

EXTENDED ABSTRACT

Modeling of Turbulence Effects on Liquid Jet Atomization and Breakup

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Abstract

Recent experimental investigations and physical modeling studies have indicated that turbulence behaviors within a liquid jet have considerable effects on the atomization process. For certain flow regimes, it has been observed that the liquid jet surface is highly turbulent. This turbulence characteristic plays a key role on the breakup of the liquid jet near to the injector exit. Other experiments also showed that the breakup length of the liquid core is sharply shortened as the liquid jet is changed from the laminar to the turbulent flow conditions. In the numerical and physical modeling arena, most of commonly used atomization models do not include the turbulence effect. Limited attempts have been made in modeling the turbulence phenomena on the liquid jet disintegration. The subject correlation and models treat the turbulence either as an only source or a primary driver in the breakup process.

This study aims to model the turbulence effect in the atomization process of a cylindrical liquid jet. In the course of this study, two widely used models, Reitz's primary atomization (blob) [1] and Taylor-Analogy-Break (TAB) [2] secondary droplet breakup by O'Rourke et al. are examined. Additional terms are derived and implemented appropriately into these two models to account for the turbulence effect on the atomization process. Since this enhancement effort is based on a framework of the two existing atomization models, it is appropriate to denote the two present models as "T-blob" and "T-TAB" for the primary and secondary atomization predictions, respectively. In the primary breakup model, the level of the turbulence effect on the liquid breakup depends on the characteristic time scales and the initial flow conditions. This treatment offers a balance of contributions of individual physical phenomena on the liquid breakup process. For the secondary breakup, an addition turbulence force acted on parent drops is modeled and integrated into the TAB governing equation. The drop size formed from this breakup regime is estimated based on the energy balance before and after the breakup occurrence. The turbulence energy is also considered in this process.

I. T-BLOB MODEL

The original formulation of the primary breakup “blob” model is based on the stability analysis performed by Reitz [1]. The main contribution of this research effort is to incorporate the turbulence effect in modeling of the liquid jet breakup. Terms and parameters associated with the turbulence behavior shall be derived and implemented appropriately to the existing *blob* model. Hence, it is proper to denote the present model as “*T-blob*” model. In order to account for the both effects of the surface wave perturbation and the turbulence motion, the phenomenological approach is chosen in this model development. The resulting model should adequately include the combination of these two phenomena in the breakup model when the both co-exist in the considered flow conditions. However, the model is also capable to primarily describe a single event only if the other is neither dominant nor present in certain flow conditions. In such a case, the original formulation should be retained. For all aspects, the model should reasonably maintain a smooth transient from the fully turbulent to non-turbulent flow regimes. Also in this phenomenological method, the time scales associated to the surface wave and turbulence characteristics are used to weight these individual effects. The consideration of the time scale for this weighting is based on a reason of which the phenomena of the smaller time scale would have a stronger influence in the liquid jet breakup process. In the course of this study, the framework of Huh et al. [3] in turbulence characterization is employed. The length scale and time scale associated with the primary breakup are comprised of the ones described in the blob model that represents for the surface wave instability and of the turbulence behavior shown in Huh et al.’s model [3].

It is proposed that the reciprocal of the primary atomization time scale is equal to the sum of the reciprocals of the time scales associated with the wave motion and the turbulence characteristics with the inclusion of the respective weighting factors as follows:

$$\frac{1}{\tau_p} = \frac{c_w}{\tau_w} + \frac{c_t}{\tau_t} \quad 1.1$$

c_w and c_t are the weighting coefficients with respect to the wave perturbation time scale and the turbulence time scale. τ_t and τ_p are the turbulence time scale and the primary atomization time scale [1]. In the work of Huh et al. the parent drops carry homogeneous isotropic turbulence starting at the injection nozzle exit. By further assuming that no additional internal turbulence is generated, they were able to obtain an analytical solution of the turbulence scale through the use of the well-known $k - \epsilon$ turbulence model. So the turbulence time scale can be expressed as a function of time:

$$\tau_t = \tau_0 + 0.0828t \quad 1.2$$

t is the time referenced from the time at which the parent drop is issued at the injection nozzle exit. τ_0 is the initial turbulence time scale evaluated from the initial turbulence kinetic energy, k_t^0 , and its corresponding dissipation rate, ϵ_t^0 , at the injector exit.

$$\tau_0 = c_\mu \frac{k_t^0}{\epsilon_t^0} \quad 1.3$$

Where:

$$c_\mu = 0.09$$

$$k_t^0 = \frac{U^2}{8L/D} \left[\frac{1}{C_d^2} - K_c - (1-s^2) \right]$$

$$\epsilon_t^0 = K_\epsilon \frac{U^3}{2L} \left[\frac{1}{C_d^2} - K_c - (1-s^2) \right]$$

$$K_\epsilon = 0.27$$

U is the injection velocity of the liquid issued from the injection nozzle, which has the length, L , and the diameter, D . C_d , K_c , and s are the discharge coefficient, the loss coefficient due to the nozzle entrance sharpness, and the downstream-to-upstream contraction area ratio of the injection nozzle, respectively. Equation 1.1 ensures that the process of the smaller time scale would have a more significant effect on the atomization process.

