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Study of cold spray and combustion stability of effervescent atomizer

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Study of cold spray and combustion stability of effervescent atomizer

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Abstract. In the present work, an effervescent atomization spray system has been built with plain-orifice atomizer powered by (water / diesel fuel) and air as atomizing gas in the "inside-out" gas injection configuration. The investigation shows the influence of operation and design parameters on the spray cone angle, liquid mass distribution throughout the spray, flame blow-off and flame length. The gas to liquid mass ratio (GLR) varies from 0.3% to 15%, the liquid mass flow rate varies from 0.5 to 10 g/s and the operating pressure varies from 1 to 6 bar. The results show that spray cone angles lie in the range of 15-22º for all gas to liquid ratios, length to diameter ratios and operating pressures. Liquid mass distribution at different axial distances downstream of the atomizer becomes more uniform at lower (L/D) ratio and higher gas to liquid ratio. Increasing (A/F) ratio leads to decreasing flame length. Moreover, an empirical correlation of cone angle with operating and design parameters has been developed.

Keywords: Twin-fluid; Effervescent atomizer; Cone angle; mass distribution; Blow-off; Flame length.

Nomenclature

GLR	Gas to liquid mass ratio	[%]	ρ	Density	[Kg/m^3]
P_{inj}	Injection pressure (g)	[bar]	σ	Surface tension	[N/m]
L	length of exit orifice	[mm]	μ	Viscosity	[Kg/m.s]
D	Orifice exit diameter	[mm]	r	radial distance	[mm]
SMD	Sauter mean diameter		H	axial distance	[mm]
$\mathring{m}/A$	Liquid mass flux	[$g/s.mm^2$]	A/F	Air to fuel mass ratio	[Kg_{air}/Kg_{fuel}]
α	Spray cone angle	[degree]			

1. Introduction

Effervescent atomizer is a type of twin-fluid atomizers, where a small amount of gas mixed with liquid before injection from the exit orifice of the atomizer. The main advantage of this atomizer is the good atomization at lower injection pressure with a small amount of gas. The good atomization means a spray with small drop sizes and uniform mass distribution of the liquid. As a result, in combustion application, lower products emissions are obtained. [1]

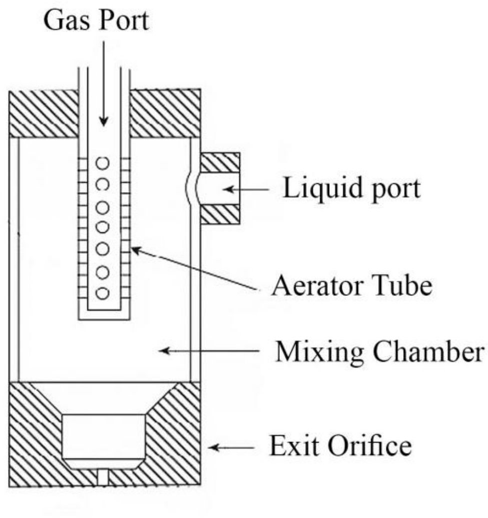

Figure 1. Effervescent atomizer “inside-out”.

Effervescent atomizer consists of four components according to its configuration as shown in figure 1 (liquid port – gas port – mixing chamber – exit orifice). The gas is supplied to the atomizer from the top port and flows through the aerator. The liquid is supplied to atomizer chamber from anther port. The gas is injected into the mixing chamber from the aerator. The mixture of gas and liquid flows down and injected through the exit orifice. The gas pressure is slightly higher than the liquid pressure to overcome the pressure drop across the aerator holes. At orifice exit the flow is exposed to sudden pressure drop and the jet of flow expand rapidly and shattering the liquid into drops. [2]

Huang et al. [3] observed that there are three regimes of flow inside the effervescent atomizer as shown in figure 2 (the bubbly flow, slug flow and annular flow). The results show that, the three flow regimes are GLR dependent. The bubbly flow is occurred at lower GLR. When increasing GLR the flow transit to slug flow. Further increasing of GLR leads to transform the flow to annular regime.
Ramamurthi et al. [4] and linne et al. [5] noted that the bubbly flow occurred at GLR ranged from 0.01 to 0.2, further the slug and annular flow occurs at higher GLR (above 0.2). Lefebvre and co-works [6] were the first using the effervescent atomization technique in 1988 as “Aerated liquid atomization”.

The atomization process of interest in most applications are drop size distribution, drop velocity distribution, spray cone angle and liquid mass distribution throughout the spray. [7]

The spray characteristics depend on liquid physical properties (i.e. density- surface tension-viscosity), operating condition (i.e. GLR – injection pressure) and atomizer design and configuration (i.e. inside-out / outside-in gas injection – size and number of aerator holes – mixing chamber size – length and diameter of exit orifice).

Chen and Lefebvre [8] studied the influence of liquid physical properties on spray cone angle at low injection pressure. The results show that, the cone angle increases with increasing of Gas/liquid ratio (GLR) up to certain value. Further increase in GLR leads to decrease the spray cone angle. The decrease in spray cone angle is due to change in flow regime with increase GLR of the flow inside the atomizer, where the flow transit from bubbly to annular flow.

This behavior is studied with ‘inside-out’ effervescent atomizer by Ochowiak et al. [9]. They noted that the spray cone angle reached its maximum value where GLR becomes 0.07. Further increase in GLR leads to decrease the spray cone angle.

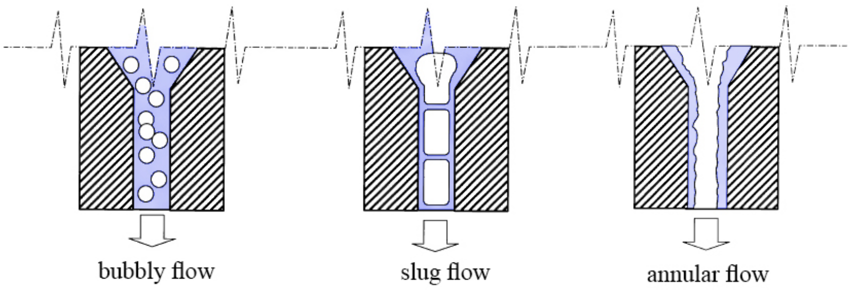

Figure 2. Flow regimes in the discharge orifice. [7]

Sovani et al. [10] and wade et al. [11] noted that spray cone angle increases with an increase in injection pressure. The results show that spray cone angle lies between 11.6 and 23° for all parameters studied, and increases linearly with increasing injection pressure at all ambient pressures.

Ochowiak et al. [12] studied the influence of atomizer internal geometry and liquid physical properties on spray cone angle at low gas / liquid ratio (GLR). The authors noted that the highest value of spray cone angle occurs by using profiled exit orifice.

