrumentation, effective extraction of data from dense population, and availability of shadowgraph-related image analysis system. Many researchers have used this technique in obtaining droplet size, spray angle, breakup length and also in visualizing the internal flow. Ow [6] determined the droplet size by freezing in time the droplets using a 0.25μs argon-stabilized single-electrode spark unit. Experimentation of sprays breakup in effervescent atomization conducted by Gadgil and Raghunandan [2] have applied the shadowgraph technique. Ghaffar *et al*. [7] utilized this technique in measuring the spray angle of swirl effervescent atomizer.

The present paper aims to describe the geometrical design of the new swirl effervescent injector and its effect on the spray breakup characteristics.

2.0 GEOMETRIES AND OPERATING PRINCIPLES OF THE NEW SWIRL EFFERVESCENT INJECTOR

This new swirl effervescent injector consists of liquid inlet, gas inlet, aeration tube, mixing chamber, swirl-generating vanes, swirl chamber, and discharge orifice. The schematic of the swirl effervescent injector is shown in Figure 1.

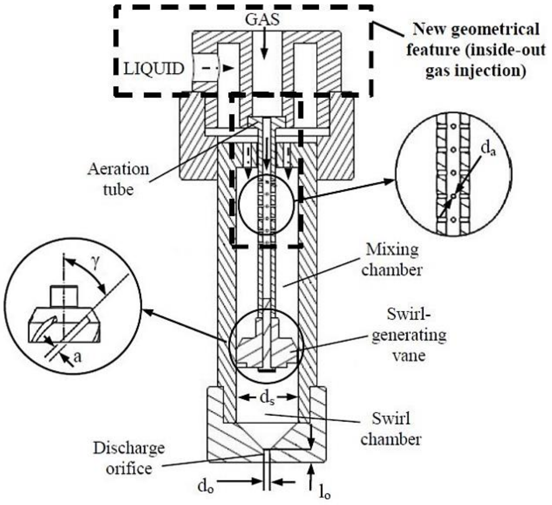


Figure 1 Schematic of swirl effervescent injector with new features

Liquid is supplied to the injector into the mixing chamber through the liquid inlet. Simultaneously, gas is injected into the injector through the aeration tube. The gas is introduced into the mixing chamber with a low velocity for the purpose of bubbling the liquid stream. The bubbles dispersed in the liquid stream and form two-phase liquid-gas mixture. The liquid-gas mixture passes through swirl-generating vanes which create swirling effects on the mixture before exiting the injector through the discharge orifice. As the mixture discharges the injector, the gas bubbles explode and shattering the liquid into small droplets. It should be noted that, although this type of injector is considered as pneumatic injector, the operating principle is not similar to other pneumatic injector which uses gas at high velocity as an additional kinetic energy for the liquid to achieve atomization.

The injector employs inside-out gas injection method for the insertion of gas. Basically, effervescent injector could be identified into two configurations based on the gas injection method which are inside-out and outside-in configurations. Inside-out is superior to be used in low liquid flow rates while outside-in is preferable in high liquid flow rates [8]. Low liquid flow-rate is intended in this study to simulate low fuel consumption thus, inside-out gas injection has been selected. Inside-out gas injection is the configuration where the gas and the liquid mixed outside of the aeration tube which is in reverse of outside-in configuration where the gas and the liquid mixed inside the aeration tube. Figure 2 shows the comparison of the inside-out and outside-in gas injection configurations.

