

We are IntechOpen, the world's leading publisher of Open Access books Built by scientists, for scientists

6,900

Open access books available

186,000

International authors and editors

200M

Downloads

Our authors are among the

154

Countries delivered to

TOP 1%

most cited scientists

12.2%

Contributors from top 500 universities



WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Numbers displayed above are based on latest data collected.
For more information visit www.intechopen.com



Fuel Jet in Cross Flow – Experimental Study of Spray Characteristics

E. Lubarsky, D. Shcherbik, O. Bibik, Y. Gopala and B. T. Zinn
*School of Aerospace Engineering, Georgia Institute of Technology, Atlanta Georgia
USA*

1. Introduction

Injection of the liquid fuel across the incoming air flow is widely used in gas turbine engine combustors. Thus it is important to understand the mechanisms that control the breakup of the liquid jet and the resulting penetration and distribution of fuel droplets. This understanding is needed for validation of Computational Fluid dynamics (CFD) codes that will be subsequently incorporated into engine design tools. Additionally, knowledge of these mechanisms is needed for interpretation of observed engine performance characteristics at different velocity/altitude combinations of the flight envelope and development of qualitative approaches for solving problems such as combustion instabilities (Bonnel et al., 1971). This chapter provides an introduction and literature review into the subject of cross-flow fuel injection and describes the fundamental physics involved. Additionally highlighted are experimental technique and recent experimental data describing the variables involved in fuel spray penetration and fuel column disintegration.

In recent years, there has been a great drive to reduce harmful emissions of oxides of Nitrogen oxides (NOx) from aircraft engines. One of the several approaches to achieve low emissions is to avoid hot spots in combustors by creating a lean homogeneous fuel-air mixture just upstream of the combustor inlet. This concept is termed as Lean Premixed Prevaporized (LPP) combustion. Creating such a mixture requires fine atomization and careful placement of fuel to achieve a high degree of mixing. Liquid jet in cross flow, being able to achieve both of these requirements, has gained interest as a likely candidate for spray creation in LPP ducts (Becker & Hassa, 2002). Since the quality of spray formation directly influences the combustion efficiency of engines, it is important to understand the fundamental physics involved in the formation of spray.

As seen in Fig. 1, the field of a spray created by a jet in cross flow can be divided into three modes: 1) Intact liquid column, 2) Ligaments, and 3) Droplets. The liquid column develops hydrodynamic instabilities and breaks up into ligaments and droplets (Marmottant & Villermaux, 2004; Madabushi, 2003; Wu et al., 1997). This process is referred to as primary breakup. The location where the liquid column ceases to exist is known as the column breakup point (CBP) or the fracture point. The ligaments breakup further into smaller droplets and this process is called secondary breakup.

The most relevant parameter for drop breakup criterion is the Weber number, $We = \rho_{air} U_{air}^2 D / \sigma_{fuel}$ (in this formula ρ_{air} and U_{air} - density and velocity of the crossing air respectively, D - diameter of the injection orifice and σ_{fuel} is the surface tension of the fuel).

We is the ratio of disruptive aerodynamic force to capillary restoring force. The critical We above which a droplet disintegrates is $We=10$ (Hanson et al., 1963). When Weber number is high ($We > 200$), another mode of breakup called the shear breakup becomes dominant. During shear breakup, aerodynamic forces exerted by the flow on the surface of the liquid jet or ligaments strip off droplets by shear. Though both modes of breakup contribute to atomization of the liquid jet, the domination of one mechanism over the other is dependent on We and on liquid jet momentum flux to air momentum flux ratio, q .

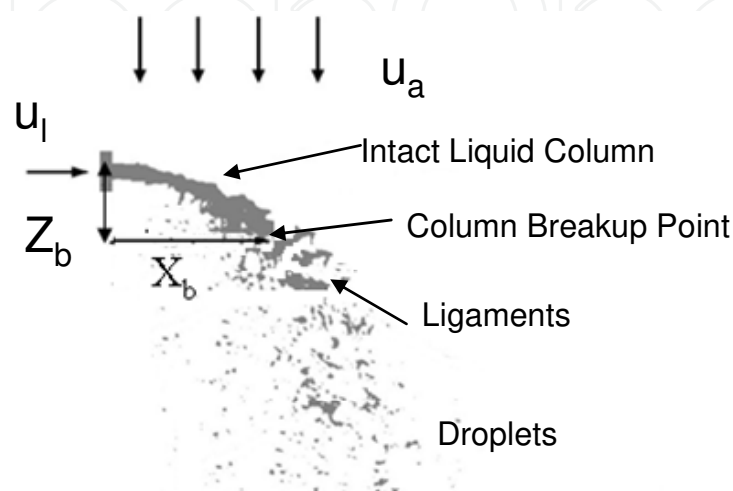


Fig. 1. Schematic of spray created by a liquid jet in cross flow (from Ann et. al., 2006)

Currently two parameters that characterize disintegration of the fuel jet in the cross flow are subjects of great interest among the users of the experimental data. They are (1) column breakup point (CBP) and (2) penetration of spray into the cross flow. The location of CBP is important for the development of computational models for the prediction of spray behavior. Since the aerodynamic drag for the liquid jet is significantly different from that of droplets, it is crucial to know the exact location of jet disintegration into droplets to be able to predict the extent to which the droplets penetrate into the air stream. On the other hand direct measurements of the spray penetration are significant for development of the design tools for use by the engine developers as well as for validation and adjustment of the spray computational models. Various researchers have measured CBP location and spray penetration with reasonable uncertainties. However, these parameters are still not explored extensively because of ambiguities in definition and due to experimental difficulties. A number of experimental studies of column breakup and spray penetration under conditions that simulate those in gas turbine engines were undertaken and are briefly reviewed below.

In the early work on the aerodynamic breakup of liquid droplets in supersonic flows researchers (Ranger & Nichollas, 1969) carried out experiments to find the time required for individual droplets dropped into a supersonic cross flow to breakup to form a trace of mist. They found this time (t_b) to be proportional to the droplet diameter (d), inversely proportional to the relative velocity between the droplet and the airflow (u_a), and proportional to the square root of liquid-to-air density ratio (ρ_l / ρ_a). Based on the images taken, they found that the constant of proportionality (t_b/t^*), defined by equation (1) to be 5. Another conclusion of their study was that the effect of the shock wave on the aerodynamic

breakup of the droplets was minimal. The main function of the shock wave is to produce the high speed convective flow that is responsible for the disintegration of droplets. This prompted subsequent researchers to use this characteristic time (t^*) for droplets in subsonic flows as well by.

$$\frac{t_b}{t^*} = \frac{t_b}{(\rho_l / \rho_a)^{1/2} d / u_a} = 5.0 \quad (1)$$

Lower values of $t_b/t^*=3.44$ were reported later (Wu et al., 1997) for liquid jet disintegration in the cross flow with Weber number in the range of $We=71 - 200$. The column breakup location for higher We flows could not be determined. They also found that the CBP was located at about eight diameters downstream of the orifice in the direction of airflow for the cases reported.

Other researchers (Sallam et al., 2004) measured column breakup point at We range of 0.5-260. Their studies yielded different value of $t_b/t^* = 2.5$. However, the uncertainties became high as We of the flow was increased. This can be explained by the fact that the experimental methods that have been employed so far for measuring the CBP position involve the analysis of the spray images obtained by back illumination technique. This method works reasonably well for low We flows in the absence of shear breakup. In the shear breakup regime, that is relevant for the gas turbine applications it becomes very difficult to analyze the spray images and find the location of CBP because of the presence of droplets in high density around the liquid column. This paper demonstrates a method to overcome this shortcoming.

Method used in the current study was first suggested by (Charalompous et al., 2007) who developed a novel technique to locate the CBP for a co-axial air blast atomizer. In this atomizer high density of droplets around the liquid jet column limited optical access to the jet. To overcome this problem, they illuminated the liquid jet column seeded with fluorescent Rhodamine WT dye with a laser beam from the back of the injector. The liquid jet acted as an optical fiber up to the point it breaks up. The jet is visible due to florescence of the dye until the location of the CBP and the light gets scattered beyond that location giving the precise location of the CBP. The current study aims at extending this technique to locate the CBP of liquid jets in cross flow.

Spray penetration into the cross flow have received significant attention by the experimentalists hence placement of fuel in a combustor is significant for its design. In 1990s researchers (Chen et al., 1993, Wu et al., 1997) have carried out experiments at different momentum flux ratios of water jets and developed a correlation of the dependence of the upper surface trajectory of jets in a cross flow with liquid to air momentum flux ratio. Later (Stenzler et al., 2003) a Mie scattering images were used to find the effect of momentum flux ratio, Weber number and liquid viscosity on jet penetration. As in other previous studies, they found that increasing momentum flux ratio increased penetration. Increasing the Weber number decreased the average droplet size and since smaller droplets decelerate faster, the overall penetration of the spray decreased. However, many of these correlations are applicable to specific operating conditions, injector geometries and measurement techniques.

It was also found (Tamaki et al., 1998, 2001) that the occurrence of cavitation inside the nozzle significantly influences the breakup of the liquid jet into droplets. The collapse of cavity bubbles increased the turbulence of the liquid jet accelerating its breakup into

droplets. Additional researchers (Ahn et al., 2006) explored the effect of cavitations and hydraulic flip of the orifice internal flow on the spray properties created by a jet in cross flow. They found that while spray trajectories followed the previously obtained correlations (Wu et al., 1997) in absence of cavitations and hydraulic flip, the presence of these phenomena resulted in significant disagreements between the observed trajectories and the ones reported (Wu et al., 1997). Consequently, they concluded that the design of the injector has a significant effect on the spray trajectories.

Practically all previous studies of fuel spray attempted to describe its penetration trajectory into the cross-flow of air in the form of equation that typically incorporate momentum flux ratio of the liquid jet to air flow, $q = \rho_{fuel} U_{fuel}^2 / \rho_{air} U_{air}^2$, Weber number and certain function that describe shape of the outer edge of the spray. Usually, these equations incorporate a number of empiric coefficients that were obtained by processing experimental data. In spite of availability of dozens of correlations their practical use remains problematic because they all provide different results. Figure 2 shows result of application of different correlations to one spray with $q=20$ and $We=1000$.

