ILASS–Europe 2017, 28th Conference on Liquid Atomization and Spray Systems, 6-8 September 2017, Valencia, Spain
http://dx.doi.org/10.4995/ILASS2017.2017.4982

Breakup Length of Urea Water Solution Jet in a Hot Cross Flow

Senthil Kumar. P[1], Shamit Bakshi [1], Anand T.N.C *[1]
[1]Department of Mechanical Engineering and National Centre for Combustion Research and Development, Indian Institute of Technology Madras, India
*Corresponding author: anand@iitm.ac.in

Abstract
Selective Catalytic Reduction (SCR) using Urea-Water Solution (UWS) as an ammonia precursor is considered as one of the best choices to meet the current stringent emission norms for reduction of NO_X in diesel engines. UWS sprayed in the engine exhaust line forms ammonia, and this ammonia reduces NO_X into nitrogen. The NO_X reduction efficiency depends on the mixing and evaporation behavior of the UWS spray in the hot exhaust gas. Spray characteristics decide the evaporation rate and hence the NO_X reduction efficiency. The spray structure is closely related to the breakup point and breakup mode of the jet. Hence, in this study, breakup length and breakup mode were investigated by injecting UWS (32.5 % by weight) through a nozzle in a hot air cross flow. A CCD camera and pulsed Nd:Yag laser were used for capturing the images. Experiments were conducted with varying nozzle size (150, 250 and 400 micron), injection pressure (0.5 to 3 bar), temperature (32 °C,150 °C and 200 °C) and air flow rate. The effect of operating parameters (nozzle size, injection pressure, air temperature and velocity) in terms of dimensionless numbers (Weber number and momentum flux ratio) on jet breakup mode and jet breakup length was studied. It was observed that the breakup length for UWS was close to that of water. The jet breakup length increases with momentum flux ratio since a jet having a higher momentum is able to penetrate a larger distance in the cross flow. Increasing the air temperature increases the velocity of the cross flow and hence reduces the breakup length. A correlation for jet breakup length was developed. The effect of inclusion of Weber number in the breakup length correlation, in addition to the momentum flux ratio, was studied. Visual observation shows that droplet sizes obtained from the plain orifice injector without preheating is large. Preheating the UWS before injection is recommended to reduce the droplet size.

Keywords
UWS, cross flow, breakup length and laser diagnostics.

Introduction
Diesel engines deliver a high thermal efficiency, high torque density and good fuel economy. However, emissions produced by diesel engines, especially oxides of nitrogen (NOx), pose a major problem to the environment and to human health. In-cylinder treatment methods like retarding injection timing, Exhaust Gas Recirculation (EGR) and exhaust after treatment methods like three-way catalysts and lean NO_X traps are not suitable to meet future US and European emission norms. Urea-SCR after treatment method has the ability to meet these norms [1].

In this method, ammonia reacts with NO_X in hot exhaust gas and reduces it to Nitrogen in the presence of a catalyst which accelerates the reduction reaction. Liquefied ammonia poses issues relating to storage, handling and transportation. Gaseous ammonia storage leads to problems of toxicity and possible explosions. Hence, the direct use of ammonia is avoided. Urea is used as a precursor for ammonia. Requirement of uniform distribution of ammonia in exhaust gas and the hygroscopic nature of urea prevent the use of solid urea. Hence, urea (32.5 % by weight) is mixed with water. The eutectic point of this solution is at -11 °C. This provides the lowest crystallization point and ensures a constant concentration even when the solution is partially frozen [1]. Urea-Water Solution namely UWS is injected into hot exhaust gas. Thermal decomposition of UWS consists of three successive stages namely evaporation, thermolysis and hydrolysis. First, water evaporates from the solution. Then, urea decomposes into ammonia and isocyanic acid in the thermolysis process. Finally, isocyanic acid reacts readily with water vapor and produces ammonia and carbon dioxide in the hydrolysis process.

