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Numerical Study of Breakup Processes of Water Jet Injected into a Cross Air Flow

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Abstract

A numerical study was carried out to investigate the effects of cross airflow on the penetration of a water jet and the secondary breakup of drops. The KIVA3 code was used along with the k-ε turbulence model and the TAB breakup model. The injector diameter, cross flow velocity, and injection velocity were varied to study their effects on drop size and location distributions and the jet penetration. Numerical results show qualitative agreement with the experimental results reported in the literature. A direct comparison was made between the numerical drop size distributions and the experimental results of Kihm et al. at two locations in the spray field and qualitative agreement was observed.

Introduction

A liquid fuel jet injected into a crossing gas flow is of importance in many practical applications. These include fuel injection in combustion processes, drop size control, and slurry-fuel injection [1,2]. It is also of fundamental interest to understand the breakup mechanisms of a liquid jet under the action of aerodynamic force. This problem therefore has received considerable research attention in the last three decades, see [1,2,3,4,5] and the references cited therein. These references also provide a good literature review on characteristics of liquid jet breakup in cross flow [1,2,3,4] and theoretical analysis of spray jets in cross flow [5].

The atomization mechanisms and breakup regimes of a liquid jet injected into a subsonic crossing gas stream have been experimentally studied by Wu et al. [1] and recently by Mazallon et al. [3]. These mechanisms were also schematically illustrated in the paper of Kihm et al. [2], see Fig.1. Kihm et al [2] obtained a correlation of the drop Sauter mean diameter (SMD) at different locations of the spray based on measurements using a Malvern laser diffraction particle sizer. Wu et al. [4] performed a more comprehensive experimental study of the spray structures of liquid jets in cross flow and measured cross-sectional distributions of SMD, drop velocity, volume flux, spray penetration, and spray width. Although extensive experimental studies have been conducted to characterize liquid jets injected into a crossing gas flow in terms of jet trajectories [1,3,6,7], breakup location [1], spray width [4], and drop size distributions [2,4,8], to our knowledge numerical studies of the atomization of a liquid jet injected into a cross gas flow have not been reported in the open literature.

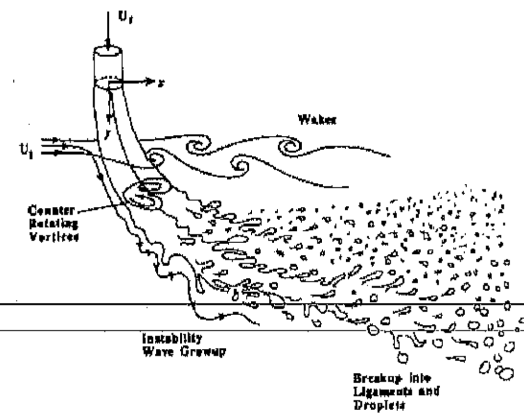

Fig.1 Atomization model for a liquid jet injected into a cross flow (reproduced from Kihm et al. [2]).

Modelling of the primary breakup of a liquid jet and the secondary breakup of drops is inherently difficult primarily due to the co-existence of many different physical mechanisms in different breakup regimes and our current understanding of these mechanisms [9,10,11]. The breakup models that are widely used in multi-dimensional modelling of diesel and gasoline engines are based on the analogy between an oscillating and distorting droplet and a spring-mass system (TAB model) [12] and Kelvin-Helmholtz instability (KH model) [13] and Rayleigh-Taylor instability (KH-RT model) [14]. By assuming a drop

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size at the injector and some other parameters, such as the amplitude of drop oscillation at the injector and the initial cone angle, these models are capable of predicting the subsequent processes of drop breakup and drop collision. While these models have been widely employed as a spray sub-model in modelling engine combustion, it is difficult to assess their performance due to the complexity of the problem in the existence of spray dynamics, chemical reactions, and turbulence. Therefore, it is desirable to evaluate these spray sub-models in modelling simple non-reacting sprays using experimental data, especially drop size distribution, in order to establish a reliable spray sub-model for complex engine modelling. Liu et al [15] have evaluated the performance of the TAB model and the KH wave model in the prediction of drop trajectory and breakup in a cross flow. They found that the TAB model predicts accurate drop trajectory but significantly underpredicts the drop SMD. On the other hand, the KH wave model predicts the drop trajectory with similar accuracy to the TAB model but much better drop SMD when their improved drop drag model was employed.