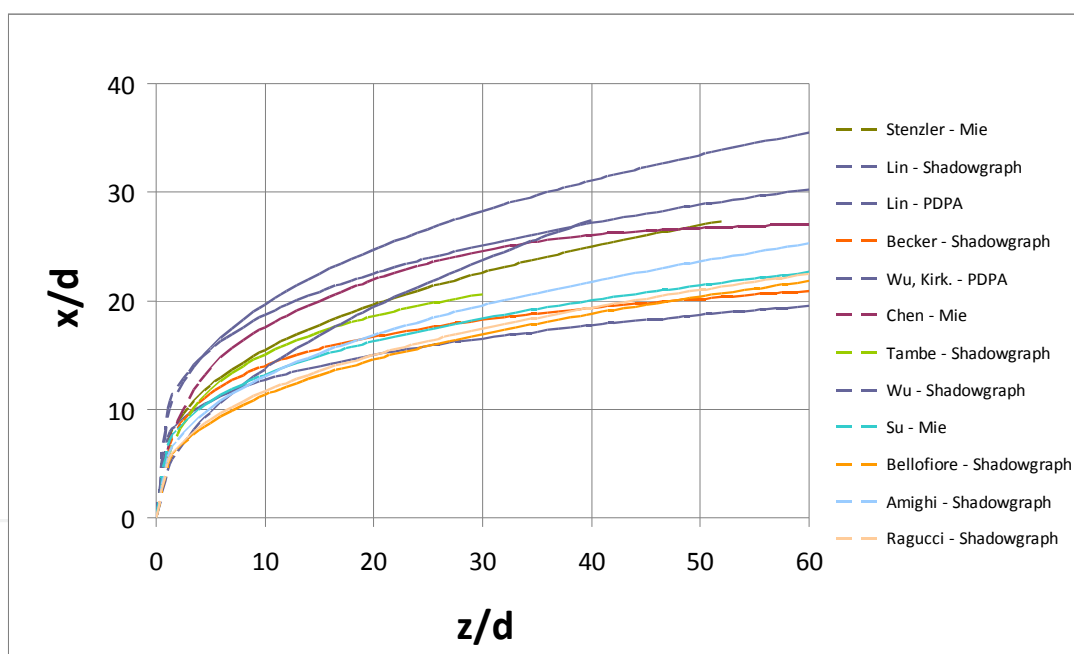


Fig. 2. Comparison of the spray penetration trajectories (x and z - coordinates in the direction of fuel injection and crossing air flow respectively, d - is diameter of the injection orifice)

It can be observed that the spray penetration trajectories differ from each other to an extent of 100%. Among factors that causes such a big difference the following ones seems to be the most important:

- Design of the injector and its position in the cross flow (i.e. l/d , shape and quality of the internal fuel path, presence or absence of the spray well or cavity between the injection orifice and the channel e.t.c).

- Factors that vary flow conditions in the experiment inconspicuously for the researcher such as temperature of the crossing air flow which may change the temperature of the injector and thus surface tension and viscosity of the injected fuel.
- Turbulence of the core and boundary layer characteristics of the crossing air flow that may significantly influence spray penetration but rarely mentioned by researches.
- Imaging technique that was used for many years for capturing spray trajectories was static photography that typically captured superposition of sprays on one image due to the fact that time constant of such oscillatory phenomena as liquid jet disintegration in the cross flow is by several orders lower than expose rate of any available camera used in most of experiments.

The objective of this study was to investigate the spray trajectories and determine locations of the column break up points (CBP) formed by the Jet-A fuel injected from the injectors of different geometries into a cross flow of air while the above mentioned influencing factors will be isolated. For this purpose:

- Both injectors used in the study that had the same diameter of the orifice and a different shape of the internal path were manufactured using the same equipment and technology. They were installed with orifices openings flush with the air channel wall (i.e. with no spray well, or cavity).
- Crossing air flow was of the room temperature. Its turbulence level in the core was ~4%. Thickness of the boundary layer was ~3mm.
- High speed imaging technique (~24,000fps) with spray illumination by the short laser flashes of 30ns duration was used to capture instantaneous images of the spray several times during its movement from maximum to minimum position. That allowed statistically relevant processing of the images and thus extracting information about the averaged spray trajectories and their RMS values.

Sprays penetration into the cross flow were investigated using Jet-A fuel for a wide range of momentum flux ratios between $q=5$ and $q=100$. Velocity of the air flow was varied to attain Weber numbers in the range of $We=400$ to $We=1600$. Air pressure and temperature in the test channel were $P=5$ atm and $T\sim 300K$ respectively. Column breakups were investigated also at higher air temperature of 550K (in addition to $T=300K$) and by using water injection in addition to jet fuel experiments in attempt to achieve wider range of non-dimensional parameters.

2. Experimental setup

Figure 3 shows a schematic of the experimental setup used to study the injection of a liquid jet from a flat surface into the cross flow of air at elevated pressure. This setup had a plenum chamber, a rectangular air supply channel, a test section with injector under investigation and a pressurized chamber with four 38mm (1.5 inch) thick windows for optical access to the spray.

Plenum chamber was 203.2 mm in diameter and 457.2mm long. Two perforated screens were installed at the entrance and at the exit of the plenum to achieve necessary level of turbulence and flow uniformity in the test section. The rectangular supply channel was 62.3mm (2.45 inch) by 43.2mm (1.7 inch) in cross-section and was 304.8mm long. It was equipped with a “bell-mouth” air intake which was connected to the bottom of the plenum chamber to smoothen the air flow. On the other end of the channel four aerodynamically shaped plates were attached to the channel creating a test section with a cross-section 31.75 x 25.4mm (1.25 x 1.00 inch).

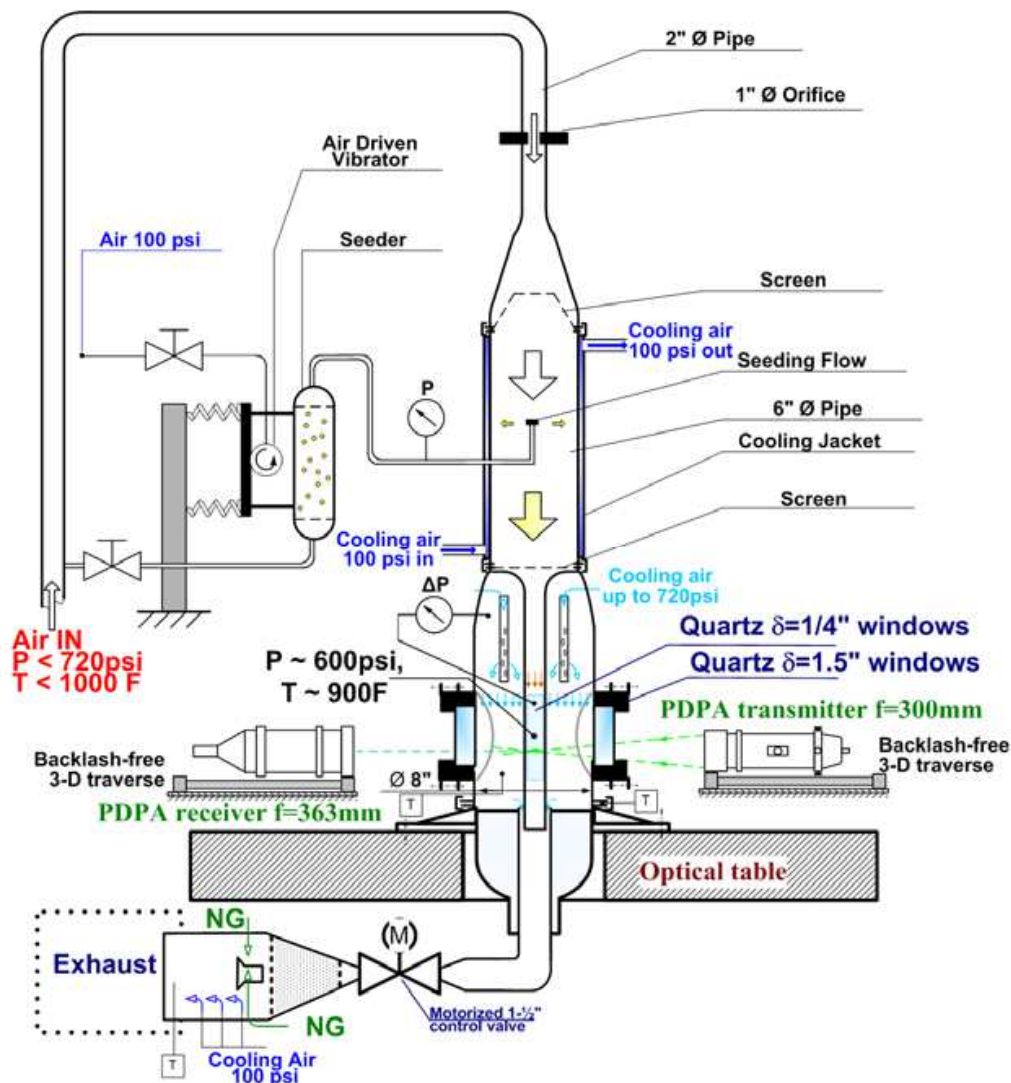


Fig. 3. Schematic of the test facility

This test section has ~50mm (2.00 inch) long, 6mm (1/4 inch) thick windows on three sides for optical access to the spray zone. The fuel injectors were installed on the centerline of the plate 10mm downstream of transparent section. The whole system was fixed to a massive optical table while optical tools were installed on a traversing mechanisms, which provides precise movement (minimal step is 0.0254mm) in three mutually orthogonal directions using step motors and electronic drivers controlled using a computer. In the current study, 1mm increments of movement were typically used for characterizing the spray. Maximum possible flow conditions in the test sections were $P=4.2\text{MPa}$ (600 psi) and $T=755\text{K}$ (900F) which correspond to supercritical flow conditions for the Jet-A fuel. These flow conditions were achieved by supplying preheated air flow from the controllable high pressure air supply at $P < 5.0\text{MPa}$ (720 psi) and $T < 800\text{K}$ (1000°F) into the plenum, where it then enters the $1.25'' \times 1.00''$ test section.

Velocity in the test section was controlled by the motorized control valve in the exhaust line (see Figure 3). Cooling of the test channel, test section as well as inner and outer windows in case of the preheated air use was achieved by pressurizing of the pressure vessel with the high pressure air flow ($P < 5.0\text{MPa}$, $T \sim 295\text{K}$). This cooling air was eventually mixed with the high temperature air from the test section in the exhaust path. Pressure of this cooling air

was ~1.4KPa (2 psi) higher than in the test section to keep temperature in its surrounding below 100°C. Mixture of the air passing the test section, injected Jet-A fuel and cooling air left the rig through the exhaust line, passing through the control valve, flow straightener and afterburner where fuel was burned in the pilot flame of natural gas to prevent fuel from entering the atmosphere.