The efficiency of the NO_X reduction reaction is affected by the availability and uniformity of ammonia present before the catalyst. However, ammonia formation is influenced by mixing and evaporation of UWS which are affected by the spray quality. All the above processes: evaporation of urea, ammonia formation, ammonia mixing with exhaust gas and reduction reaction need to be completed within a short period of time or distance. This is the major challenge in mobile engines, especially at low exhaust gas temperatures, since only a short distance is available for mixing, evaporation and reaction. Typical cross flow spray characteristics are shown in Figure1. The actual spray structure starts from the jet breaking point. This will decide the other parameters of the spray such as the width, trajectory, droplet size and distribution. This motivates the study of the breakup length of UWS jet in hot cross flow. The objective of this study is to find a correlation for breakup length of UWS jet in the hot cross flow by conducting experiments with different nozzle sizes, injection pressures, air velocities and temperatures. Here, breakup length refers to the vertical distance between the nozzle exit and the point where the jet breaks and forms ligaments. This is also referred to as the transverse breakup length, jet transverse penetration or column fracture height [2].

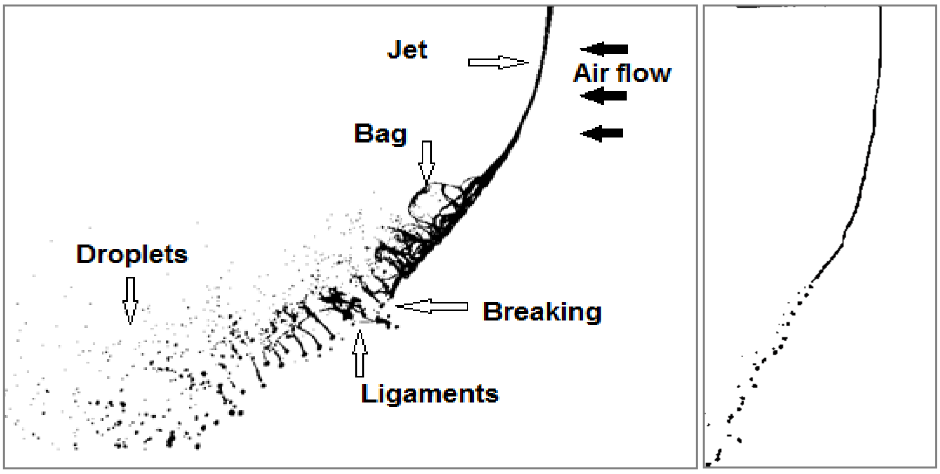

Figure 1. Typical jet in cross flow showing bag breakup and column breakup regimes (not to scale)

In previous studies, researchers have developed several correlations for breakup length in different forms. Table 1 shows the correlations for breakup length from different studies. In studies [3] to [7], correlations were developed for breakup length in terms of the momentum flux ratio. In addition to the momentum flux ratio, Ohnesorge number was included when liquid viscosity exceeds 0.019 Pa.s in [4]. Two separate correlations were proposed based on Weber number (≤ 8 and ≥12) in [7]. Aerodynamic Weber number and Reynolds number were added along with momentum flux ratio in [8] and [9] respectively.

Table 1. Correlations for breakup length from literature

Author	Correlation	Equation number
Wu et al. [3], 1997	$\frac{y_b}{d} = 3.07\ q^{0.53}$	(1)
Birouk et al. [4], 2003	$\frac{y_b}{d} = 3.13\ q^{0.53}$ $\mu_l < 0.019$ Pa.s $\frac{y_b}{d} = 8.60\ q^{0.87} Oh^2$ $\mu_l > 0.019$ Pa.s	(2a) (2b)
Costa et al. [5], 2006	$\frac{y_b}{d} = 8.05\ q^{0.5}$	(3)
Wang et al. [6], 2011	$\frac{y_b}{d} = 2.50\ q^{0.53}$	(4)
Y.Zheng et al. [7], 2011	$\frac{y_b}{d} = 10.7\ q^{0.40}$ for We(air) ≤ 8 $\frac{y_b}{d} = 4.46\ q^{0.40}$ for We(air) ≥ 12	(5a) (5b)
Ragucci et al. [8], 2007	$\frac{y_b}{d} = 4.355\ q^{0.416} \mathrm{We}_{\mathrm{aero}}^{0.135}$	(6)
Bellofiore et al. [9], 2007	$\frac{y_b}{d} = 1.499\ q^{0.476} \mathrm{Re}_{\mathrm{a}}^{0.135}$	(7)