The liquid mass distribution throughout the spray is important in many applications (i.e. combustion applications, paint and agricultural purposes). In combustion, the heat release and emission concentration depend on fuel distribution throughout the spray.

Lefebvre and whitlow [13] observed that the liquid mass flux increases with increase in radial distance from spray axis, reached maximum value at half distance between the spray boundary and its axis. Moreover, they found that, the liquid mass flux decreases with increasing radial distance.

Drop size distribution and drop velocity distribution have been investigated in most of effervescent atomization studies. However, a little information is available about the effect of the atomizer internal geometry, axial distance downstream of the atomizer and injection pressure on the radial distribution of liquid mass flux.

The flame speed is an important property of the flame which plays an important role in some phenomena such as flash-back, blow-off and blow-out. Mavrodineanu et al. [17] and Manhou et al. [18] studied several combustion characteristics which played a role in the radiation of flames. The limits of flammability of various combustible mixtures.

Kim et al. [19] noted that the flame length was found to decrease with increased oxygen velocity due to higher turbulent mixing. At higher (A/f) ratio condition the flames become shorter and non-sooting.

In the present work, the spray and combustion characteristics produced by an effervescent atomizer is investigated experimentally at different designs and operating conditions for achieving clean combustion with high efficiency. The experimental work investigates spray characteristics (***Cold study***) and combustion characteristics (***Hot study***). The part of cold study investigates the spray cone angle and liquid mass distribution throughout the spray cone. As well as an empirical correlation of cone angle with operating and design parameters has been developed. While, the hot (combustion) section investigates the combustion process, combustion stability and flame length.

2. Experimental set-up

The effervescent atomizer used in the present work is a plain-orifice atomizer, made from steel and “inside-out" configuration, where the air is injected into the mixing chamber from the aerator. The water surrounds the aerator as shown in the figure 3. The atomizer cross section area is cylindrical shape of 40 mm diameter. The internal diameter of the mixing chamber is 20 mm. The aerator is made from steel tube with 5mm inner diameter. A two air injection holes of 0.5 mm diameter were drilled at 5 mm from the aerator end. The aerator holes are located 15mm from orifice exit.

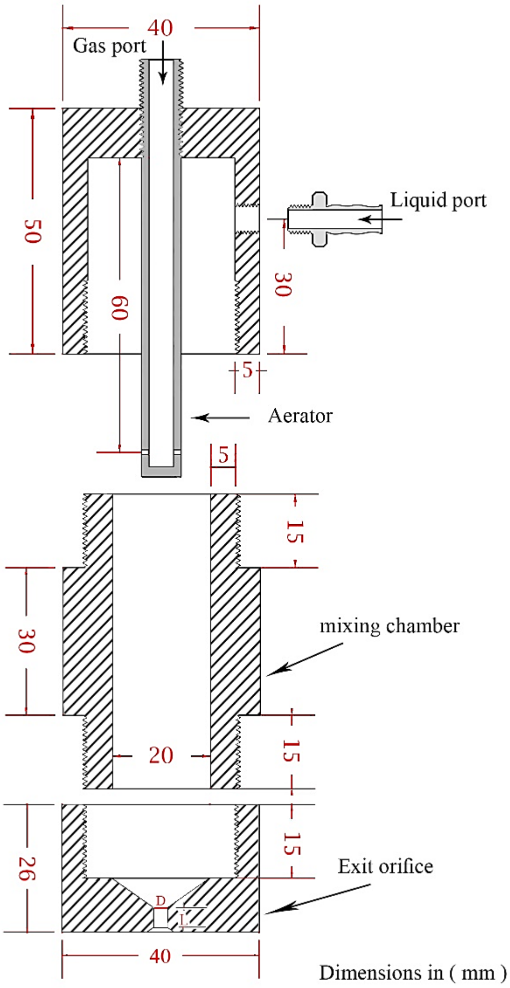

Figure 3. Effervescent atomizer tested.

Layout of experimental test rig is illustrated in figure 4. Atomizer is supplied by air from large screw compressor equipped with large capacity air vessel. Vessel pressure is kept constant via pressure regulator. This configuration ensures steady liquid flow to the atomizer. The pressures of (liquid - air) are controlled by pressure regulators. The injection pressure is measured by pressure gauges mounted close to the atomizer. The air pressure is slightly higher than the water pressure to overcome the pressure drop in the aerator holes. In present experimental work, the operating pressure varies from 1 to 6 bar. The atomizing air pressure is slightly higher of the liquid pressure. Therefore, check valve is used to prevent the water from flowing back. The flow rates for both liquid and air are controlled by adjusting pressure regulators. The flow rates are measured by calibrated orifice flow meter. Three nozzle cups with different orifice diameters are used in the present experimental work. Orifice dimensions of the cups are given in the following table.

Table 1 Nozzle dimensions

D (mm)	L (mm)	L/D	θ °
1	5	5	45
2	5	2.5	45
3	5	1.67	45

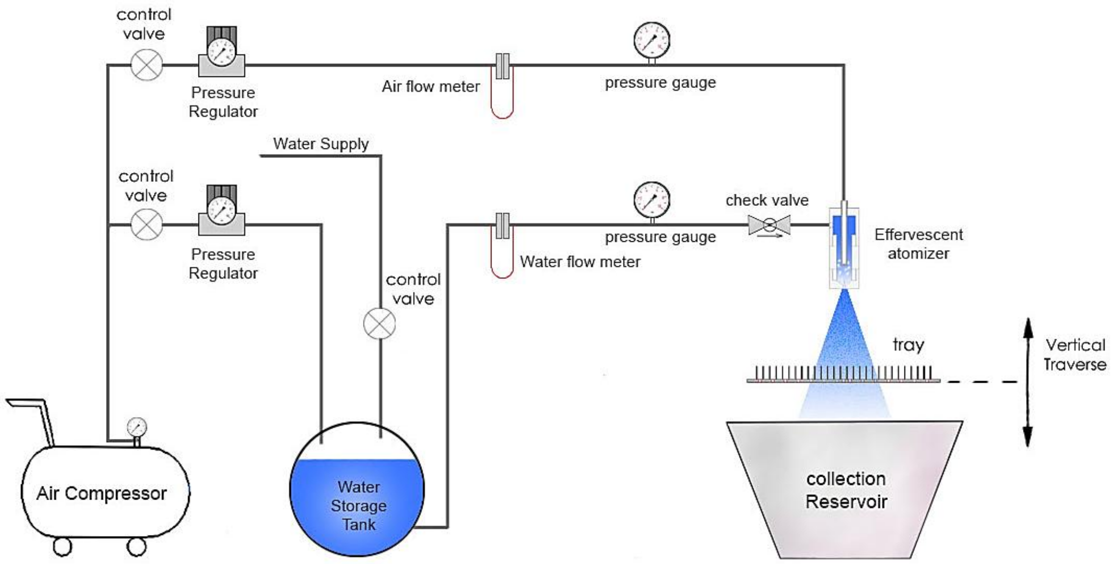

Figure 4. Schematic diagram of experimental set-up.