Flow conditions in the test section were monitored using 3mm (1/8inch) diameter Pitot tube and thermocouple, which were located within the 2.45" × 1.70" test channel (see Figure 4). An additional pressure transducer and thermocouple were installed just downstream of the test section. Differential pressure sensor measured pressure drop along test section to support flow velocity measurements by the Pitot tube. Axes of the coordinate system used in this study were designated as shown on the Figure 5. X was direction of fuel injection. Y – Lateral spread of the spray and Z – Direction of the air flow.

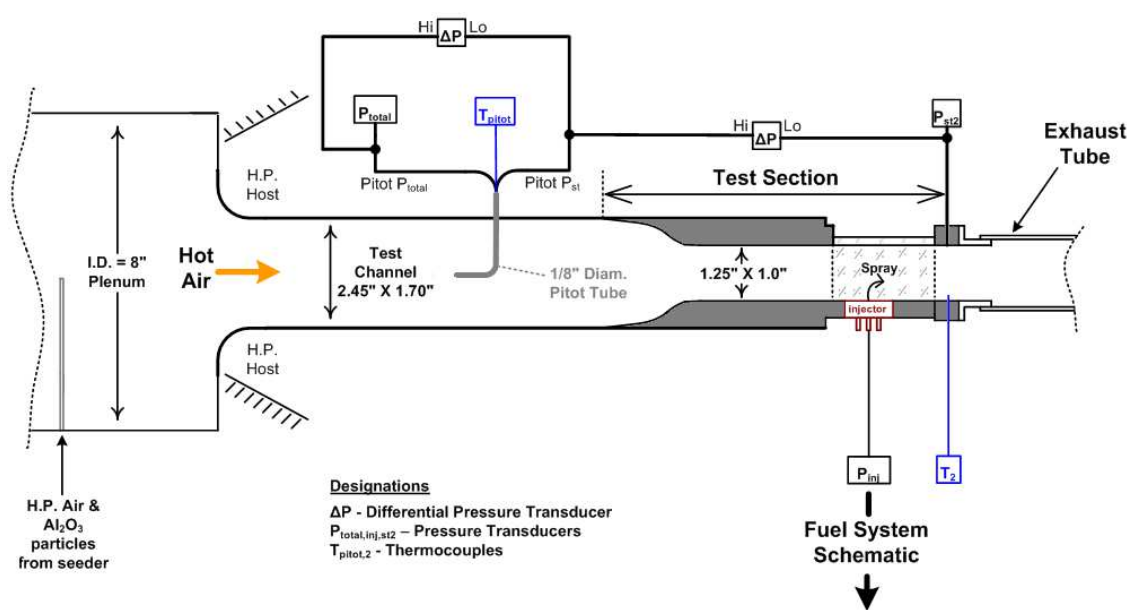


Fig. 4. Instrumentation of the test section

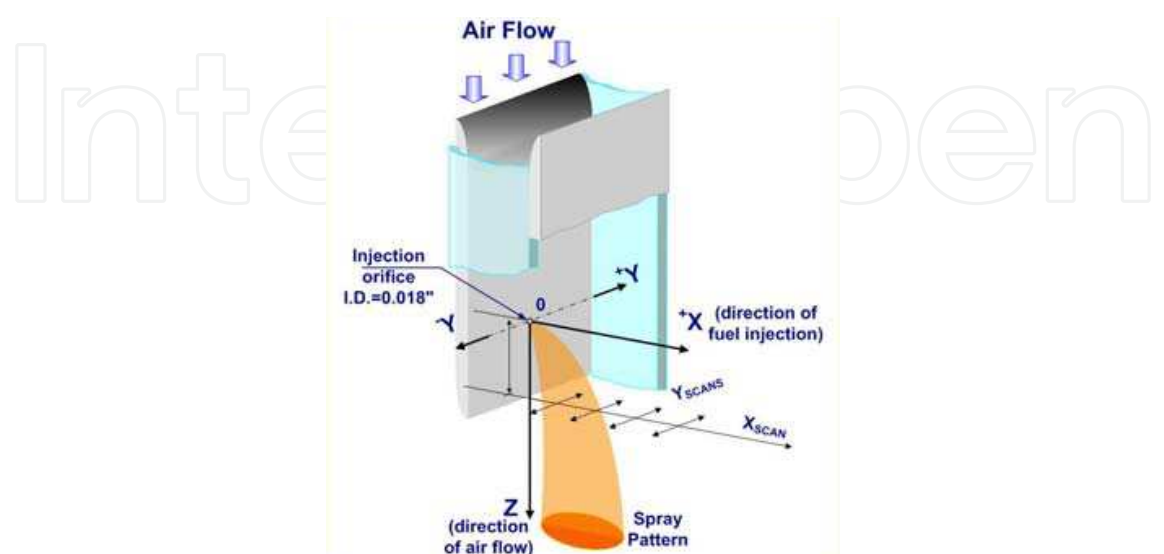


Fig. 5. Coordinate system for spray characterization

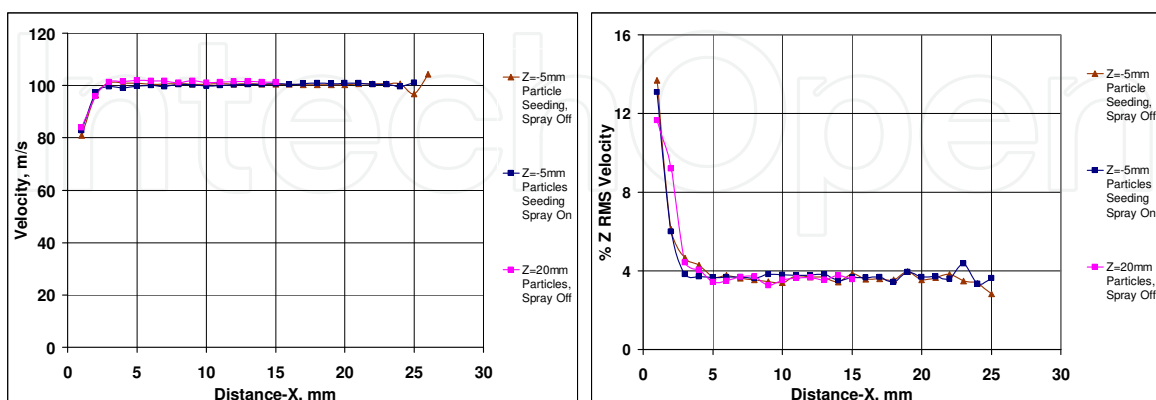
3. Results and discussion

This section consists of several parts including

- Characteristics of the incoming air flow;
- Characteristics of the tested fuel injectors which include:
 - Hydraulic characteristics
 - Images of the fuel jet exiting from both injectors in the absence and in the presence of the crossing air flow
 - Droplet sizes
- Locating of the jet breakup position
- Results of the spray penetration measurements obtained by processing of images obtained at different Weber numbers and different momentum ratios
- Development of the empirical correlations for spray penetration into the cross flow

3.1 Characteristics of the incoming air flow

Velocity profiles of the incoming air flow in the test channel were measured in three representative cross-sections in the presence and in the absence of spray using three dimensional (3-D) Laser Doppler Velocimetry (LDV) system. This system consisted of two transceivers oriented 90 degrees apart, which were installed on the rail connected to the 3-D remotely controlled traversing mechanism. This system optically accessed test section from the orifice plate ($X=0$) to the coordinate $X<25\text{mm}$. To obtain velocity measurements incoming air was seeded with 3-5 μm alumina particles. Results of measurements are presented on Figure 6 in the form of the mean and RMS velocity profiles. It is clear that the mean and RMS velocity profiles are of trapeze-shape form typical for turbulence flow in tubes. Presence and absence of spray did not produce any significant differences in velocity profiles. No significant differences in the profiles were indicated while measured across the test channel 5mm upstream ($z/d \sim 10$) and 20mm downstream ($z/d \sim 40$) of the point of injection.



(a) Mean velocity

b) Velocity RMS

Fig. 6. Characterization of the crossing air velocity field in the test section

3.2 Characteristics of injectors

The main difference between the investigated injectors was shape of the surface between the plenum and the injection orifice.

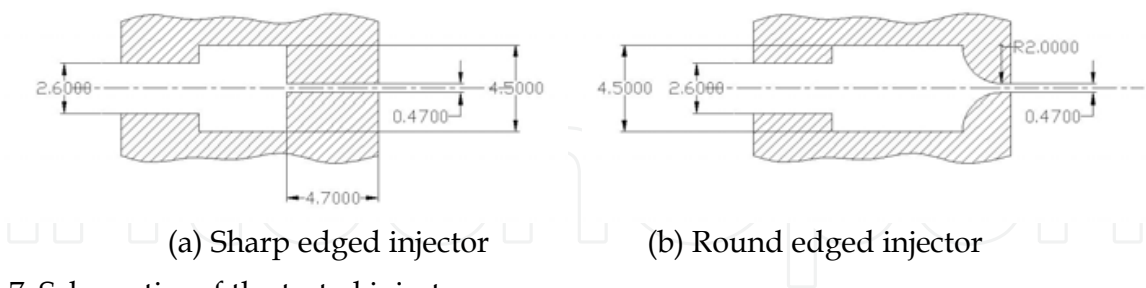


Fig. 7. Schematics of the tested injectors

One injector had sharp edge as shown on the Fig 7-a and the other one had smooth transition path from the plenum to the orifice (i.e., round edge, see Fig 7-b). Their hydraulic characteristics presented on the Fig. 8 reflect this difference in the injector’s internal shape.

Specifically, discharge coefficient $C_d = \frac{\dot{m}_{fuel}}{A_{inj} \sqrt{2\rho_{fuel} \Delta P_{inj}}}$ of the sharp edge orifice was relatively constant $C_d \sim 0.75$ in the tested range of Re_D numbers while the discharge coefficient of the round edge orifice is $C_d \sim 0.96$ at the Reynolds numbers exceeding $Re_D = 10,000$ ($\Delta P_{inj} > 60\text{psi}$) which is relevant to the current study.