Correlations (1), (2a), (3) and (4) appear close to each other in terms of the constants and exponents, even though different liquids (water, ethyl alcohol, lubrication oil, Jet A fuel) were used for the experiment. Experiments were conducted in different air flow conditions: normal temperature and pressure in [3] to [7], elevated pressure (10 bar) in [8], and elevated temperature (327 °C) and pressure (10-20 bar) in [9]. Higher Weber number and lower length to diameter of the nozzle (l/d) were used in [3], where as lower Weber numbers and higher length to diameter ratio of the nozzle were used in [7]. Studies [3] and [6] gave a single equation for a wide range of momentum flux ratio. Liquid was injected at an angle of 15°, 30° and 45° with the air flow direction in [5].

Table 2. Experiment Input conditions for the cases 1 and 2

<table>
<tr><td>Parameters</td><td colspan="3">Case1</td><td>Case2</td><td>Parameters</td><td>Case1</td><td>Case2</td></tr>
<tr><td>Weber number</td><td colspan="3">7 -16</td><td>2.4-5</td><td>Liquid Injection pressure (bar)</td><td>0.5-3</td><td>0.5-3</td></tr>
<tr><td>Momentum flux ratio</td><td colspan="3">22-149</td><td>36-436</td><td>Liquid Injection Velocity (m/s)</td><td>8-20</td><td>8-20</td></tr>
<tr><td>Liquid</td><td colspan="3">Water, UWS</td><td>UWS</td><td>Air Temperature (°C)</td><td>150,200</td><td>32, 150,200</td></tr>
<tr><td>Nozzle diameter (micron)</td><td>152</td><td>254</td><td>406</td><td rowspan="2">152,254</td><td rowspan="2">Air Velocity (m/s)</td><td rowspan="2">45 -55</td><td rowspan="2">35-50</td></tr>
<tr><td>Length/diameter ratio</td><td>0.62</td><td>1</td><td>1.67</td></tr>
</table>

In the present study, the experiments were conducted by injecting UWS into the cross flow of air at elevated temperature. The input conditions used in this experiment are given in Table 2. Surface tension and density of UWS are taken as 0.065 N/m and 1090 kg/m^3, respectively [10]. Maximum uncertainty values calculated for Weber number and momentum flux ratios are 8.8 % and 9.4 % respectively.