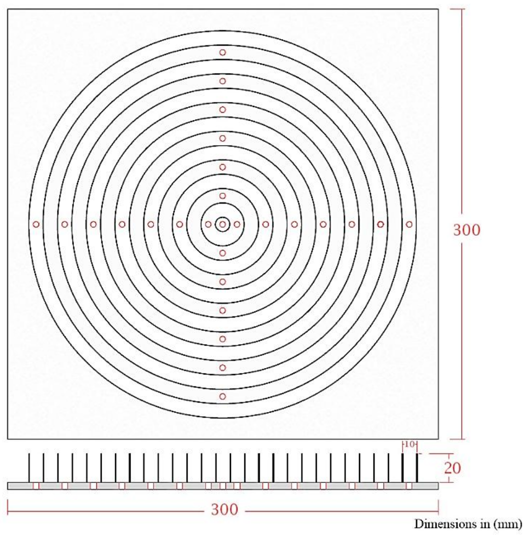

Figure 5. Schematic diagram of the Tray.

A circular tray is employed to collect the amount of spray droplets at different spray cross section. The tray has uniform width ring grooves as shown in figure 5. This design enables the measurement of radial mass distribution as well as the mass flux. Vertical traverse mechanism is used to locate the tray at different heights from injector nozzle. The base of the tray made from acrylic with cross section 300*300 mm. A steel rings with height 20 mm are fixed on the tray base to form plate. The rings diameter varies from 10 to 300 mm with step 10 mm from ring to another. Two holes are drilled in base between every two rings with diameter 5mm to collect water in sampling tubes. Spray cone angles and flame length were measured by capturing images using full frame DSLR camera. The spray cone angle was measured by image processing software developed by talon [14].

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The accuracy of software depends on pixel size which is as small as 10 µm. Spray cone angles and flame length were measured by capturing images using full frame DSLR camera. The spray cone angle was measured by image processing software developed by talon [14]. The accuracy of software depends on pixel size which is as small as 10 µm. Figure 6. Shows samples of spray images at different operating condition. The images show that the spray boundary is not well defined because of blurriness showed near the spray edge. The population of small droplet size increases near spray boundary. Accordingly, they lose their momentum rapidly and their motion become dependent on turbulence of entrained air. Which in turn reflects a random radial motion near the spray boundary and this is the reason for blurriness showed at spray boundary. Therefore, software depends on measuring the variation in contrast to define the spray boundary.
Experimental errors associated with the present investigation result from a number of sources including systematic measurement errors, and errors arising from the fluctuations is found in the pressure drop across orifice meter. Uncertainty of Atomizing air mass flow rate, Fuel mass flow rate, Combustion air mass flow rate, Flame Length, Spray cone angle are ± 0.85 %, ± 1.11 %, ± 0.16 %, ± 0.5 mm, 0.05 ˚ respectively.

(a) (b) (c)

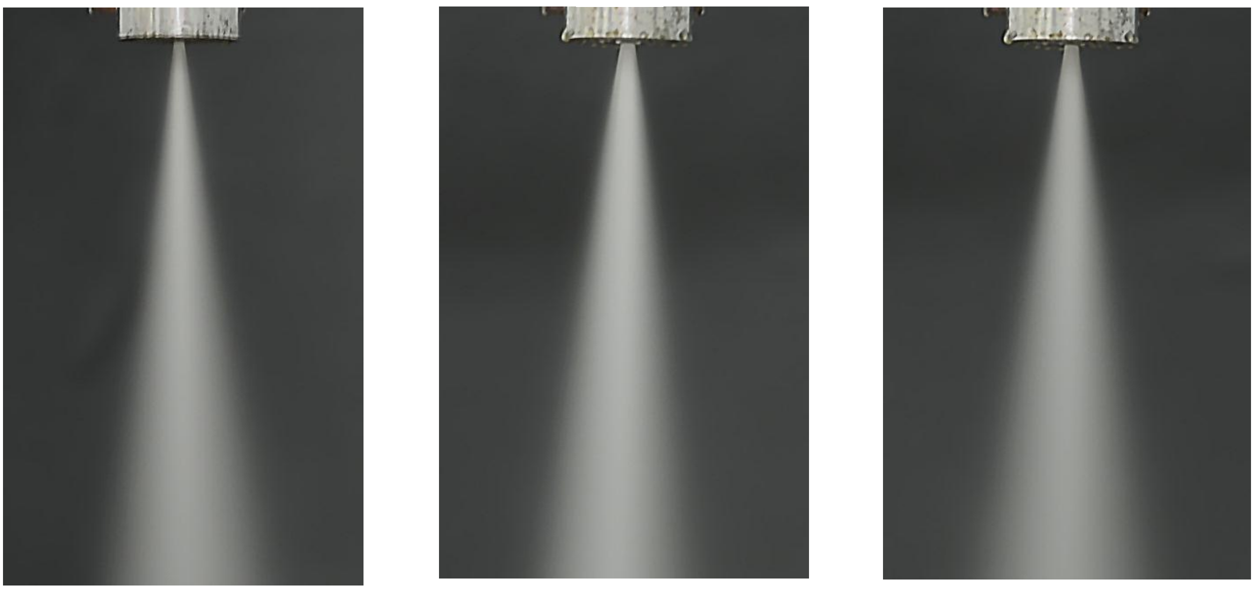

Figure 6. Representative spray images at different conditions. (a) D=2 mm, P=4bar, GLR=5% (b) D= 3 mm, P= 6 bar, GLR= 1 % (c) D= 3 mm, P= 5 bar, GLR=2 %

3. Results and discussion

3.1. Spray cone angle (α)
In present experimental work, spray cone angle is assigned at different GLR, (L/D) ratio and injection pressure. The results are summarized as follows.

3.1.1. Influence of GLR
The spray cone angle (α) is plotted versus GLR at constant injection pressure (p_{inj}) as shown in figure 7. The four curves at different constant injection pressure using orifice diameter D=3mm. Until GLR reach 2% the flow regime is bubbly flow. The volume of bubbles inside the atomizer expand downward due to decreasing the pressure gradually until the bubbles Explodes at the exit orifice and atomizing the liquid. At this flow regime (bubbly flow) the increasing of GLR increases the bubbles then the spray widens. Furthermore, the increasing of GLR changes the flow regime into annular flow.

The liquid squeezed between atomizing gas and inner wall of exit orifice. The liquid velocity increases at exit orifice due to decreasing the cross section of the liquid. The momentum of the liquid droplets in axial direction is greater than the radial direction. Therefore, the spray cone angle decreases.