In the present study, the KIVA3 code [16] was used to calculate the secondary breakup of a water jet injected into a cross airflow along with the TAB model [12]. The objectives of this study are (1) to numerically investigate the effects of the cross flow on the secondary breakup of the liquid jet, and (2) to evaluate the TAB model in this situation by comparing the predicted drop size distribution with the experimental data of Kihm et al. [2].

Numerical Method and Computational Conditions

The KIVA3 code solves the unsteady three-dimensional compressible Navier-Stokes equations coupled with chemical reactions and spray dynamics using the control volume method. Details of the numerical method and physical models employed in the code are discussed in [16,17]. In the present calculations, the gas phase turbulence was modelled using the k-ε model and the effect of turbulence on drop dynamics was taken into account. The TAB model [12,17] was employed to simulate the secondary breakup processes of the liquid jet. The model assumes that the size of drop parcels at the injector is the same as the injector diameter. The TAB model was discussed in detail by O'Rourke and Amsden [12] along with its limitations. The TAB model parameters employed in KIVA3 are: $C_d = 10$, $C_k = 8$, $C_b = 1/2$, and $C_F = 1/3$.

In order to use the experimental drop size distributions reported by Kihm et al. [2] in the present evaluation study of the TAB model, numerical calculations were performed in a rectangular channel having the same cross section as that used in their experimental work. The dimensions of the channel are 70mm (length) × 33mm (height) × 25mm (depth). The solution domain is defined as x between [-20 mm, 50 mm], y between [0, -33 mm], and z between [-12.5 mm, 12.5 mm]. The solution domain was schematically shown in Fig.2. The channel was divided into 21×16×10 control volumes with non-uniform grids used in x direction (gas flow direction) and uniform grids placed in y (along the height of the channel) and z directions. The crossing airflow was introduced at x = -20 mm and along the positive x direction. The injector was located at (x,y,z)=(0,-2 mm,0), which was at the same location as the experiment of Kihm et al. [2]. The liquid (water in this study) was injected downward. The amplitude of drop oscillation at injector (A_0) and the initial cone angle (θ) were set to 1.0e-6 and 8° respectively. The number of spray parcels injected was 20,000 for all the calculations. Unless otherwise stated, the drop drag coefficient is calculated as that for a rigid sphere [17].

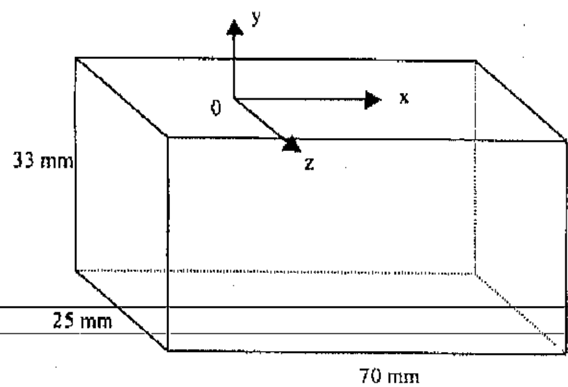

Fig.2 Dimensions and coordinate origin of the solution domain.

Results and Discussions

The injector for this study is a simple pressure atomizer. The injector hole diameter used in the calculations was d_0 = 0.5, 0.6, and 0.7 mm. The discharge coefficient was assumed to be 1.0 and this assumption should not affect the conclusions of the present study. The water injection rate considered was 2.45, 3.68, and 5.52 ml/s. To investigate the effects of the crossing flow on the atomization of the water drops, four gas velocities were considered: V_g =15, 30, 45, and 60 m/s. Various combinations of cross flow velocity, injection velocity, and nozzle diameter were made to investigate their effects on jet penetration and drop size. A summary of these combinations are given in Table 1 for the convenience of the readers. The base case, d_0 =

0.6 mm, V_l = 13 m/s, and V_g = 45 m/s, was repeated in these figures for comparison purposes.