The results of the experiments conducted by Faeth et al. [3-4] showed that the drops produced from the on-set breakup regime have their sizes in the same order-of-magnitude of the turbulence length scale. Furthermore, in his blob model, Reitz set the radius of the product drop to be proportional to the wave length corresponding to its fastest growth rate. These indications suggest that it is reasonable to choose the radius of the product drops as the characteristic length scales for both the wave perturbation and turbulence phenomena. It is proposed that the characteristic length scale is expressed as:

$$\frac{1}{r_p} = \frac{c_w}{r_w} + \frac{c_t}{r_t} \Rightarrow r_p = \frac{r_w r_t}{(1-c_t)r_t + c_t r_w}, \quad 1.4$$

r_p is the radius of the product drop. The radius r_w associated with the wave motion can be determined from Reitz's model. For the value of r_t , the formulation of estimating the product drop size proposed by Huh et al. is employed. The drop size can be represented by a probability density function (PDF), which is given to be proportional to the ratio of the turbulence energy spectrum and the atomization time scale. The notion for this representation is that an eddy motion with larger turbulence kinetic energy and a shorter atomization time most likely causes the drop breakup more frequently than others containing the lower energy level and the longer atomization time. It should be noted that the authors assume the atomization time scales to be a linear sum of the turbulence and wave growth time scales. This time scale, however, is set equivalent to the primary atomization time scale defined in equation 1.1 for the present model. By assigning the wave number of the turbulence energy spectrum as the inverse of the product drop diameter, the PDF for the product size distribution can be shown in a form as:

$$P(r_t) = \frac{C}{\tau_p} \frac{\left(\frac{L_t}{1.5r_t}\right)^2}{\left(1 + \left(\frac{L_t}{1.5r_t}\right)^2\right)^{11/6}} \quad 1.5$$

τ_p is evaluated by equation 1.1. L_t is the turbulence characteristic length scale and is modeled using the analytical solution of the $k - \epsilon$ turbulence model [7]:

$$L_t = L_t^0 \left(1 + \frac{0.0828t}{\tau_t^0}\right)^{0.457} \quad 1.6$$

The initial turbulence length scale L_t^0 is obtained from the turbulence kinetic energy and its dissipation rate as:

$$L_t^0 = c_\mu \frac{(k_t^0)^{3/2}}{\epsilon_t^0} \quad 1.7$$

The constant C in equation 1.5 is determined by the normalization condition imposed on the PDF of the drop size distribution as:

$$\int P(r_t) dr_t = 1 \quad 1.8$$

In the T-blob model, the rate of change in the parent drop radius is taken the same form as the blob model:

$$\frac{da}{dt} = -\frac{a - r_p}{\tau_p} \text{ when } r_p \leq a \quad 1.9$$

It should be noted that when $a < r_p$ the parent drop would no longer strip its mass to create the product drop. An example for parent drop diameter change vs. time is given in figure 1.

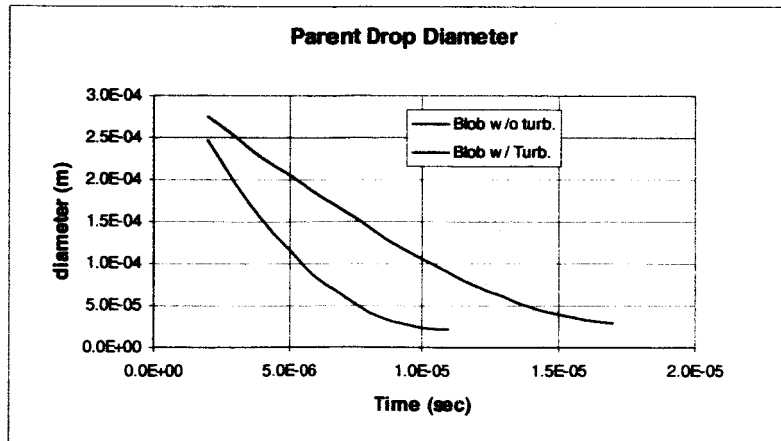


Figure 1. Parent drop diameter vs. time

The velocity and properties of the product drops in the present model are formulated in the same manner as in Reitz's model. In each breakup event, the product drops were given the same fluid properties and physical location as the parent. For the velocity, the product drops would carry the same velocity, V , of the parent along with extra two normal velocity components, v and w , in reference to the trajectory of the parent drop to be added. v and w are given by

$$\begin{aligned} v &= |V| \tan(\theta/2) \sin \phi \\ w &= |V| \tan(\theta/2) \cos \phi \end{aligned} \quad 1.1$$

Where

$$\tan(\theta/2) = A_1 \Lambda \Omega / U$$

ϕ is chosen at random on the interval $(0, 2\pi)$ and the constant A_1 is set equal to 0.188 for sharp entrance constant diameter tube injection nozzles.