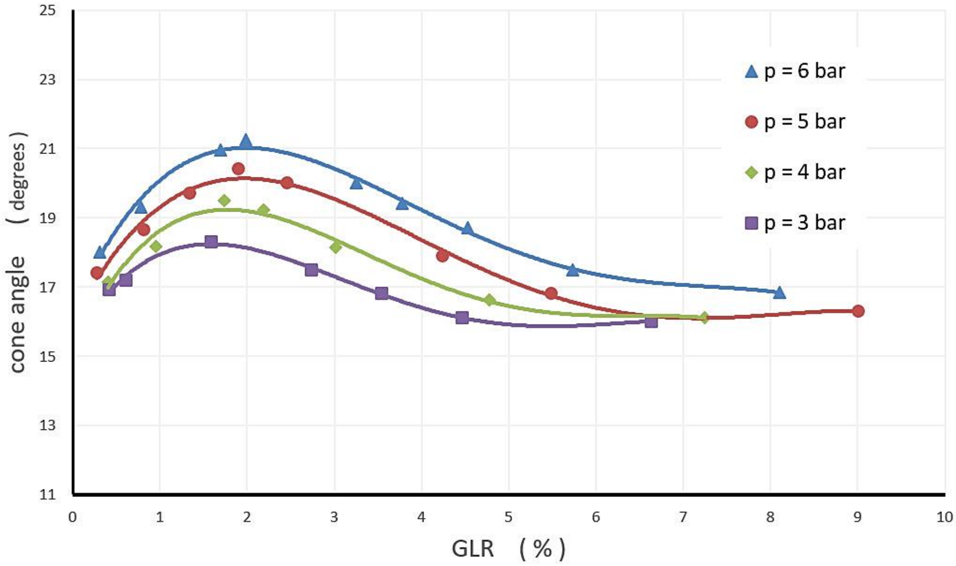

Figure 7. Variation of spray cone angle with injection pressure and GLR with D= 3 mm.

3.1.2. Influence of (L/D) ratio.

Figure 8. shows the variation of (L/D) ratio on spray cone angle at different GLRs at constant injection pressure p_{inj} =4 bar. The large exit orifice allows large number of bubbles to pass through the exit orifice together. In small exit orifice, the bubbles through the exit orifice one by one with small diameter. Therefore, the large exit orifice increases the spray cone angle in bubbly flow.

In annular flow, the degree of freedom of liquid motion increases at large exit orifice diameters. The amount of atomizing air increases with increasing exit orifice diameter. Therefore, the spray cone angle increases with increasing exit orifice diameter.

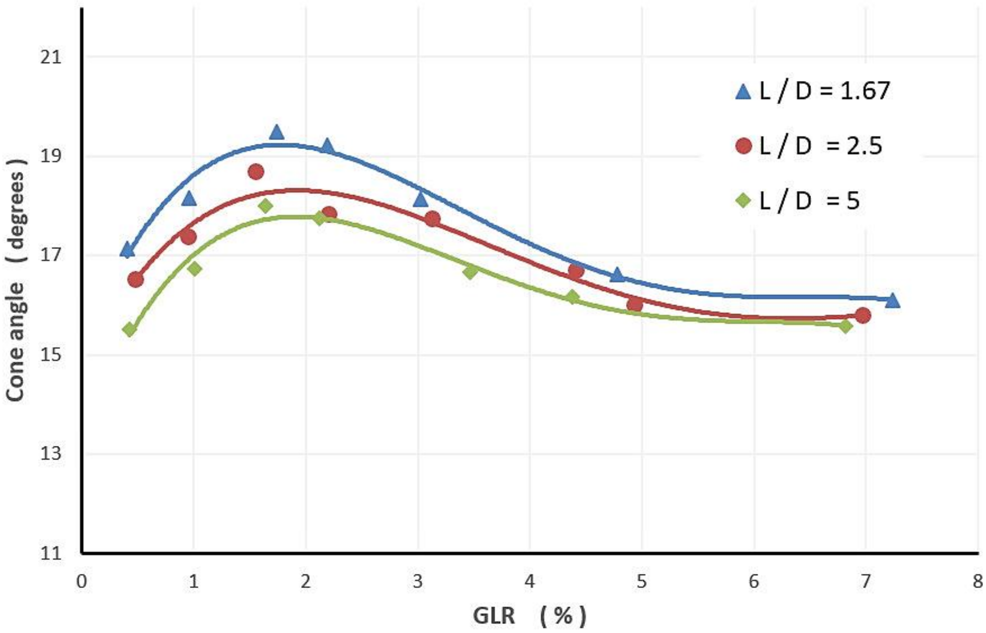

Figure 8. Variation of spray cone angle with (L/D) and GLR at p_{inj} = 4 bar.

3.1.3. Influence of injection pressure

Figure 9. shows the effect of injection pressure (g) on the spray cone angle at different GLRs using orifice diameter D=3mm. The increasing of injection pressure increases the bubbles pressure respectively. Furthermore, the difference between bubbles pressure and ambient air increases. This leads to higher expansion ratio. The available energy of the bubbles increases the spray cone angle as shown in figure (9-a). In annular flow, the increasing of injection pressure increases the flow velocity and turbulence of the flow. The air turbulence makes a wavy surface of the liquid and energy transfer of the liquid. Therefore, the rate of increasing of spray cone angle in bubbly flow is higher than the rate of increasing in annular flow.

3.1.4. Correlation

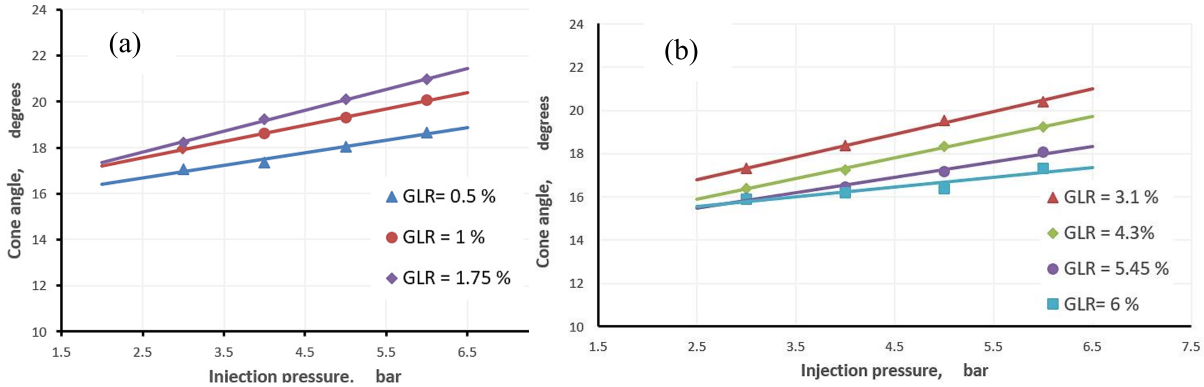

Figure 9. Effect of injection pressure on spray cone angle at different

The following empirical correlation was developed based on the experimental results at different GLR, (L/D) and injection pressure.

