Study of Two-Dimensional Transverse Liquid Injection into Subsonic Air Stream

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Abstract

Numerical simulation of transverse liquid injection into subsonic air stream is presented in this study. The two-dimensional Reynolds Averaged Navier-Stokes equations along with the standard k-ε turbulence model are solved using FLUENT software. Two-phase flow is simulated by the Eulerian multiphase model. Nine different cases are studied and the results for the liquid jet boundaries and flow fields for water and air are presented. It is found that volume fraction of water decreases as the liquid jet flows downstream. The liquid to air mass ratio also decreases as the jet moves downstream. However, the liquid jet is bent and its width is increased. Velocity fields of water and air and static pressure of mixture increase with free-stream Mach number, M. However, the Mach number has only a marginal effect on break-up length, penetration height, and liquid to air mass ratio. Velocity of air, velocity of water, static pressure of mixture, liquid to air mass ratio, break-up length and penetration height increase when momentum ratio, q, is increased.

Key words: Transverse liquid jet, Penetration Height, Break-up length, FLUENT

Introduction

Transverse liquid jet injection into air flow finds important applications in pollutant dispersion, main combustors, afterburner of jet engines, furnaces, rocket engines, and dump combustors, etc. In general, successful development of liquid hydrocarbon fuelled combustor includes deeper fuel penetration into the air-stream for better mixing, generation of smaller liquid fuel droplets for faster evaporation, appropriate flame stabilization mechanism for piloting and sustaining combustion and substantial reduction in drag losses associated with processes of mixing and flame holding. In a combustion system, liquid fuel jets are injected from walls of combustors or bluff body flame holders into the air-stream. The processes involved in jet breakup dictate the combustion efficiency and overall performance of combustors. Generally, the dynamic force of the air causes the liquid jet to bend in the flow direction and to deform in its cross section. The cohesive and disruptive forces on the surface of the jet give rise to oscillation and perturbation. As a result, the waves begin to propagate on the windward surface of the jet, and their growth is magnified until jet column fracture occurs. This leads to formation of clumps, ligaments and larger droplets. It is known as primary atomization. If droplets and ligaments exceed the critical size then they undergo secondary atomization until the droplets attain a size that is limited by the critical Weber number. Besides this, liquid stripping from the downstream side of the jet may also occur before the point of column fracture.

Most of the studies on transverse liquid injection into a subsonic cross-flow available in literature are with experimental method [1, 3, 9-11]. The experimental studies mainly deal with the jet break-up length. However, few experimental studies are available on other important parameters such as penetration height, liquid to air mass ratio, velocity and pressure distribution. There are few analytical [1-4] and numerical studies. Nguyen and Karagozian [4] used the two-dimensional Euler equations to find out the behavior of a transverse liquid jet for subsonic flows. They used second order total variation diminishing (TVD) scheme and the first order Godunov scheme for solving the equations. The effect of mass loss due to boundary layer stripping as well as evaporation (with and without combustion) has been shown to be relatively unimportant to the actual jet trajectory shape. Campolo and Cortelezzi [13] studied the dynamics and dispersion mechanisms of transverse jets for subsonic cross flow. The Reynolds Averaged Navier-Stokes (RANS) equations were solved by using a commercial, finite volume code (Star-CD). They demonstrated the importance of including a segment of pipe of appropriate length into the simulation of a transverse jet. In addition, they evaluated the jet penetration with different boundary conditions imposed at the jet exit. Recently, Ryan [14] predicted the deflection and deformation of a liquid jet in a non-uniform air cross-flow, using the Jet Embedded (JE) into Volume of Fluid (VOF) approach.

There is a need to characterize numerically the detailed flow fields of transverse liquid injection into a subsonic cross-flow. However, the present study is limited to a two-dimensional liquid jet injection into subsonic air flow. The main objectives of the present numerical study are to compute the flow fields for liquid and air, to determine break-up length and penetration height and the mass ratio of liquid to air at downstream locations of liquid jet break-up.