Along with the inclusion of the turbulence effect on the primary atomization process, the subject phenomena will be also considered in the secondary droplet breakup model, which will be discussed in the next sections. At any rate, this model requires the initial velocity fluctuation quantity of the product drops right after their formation. In order to evaluate such a quantity, the energy budget of the parent drop during the primary breakup would be examined. This consideration is based on the notion that the overall energy of the parent drop combined with the one of the product drops has to be conserved during the breakup process [7]. One example of the energy budget is shown in figure 2. Detailed derivation will be given in the full paper.

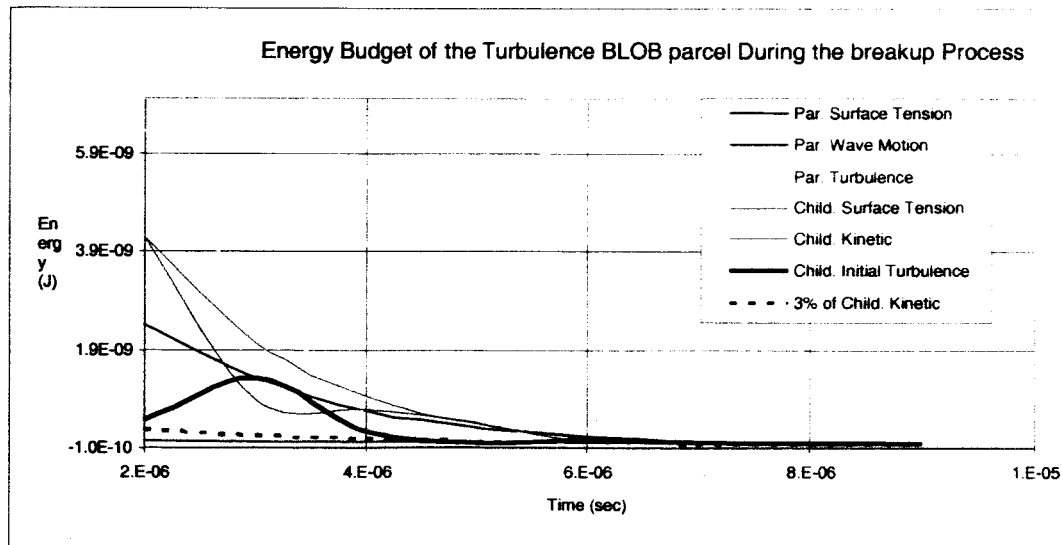


Figure 2. Energy budget during breakup process

II. Derivation of turbulence term in T-TAB model:

In an attempt to account for the effect of the turbulence on the secondary droplet breakup, a term, F_t , representing a force associated the turbulence behavior is introduced to the right-hand side of the original Taylor Analogy Breakup [2] equation:

$$m\ddot{\zeta} = F + F_t - k\zeta - d\dot{\zeta} \quad 2.1$$

In order to derive a force term to account for the turbulence behavior in a liquid droplet, a force associated with turbulence kinetic motion of an eddy within a liquid droplet is set to a function of a turbulence characteristic velocity scale, ϑ , and a turbulence characteristic length scale, ℓ , of the subject eddy as follows:

$$F_{\text{eddy}} \sim \rho_l \vartheta^2 A \quad 2.2$$

Where

ρ_l Density of liquid

A Cross-sectional area of an eddy

The proportionality in equation 2.2 is implied to account for the effect of ellipticity, non-uniform velocities within the eddy and the efficiency of the conversion of the turbulence force to the displacement oscillation and distortion of the droplet. Since the subject eddy has a turbulence length scale of ℓ . It is logical to define the cross-sectional area, A , to be proportional to this length scale as follows:

$$A \sim \ell^2$$

Thus,

$$F_{\text{eddy}} \sim \rho_l \vartheta^2 \ell^2 \quad 2.3$$

It is reasonable to assume that the turbulence characteristic velocity and length scale of an eddy with the inertial range of the turbulence spectrum are related as follows [5]:

$$\vartheta = \bar{v}_o \left(\frac{\ell}{\lambda} \right)^{\frac{1}{3}} \quad 2.4$$