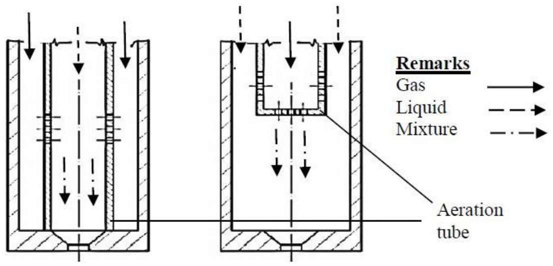


Figure 2 Redrawn of (a) outside-in and (b) inside-out gas injection configurations from [9]

3.0 INJECTOR DESIGN

3.1 Parametric Comparison

The injector was designed by matching the design and operating parameters with several existing injectors. This technique is called similitude which was adapted from Rahman *et al*. [10]. Since the injector mechanism consists of swirl and effervescent injectors, the references for the new injector design were on these two types of injectors. Design of the effervescent part (aeration tube) of this injector is based on effervescent/aerated-liquid injectors constructed by Gadgil and Raghunandan [2] and Lefebvre [11]. The swirl injector part (swirl-generating vane) was designed based on Hamid and Atan [3] jet-swirl injector. The schematic of the Lefebvre's and Hamid and Atan's injector are shown in Figure 3 and 4 respectively.

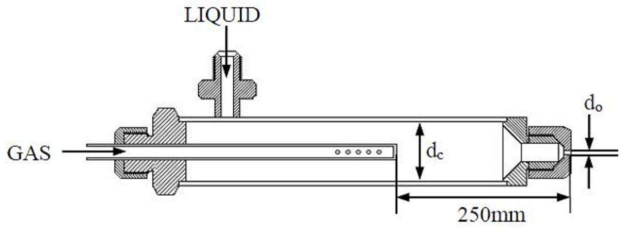


Figure 3 Redrawn schematic of aerated-liquid injector by Lefebvre [11]

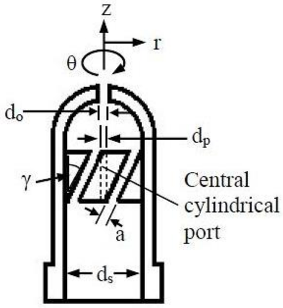


Figure 4 Redrawn schematic of jet-swirl injector by Hamid and Atan [3]

The swirl chamber diameter, d_s of the new injector is adapted from the mixing chamber diameter, d_c of the Lefebvre's aerated-liquid injector. The operating parameters (GLR) of the new injector were attempted to be similar to Gadgil and Raghunandan [2]. GLR is defined as:

$$GLR = \frac{\dot{m}_G}{\dot{m}_L} \qquad (1)$$

Where $\dot{m}_G$ and $\dot{m}_L$ are the gas and liquid flow rates, respectively.

Comparison of design and operating parameters between the new and previous injector are shown in Table 1. The intention of combining previous design parameters from both effervescent and jet-swirl injectors in this new injector is to improve the performances of the previous injectors.

The purpose of varying the swirl-generating vane tip angle, γ, is to investigate the swirl intensity effect on the spray characteristics. Swirl intensity could be determined through swirl number, S which defined as:

$$S = \frac{1}{2}\left[\frac{1-\left(\frac{r_p}{r_s}\right)^4}{1-\left(\frac{r_p}{r_s}\right)^2}\right]\tan\gamma \qquad (2)$$

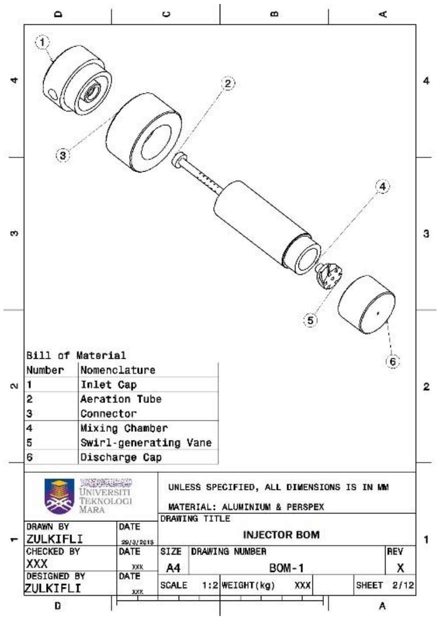
where r_s is the radius of the swirl chamber and r_p is the radius of central cylindrical port. In addition, variation in the diameter of discharge orifice was intended for analysing the effect of this parameter towards the spray characteristics. The study of the effect of swirl injector's discharge orifice diameter variation towards spray characteristics has been performed by Hussein [4] but no study has been made for swirl effervescent injector.