Numerical Solution

In the present study, injection of a two-dimensional water jet into a subsonic air stream is simulated numerically by considering two-dimensional Reynolds Averaged Navier-Stokes equations, by using FLUENT 6.1.22 [15]. In addition, the turbulence modeling is performed by using the standard k-ε model with help of wall function at the wall. Two-phase flow is simulated by using the Eulerian multiphase model. In the present numerical simulation, the reference coordinate system is centered at the bottom of the air inlet section. The boundary conditions for the numerical simulations are: (i) Uniform velocity profiles at the air inlet, (ii) Uniform velocity profile at the water injection inlet, (iii) Zero-gradient outflow condition at the test-section outlet, and (iv) No-slip conditions at the wall. The computational domain is 128 mm by 70 mm and the size of water injector is 1.6 mm. The grid spacing in X-direction is 0.32 mm and in Y-direction 0.3 mm. In the present study, nine different cases (Table 1) are considered by varying the free stream Mach number (0.2, 0.45, and 0.6) and liquid to air momentum ratio (0.5, 1.0, and 1.5). Steady state solution is obtained by using a false transient approach and grid independent results are presented below.

Results and Discussion

Results for all the nine cases under consideration are obtained for the velocity field, pressure field and volume fraction for both water and air. However, results are presented only for Case 4, due to limitation of space. Results include jet boundaries, flow fields, break-up length, penetration depth, and mass ratio of liquid to air.

Figure 1 shows the volume fraction contour of water (α_w). α_w has a maximum value of unity near injection point. It can be noted that the volume fraction along the core region changes marginally from unity value indicating presence of liquid column. The liquid jet spreads progressively as it moves downstream and results in the decrease of volume fraction of water due to entrainment of air into liquid jet. When the volume fraction of water decreases substantially, it is assumed to be the onset of liquid break-up. α_w decreases indicating the interaction of cross-stream of air and liquid jet towards upper and lower boundary of liquid jet. In the lower portion of the liquid jet from its injection point, the volume fraction of water turns out to be almost zero indicating that cross-stream could not penetrate into liquid jet. Thus, the liquid column remains intact for certain distance. Jet width increases significantly with increase in liquid to air momentum ratio. This observation can be attributed to transfer of momentum between jet and cross-flow. The results for α_w are used to identify the liquid jet boundaries. There is no definite criterion available in the literature to identify the jet boundary. In the present study, the upper and lower jet boundaries are obtained by considering α_w value of the order of 10^{-05} as it is quite small in comparison to the value at the inlet of liquid jet. The upper and lower jet boundaries (Fig. 2) indicate the liquid jet is bent due to the impact of cross-flow of air stream. The jet width is increased from 10 mm at jet inlet to about 20 mm at section outlet. The effect of free-stream Mach number on the jet width is found to be negligible over the range of Mach numbers studied in this study. However, the liquid to air momentum ratio affects the jet width. An increase in liquid velocity increases the liquid column length and occurrence of jet break up shifts towards downstream side. Thus, the overall width of the jet decreases.

Velocity field of water is presented in Fig. 3. The maximum value (24 m/s) shows that the water velocity, U_w, has increased, considerably, as compared to injection velocity (3.75 m/s). The sudden increase in velocity of water is due to the breaking-up of the liquid jet and formation of ligaments and droplets. The maximum velocity for water is increased with the increase in free-stream Mach number, M, due to augmentation of momentum of liquid ligaments and droplets. Similar trend, though to a lesser extent, is also observed with the increase in liquid to air momentum ratio, q. The air velocity, U_a of 153 m/s (at the air inlet section) decreases in the vicinity of the liquid jet as it cannot penetrate into liquid column. However, air gets deflected towards the upper boundary of the duct and attains a higher velocity due to contraction in air passage. In the process, it interacts with the liquid jet surface, effecting interfacial drag along the surface of liquid column. As a result, the liquid jet deflects towards the leeside of the flow.

The static pressure, p, of mixture is more on windward side compared to that on the leeward side near the injection point. This occurs as air impinges into the liquid column and is brought to rest resulting in an increase in static pressure in this zone. The pressure downstream of liquid jet at its root becomes negative indicating the occurrence of recirculating zone which can be observed in the velocity plots. However the pressure increases along Y-direction in the downstream of liquid jet due to air entrainment into liquid jet. The static pressure of mixture varies from –8.2 kPa to 7.7 kPa. It has been observed that magnitude of the static pressure of mixture increases with increase in liquid to air momentum ratio, q, which may be attributed to the increase in momentum of fluid flow.