Table 1 Summary of the computational conditions

Figure	d_0 (mm)	Vl (m/s)	Vg (m/s)	Crossflow Weber number	Drop drag coefficient
3(a)	0 6	13	15	1.9	Rigid sphere
3(b)	0 6	13	30	7.7	Rigid sphere
3(c)	0.6	13	45	17.4	Rigid sphere
3(d)	0 6	13	60	30.9	Rigid sphere
4(a)	0 6	8 67	30	7 7	Rigid sphere
4(b)	0.6	13	45	17.4	Rigid sphere
4(c)	0 6	19 5	60	30 9	Rigid sphere
5(a)	0 5	18 7	45	14 5	Rigid sphere
5(b)	0 6	13	45	17.4	Rigid sphere
5(c)	0 7	9.55	45	20.3	Rigid sphere
6(a)	0 5	13	45	14.5	Rigid sphere
6(b)	0 6	13	45	17.4	Rigid sphere
6(c)	0 7	13	45	20.3	Rigid sphere
7(a)	0 6	13	45	17.4	Rigid sphere
7(b)	0 6	13	45	17 4	modified

The calculated drop location and relative drop size for the four different airflow velocities while keeping the jet velocity constant at V_l =13 m/s and d_0 = 0.6 mm (corresponding to water injection rate of 3.68 ml/s) are shown in Figs.3(a), 3(b), 3(c), and 3(d) in order of increasing the cross air stream velocity. As the crossing airflow velocity is increased while the jet velocity is held constant, the breakup length of the jet decreases and so does the jet penetration. This is because of the increased air-to-liquid momentum ratio. The 'breakup length' used here is the numerical length of the liquid jet where the drop size remains the same as the injection drop size, i.e. the injector diameter. This 'breakup length' should not be mixed up with the concept of breakup length defined as the length of the intact liquid near the injector exit in a stagnant gas [18]. These figures also demonstrate the effects of the crossing flow on the liquid jet atomization: finer drops are produced at a given *y* location beyond the breakup point, which is marked in each figure except Fig.3(a) where no breakup occurs within the height of the solution domain. This is attributed to the increased Weber number as the crossing airflow velocity increases. These results are indeed expected and in qualitative agreement with the experimental observations of Wu et al. [1].

To investigate the effects of the magnitude of the crossing flow velocity on the penetration and atomization of the water jet while keeping the air-to-liquid momentum ratio constant, calculations were carried out for two additional sets of cross flow and jet velocities: (1) V_l = 8.67 m/s, V_g = 30 m/s, and (2) V_l = 19.5 m/s, V_g = 60 m/s. These two calculations have the same air-to-liquid momentum ratio as that shown in Fig.3(c) for V_l = 13 m/s and V_g = 45 m/s. The drop location and relative size of these three calculations are shown in Fig.4. It is interesting to see from this figure that the jet penetration into the cross flow decreases with increasing the cross gas flow velocity even though the air-to-liquid velocity ratio (also momentum ratio) remains unchanged. These results are in agreement with those obtained by Nguyen and Karagozian [6] who showed that the jet penetration strongly depends on the air-to- liquid momentum ratio but also depends on the cross flow velocity to a lesser extent. For a given air-to-liquid momentum ratio, the decreased jet penetration with increasing cross flow velocity is caused by the enhanced atomization of the drops as a result of increased Weber number due to increased relative velocity between the air flow and the drops. This is evident from the relative drop sizes shown in these this figure.

When keeping the air-to-liquid momentum ratio constant, the dependence of the jet penetration on the cross flow velocity obtained in this work and by Nguyen and Karagozian [6] is somewhat in contradiction with the experimental observation of Kihm et al. [2] who observed similar spray development and penetration as the cross flow velocity increases. This apparent contradiction may be explained by the fact that Kihm et al. did not vary the cross flow velocity to the extent that its effect on the jet penetration becomes significant. Kihm et al. only varied the cross flow velocity by less than 20% and it was therefore difficult to observe any change in jet penetration due to the relative weak dependence of jet penetration on the magnitude of the cross flow velocity.