Table 1 Comparison of injectors design parameters between previous and the present study

Design and operating parameters	Present study	Gadgil & Raghunandan [2]	Lefebvre [11]	Hamid & Atan [3]	Rashid *et al.* [12]
Swirl-generating vane angle, γ (°)	30, 45, 60	n/a	n/a	60	n/a
Diameter ratio of orifice to swirl chamber, d_o/d_s	0.06, 0.08, 0.1	n/a	n/a	0.16	0.06, 0.08, 0.1
Mixing chamber diameter, d_c (mm)	25	16	25.4	n/a	n/a
Discharge orifice diameter, d_o (mm)	1.5, 2, 2.5	2, 3	0.8, 1.6, 2.4	1.6	2.8, 3, 3.2, 3.75
Liquid injection pressure, P_L (bar)	0.2 - 2.2	2.45, 3.43	0.345, 1.38, 3.45, 6.9	1.5 - 5	2, 4, 6, 8
Gas-to-liquid ratio, GLR	3.33×10^{-4}, 6.67×10^{-4}, 9.98×10^{-4}	3.53×10^{-4}, 7.57×10^{-4}, 14.02×10^{-4}, 33.09×10^{-4}, 53.75×10^{-4}	0 - 0.24	n/a	n/a

3.2 CAD Drawing

The drawing of the injector was carried out using CATIA software. The Bill of Material (BOM) of the new swirl effervescent injector which enlisted all the components is shown in Figure 5.



Bill of Material

Number	Nomenclature
1	Inlet Cap
2	Aeration Tube
3	Connector
4	Mixing Chamber
5	Swirl-generating Vane
6	Discharge Cap

UNLESS SPECIFIED, ALL DIMENSIONS IS IN MM
MATERIAL: ALUMINIUM & PERSPEX
DRAWING TITLE INJECTOR BOM
DRAWN BY ZULKIFLI DATE 29/3/2013
CHECKED BY XXX DATE XXX
DESIGNED BY ZULKIFLI DATE XXX
SIZE A4
DRAWING NUMBER BOM-1
REV X
SCALE 1:2
WEIGHT(kg) XXX
SHEET 2/12

Figure 5 Bill of Materials of swirl effervescent injector generated from CATIA

In producing the drawing, details considerations were made on sharp edges of the components to be drawn. All sharp edges were either chamfered or filleted based on designing preferences. The dimensions of the components have been rounded up to 1 decimal point for simplification of machining since the components were not machined using a CNC machine. To facilitate the drawing process, the atomizer was divided into 6 components which are inlet cap, aeration tube, connector, mixing chamber, swirl-generating vane and discharge cap.

4.0 INJECTOR FABRICATION

The injector which has been divided into 6 components were machined from either Perspex or aluminum rod. The inlet cap and swirl-generating vane were machined from aluminum rod. The rest of the components were specifically made from Perspex. Fabrication of the injector was particularly more challenging as it involved different machining processes such as cutting, turning, milling, drilling and threading. Perspex was specifically chosen for fabricating the injector's main body so as to facilitate internal flow observations during testing. Figure 6 depicted the progression of mixing chamber fabrication from an early stage of raw material to the final completion of machining.

After the final completion of machining, the surface of the components was rough and had to undergo subsequent surface finishing processes to improve the surface condition. For aluminium components, the required surface finished was achieved by grinding process. In the case of Perspex-based component i.e the injector, a special process called smoothing was deployed using a hand tool called "file" to prevent the Perspex from being excessively ground in the process. Eventually, the polishing process was applied to achieve the desired surface finish of the Perspex component. Figure 7 shows a comparison of discharge cap before and after completion of surface finishing to show justice of the various processes applied.