Experimental set up and procedure

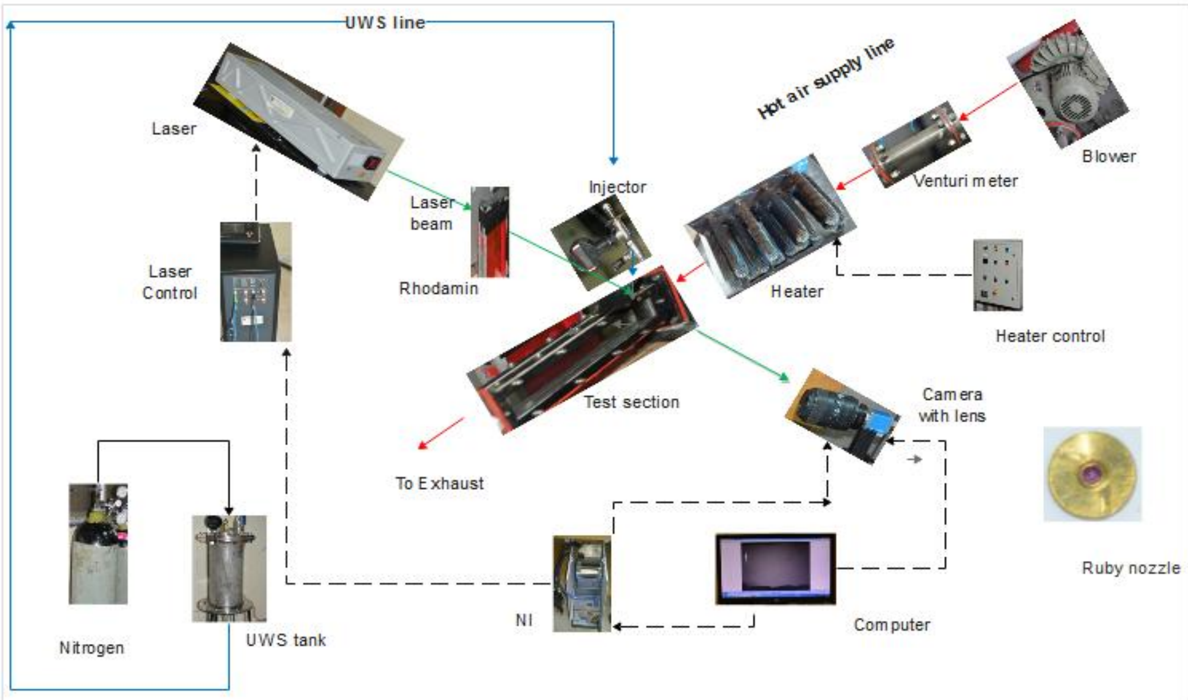

Figure 2a. Schematic of the experimental set up.

A schematic view of the experimental set up is shown in Figure 2a. The experimental setup includes three main subsystems: hot air supply line, UWS injection line and optical components for imaging. The air supply line consists of a blower to draw air, a venturi meter to measure the volume flow rate of air, a heater (30 kW) to heat the air, a test section and an exhaust arrangement. The test section has a length of 250 mm and a cross section of 40 mm (height) x 25 mm (width). The walls of the test section are made of toughened glass to visualize the spray. The urea injection line consists of a N_2 cylinder, pressure vessel to store the UWS and an injector with a ruby nozzle. Nitrogen pressurizes the vessel and the liquid was injected through the injector into the test section. A cylindrical, straight hole ruby nozzle having diameter of 152, 254 or 406 micron size with the corresponding length/diameter ratio of 0.62, 1 and 1.67 respectively was used. The dimension, shape and assembly of the ruby nozzle with brass plate fixed in the injector are shown in Figure 2b. The plain orifice injector has been selected for this experiment due to the following reasons: it is simple in design, allows for easy cleaning and can be easily mounted or removed from the test section for change of nozzle size. The jet coming from the hole does not get disturbed by the jet coming from the other holes which would be present in a multi hole injector and this helps to understand the spray structure and make it suitable for image processing.

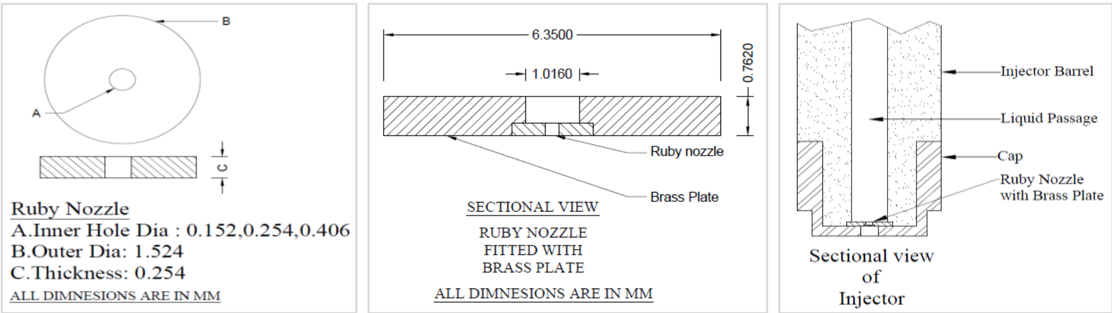

Figure 2b. Ruby Nozzle, Ruby nozzle fitted with brass plate and the Injector

The optical sub system contains an Nd:Yag laser (532 nm) for illumination, a CCD camera fitted with a lens (105 mm) to capture the spray image and an National Instruments device to trigger and synchronize the laser and the camera at 10 fps. Rhodamine-B solution based diffuser is placed in between the laser and the test section to reduce the speckle in the images [11]. The hot air from the heater was passed through the test section and the UWS in room temperature was injected perpendicular to this hot air stream. The bottom of the injector (cap) was exposed to the hot air. The liquid temperature inside the injector, near the nozzle was measured using a thermocouple while conducting some of the trials. During continuous injection of the liquid, the temperature of the liquid was observed to be slightly (5°C) above the room temperature (30°C). In the calculation it was taken as room temperature. Backlight imaging technique was employed to capture spray images by using the pulsed laser and camera. Finally, the images were processed using MATLAB [12].