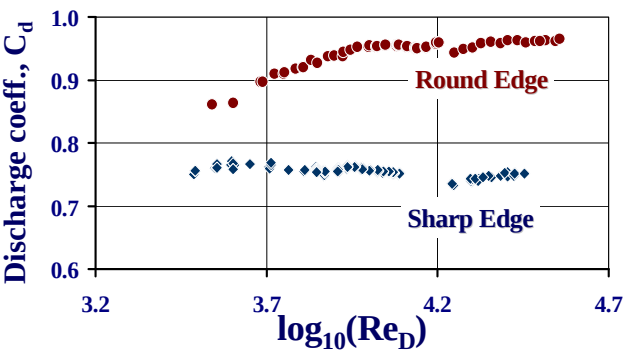


Fig. 8. Hydraulic characteristics of the tested injectors ($Re_D = \rho_{fuel} D_{inj} U_{fuel} / \mu_{fuel}$)

Effect of injector geometry on jet disintegration was first demonstrated without cross flow of air. Images of the fuel jets injected from both injectors into the atmosphere are presented on the Fig. 9. It is clearly seen that the jet coming out of the sharp edged orifice disintegrated forming spray structures, ligaments and droplets (see Figure 9-a) while jet injected from the round edge orifice was relatively smooth and intact (Figure 9-b).

A closer look on these fuel jets without cross flow in a near field (see Figure. 10) reveals that the jet injected from the sharp edge orifice expands and disintegrates while the jet from the round edge orifice shows the development of the hydrodynamic instabilities (see Figures 10-a and 10-b respectively). This observation suggests that internal turbulence created by the sharp edge at the entrance of the cylindrical orifice ($L/D \sim 10$) dramatically change jet boundaries and may lead to the differences in spray creation especially when the mechanism of the jet disintegration in the cross flow at elevated Weber numbers ($We > 200$) is “shearing”. In fact images of the fuel jets shown on the Figure 11 clearly indicate that significant scale difference in liquid border structure on the outer edge of the jet remain

while jets are injected into the cross flow. Size of the outer border structures on the jet exiting from the round edge orifice (Figure 11-b) is at least ten times smaller and more organized than on the jet exiting from the sharp edged orifice (Figure 11-a).

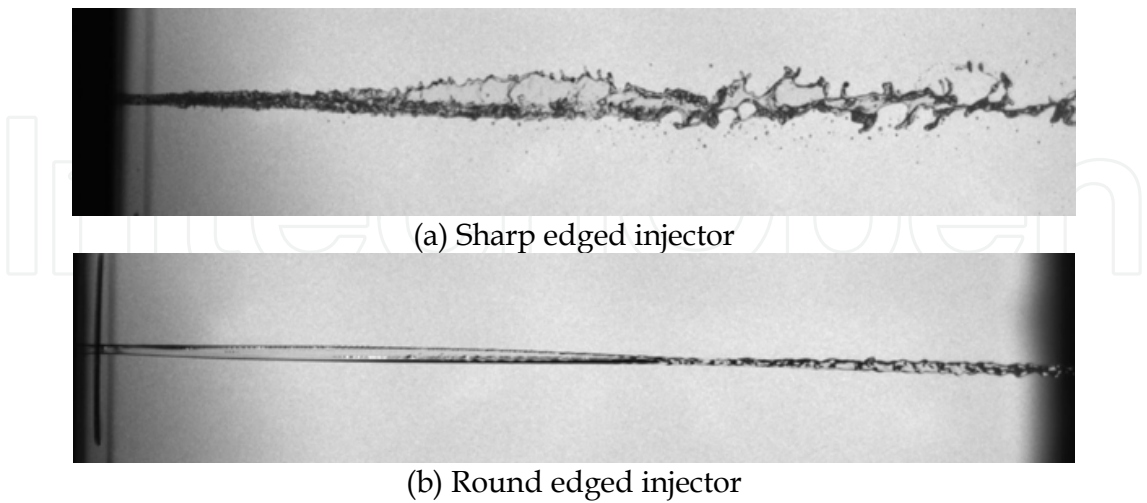


Fig. 9. Images of the fuel jet injected into the atmosphere (no cross flow) from injectors

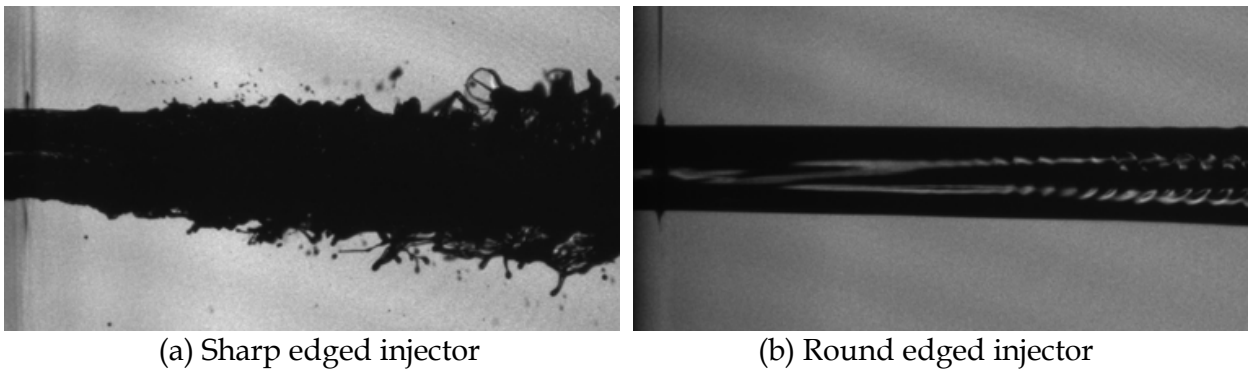


Fig. 10. Zoom in the liquid jets injected into the atmosphere (no cross flow) from injectors

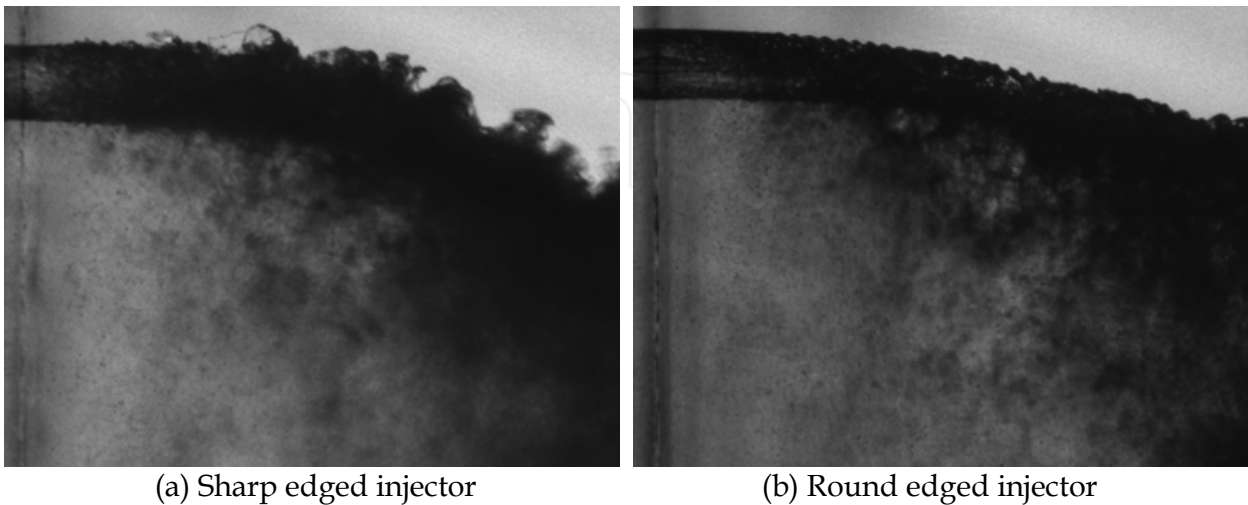


Fig. 11. Images of the fuel jet injected into the cross-flow of air at $We=1000$, momentum flux ratio $q=20$ and $Re=14,700$.

The above mentioned difference in the outer border structure of the jet can potentially influence size of the created droplets. In fact, sharp edged injector used in the current study produces larger droplets as indicated on the counter plots of the Sauter Mean Diameter $SMD = D_{32} = \sum D_i^3 n_i / \sum D_i^2 n_i$, with D_i - diameter of the individual droplet) presented for both tested orifices (sharp and round edged) on the Figure 12 (-a and -b respectively). Measurements were undertaken using PDPA in the representative cross-section of the spray located 60 orifice diameters downstream of point of injection ($z/d=60$) where spray was fully developed at the same flow conditions ($We=1000$ and $q\sim 20$) for both orifices. Comparison of the SMD along the center line in the same plane ($z/d=60$) presented in the Figure 13 reveals $\sim 10\%$ larger droplets on the periphery of the spray produced by the sharp edge orifice.

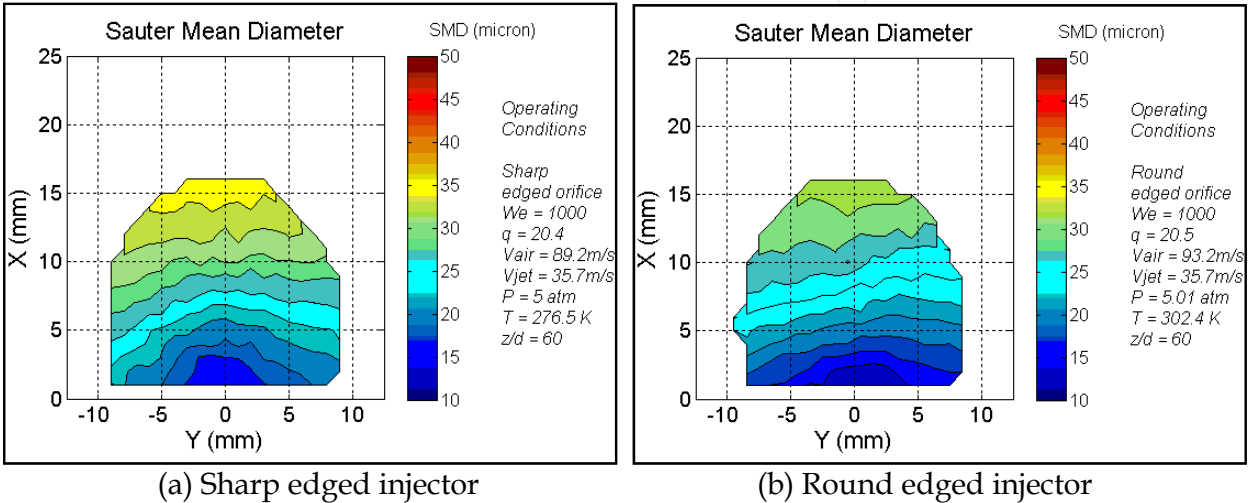


Fig. 12. Sauter Mean Diameter (SMD) in the cross plane of the spray at $z/d=60$ for tested injectors