Break-up length is defined as the horizontal distance between the point of injection and the point where the liquid jet column fracture starts. However, it is difficult to identify the beginning of liquid jet fracture, from the numerical results. In the present work, following procedure is adopted to find out the break-up length. The maximum value of volume fraction of water, $(\alpha_w)_{max}$, as a function of X is obtained from the results for volume fractions of water over the whole domain. It has been observed that $(\alpha_w)_{max}$ is decreasing continuously along the trajectory of the liquid column. The beginning of jet break-up is considered to be the location where the maximum value of volume fraction of water, $(\alpha_w)_{max}$ attains a value of 0.10. Hence, the break-up length is estimated as the axial distance from the injection point to the jet break-up point. It can be noted that break-up length, L, increases with momentum ratio, q, for all three cross flow velocities. In the presence of the cross-flow, an increase in liquid velocity results in a longer liquid column which leads to shifting of the breakup mechanism towards the downstream side. However, free stream Mach number, M, has only marginal effects on break-up length, L. Increase in M also results in increase of liquid velocity, to keep the momentum ratio, q, constant. Thus, effect of increase in air velocity (to decrease the break-up length) is nullified by the effect of increase in liquid velocity (to increase the break-up length). Comparing the results with those of Sallam et al. [11] it is found that for free-stream Mach number, M = 0.2, each value of break-up length, L, is overestimated, except for M = 0.45 and 0.6, where it is underestimated. This difference in the trend of present results may be attributed to the two-dimensional flow assumption used in the present computations. The present results are also in qualitative agreement with the earlier studies on break-up length [1, 8, 9]. An empirical equation between non-dimensional break-up length and momentum ratio has been derived by using linear regression analysis with the present computed data (Fig. 4).

$$L/d = 8.19 * q + 11.36 \qquad (1)$$

In equation (1), the correlation coefficient R = 0.976. It must be noted that Eq. 1 is valid for the ranges of q values used in the present work. In addition, effect of injector size, d, on L, has not been studied in the present work. It may be noted that M has not been included in Eq. 1, as its effect is only marginal.

Penetration height, h, plays an important role in characterizing the liquid jet injection into cross-flow stream. It is defined as the maximum vertical distance that the liquid jet penetrates into the free-stream. In the present work, an attempt has been made to determine penetration height from the slope of upper boundary of liquid jet. As mentioned earlier, the upper boundary of liquid jet is found out from the volume fraction of water. The starting point of the minimum slope is considered to be the location of penetration distance, X_h, from the liquid injection point. Then, penetration height, h, is the vertical distance up to the upper boundary of liquid jet corresponding to this point. The variation of non-dimensional penetration height, h/d, is plotted with momentum ratio, q (Fig. 5). It can be noted that penetration height, h, and location of penetration, X_h, increase with increase in momentum ratio, q. Increase in the liquid velocity results in higher momentum carried by the liquid jet which leads to increase in jet penetration. However, the Mach number of cross flow has only a marginal effect on the penetration height, h. Present predicted penetration height, h, is only qualitatively accurate and it overestimates the value of penetration height. It is expected as the present computation is for two-dimensional flow simulation of cross flow injection. Present results also agree qualitatively with the earlier results on penetration height [2, 5, 6].

As the present work is concerned with single injection diameter, an attempt has been made to derive an equation between non-dimensional penetration height and momentum ratio by using regression analysis (Fig. 5).

$$h/d = 18.329\,(q)^{0.5} + 1.5374 \qquad (2)$$

The correlation coefficient R = 0.99 for Eq. 2, which is valid for the ranges of q values used in the present work. It can be noted that free-stream Mach number, M, is not included in Eq. 2 as its effect on penetration height, h, is only marginal. This expression may be useful to design and to develop cross flow liquid injection systems.

Mass ratio of liquid to air is an important parameter in the study of liquid jet in transverse air flow as it determines the rate of fuel consumption in case of combustors. Thomas and Schetz [6] calculated the liquid to air mass ratio distribution at a distance of 30 mm downstream of the injector and showed that for simulated fuel and air mixing; at least one order of more air must be mixed with the liquid to bring the ratios close to stochiometric for a hydrocarbon-air mixture. In the present work, liquid to air mass ratio, R_m, can be estimated by determining the volume fraction of water, $\alpha_{w,}$ the volume fraction of air, α_w the density of water, ρ_w and the density of air ρ_a in each cell at each X location from the liquid jet injection point and by using Eq. 3.

$$R_m = \frac{\alpha_w \times \rho_w}{\alpha_a \times \rho_a} \quad (3)$$

Variation of maximum values of liquid to air mass ratios, $(R_m)_{max}$, for different values of q, along horizontal direction is shown in Fig. 6. As expected, an increase in the liquid to air momentum ratio, q, results in a higher mass ratio, R_m, because the increase in q results in the increase of amount of water. However, it has been observed that Mach number (M) of the cross flow affects the mass ratio, R_m, only marginally. It may be noted that an increase in M keeping q constant results in increase in water jet. Thus, the effects of velocities of water and air nullify each other for the range of values presented in this study. It may be noted that the present results corroborate the results of Thomas and Schetz [6], qualitatively.