Image processing

Two thousand images of the spray structure were captured for each test condition. Each gray scale image was subtracted from the reference (background) gray scale image. Then, the subtracted image was converted into a binary (black and white) image using a suitable threshold (cut-off intensity) value, which is shown in Figure 3. From this binary image, the distance between the jet origin and the jet breakup point in transverse direction was calculated in terms of pixels. Breakup length was obtained by pixel-to-millimeter conversion using a scale image, taken during the experiment. Typically, a 50.7 mm x 37.9 mm and 55.5 mm x 41.5 mm field of view with a pixel resolution of 36 and 40 µm/pixel was imaged.

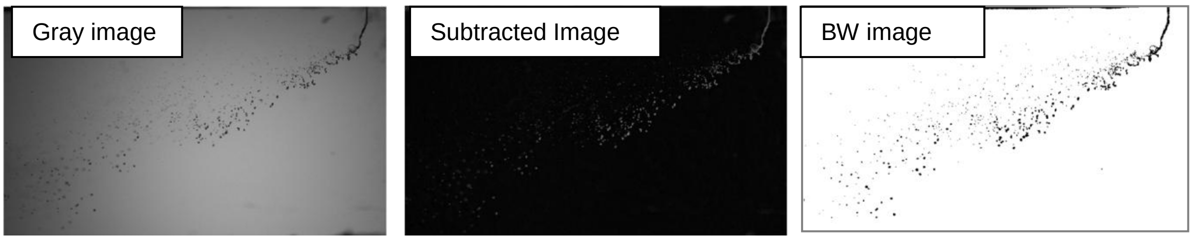

Figure 3. Stages of image processing employed in the present study.

Results and discussion

Breakup mode

Bag breakup mode was observed in the Weber number range of 7-16 (case 1) and column breakup mode was observed in the Weber number range of 2.4-5 (case 2) as shown in Figure 1. A large number of droplets are formed during bag breakup and only a few are formed during column breakup.

Breakup length

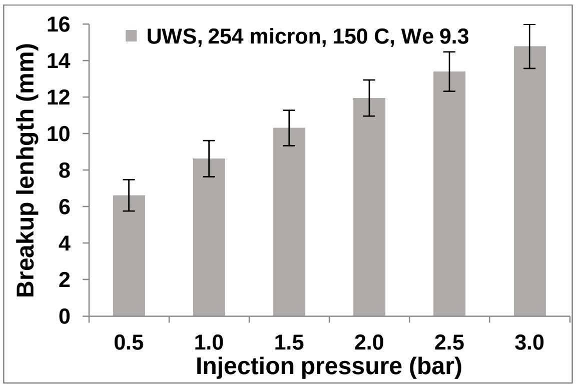

Figure 4a. Effect of injection pressure on the breakup length

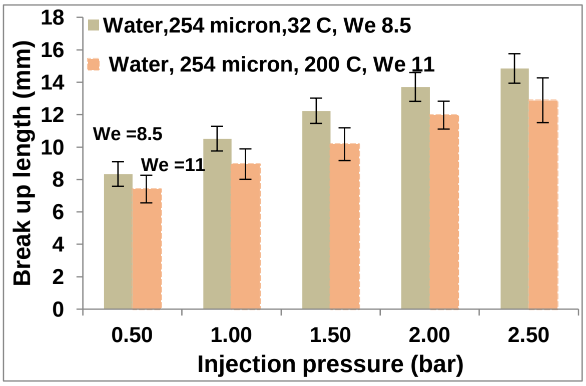

Figure 4b. Effect of temperature on the breakup length

Figure 4a shows the breakup length results for two experimental conditions: liquid: UWS, nozzle diameter: 254 micron, temperature: 150 °C, We: 9.3. Breakup length increases with an increase in the momentum flux ratio. Momentum flux ratio was increased by increasing the injection pressure, and hence the injection velocity.