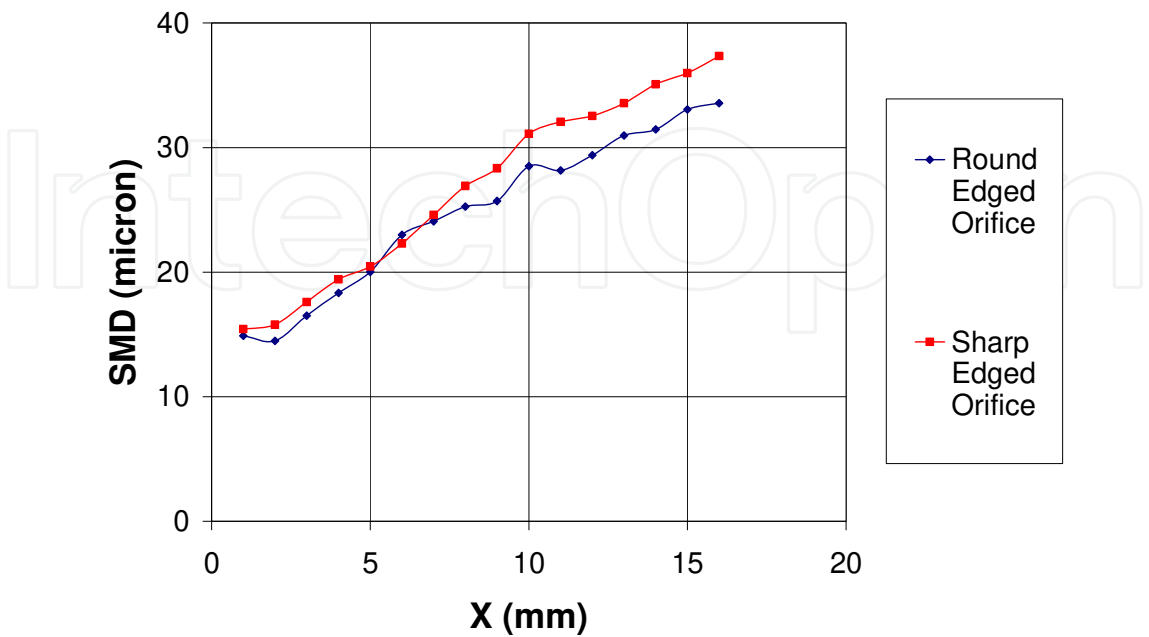


Fig. 13. Comparison of the SMDs along the central plane at $z/d=60$

3.3 Locating of the jet breakup position

Liquid column breakups were investigated using the same pair of the injectors (sharp and round edge) shown on the Figure 7. For this purpose injectors were modified to allow installation of the fiber optic connector coaxially with the injector orifice to provide capabilities for application of the light guiding technique. Measurements were conducted at the room and elevated temperature of the crossing air flow ($T=300\text{K}$ and 555K respectively). Two liquids (Jet-A and water) were used to extend range of possible correlation of the jet location versus non-dimensional parameter.

Figure 14 schematically shows liquid jet light guiding technique that was used for locating the column breakup point (CBP) by letting the liquid jet act as an optical fiber and transmit light through it.

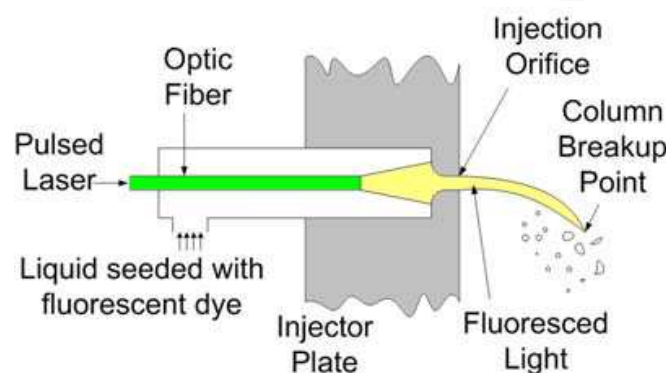


Fig. 14. Experimental schematic for the liquid jet light guiding technique

Pulsed laser light was introduced from the back of the injector using an optical fiber to illuminate the liquid jet. The laser light propagates through the liquid in the injector and reaches the liquid jet column. Light coming out of the orifice undergoes total internal reflection and is guided by the liquid jet like in optical fibers. This effect is based on the fact that the critical angle for total internal reflection for the interface between the Jet-A and air is 43° . In other words, if the liquid jet column bends by over 43° abruptly, a ray of light entering the liquid jet parallel to the injector will also be refracted out of the liquid jet column in addition to being reflected. No such abrupt bends were observed in this study. This ensures that the attenuation of light intensity in the liquid jet column due to refraction is not significant enough to completely terminate the light propagating through the jet.

Slightly different jet illumination techniques were used in this study for the Jet-A and water. When the liquid used was Jet A, Metalaser Technology MTS-20 pulsed Copper Vapor laser with tunable pulse frequency (in the range of 5 kHz – 8 kHz) and a power of about 5mJ per pulse was used for illuminating the liquid jet. When water was used as the liquid for creating the spray, a Nd:YAG laser with a frequency of 10 Hz and a power of about 50mJ per pulse was used for illumination. To make the entire mass of the liquid through which light is passing visible both liquids were seeded with a fluorescent dye. The dyes used were Pyrromethene 567 with Jet A and Fluorescein with water. Both these dyes absorb the laser light and fluoresce in the yellow region. An optical filter was used to cut off the scattered light. The farthest visible point from the center of the orifice in the image is considered to be the CBP.

Figure 15-a shows a typical image of a jet in cross flow obtained by employing the liquid jet light guiding technique. This raw image was eventually inverted into a binary field shown

in Figure 15-b by application of the threshold that was set to the intensity of the image which corresponds to the sharp fall in intensity of the liquid jet. The edge of this binary field was tracked to obtain the complete boundary of the liquid jet (see Figure 15-c). The farthest point on this boundary from the center of the orifice is defined as the CBP in this study. This CBP position was averaged over 150 images. Figure 15-d shows the averaged image of the liquid jet obtained using this technique with crosses indicating individual CBPs and circle indicating the average CBP location for the investigated operating conditions. Figures 16-a and -b show the coordinates of the mean location of the CBP in the direction of fuel injection (X) and airflow (Z) downstream of the orifice respectively. Data of all four experimental series demonstrate the same effect of the CBP approximation to the orifice with the growth of momentum flux ratio (q). Two competing factors control position of the CBP: (1) Increase of the liquid jet velocity with the growth of q and (2) acceleration of the jet disintegration with the growth of the liquid velocity and thus its internal turbulence. This competition is clearly indicated by the maximum on the graph, which shows X/d coordinate of CBP on the Figure 16-a. This effect is much stronger for the sharp edged orifice at higher temperature of the crossing air flow. This fact supports hypothesis of the influence of internal turbulence of liquid jet upon the location of CBP because of possibility of cavitation at increased temperature of the injector internal surfaces caused by the high temperature of the crossing air.

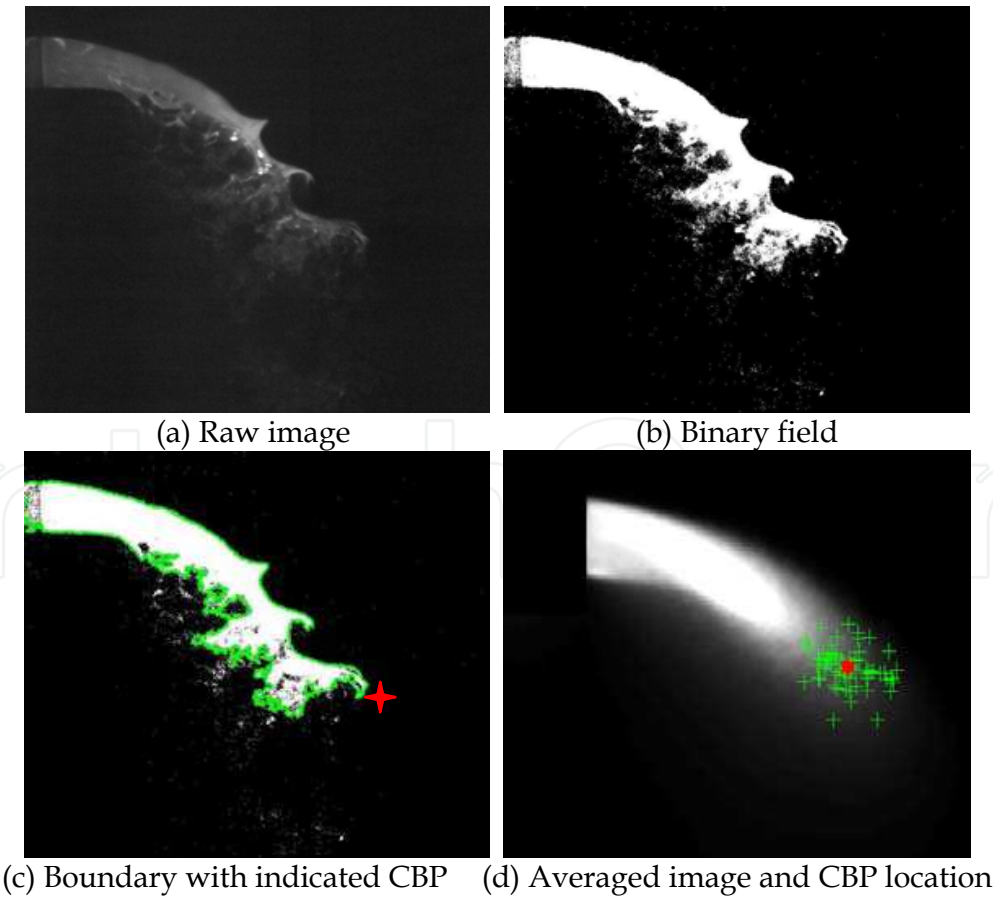


Fig. 15. Methodology for locating the column breakup point (CBP)