Conclusion

In the present study numerical simulations for a transverse two-dimensional liquid jet in subsonic air stream was performed using FLUENT 6 [15]. The two phase flow was simulated numerically by using Reynolds Averaged Navier-Stokes equations and k-ε turbulence model. Obtained results for the flow field indicated that volume fraction of water and liquid to air mass ratio decreased as the liquid jet propagated towards downstream. However, the liquid jet width increased. Velocity fields of water and air and static pressure of mixture increased with increase in free-stream Mach number, M. However, M, only marginally affected the break-up length, penetration height, and liquid to air mass ratio. Velocity of air, velocity of water, static pressure of mixture, liquid to air mass ratio, break-up length and penetration height were increased when momentum ratio, q, was increased.

References

[1] Clark, B.J., 1964, "Break-up of a Liquid Jet in a Transverse Flow of Gas," NASA TN D- 2424, pp.1-45.
[2] Adelberg, M., 1967, "Break-up Rate and Penetration of a Liquid Jet in a Gas Stream," AIAA Journal, Vol. 5, No. 8, pp. 1408-1415.
[3] Kitamura, Y. and Takahashi, T., 1976, "Stability of a Liquid Jet in Air Flow Normal to the Jet Axis," Journal of Chemical Engineering of Japan, Vol. 9, No. 4, pp. 282-286.
[4] Nguyen, T.T. and Karagozian, A.R., 1992, "Liquid Fuel Jet in Subsonic Cross-flow", Journal of Propulsion and Power, Vol. 8, No. 1, 1992, pp. 21-29.
[5] Less, D. M., and Schetz, J. A., 1983, "Penetration and Break-up of Slurry Jets in a Supersonic Stream," AIAA Journal, Vol.21, No. 7, pp. 1045-1046.
[6] Thomas, R.H. and Schetz, J.A., 1985, "Distributions across the Plume of Transverse Liquid and Slurry Jets in Supersonic Airflow," AIAA Journal, Vol. 23, No. 12, pp.1892-1901.
[7] Sallam, K.A., Dai, Z., Faeth, G.M., 1999, "Drop Formation at the Surface of Plane Turbulent Liquid Jets in Still Gases", International Journal of Multiphase Flow, pp. 1161-1180.
[8] Sallam, K.A., Dai, Z., Faeth, G.M., 2002, "Liquid Break-up at the Surface of Turbulent Round Liquid Jets in Still Gases", International Journal of Multiphase Flow, pp. 427–449.
[9] Schetz, J. A., and Padhye, A., 1977, "Penetration and Break-up of Liquids in Subsonic Airstreams," AIAA Journal, Vol. 15, No. 10, pp. 1385-1390.
[10] Inamura, T. and Nagai, N., 1997, "Spray Characteristics of Liquid Jet Traversing Subsonic Airstreams," Journal of Propulsion and Power, Vol. 13, No. 2, pp. 250-256.
[11] Sallam, K.A., Aalburg, C., and Faeth, G.M., 2004, "Break-up of Round Non-Turbulent Liquid Jets in Gaseous Cross-flow", AIAA Journal, Vol.42, No.12, pp.2529-2540.
[12] Heister, S. D., Nguyen, T. T., and Karagozian, A. R., 1989, "Modelling of Liquid Jets Injected Transversely into a Supersonic Cross-flow," AIAA Journal, Vol. 27, No. 12, pp. 1727-1734.
[13] Campolo, M., and Cortelezzi, L., 2005, "Influence of Jet Inlet Conditions on Time-Average Behaviour of Transverse Jets", AIAA Journal, Vol.43, No.7, pp.1549-1555.

[14] Ryan, Matthew J., 2006, "CFD Prediction of the Trajectory of a Liquid Jet in a Non-Uniform Air Cross-flow", Computers & Fluids, No. 35, pp. 463-476.
[15] FLUENT 6 User's guide, 2001, FLUENT incorporated, India.