Figure 4b shows the breakup length results for two experimental conditions (liquid: water, nozzle diameter: 254 micron, temperature: 32 °C, We: 8.5 and liquid: water, nozzle diameter: 254 micron, temperature: 150 °C, We: 11). An increase in air temperature (32 °C to 200 °C) increases air velocity and hence the Weber number, but reduces the momentum flux ratio. A decrease in the breakup length was observed with an increase in air temperature for the same liquid injection velocity. There is not much difference between the breakup length for water and UWS as the properties (surface tension, viscosity) of both liquids are close to each other.

Breakup length Correlation

Correlations for breakup length were obtained for the entire Weber number range (2-16) and momentum flux ratio (22-436) in terms of momentum flux ratio, without Weber number and with Weber number in equations (8) and (9) respectively as:

$$Y_b = d * 2.32 * q^{0.687} \tag{8}$$

$$Y_b = d * 8.06 * q^{0.516}\, We^{-0.227} \tag{9}$$

Figure (5a) shows the plot between momentum flux ratio and breakup length at a Weber number of 16 (nozzle size: 406 micron, air temperature: 208 °C). Including Weber number in equation (9) reduces the average deviation between the predicted breakup length values with the experimental values (from 13.3 % to 10.3 %), in comparison with equation (8). This is observed for all the experimental conditions.

Figure (5b) shows the plot between momentum flux ratio and breakup length at a Weber number of 5 (Nozzle size: 152 micron, Air temperature: 156 °C). Similar to the previous case, inclusion of Weber number in the correlation brings the predicted breakup length values close to the experimental values.

Separate correlations were obtained for the Weber numbers in the range 7-16 (bag breakup) and Weber numbers in the range 2.4-5 (column beak up) as shown in equations (9a) and (9b) respectively. These correlations further reduce the average deviation between the predicted and the experimental values (9.2 % for 9a and 9.5 % for 9b) and bring the result much closer to the experimental values, as shown in Figure 5a and 5b.