The effects of the injector diameter on the jet penetration and secondary drop breakup were investigated by conducting calculations for d_0 = 0.5, 0.6, and 0.7 mm while keeping V_g = 45 m/s and the injection flow rate 3.68 ml/s. The predicted relative drop size and drop location are shown in Fig.5. For a given injection liquid flow rate, comparison between results displayed in Figs.5(a), 5(b), and 5(c) show that the smaller the injector diameter, the deeper the jet penetration into the cross flow and the finer the drop size. The deeper penetration is caused by the decreased air-to-liquid momentum ratio. While the finer drops are produced by the increased relative velocity between the airflow and the drop parcels as well as the smaller drop size at the injector. The opposite trend is observed from the results shown in Fig.5(c) for d_0 = 0.7 mm for the very same reason. These results are in qualitative agreement with the experimental results of Kihm [2].

The effects of the nozzle diameter on the spray structure under the conditions of constant cross flow and injection velocities were also investigated. The results are shown in Figs.6(a), 6(b), and 6(c) for d_0 = 0.5 and 0.7 mm, respectively.

Comparison between results shown in these figures indicates that the jet penetration into the cross flow is almost identical for the reason that these three calculations have the same cross flow and injection velocities. Experimentally, it has been found that the jet penetration can be well correlated to the air-to-liquid momentum ratio [4]. For d_0 = 0.7 mm, Fig.6(c), the jet penetration is slightly deeper than those for d_0 = 0.5 and 0.6 mm, Figs.6(a) and 6(b). This is attributed to the fact that the drop sizes are slightly bigger for d_0 = 0.7 mm since the initial drop size at the nozzle is assumed to be