Table 1. Cases of Study

Cases	M	q	V_a in m/s	V_w in m/s
1	0.20	0.5	68	1.67
2	0.20	1.0	68	2.36
3	0.20	1.5	68	2.89
4	0.45	0.5	153	3.75
5	0.45	1.0	153	5.30
6	0.45	1.5	153	6.50
7	0.60	0.5	204	5.00
8	0.60	1.0	204	7.07
9	0.60	1.5	204	8.66

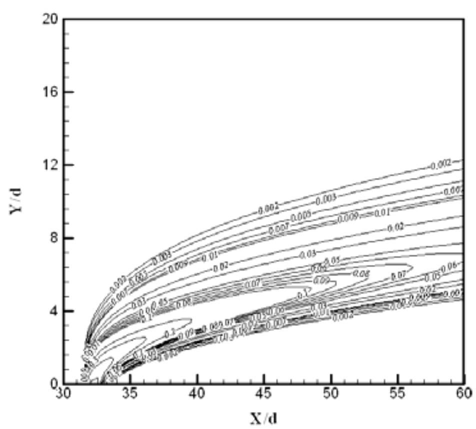

Figure 1. Volume fraction of water (Case 4)

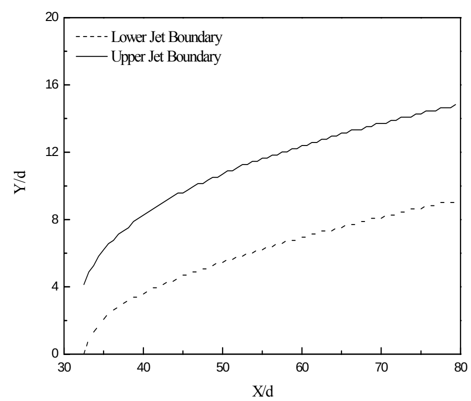

Figure 2. Liquid jet boundary (Case 4)

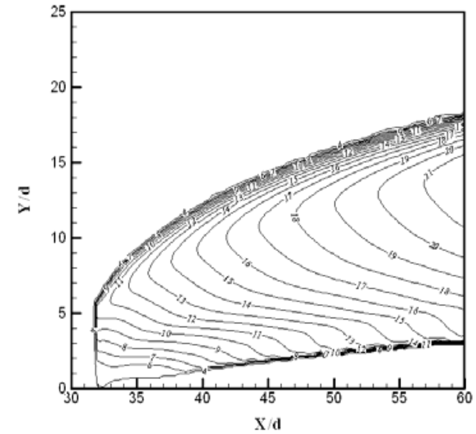

Figure 3. Velocity of water (Case 4)

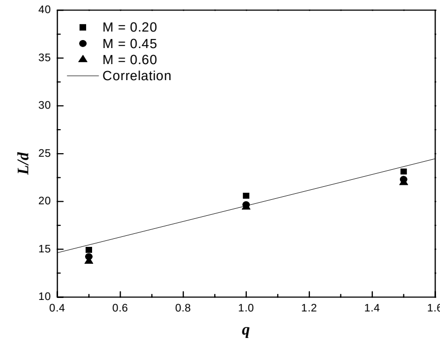

Figure 4. Effect of momentum ratio on break-up length

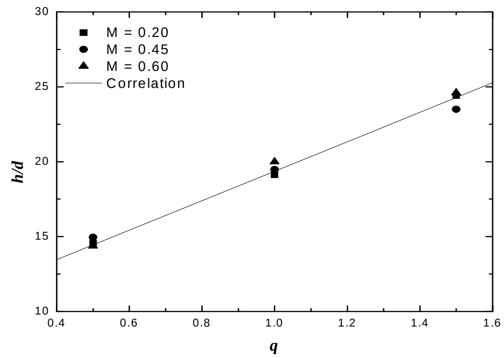

Figure 5. Effect of momentum ratio on penetration height

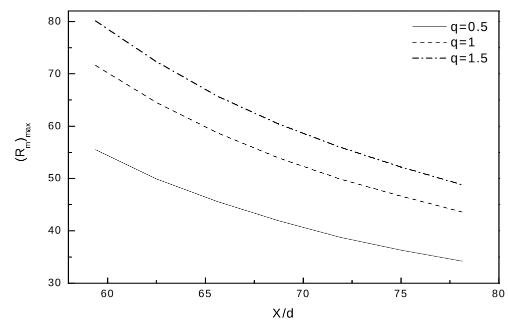

Figure 6. Distribution of liquid to air mass ratio (M = 0.45)