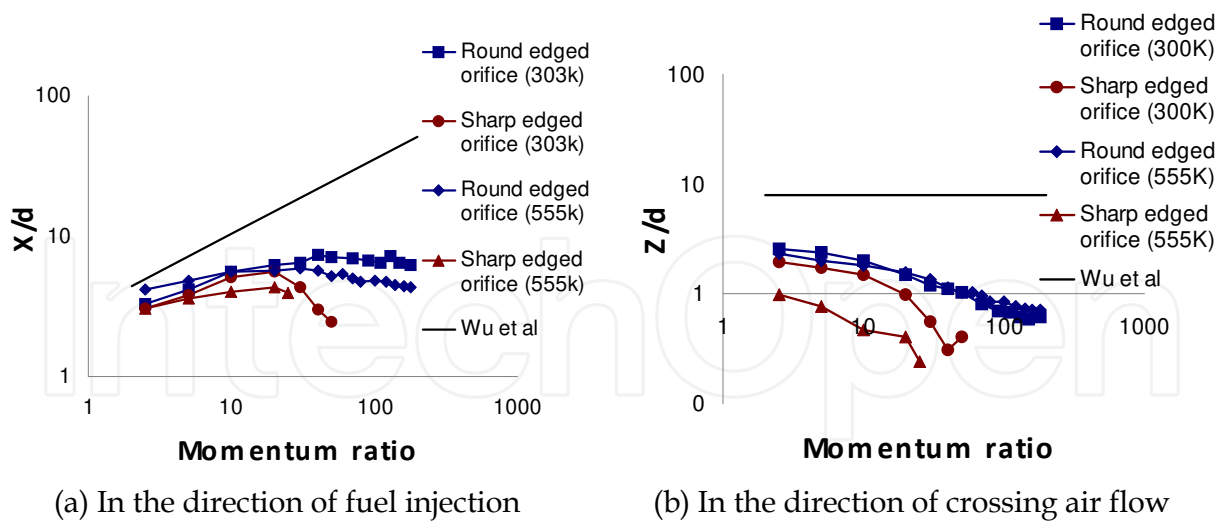


Fig. 16. Location of the column breakup point (CBP)

Figure 17 shows position of the CBP as a function of Weber (We) number. In fact CBP location was determined to be at about 1-4 diameters downstream of the orifice. This distance is reduced with increase of We similar to the dependence upon the momentum flux ratio in Figure 16. This occurs because an increase of We causes an increase of the fuel flow rate and thus velocity of liquid which in turn enlarge the scale of structures (see Figure 11) in the jet boundary. Presumably these larger structures accelerate process of jet disintegration by aerodynamic shearing.

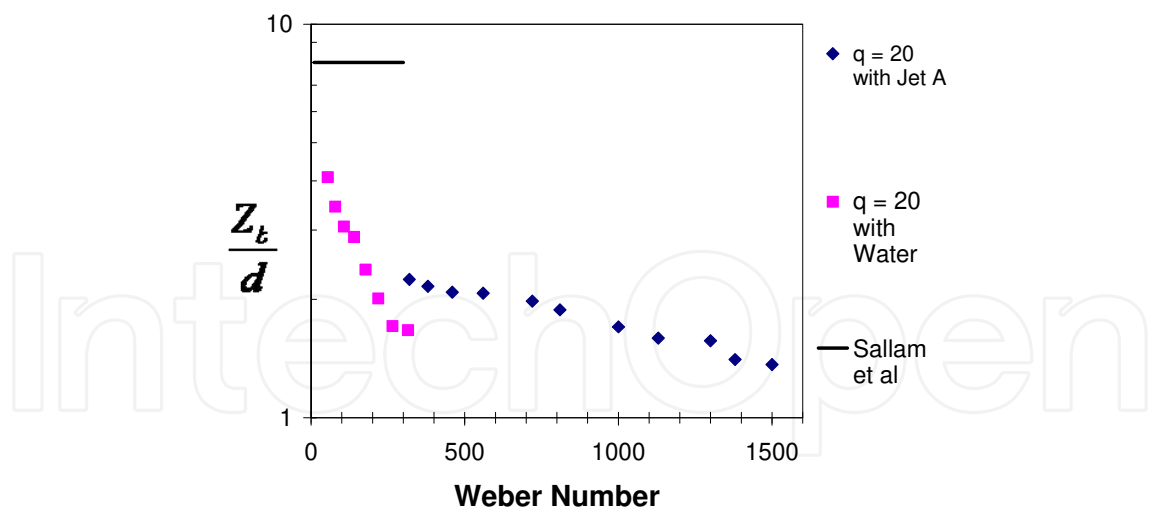


Fig. 17. Typical dependence of the CBP location upon the Weber number for the round edge orifice

It is worth to note that distances at which fuel jet disintegrates in this study are much shorter compared to prior studies (Wu et al., 1997; Sallam et al., 2004) that reported the CBP to lie at a distance of 8 diameters downstream of the orifice for most of the investigated cases. This discrepancy can be attributed to the difference of operating conditions and measuring techniques used for the CBP locating.

Finally, the entire set of CBP obtained in this study for various values of airflow velocities (66 – 140 m/s) and velocity of the liquid jet (19 – 40 m/s) for two liquids (Jet-A and water) at two different cross flow air temperatures was summarized in the form of non-dimensional breakup time (t_{cb} , defined in equation 1), which was calculated from the experimental data with the assumption that velocity of the jet in the X direction does not change until the column breaks up. t_{cb} was obtained by dividing the X distance of the column breakup point from the orifice by the jet exit velocity. Dependence of the t_{cb} upon the liquid jet Reynolds number (Re_j) is shown in the Figure 18. Non-dimensional breakup time (t_{cb}) is chosen as a parameter that is commonly used in computational models of spray formation (Wu et al., 1995). Choice of the Re number is self explained by the fact that only one injector diameter was used in the current study and any variations in the Weber number (We) and momentum flux ratio (q) led to strong variation of velocity of the liquid jet (19 – 40 m/s) and thus of the Re number. This correlation is described by Equation 2 and as shown on the Figure 17 to be valid in the Re_j range of 2,700 – 45,000.

$$\frac{t_{cb}}{t^*} = 9.98 - 0.908 \ln(Re_j) . \tag{2}$$

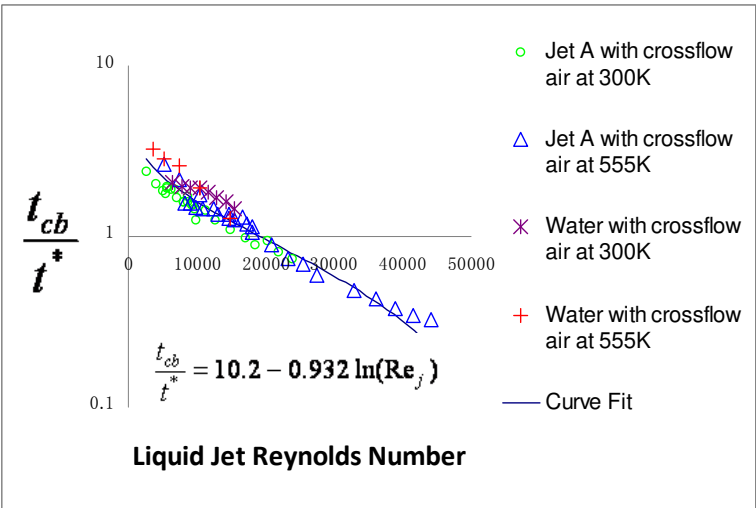


Fig. 18. Non-dimensional breakup time dependence upon the Reynolds number of liquid jet

3.4 Results of the spray penetration measurements

Measurements of spray penetration were obtained using NAC GX-1 high speed camera that captured shadowgraph high definition images of the spray at the rate of 24,000fps at a resolution ~8.5 pixel/mm with a record length of about 20,000 frames. Illumination of the spray was achieved by the copper-vapor laser flashes (30ns) synchronized with the shutter openings. Laser light was introduced into the test section through the 1mm diam. quartz fiber from the laser. Collimator lens and diffusing glass plate created a uniform light beam that illuminated spray from one side through the window in the pressure vessel. Camera that was installed on the other side of the pressure vessel captured shadowgraph images of the spray. Each of several thousands images (see example on the Figure 19-a) that compose a high speed movie of the fluctuating spray was processed individually in order to characterize the outer border of the spray pattern. For this purpose the following procedure was applied:

- Each image was corrected by subtraction of the averaged background. Images of the background were captured before any fuel was injected at each flow condition and then averaged for the experimental series to be processed.
- Dynamic range of each image was adjusted to eliminate possible influence of laser pulse intensity fluctuations (i.e. to avoid affecting the overall brightness of the image).
- Threshold was applied to all images in the series to equalize pixel intensity value in the spray region to unity and background region pixels to zero. The result of this conversion to a binary field is shown on the Figure 19-b. Line that divided white and black zones on the image represented outer border of the spray.

In the final stage of processing, standard algorithms for calculating mean and maximum values and RMS were applied to the spray border lines.

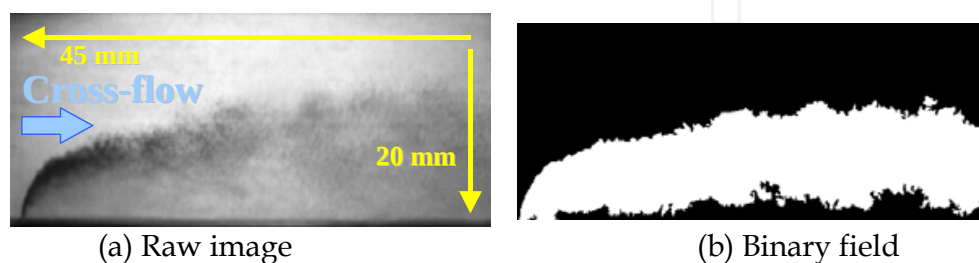


Fig. 19. Procedure for characterization of the outer border of the spray

All together 58 high speed movies of the spray were captured at different flow conditions that are divided into two series. In the first one (so called *We-sweep*) fuel to air momentum flux ratio was kept constant equal to $q=20$ while Weber number was changed from movie to movie. Spray movies at $We=400, 600, 800, 1000, 1200, 1400$, and 1600 were captured.

In the other series of experiments (so called *q-sweep*) Weber number was kept constant ($We=1000$) while momentum flux ratio was varied from movie to movie. In the *q-sweep* momentum ratios of $q=5, 10, 20, 40, 60, 80, 100$ were examined. *We-sweep* and *q-sweep* were performed for both sharp and round edged injectors.

Typical results of the *We-sweep* are presented on the Fig. 20 in the form of the mean positions of the spray outer borders at different Weber numbers (see Figure 20-a) and their RMS values (Figure 20-b). It is clearly seen that the position of the spray outer edge and its RMS are practically independent of We number. RMS value increases almost linearly with axial position downstream the injection point. Similar result (lack of dependence on the Weber number) was obtained in the *We-sweep* performed with the round edged injector. Lack of dependence of the spray outer border on the Weber number allows significant simplification of the correlation function.