(a) (b)

Figure 6 Picture of mixing chamber (a) as raw perspex rod and (b) after completion of machining

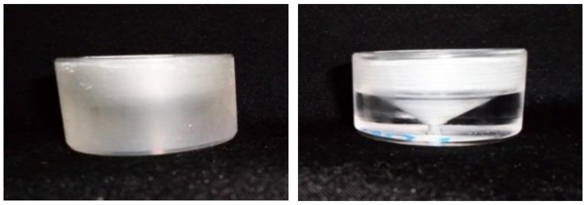

(a) (b)

Figure 7 Discharge cap (a) before and (b) after surface finishing process

5.0 EXPERIMENTAL METHODS

5.1 Injector Performance Test

An experimental test rig was constructed to examine the injector performance. Water was used as the working fluid and nitrogen as the atomizing gas. A line diagram and photograph of the test-rig are shown in Figure 8 and 9 respectively. A centrifugal pump was utilized for delivering water from the water supply tank to the atomizer through the water-line. Ball valve was installed at the pump outlet to control the amount of water flowing out of the pump. Pressure regulator was used for controlling the amount of gas flow from the nitrogen gas cylinder to the atomizer. Measurement of water flow rate and gas flow rate in the system was obtained from water flow meter and gas flow meter respectively. The flow of both water and gas were controlled by globe valves. Water strainer was installed at the inlet of water flow meter to prevent unwanted debris passing through the meter which could cause malfunctioned. Water and gas injection pressures were measured by digital pressure gauges. Water flow and gas flow check valves were installed at the inlet of the injector to allow only one-direction flow. The injector was fixed in vertical downward position and produce water sprays into a water collection tank. A submersible pump delivered the water back into the water supply tank to complete the cycle. The water flowrate was held at a constant value. The video recordings of the resultant sprays produced were captured by a high-speed video camera with 800x600 resolutions at 1000 frames per second. The shutter speed was set to a maximum value of 5μs. Shadowgraph technique was deployed in acquiring the resultant sprays video recordings. The video recordings obtained via data acquisition were converted to image sequences for further processing

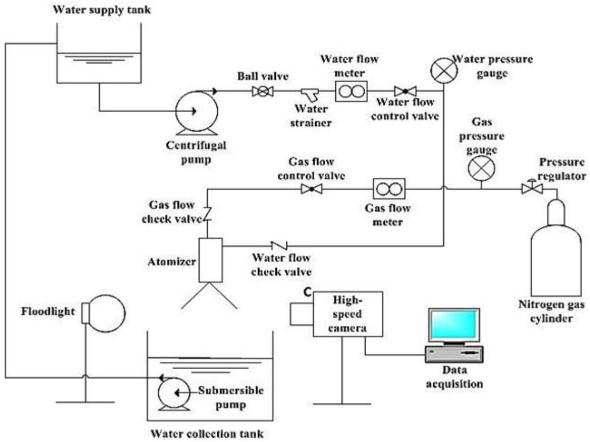


Figure 8 Line diagram of test rig

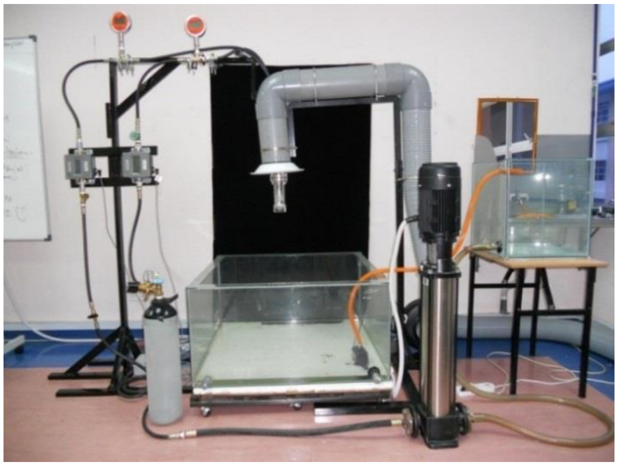


Figure 9 Photograph of test rig (without high-speed camera, floodlight and data acquisition)