$$\alpha = 14.077 \times \left(\frac{L}{D}\right)^{0.0775} \times p_{inj}^{\,0.17} \times GLR^{0.0802} \qquad 0.3\% < GLR < 2\% \text{ (bubbly flow)}$$

$$\alpha = 16.588 \times \left(\frac{L}{D}\right)^{-0.0484} \times p_{inj}^{\,0.196} \times GLR^{-0.145} \qquad 2\% < GLR < 10\% \text{ (annular flow)}$$

where (α) is the spray cone angle in degrees, (L/D) is the length to diameter ratio of nozzle, GLR is gas to liquid ratio by mass in % and (p_{inj}) is injection pressure in bar. The two relations predict the spray cone angle at different flow regime (bubbly - slug - annular). Figure 10 shows calculated cone angle using this correlation against the measured cone angle. This correlation is accurate to 5.5 % (standard deviation of error).

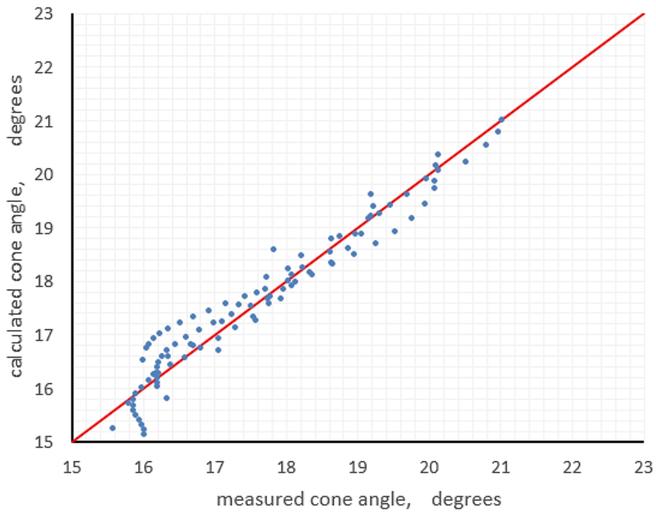

Figure 10. Correlation accuracy plot.

3.2. Mass distribution

Mass distribution (radial - axial) throughout the spray cone is important in many applications. Especially in combustion systems, where mass distribution effects on local equivalence ratio, local temperature, heat release rate, emissions and combustion efficiency.

3.2.1. Influence of GLR

The liquid mass percentage (%) and mass flux (g/s.mm^2) are plotted versus radial distance (mm) at Constant injection pressure p= 2.5 bar, H=200 mm, and D=1 mm as shown in Figure 11(a-b). The liquid mass percentage increases with increasing radial distance until the half distance between the spray axis and outer edge of the spray. After the main peak the Liquid mass percentage decreasing making the tailing. The increasing of GLR decreases the droplets mean diameter (SMD) [16] and increases the spray cone angle. Therefore, the increasing of GLR makes main peak lower and moving to the outer edge of the spray. Comparing with schroeder and sojka [14] the results show that the volumetric density distribution increases with increasing radial distance reaching main peak, then decreasing making the tailing. The mass flux decreases with increasing radial distance as shown in figure 11-b. the liquid mass flux depends on the liquid velocity. Therefore, the liquid drops velocity decreases with increasing radial distance.

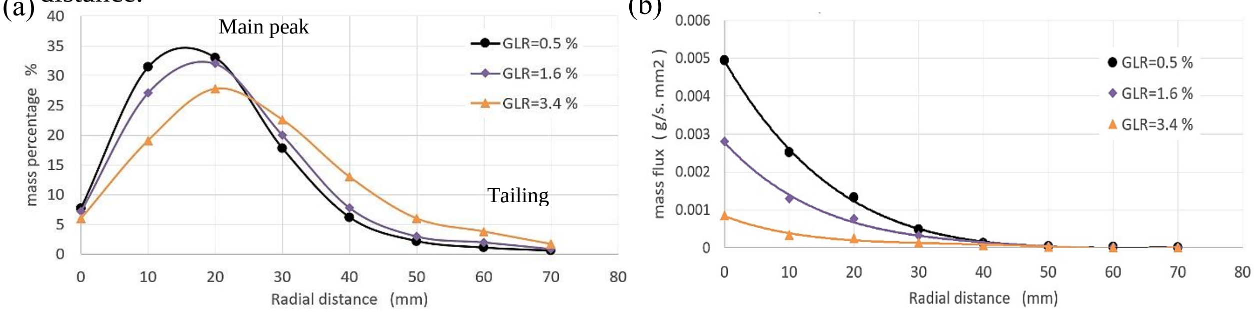

Figure 11. Effect of GLR on liquid mass distribution and mass flux.
at p_{inj}=2.5 bar, H=200 mm and (L/D) =5

3.2.2 Influence of injection pressure

Figure 12(a-b) shows the effect of injection pressure on mass distribution and mass flux at constant GLR= 1%, H=200 mm and D=3 mm. The increasing of injection pressure increases the axial velocity of liquid drops. Therefore, the increasing of injection pressure increases the mass flux.

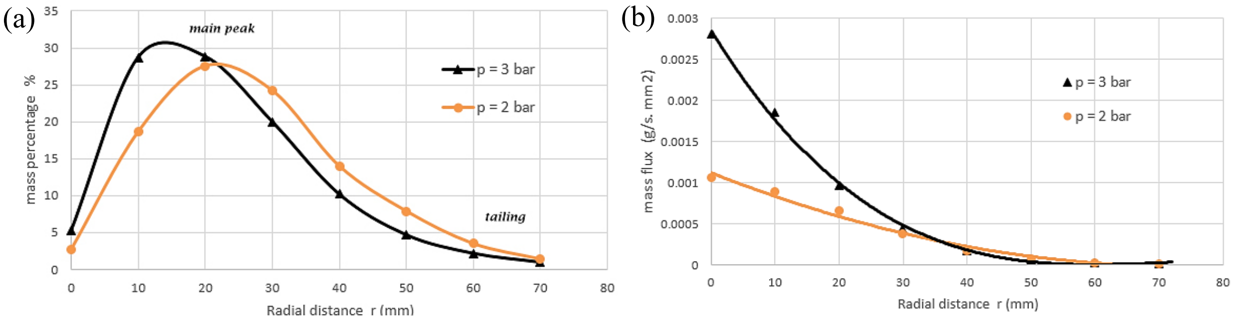

Figure 12. Effect of injection pressure on mass distribution and mass flux
at GLR=1%, H=200 mm and (L/D) =1.67

Figure 12-a shows that the increasing of injection pressure makes the main peak higher and moving towards the spray axis.