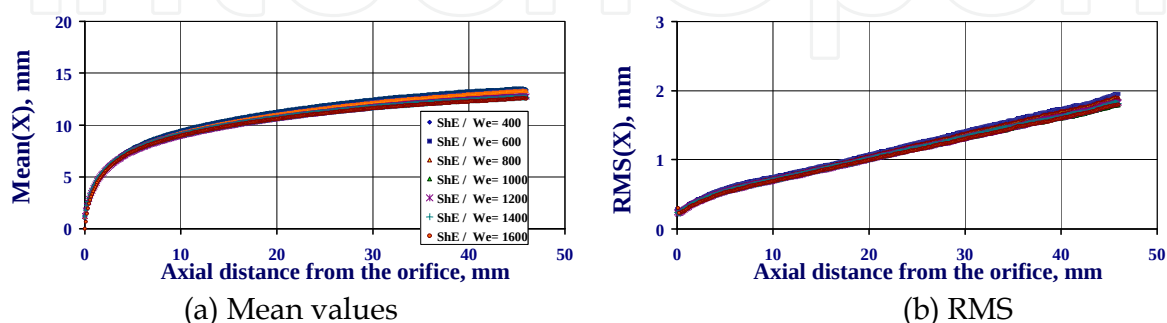


Fig. 20. Spray penetration (X) into the cross-flow of air at different Weber numbers ($We=400 \dots 1600$) for sharp edge injector

Series of curves each representing the mean position of the spray outer border at a certain momentum flux ratio (*q-sweep*) are shown on the Fig. 21 for the sharp- and round-edged orifices. Graphs reveal strong dependence of the spray border upon the momentum flux ratio. Both series of curves follow the same trend. At the same time they indicate greater spray penetration into the cross flow (~12%) for the sharp edge orifice comparing to the round edged orifice.

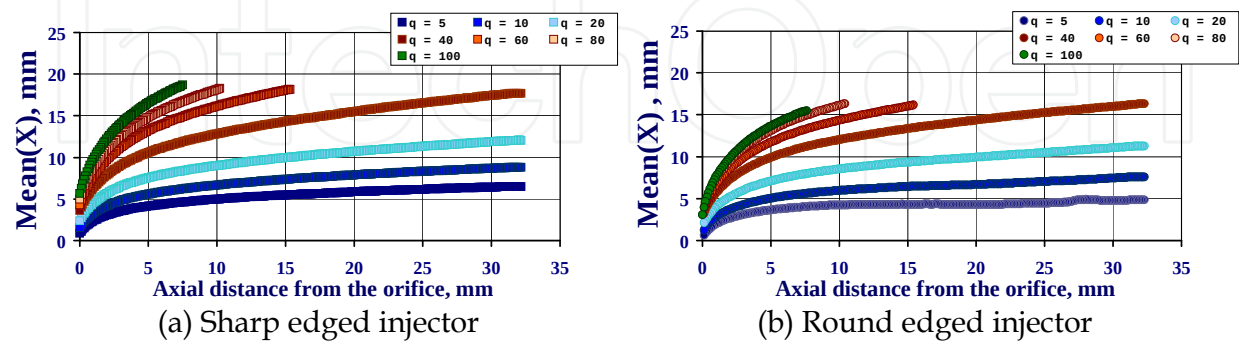


Fig. 21. Mean spray penetration into the cross flow of air at different momentum flux ratios ($q=5\dots100$). Note: $We=1000=const$.

This difference can be attributed to the larger droplets size created by the sharp edge orifice shown on the Figures 12 and 13 and to the difference in the fuel velocity profiles reflected by the difference in flow coefficients C_d of the two tested injectors (see curves on the Fig. 8). Both factors are working towards higher spray penetration. In spite of the fact that the average fuel velocity discharged from the sharp edge orifice is lower than from the round edge orifice because of hydraulic losses, velocity in the center of the jet may be higher and at least some droplets will have higher momentum exclusively because of velocity difference. It is worth to note that the spray border curves obtained for both orifices converge significantly while being normalized by the C_d , (i.e., by the maximum velocity) and by the diameter (D_{32}) of droplets.

Curves on the Fig. 22 were obtained by normalizing the jet penetration into the cross flow by square root of the momentum flux ratio value, q . All the curves obtained in a wide range of $q=5\dots100$ and previously shown on the Figure 21 collapsed here in one line. This fact provides a good opportunity for the approximations of the spray penetration X using self explained physical dependence $X\sim\sqrt{q}\sim U_i$.

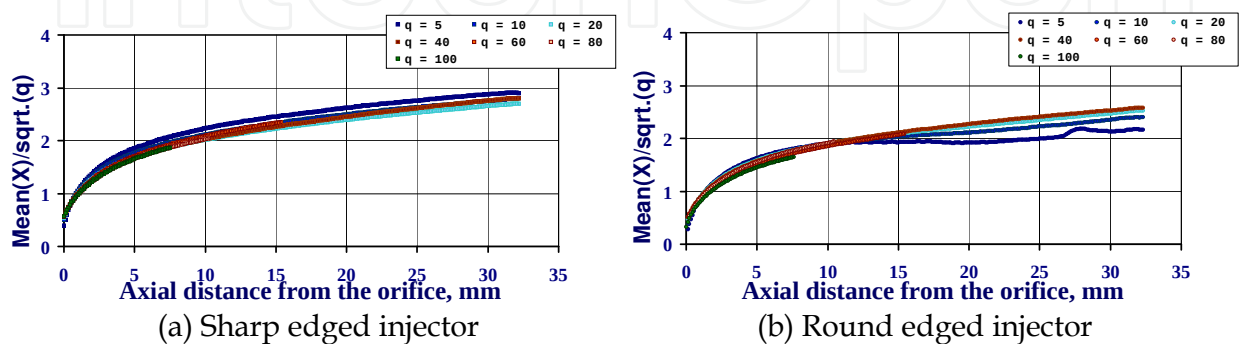


Fig. 22. Normalized values of the mean spray penetration into the cross flow of air at different momentum flux ratios (q)

Measurements of the spray border obtained in the current study using high speed imaging technique were compared with the spray border data obtained using Phase Doppler method. For this purpose the data rate measured with the PDPA is used as a metric to locate the edge of the spray. The edge of the spray is assumed to be around a region showing 10% of the maximum data rate as shown in Fig. 23-b. Figure 23-a demonstrates a good agreement between the spray trajectories obtained using statistically relevant high speed imaging technique and borders of the spray measured by the processing of the PDPA data rate. It is clearly seen that the maximum spray penetration determined as $X^*=X_{mean} + 2.8RMS$ is equal to the border determined at the level of 10% threshold of the PDPA data rate curve maximum.

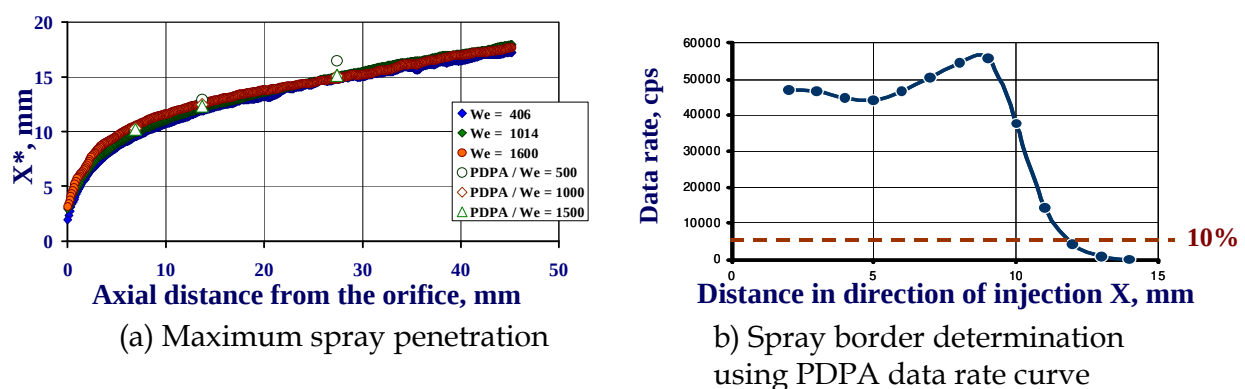


Fig. 23. Comparison of the maximum spray penetration (i.e. $X^*=X_{mean} + 2.8RMS$) at $q=20$ measured by the high speed (HS) imaging technique and by the PDPA

3.5 Development of the empirical correlations for spray penetration into the cross flow

Literature sources suggest correlations for the spray outer border $x/d=f(z/d)$ in several different forms that definitely include power function of the momentum flux ratio q^n . Correlations may or may not include power function of Weber number. Shape of the spray pattern is typically described using logarithmic or power function. In spite of the fact that the accuracy of correlation can be improved by increasing number of empiric constants, current study seeks to simplify correlations. This was achieved by using self explained proportionality of droplets penetration into the cross flow to their velocity at the point of discharge (i.e. $x/d \sim U_r \sim q^{0.5}$) and reducing number of the empiric constants by one (i.e. $q^n = q^{0.5}$). This significant simplification was proved experimentally on both tested injectors in a wide range of momentum ratios between $q=5$ and $q=100$.

Another simplification of correlation function was attained by limitation of the Weber number range between $We=400$ and $We=1600$. This in turn limited number of possible mechanisms of the jet disintegration to only one mode of liquid jet breakup; i.e., shear breakup excluding column break up. Independence of spray penetration upon the Weber number in the investigated range allowed an exclusion of the Weber number from correlations.

As a result spray penetration for both injectors was correlated using only one empiric coefficient (a_1) that depends only upon the shape of the injector internal surface by the following formula:

$$\frac{x}{d}=a_1\sqrt{q}\left(\frac{1}{\left(1+a_2\frac{z}{d}\right)}+\ln\left(1+a_2\frac{z}{d}\right)\right)$$

(3)

The other coefficient (a_2) only shaped the spray border described by the logarithmic function and was independent of the injector design. Thus average and maximum spray penetrations were correlated using coefficients a_1 and a_2 presented in the table 1.

Penetration→	Average		Maximum	
Injector Type↓	a_1	a_2	a_1	a_2
Sharp Edge	1.2181	1.8806	1.9866	0.7403
Round Edge	1.0724		1.8641	

Table 1. Empirical correlation coefficients for the average and maximum spray penetration into the cross flow.

Comparison of the experimentally measured and correlated spray penetrations X are presented on the Fig. 24 for the average and maximum penetration of the spray created by the sharp edged injector.