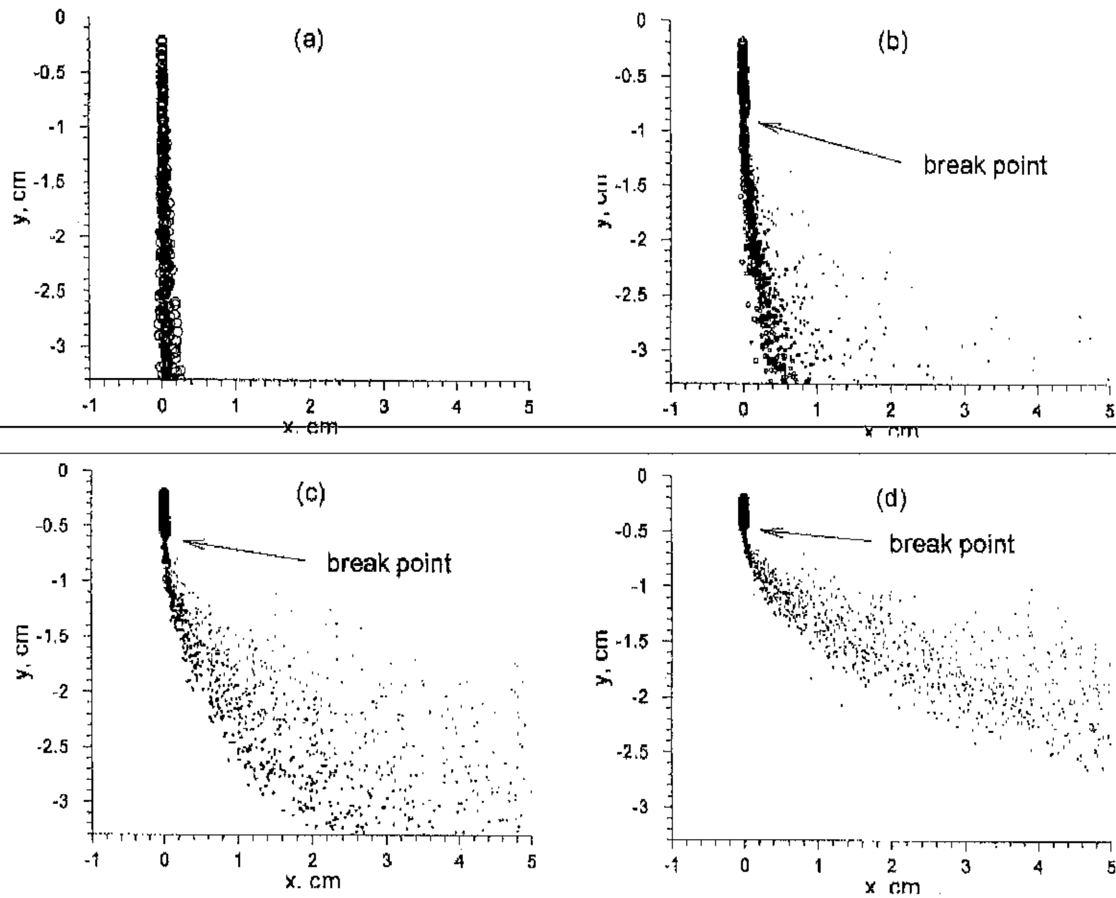

Fig.3 Effects of the cross flow velocity on drop location, drop size, and break point for d_0 = 0.6 mm, V_l = 13 m/s. (a) V_g = 15 m/s, (b) V_g = 30 m/s, (c) V_g = 45 m/s, and (d) V_g = 60 m/s.

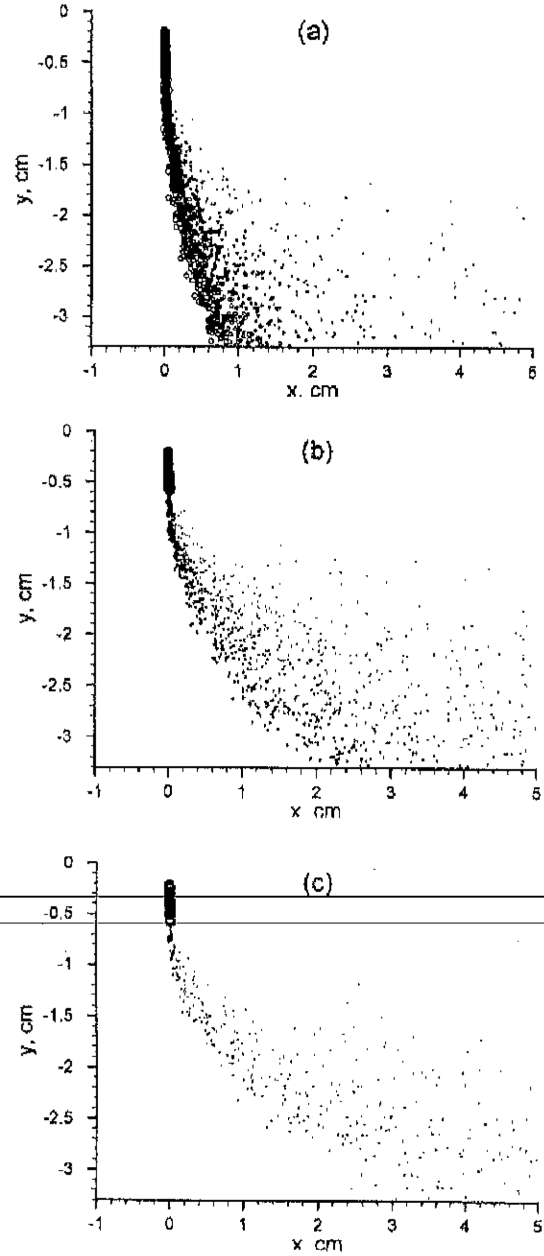

Fig.4 Effect of the crossing airflow velocity with constant air-to-liquid momentum ratio for $d_0 = 0.6$ mm: (a) $V_l = 8.67$ m/s, $V_g = 30$ m/s, (b) $V_l = 13$ m/s, $V_g = 45$ m/s, and (c) $V_l = 19.5$ m/s, $V_g = 60$ m/s.