5.2 Spray breakup length measurement

The spray breakup is quantified in terms of the distance of bubble bursting prior to the discharge orifice. Using ImageJ, measurement of the distance was performed by constructing a vertical straight line (red line) from the discharge orifice till the point of bubble bursting occurs as depicted in Figure 10. Since spray breakup was influenced by the conditions of the bubbles inside the mixing chamber, the spray breakup length was measured only when there were gas bubbles passing through the discharge orifice. This phenomenon is called bubble bursting. In Figure 11, two common types of flow may be observed passing through the orifice. Figure 11(b) illustrates the two-phase flow condition necessary for bubble bursting to occur.

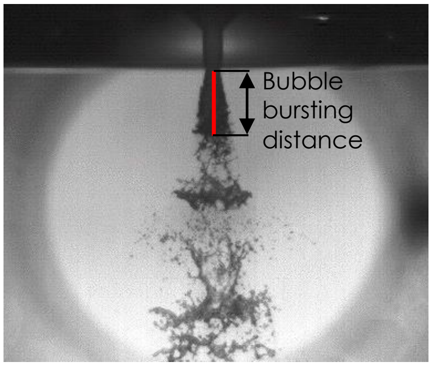


Figure 10 Measurement of bubble bursting distance

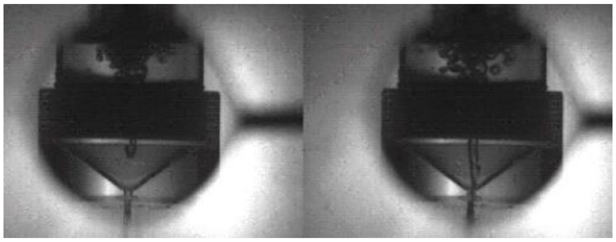

(a) (b)

Figure 11 Images showing (a) single phase and (b) two-phase flow through discharge orifice at different time instants

6.0 PRELIMINARY RESULTS AND DISCUSSIONS

Figure 12 illustrates the effect of GLR on the spray breakup length. It was observed that the breakup length was found to decrease with increasing GLR. The spray breakup length shortened to 12.14mm as the GLR reached 0.9×10^{-3}. This is probably caused by the size of the gas bubbles formed inside the mixing chamber [2]. Sovani *et al.* [8] stated the key feature of an effervescent atomizer that is, on discharging the atomizer, the gas bubbles experience pressure relaxation and expand rapidly, thereby shattering the liquids into droplets. Bubbles with larger diameter formed inside the mixing chamber tend to burst nearer to the discharge orifice because it experience higher pressure drop as it leaves the atomizer. Since the size of the gas bubbles is governed by the rate of gas injected, a higher GLR resulted in the production of a shorter breakup length.

In Figure 12, results on the resultant spray breakup length obtained in the present study at every GLR are shorter than those reported in Gadgil and Raghunandan [2]. The percentage difference in the break up length is shown in Table 2. The difference is believed due to the presence of swirl-generating vanes in the new design. The effect of vane angels on the break up length has been reported but for other atomizer designs. For the newly design atomizer in this study, a similar investigation is to be conducted in future to further understand the effect of swirl-generating vane on atomization behavior.

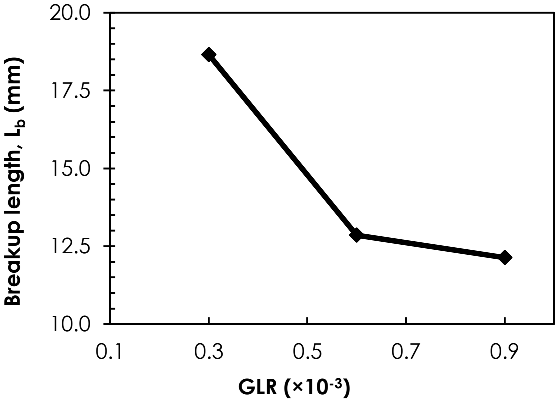


Figure 12 Effect of GLR on breakup length

Table 2 Comparison of the spray breakup length between present study and Gadgil and Raghunandan study