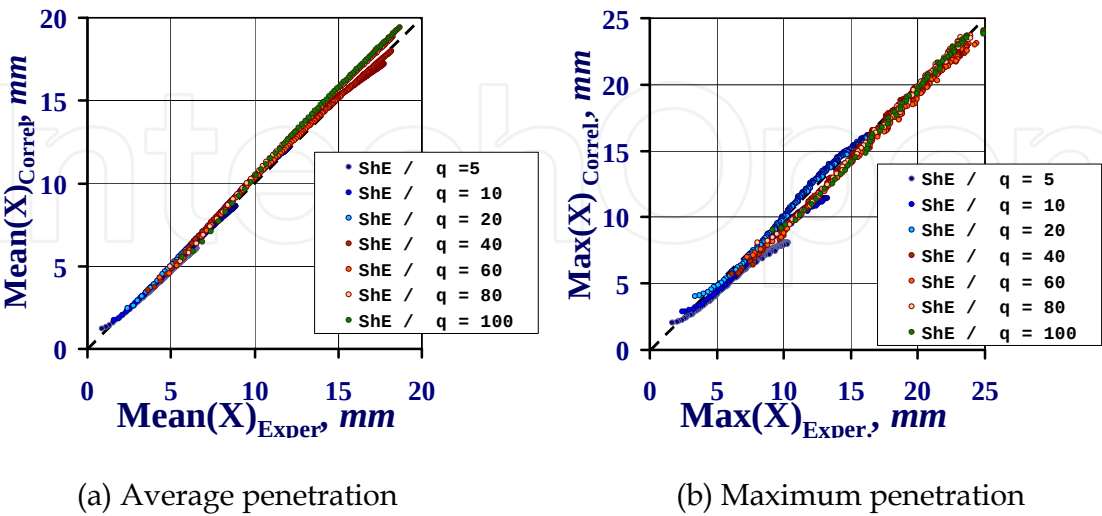


Fig. 24. Comparison between the correlated and experimentally measured values of spray penetration X

4. Conclusions

1. Outer borders of the Jet-A spray trajectories created as a result of fuel jet disintegration in the cross flow of cold air at elevated pressure of 5 atm were measured by application the high speed imaging technique that allowed obtaining series of instantaneous images of the fluctuating spray. Locations of the liquid column breakup points (CBP) were determined using the light guiding technique that make mass of liquid illuminated from inside fluoresce till the moment jet losses its continuity.
2. Crossing air flow had core turbulence $\sim 4\%$ and thickness of the boundary layer near the rectangular channel walls $\sim 3\text{mm}$.
3. Both injectors used in the study had the same diameter of the orifice $d=0.47\text{mm}$ and a different shape of the internal path (i.e., sharp and round edge orifice) were manufactured using the same equipment and technology. They were installed with orifices openings flush with the channel wall.
4. Application of light guiding technique significantly improved accuracy of the jet in cross flow column breakup point (CBP) determination especially at elevated Weber number ($We>200$) when traditional shadowgraph methods are not effective because of presence of droplets in high density around the liquid column.
5. CBP was found to be strongly dependent upon velocity of the jet and internal turbulence of liquid inside the orifice. Jet injected from the sharp edge orifice disintegrates earlier compared to the round edge orifice. Dependence of the CBP location upon temperature of injector is much stronger in the sharp edge orifice compared to the round edge orifice.
6. CBP locations were well correlated while converted to the non-dimensional form of characteristic time against the liquid Reynolds number. In fact, CBP location determined in this study were found to be 1-4 diameters of the jet downstream from the injection orifice which is much closer than it was reported in the previous studies ($z/d\sim 8$).
7. Spray trajectories were found to be independent upon Weber number in the investigated range between $We=400$ and $We=1600$ due to only shear breakup mode of liquid jet disintegration.
8. Spray penetration into the cross flow was found to be proportional to square root of momentum flux ratio of the fuel jet to crossing air in the investigated range between $q=5$ and $q=100$ due to self explained dependence of droplet penetration upon the jet velocity at the point of injection.
9. Spray created by the sharp edge injector penetrated 12% further into the cross flow than from the round edge orifice. This observation was attributed to a larger droplet size created by sharp injector and, possibly by the higher velocities of some droplets.
10. Good agreement between the spray trajectories obtained using high speed imaging technique used in the current study and borders of the spray measured by the processing of the PDPA data. It was found that that the maximum spray penetration determined as $X_{max}=X_{mean}+2.8RMS$ is equal to the border determined at the level of 10% threshold of the PDPA data rate maximum.
11. Simple correlations for the spray trajectories were obtained using only two empirical coefficients. One of them corresponded to the shape of the injector internal path and the other one only adjusted shape of the logarithmic function that determined average or maximum penetration of the spray and was independent of the injector design.

5. Acknowledgment

The authors would like to thank General Electric-Aviation (Dr. Nayan Patel, contract monitor) for the fund that allowed conduct this study and for additional technical guidance.

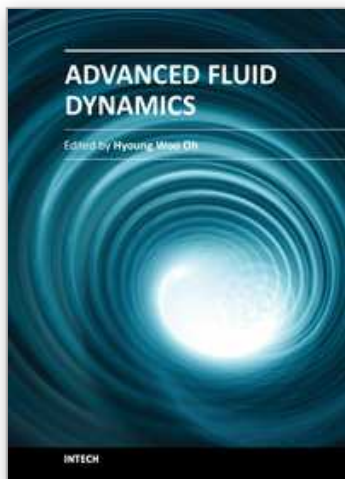
6. References

- Ahn, K., Kim, J., & Yoon, Y. (2006). Effects of Orifice Internal Flow on Transverse Injection into Subsonic CrossFlows: Cavitation and Hydraulic Flip. *Atomization and Sprays*, Vol. 16, pp.15-34
- Becker, J. & Hassa, C. (2002). Breakup and Atomization of a Kerosene Jet in Cross flow at Elevated Pressure. *Atomization and Sprays*, Vol. 11, pp. 49-67
- Bonnell, J. M., Marchall, R. L., & Riecke, G. T. (1971) Combustion Instability in Turbojet and Turbofan Augmentors", AIAA 71-698, *Proceedings of 7th AIAA/SAE Propulsion Joint Specialist Conference Exhibit*, Salt Lake City, UT 1971.
- Charalampous, G., Hardalupas, Y., & Taylor, A. M. K. P. (2007). A Novel technique for measurements of the intact liquid jet core in a coaxial air-blast atomizer, AIAA 2007-1337, *Proceedings of 45th Aerospace Science Meeting & Exhibit*, Reno, NV 2007.
- Chen, T. H., Smith, C. R., & Schommer, D. G. (1993). Multi-Zone Behavior of Transverse Liquid Jet in High-Speed Flow. *AIAA Paper*, 93-0453, *Proceedings of 31st Aerospace Science Meeting & Exhibit*, Reno, NV, 1993
- Hanson, A. R., Domich, E. G., & Adams, H. S. (1963) Shock tube investigation of the breakup of drops by air blasts. *Physics of Fluids* Vol. 6, pp.1070-1080
- Madabushi, R. (2003). A Model for Numerical Simulation of Breakup of a Liquid Jet in Crossflow, *Atomization and Sprays*, Vol 13, pp. 413-424
- Marmottant, P. & Villermaux, E. (2004). On spray formation. *Journal of Fluid Mechanics*, Vol. 498, pp. 73-111
- Ranger, A. A. & Nicholls, J. A. (1969). The Aerodynamic Shattering of Liquid Drops. *AIAA Journal*, Vol. 7, No. 2, pp. 285-290.
- Sallam, K.A., Dai, Z., & Faeth, G.M. (2002). Liquid breakup at the surface of turbulent round liquid jets in still gases. *International Journal of Multiphase Flow* Vol. 28.
- Sallam, K. A., Aalburg, C., & Faeth, G. M. (2004). Breakup of Round Non-Turbulent Liquid Jets in Gaseous Cross Flow. *AIAA Journal*, Vol. 42, No. 12, December 2004.
- Stenzler, J. N., Lee, J. G., and Santavicca, D. A., "Penetration of Liquid Jets in a Crossflow", AIAA 2003-1327, *41st Aerospace Science Meeting & Exhibit*, , Reno, NV 2003.
- Tamaki, N., Shimizu, M., Nishida, K., and Hiroyasu, H., "Effects of cavitation and internal flow on atomization of liquid jet," *Atomization and Sprays*, Vol. 8, No. 2, 1998, pp. 179-197.
- Tamaki, N., Shimizu, M., and Hiroyasu, H., "Enhancement of the atomization of a liquid jet by cavitation in a nozzle hole," *Atomization and Sprays*, Vol. 11, No. 2, 2001, pp. 125-137.
- Wu, P.-K., Miranda, R. F., & Faeth, G. M. (1995). "Effects of Initial Flow Conditions on Primary Breakup of NonTurbulent and Turbulent Round Liquid Jets," *Atomization and Sprays*, Vol. 5, No. 2, pp. 175 – 196.

Wu, P.-K., Kirkendall, K. A., Fuller, R. P., & Nejad, A. S. (1997), Breakup Processes of Liquid Jets in Subsonic Cross-flows. *Journal of Propulsion and Power*, Vol. 13, No. 1, pp. 64 -73.

IntechOpen

IntechOpen



Advanced Fluid Dynamics

Edited by Prof. Hyoung Woo Oh

ISBN 978-953-51-0270-0

Hard cover, 272 pages

Publisher InTech

Published online 09, March, 2012

Published in print edition March, 2012

This book provides a broad range of topics on fluid dynamics for advanced scientists and professional researchers. The text helps readers develop their own skills to analyze fluid dynamics phenomena encountered in professional engineering by reviewing diverse informative chapters herein.

How to reference

In order to correctly reference this scholarly work, feel free to copy and paste the following:

E. Lubarsky, D. Shcherbik, O. Bibik, Y. Gopala and B. T. Zinn (2012). Fuel Jet in Cross Flow - Experimental Study of Spray Characteristics, Advanced Fluid Dynamics, Prof. Hyoung Woo Oh (Ed.), ISBN: 978-953-51-0270-0, InTech, Available from: <http://www.intechopen.com/books/advanced-fluid-dynamics/fuel-jet-in-cross-flow-experimental-study-of-spray-characteristics>

INTECH
open science | open minds

InTech Europe

University Campus STeP Ri
Slavka Krautzeka 83/A
51000 Rijeka, Croatia
Phone: +385 (51) 770 447
Fax: +385 (51) 686 166
www.intechopen.com

InTech China

Unit 405, Office Block, Hotel Equatorial Shanghai
No.65, Yan An Road (West), Shanghai, 200040, China
中国上海市延安西路65号上海国际贵都大饭店办公楼405单元
Phone: +86-21-62489820
Fax: +86-21-62489821

© 2012 The Author(s). Licensee IntechOpen. This is an open access article distributed under the terms of the [Creative Commons Attribution 3.0 License](https://creativecommons.org/licenses/by/3.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

IntechOpen

IntechOpen