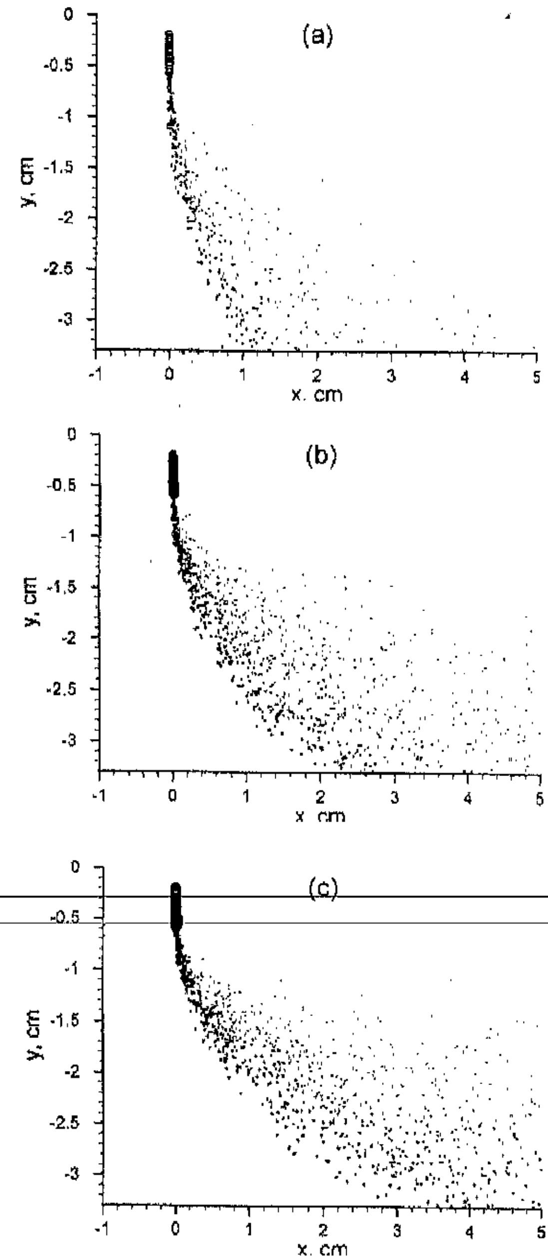

Fig.5 Effect of the nozzle diameter with constant water flow rate of 3.68 ml/s and constant crossing airflow of 45 m/s: (a) $d_0 = 0.5$ mm, $V_l = 18.7$ m/s, (b) $d_0 = 0.6$ mm, $V_l = 13$ m/s, (c) $d_0 = 0.7$ mm, $V_l = 9.55$ m/s.

the nozzle size. These results are again in qualitative agreement with the experimental study of Kihm et al. [2] who observed a similar trend on the effects of the nozzle diameter on drop size distribution under the condition of constant cross flow and injection velocities.

In addition to the drop breakup model itself, drop drag coefficient is also a very important part of drop breakup modelling since it affects the drop acceleration, drop physical location, and the relative velocity between a drop parcel and the gas flow [15]. The drag coefficient for a rigid sphere has been widely used in spray modelling. The underlying assumption is that a liquid drop can be treated as a sphere. In reality, however, a liquid drop undergoes deformation and oscillation upon breakup. Liu et al. [15] proposed an improved drop drag coefficient model to account for the departure of drop shape from sphere under the action of aerodynamic force. In this model, the drop drag coefficient is modified according to the following equation

$$C_d = C_{d,sphere}(1+2.632y)$$

where $C_{d,sphere}$ is the drop drag coefficient based on the rigid sphere assumption and y is the drop distortion calculated in the TAB model. The effect of this improved drop drag coefficient model on the results of the present study was investigated by repeating the calculations for conditions shown in Fig.3(c) using the modified drop drag coefficient. The results are shown in Fig.7. Comparison of the results shown in Figs.7(a) and 7(b) indicates that the jet penetration was considerably reduced when the drop drag coefficient of Liu et al [15] was used. This is expected due to the increased drag force acting on drops in the cross flow direction. The significant effect of the drop drag coefficient on the jet trajectory and penetration observed from the results shown in these two figures disagrees with the finding of Liu et al. [15] who concluded that the TAB model was relatively insensitive to the drop drag coefficient due to the instantaneous breakup of parent drops. This may be attributed to the much smaller injection drop size (170 μm diameter) considered in their study.