3.2.3. Influence of (L/D) ratio

Figure 13(a-b) shows the effect of (L/D) ratio on mass distribution and mass flux at constant GLR= 0.5 %, H=200 mm and p_{inj} =2 bar. The increasing of exit orifice diameter decreases the axial velocity of liquid drops. Therefore, the increasing of orifice diameter leads to uniform mass distribution along radial distance of the spray. Moreover, the increasing of orifice diameter makes main peak lower and moving to the outer edge of the spray.

3.2.4. Influence of axial distance

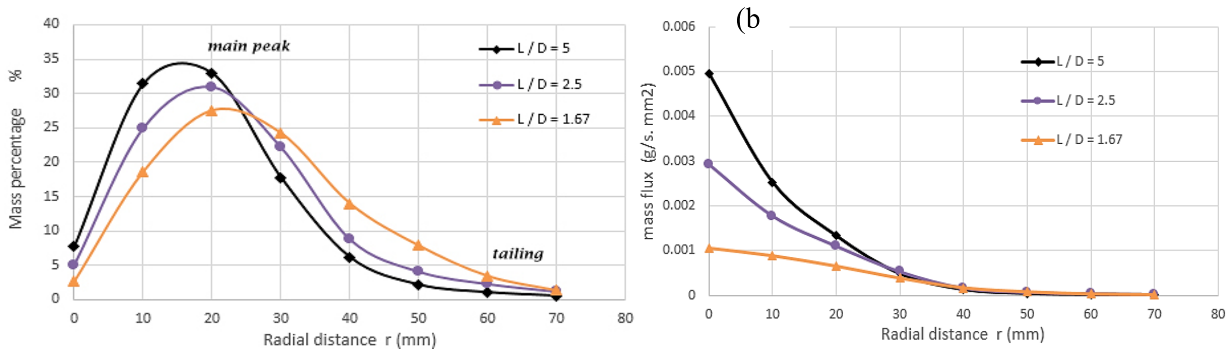

Figure 13. Effect of (L/D) ratio on mass distribution and mass flux.
at p_{inj} = 2 bar, GLR = 0.5 % and H = 200 mm

The mass distribution was measured at three location downstream the exit orifice (H=100 mm, H= 200 mm, H= 300 mm) throughout the spray cone. Figure 14(a-b) shows the effect of axial distance on mass distribution and mass flux at constant injection pressure p= 3 bar, GLR= 3 % and D= 2 mm. the spray cone widens at the cone base. Therefore, the increasing of axial distance (H) makes the main peak lower and shifting to the outer edge of the spray. Figure 14-b shows that the liquid mass flux becomes uniform distribution with increasing axial height (H) due to the secondary atomization of drops and dispersion of drops.

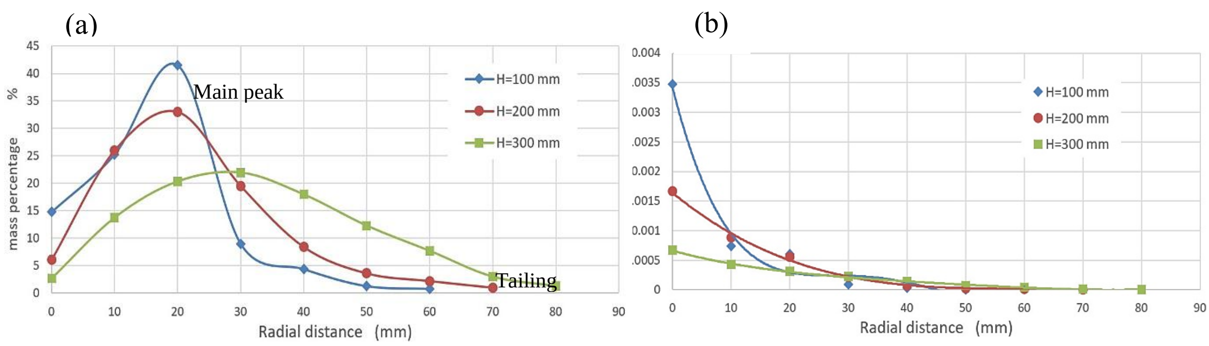

Figure 14. Effect of axial distance on mass distribution and mass flux.
at p_{inj} = 3 bar, GLR = 3 % and (L/D) = 2.5

3.3. Flame length.

Flame Length is an important characteristic of diffusion flames. Therefore, the hot (combustion) study investigates the combustion process, combustion stability and flame length.

3.3.1. Influence of GLR ratio.

As mentioned before in Figure 7 increasing of GLR leads to increasing on spray cone angle in bubbly flow. Moreover, the increasing of GLR makes liquid mass distribution more uniform with small drop size as shown in Figure 11 That explain, the increasing on GLR leads to good mixing of fuel with air and good combustion process with non-smoke flame. Figure 15 shows the influence of GLR ratio on flame length at constant A/f ratio= 25 and p_{inj} =2 bar with orifice diameter D=2 mm. Increasing of GLR decreases the flame length and widens the flame. Figure 16 shows the flame length and width at different GLR.

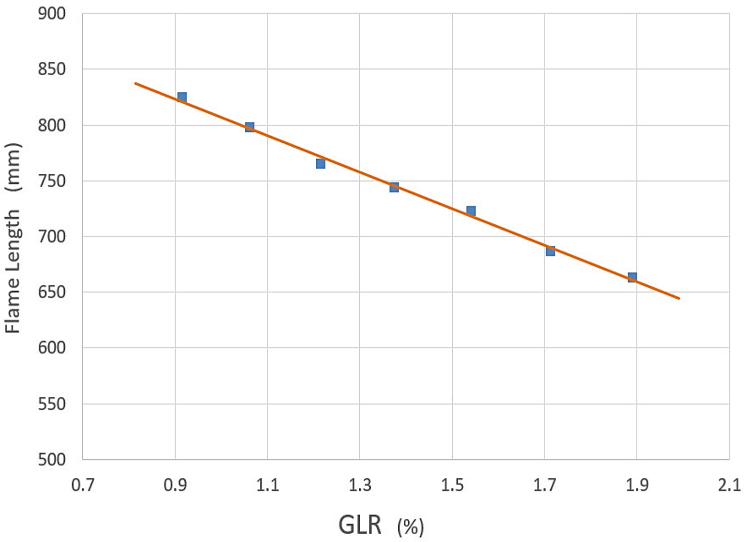

Figure 15. Effect of GLR on flame length
at A/F= 25, p_{inj} = 2 bar, D= 2 mm.