$$Y_b = d * 4.69 * q^{0.55}\, We^{-0.073} \tag{9a}$$

$$Y_b = d * 9.41 * q^{0.483}\, We^{-0.204} \tag{9b}$$

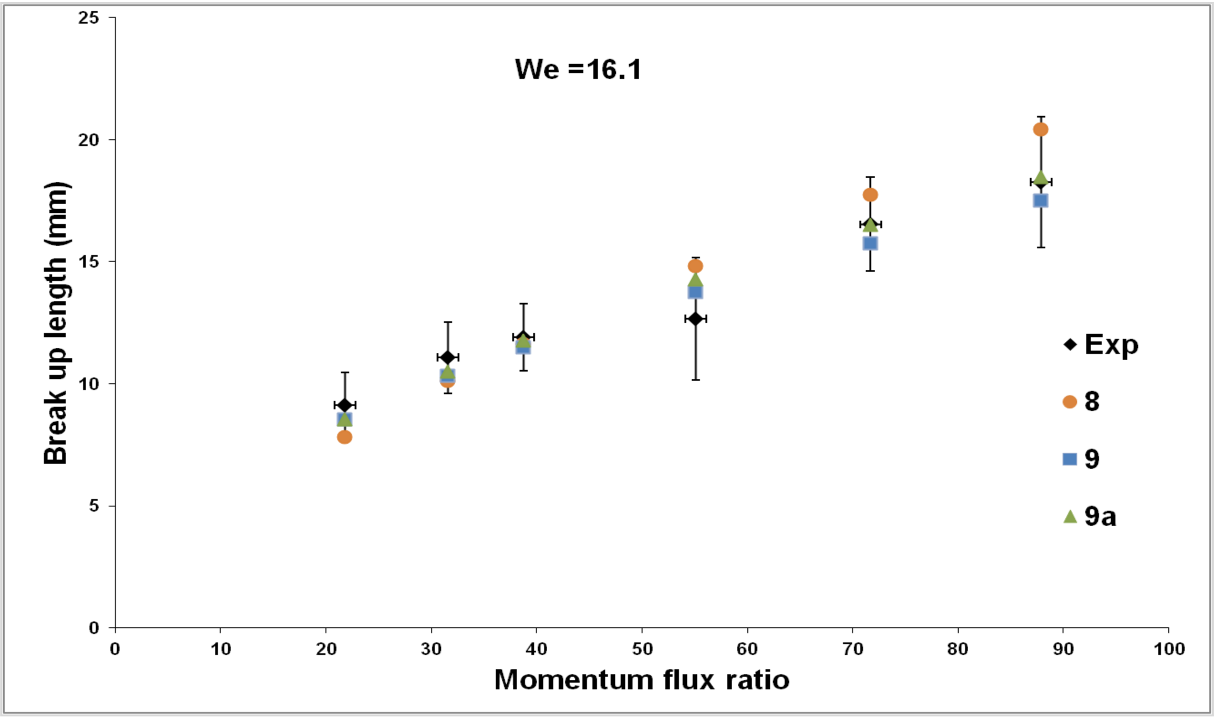

Figure 5a. Effect of momentum flux ratio on the breakup length (We =16). Experimental values are plotted along with the values predicted by equations (8), equation (9) and equation (9a)

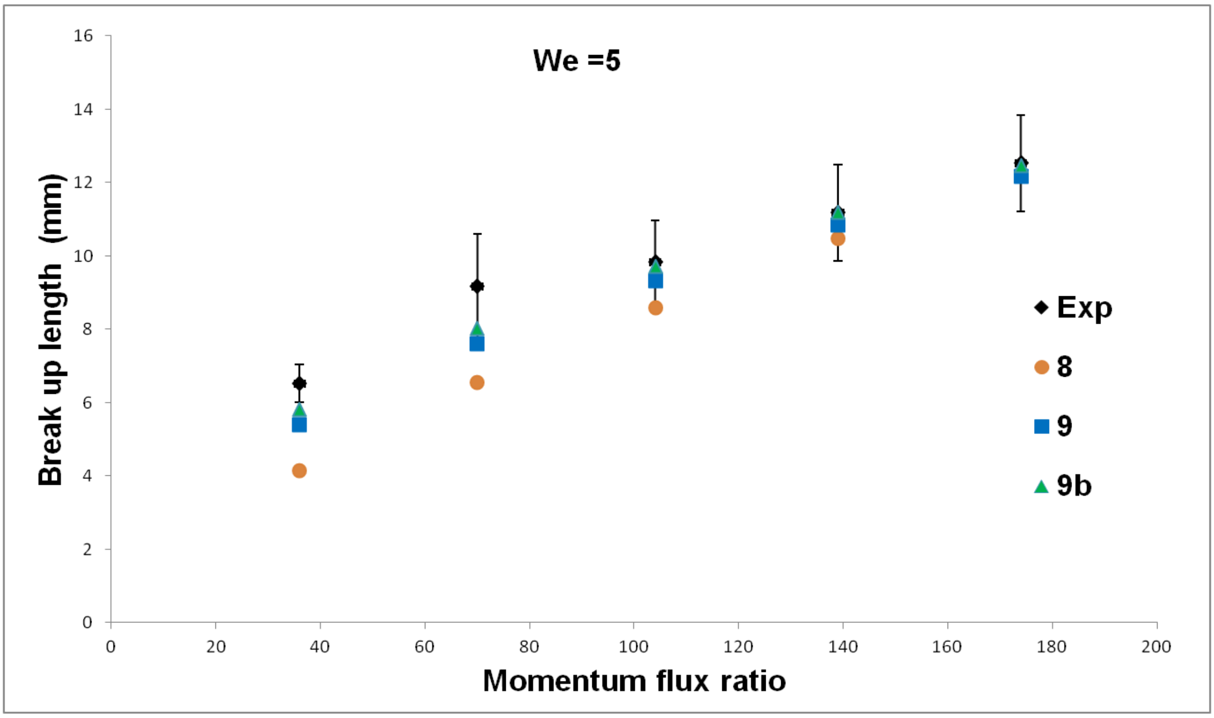

Figure 5b. Effect of momentum flux ratio on the breakup length (We =5). Experimental values are plotted along with the values predicted by equations (8), equation (9) and equation (9b)

Droplet
Visual observation shows that the maximum size of the droplet is nearly equivalent to the nozzle size. Droplets of this size are not small enough to evaporate before they reach the catalyst in the exhaust pipe. Injecting the liquid through the plain orifice injector without preheating the liquid is thus not suitable for injecting UWS. Preheating the UWS before the injection is could help to reduce the droplet size and obtain more efficient evaporation.