The predicted drop size distributions at x = 10 mm downstream of the injector and two y locations, y = -15 mm and –22.5 mm, are compared to the measured drop size distributions of Kihm et al. [2] in Fig.8. Calculations were conducted using the drop drag coefficient of the rigid sphere and of the dynamic model due to Liu et al. [15]. This figure shows that the TAB significantly underpredicts the drop size at both locations. The effect of drop drag coefficient on the predicted drop size is insignificant and use of the drop

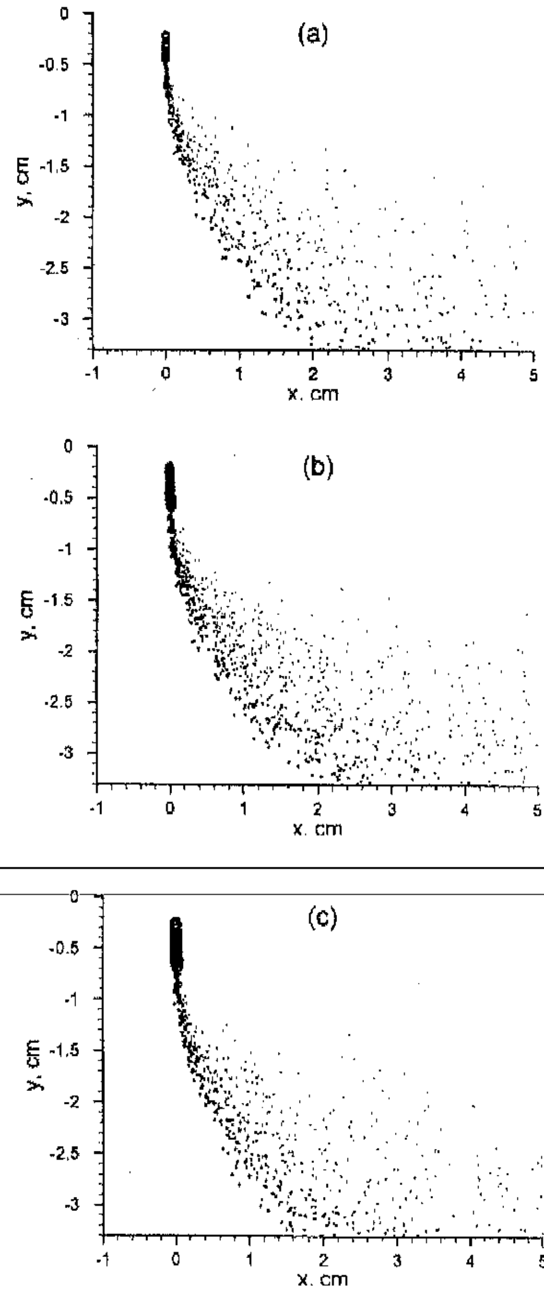

Fig.6 Effect of nozzle diameter with constant injection velocity for V_l = 13 m/s, V_g = 45 m/s: (a) d_0 = 0.5 mm, (b) d_0 = 0.6 mm, and (c) d_0 =0.7 mm.

drag coefficient suggested by Liu et al. [15] results in the drop size distributions slightly shifted towards larger size. Results shown in Fig.8 confirms the earlier finding of Liu et al. [15] that the TAB model considerably underpredicts the drop size.