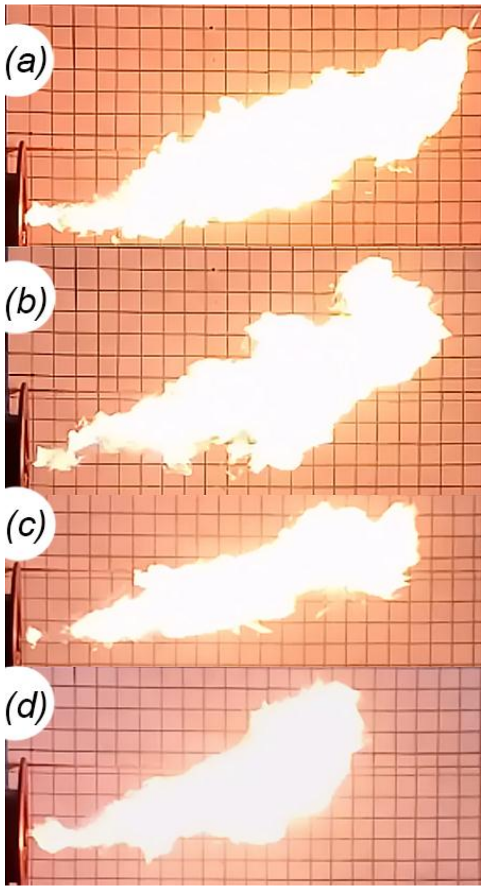

Figure 16. Representative combustion images at different GLRs.
(a) GLR= 0.91% (b) GLR= 1.06 %
(c) GLR= 1.2% (d) GLR= 1.54%

3.3.2. Influence of A/F ratio.

The main parameter effects on flame length is A/F ratio. Figure 17 shows the effect of A/f ratio on flame length at constant GLR= 1.46 %, p_{inj} =2 bar and orifice diameter D= 3 mm. The increasing on A/F ratio decreases the flame length. At small A/F ratio, the fuel needs to air to complete combustion. So, the flame stretches until all amount of fuel burned. The small amount of air leads to incomplete combustion and smoke appears with flame. Increasing of combustion air secures the necessary amount for complete combustion and non-smoke flame. Above that the turbulence of combustion air makes good mixing of air with fuel and increases combustion rate. Figure 18 shows the fuel combustion process in turbulent air; every drop of fuel makes a core of fire collected together making the flame. All fuel drops find the sufficient air to burn simultaneously. This behavior can be interpreted that excess air (A/F ratio is greater than 14) decreases the flame length.

3.3.3. Influence of injection pressure.

Effervescent atomizer achieves good atomization at small injection pressure compared with other atomizers. The increasing of injection pressure increases the spray cone angle as shown in Figure 9. Increasing of injection pressure increases the difference between air velocity and fuel drops due to change in their momentum. This change assist in fuel atomization. Figure 19(a-b) shows the influence of injection pressure on flame length. The increasing of injection pressure decreases the flame length. Because the increasing of injection pressure increases spray velocity and the fuel drops evaporation. The influence of injection pressure on flame length is less than the influence of GLR.

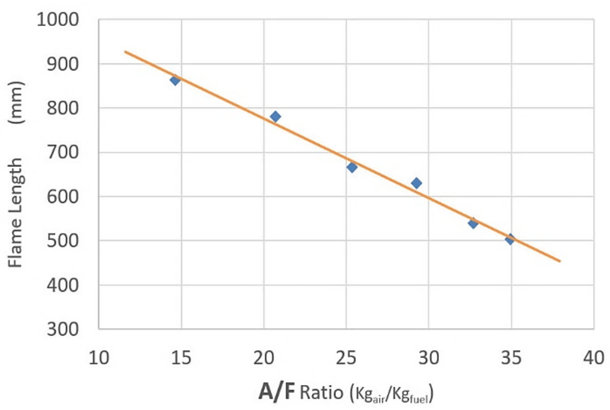

Figure 17. Effect of A/f ratio on flame length at GLR= 1.46 %, p_{inj} = 2 bar, D= 3 mm.

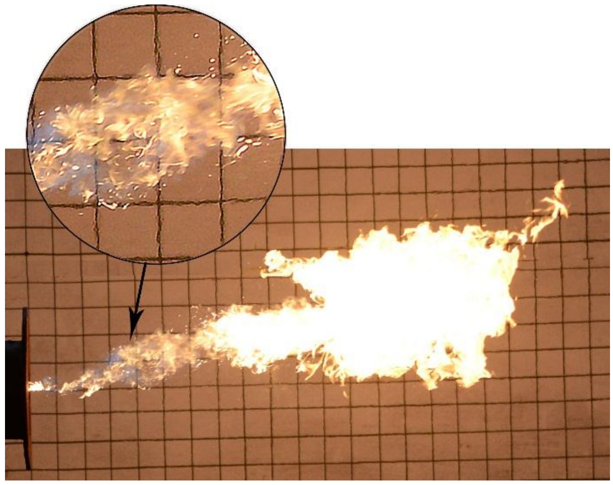

Figure 18. Representative image shows fuel droplet combustion.

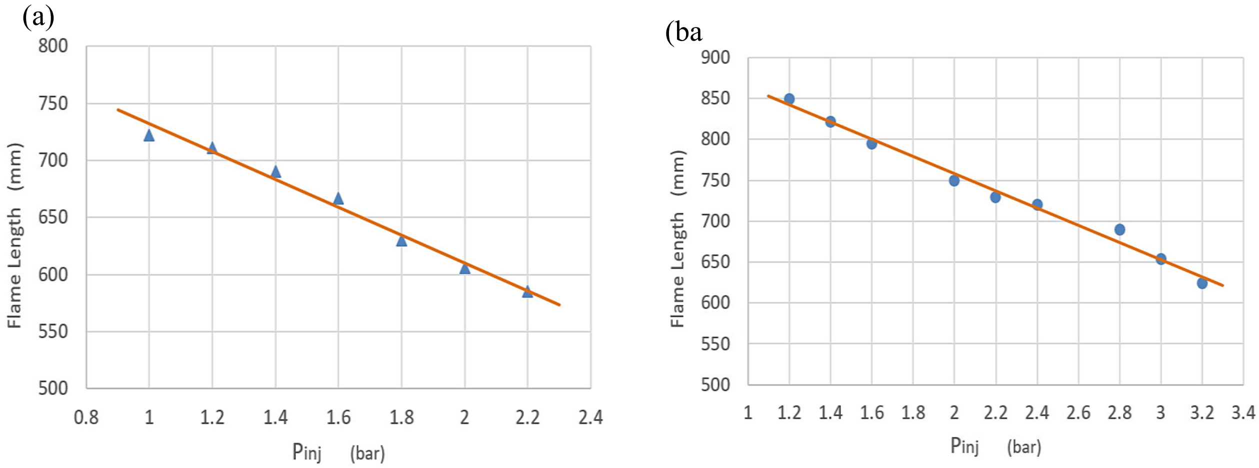

Figure 19. Effect of injection pressure on flame length
(a) GLR= 0.65 %, A/F = 17 and D= 1 mm. (b) GLR= 1.03 %, A/F= 20 and D= 3 mm.