Conclusion
An attempt was made to study UWS jet in a hot cross flow in Weber number range 2.4-16 and momentum flux ratio range 22-436. Bag breakup mode was observed for Weber numbers in the range 7-16 and column breakup mode for Weber number range 2-5 for the jet. The breakup length increases with an increase in the momentum flux ratio. The effect of temperature is incorporated in the Weber number and momentum flux ratio. Including the Weber number along with the momentum flux ratio in the breakup length correlation, reduces the deviation from the experimental values. Individual correlations for particular breakup modes (Weber number range) predict the breakup length values closer to the experimental values. This preliminary experimental investigation using plain orifice injector shows that the size of the droplet is large particularly at low air velocities. The droplet may not evaporate within the limited exhaust pipe length and time. Preheating the UWS before the injection is required to reduce the droplet size and obtain more efficient evaporation.

Acknowledgement
The authors gratefully acknowledge the financial support from Caterpillar India which made this work possible and Dr. Kameswara Rao Anupindi, IIT Madras, for proof-reading this article.

Nomenclature
Dimensionless numbers

$$We = \frac{\rho_a v_a^2 d}{\sigma_l}$$

$$q = \frac{\rho_l \ v_l^2}{\rho_a \ v_a^2}$$

$$We(aero) = \frac{\rho_a v_l^2 d}{\sigma_l}$$

$$Re_a = \frac{\rho_a \ v_a \ d}{\mu_a}$$

$$Oh = \frac{\mu_l}{\sqrt{\rho_l \ d \ \sigma_l}}$$

d	Diameter of nozzle [m]
v	Velocity [m/s]
Oh	Ohnesorge number
q	Momentum flux ratio
We	Weber number
Y_b	Breakup length [mm]
Re_a	Reynolds's number
l	Liquid
a	Air
ρ	Density [kg/m^3]
μ	Dynamic viscosity [Ns/m^2]
σ	Surface tension [N/m]

References
[1] M. Koebel., M. Elsener., and M. Kleemann. , 2000, Catalysis Today, 335-345.
[2] Soo-Young No., Sep. 2.-6. 2012, ICLASS 2012, 12th Triennial International Conference on Liquid Atomization and Spray Systems, Heidelberg, Germany.
[3] Wu, P-K., Kirkendall, K.A., Fuller, R.P.,1997, Journal of Propulsion and Power, 13(1):64-73.
[4] Birouk, M., Stabler,T., Azzopardi, B.J., 2003, Particle and Particle Systems Characterization, 20:39-46.

[5] Costa, M., Melo, M.J., Sousa, J.M.M., Levy, Y., 2006, AIAA Journal, 44(3): 646-653.
[6] Wang, Q., Mondragon, U.M., Brown, C.T., McDonell, V.G., 2011, Atomization and Sprays, 21(3): 203-219.
[7] Yinghui Zheng., Andr´eW. Marshall., 2011, Atomization and Sprays, 21 (7): 575–589.
[8] Ragucci, R., Bellofiore, A., Cavaliere, A., 2007, Atomization and Sprays 17:47-70.
[9] Bellofiore, A., Cavaliere, A., Ragucci,R., 2007, Combustion Science and Technology,179:319-342.
[10] Sauli Halonen., Teija Kangas ., Mauri Haataja., Ulla Lassi ., Emiss. Control Sci. Technol, 10.1007/ s40825-016-0051- 1
[11] Saransh Jain., S Somasundaram., and T N C Anand., 2016, Measurement Science and Technology, 27(2016) 025406 (7pp)
[12] MATLAB and Statistics Toolbox Release 2012a, The MathWorks, Inc., Natick, Massachusetts, United States, http://www.Mathwork.com.