GLR ($\times10^{-3}$)	Present study {A}	Gadgil and Raghunandan {B}	Percentage Differences ({B}-{A}) (%)
~0.3	18.65mm	38.0mm	50.90
~0.6	12.85mm	33.5mm	61.64
~0.9	12.14mm	27.5mm	55.85

7.0 CONCLUSIONS

The development of a new swirl effervescent injector starting from design stage until fabrication was successfully performed. The parametric (geometry and operating conditions) comparison among 4 existing injectors was carried out during the design process, hence, resulting in a new injector desgin with improved performances. Results have shown that the introduction of the swirl-generating vane prior to the discharge orifice has assisted in shortening the spray breakup length at any amount of GLR. Shorter break up length is desirable in many applications such as in engine combustion and coating as it promotes efficient processes and operation. This purpose built injector is to facilitate more investigations related to swirl effervescent type in further studies. Other performance parameters investigated are discussed in future papers.

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References

[1] Ghaffar, Z. A., A. H. A. Hamid, and M. S. F. M. Rashid. 2012. Spray Characteristics of Swirl Effervescent Injector in Rocket Application: A Review. *Applied Mechanics and Materials*. 225: 423-428.

[2] Gadgil, H. and B. N. Raghunandan. 2011. Some Features of Spray Breakup in Effervescent Atomizers. *Experiments in Fluids*. 50: 329-338.

[3] Hamid, A. H. A. and R. Atan. 2009. Spray Characteristics of Jet–swirl Nozzles for Thrust Chamber Injector. *Aerospace Science and Technology*. 13: 192-196.

[4] Hussein, A., M. Hafiz, H. Rashid, A. Halim, W. Wisnoe, and S. Kasolang. 2012. Characteristics of Hollow Cone Swirl Spray at Various Nozzle Orifice Diameters. *Jurnal Teknologi*. 58: 1-4.

[5] Jagannathan, T. K., R. Nagarajan, and K. Ramamurthi. 2011. Effect of Ultrasound on Bubble Breakup Within the Mixing Chamber of an Effervescent Atomizer. *Chemical Engineering and Processing: Process Intensification*. 50: 305-315.

[6] Ow, C. S. 1980. *Studies of Two-Phase Turbulent Pipe Flow*. PhD Thesis. Mechanical Engineering Department, Imperial College, London.

[7] Ghaffar, Z. A., S. Kasolang, and A. H. A. Hamid. 2014. Characteristics of Swirl Effervescent Atomizer Spray Angle. *Applied Mechanics and Materials*. 607: 108-111.

[8] Sovani, S. D., P. E. Sojka, and A. H. Lefebvre. 2001. Effervescent Atomization. *Progress in Energy and Combustion Science*. 27: 483-521.

[9] Jedelsky, J., M. Jicha, J. Slama, and J. Otahal. 2009. Development of an Effervescent Atomizer for Industrial Burners. *Energy & Fuels*. 23: 6121-6130.

[10] Rahman, M. A., M. Balzan, T. Heidrick, and B. A. Fleck. 2012. Effects of the Gas Phase Molecular Weight and Bubble Size on Effervescent Atomization. *International Journal of Multiphase Flow*. 38: 35-52.

[11] Lefebvre, A. H. 1988. A Novel Method of Atomization with Potential Gas Turbine Applications. *Defense Science Journal*. 38: 353-361.

[12] Rashid, M. S. F. M., A. H. A. Hamid, O. C. Sheng, and Z. A. Ghaffar. 2012. An Experimental Investigation on the Effect of Various Swirl Atomizer Orifice Geometries on the Air Core Diameter. *Applied Mechanics and Materials*. 225: 32-37.