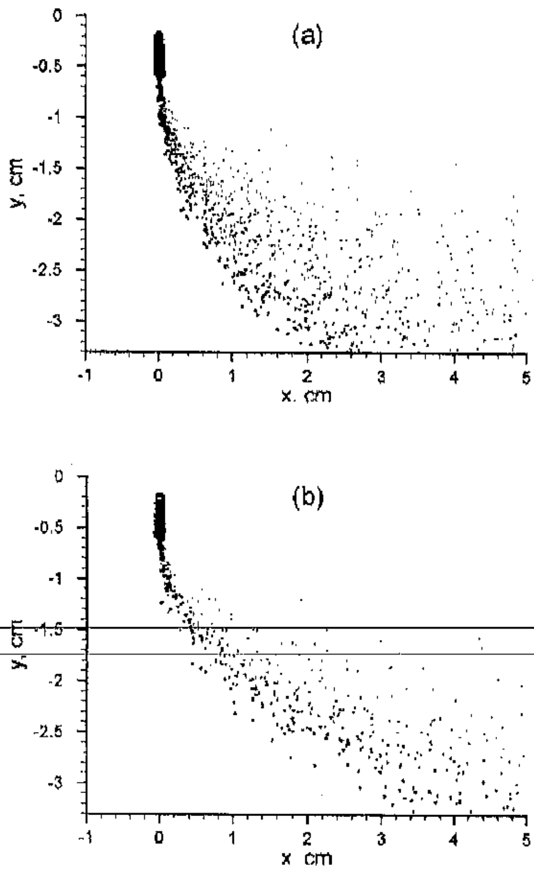

Fig.7 Effect of the drop drag coefficient for d_0 = 0.6 mm, V_l = 13 m/s, V_g = 45 m/s: (a) rigid sphere model, (b) modified model by Liu et al. [15].

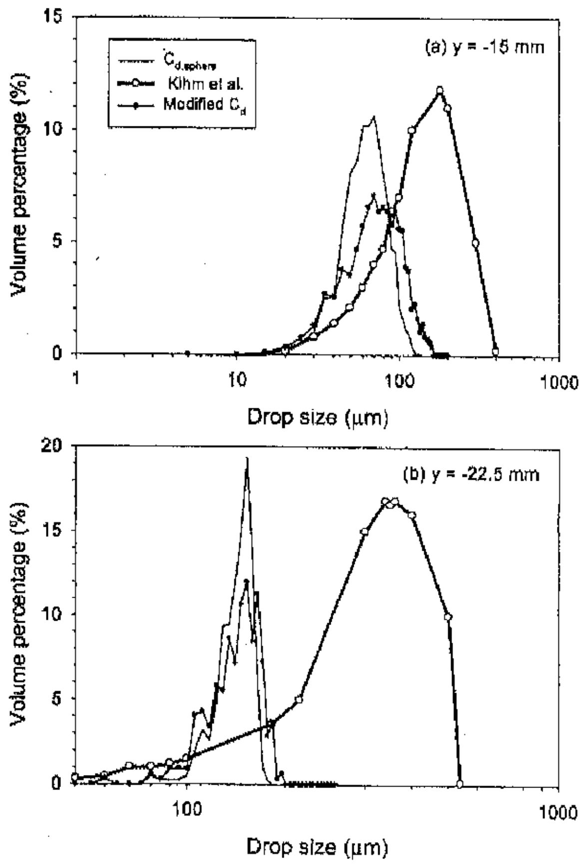

Fig.8 Comparison between the predicted and experimental drop size distributions at two heights at x = 10 mm for d_0 = 0.6 mm, V_l = 13 m/s, V_g = 45 m/s.

Concluding Remarks

It was found from the results of the present study that the TAB model predicts qualitatively correct effects of varying different physical parameters, such as the cross flow velocity, the injection velocity, and the injector diameter, on the spray pattern for a water jet injected into a cross airflow. However, the TAB model significantly underpredicts the drop size. Therefore, the TAB is useful to perform parametric studies on the effects of different physical properties on the liquid spray under consideration. It is recommended that the TAB model should not employed when accurate drop size distribution is to be predicted.

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