3.3.4. Influence of L/D ratio

Figure 20 shows the influence of orifice diameter on the flame length at constant GLR= 1.46 % and p_{inj} = 2 bar. The increasing of orifice diameter decreases the flame length. As a result of increasing of orifice diameter increases spray cone angle as mentioned in Figure 8. The increasing on orifice diameter makes the mass of fuel distribution more uniform along the spray cone. The exit orifice diameter effects on combustion and flame length. Good atomization and combustion with non-sooting flame is achieved with large orifice exit diameter. This is one advantage of effervescent atomizer (b)

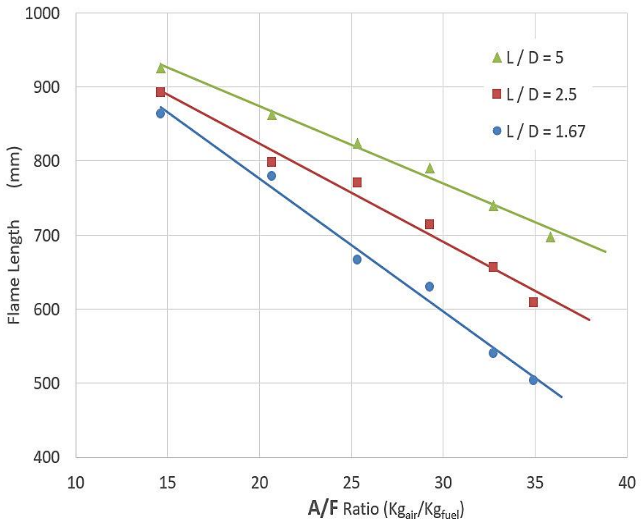

Figure 20. Effect of orifice exit diameter on flame length at GLR= 1.46 %, p_{inj} = 2 bar.

3.4 Combustion stability.

Providing stable flame at wide range of operating conditions is an obvious requirement of combustion. Usually, it means various A/F ratios, injection pressures, and temperatures. The flame speed is an important property of the flame which plays an important role in some phenomena such as flash-back, blow-off and blow-out. The injection pressure has a very strong influence on flame stability. Changing on injection pressure changes the overall flame stability limits. the increasing of injection pressure increases the drop velocity and decreases SMD of droplets. Achieving rapid fuel evaporation with high flame speed and good combustion with stable flame. Therefore, the increasing on injection pressure increasing the stability zone as shown in Figure 21.

Figure 22 shows influence of orifice exit diameter on flame stability. The increasing on orifice exit diameter increases the flame stability. As mention before, increasing on orifice exit diameter increases the spray cone angle. Achieving good mixing of fuel with air and stable combustion.

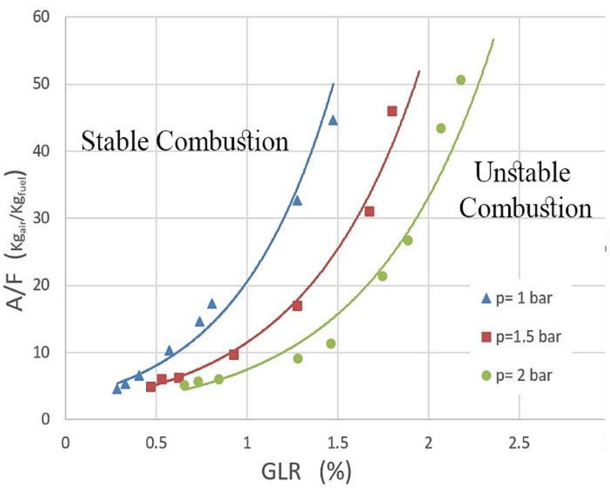

Figure 21. Effect of injection pressure on flame stability.

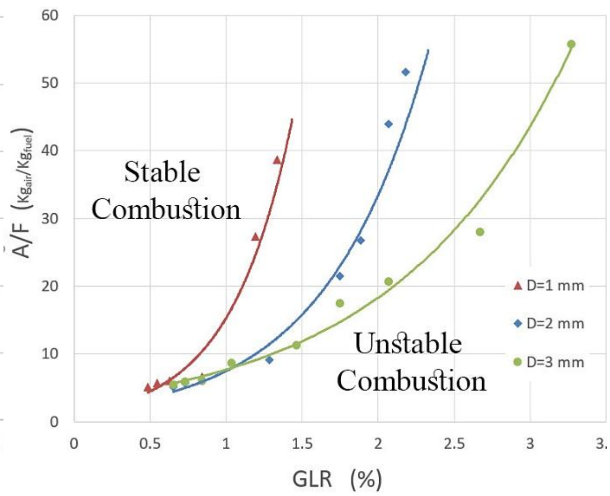

Figure 22. Effect of exit orifice diameter on flame stability.

4. Conclusion

The present work has been focused on characterizing a low-pressure spray produced by an effervescent atomizer at different operating and design condition.

1- The gas to liquid mass ratio (GLR) is the main parameter effects on the effervescent atomization. In bubbly flow, the spray cone angle increases with increasing of GLR, as available energy in the bubbles. The fuel mass flux becomes more uniform with increasing on GLR. Achieving good combustion with short stable flame. In annular flow, the spray cone angle slightly decreases with increasing of GLR. The increasing of GLR enhances the mass distribution throughout the spray cone and decreases the flame length.

2- All experimental results showed that the increasing in radial distance measured from the spray axis to outer edge of the spray changes the mass distribution first to increase up to maximum (main peak) and the gradually to decline (tailing). The main peak becomes lower with increasing GLR, orifice exit diameter (D) and axial distance (H).

3- The main parameter effects on flame length is A/F ratio. The increasing on A/F ratio decreases the flame length. Increasing of combustion air secures the necessary amount for complete combustion and non-smoke flame. Increasing on A/f ratio leads to widen stable combustion zone. The increasing on orifice exit diameter (D) achieves uniform mass flux throughout the spray cone, increases spray cone angle and increases the flammability limits.

4- The injection pressure has a very strong influence on spray cone angle, mass flux, flame stability, flame length. The increasing on injection pressure widens the spray cone angle, as radial drop velocity increases with increasing injection pressure. the increasing on injection pressure increases the drop velocity and decreases SMD of droplets. Achieving uniform mass flux of fuel and good combustion with stable flame. Therefore, the increasing on injection pressure increasing the stability combustion zone.

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