Where

\bar{v}_o Time-averaged mean of fluctuation velocity

λ Radial integral length scale associated with turbulence

The fluctuation velocity \bar{v}_o can be obtained from the initial turbulence kinetic energy:

$$\begin{aligned} (E_{\text{tur}})_{\text{prod}} &= \frac{3}{2} m_p \bar{v}_o^2 = \frac{3}{2} \left(\frac{4}{3} \pi r_p^3 \rho_l \right) \bar{v}_o^2 \\ \Rightarrow \bar{v}_o &= \sqrt{\frac{(E_{\text{tur}})_{\text{prod}}}{2\pi r_p^3 \rho_l}} \end{aligned} \quad 2.5$$

and,

$$F_{\text{eddy}} \sim \rho_l \bar{v}_o^2 \frac{\ell^{\frac{8}{3}}}{\lambda^{\frac{2}{3}}} \quad 2.6$$

In a study of the onset of turbulence primary break up, Faeth et al. chose the radial integral length scale, λ , and the turbulence length scale, ℓ , to be comparable to the initial liquid jet diameter and Sauter-mean diameter (SMD) of the breakup droplet. Consequently, the force associated with the turbulence process on a droplet is expressed as:

$$F_t \sim F_{\text{eddy}} \frac{r_p^2}{\ell^2} \sim \rho_l \bar{v}_o'^2 r_p^{\frac{4}{3}} \ell^{\frac{2}{3}} \quad 2.7$$

Faeth et al. have observed that the liquid jet surface fluctuation and the drop size resulted from the on-set breakup have the same order of the turbulence length scale. Hence, it is logical to also assume that the droplet distortion displacement in the present study has the same order of this length scale. This leads to a hypothesis of having the characteristic turbulence length scale to be proportional to the displacement distortion ζ from the drop equilibrium position. That is

$$\ell \sim \zeta$$

Therefore equation 2.7 becomes

$$F_t \sim \rho_l \bar{v}_o'^2 r_p^{\frac{4}{3}} \zeta^{\frac{2}{3}} \Rightarrow F_t = C_{pt} \rho_l \bar{v}_o'^2 r_p^{\frac{4}{3}} \zeta^{\frac{2}{3}} \quad 2.8$$

and equation 2.1 becomes

$$\ddot{\zeta} = C_F \frac{\rho_g}{\rho_l} \frac{W^2}{r_p} + C_{pt} \frac{3}{4\pi} \frac{\bar{v}_o'^2}{r_p^{\frac{2}{3}}} \zeta^{\frac{2}{3}} - C_k \frac{\sigma}{\rho_l r_p^3} \zeta - C_d \frac{\mu_l}{\rho_l r_p^2} \dot{\zeta} \quad 2.9$$

Similar to the method of estimating the product drop size in the TAB model, the energy balance between the parent and product drops is used to determine the Sauter-mean radius of the product drops in the present model. Hence, individual energy forms contained in the both parent and product drops are formulated. The turbulence energy is also included in this process. Detailed derivation will be presented in the full paper.

Examples:

Figure 3 shows the penetration of a diesel jet into a 5MPa chamber and figure 4 shows the snap shot of droplet distribution of the atomizing jet at 4.50 msec. More detailed comparison for both non-evaporating and evaporating atomizing sprays will be presented in the final paper.

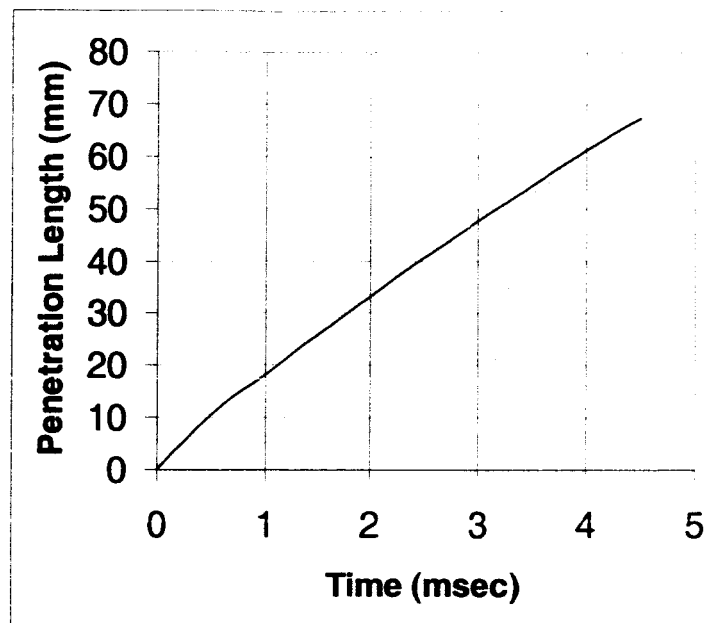


Figure 3. Penetration length vs. time

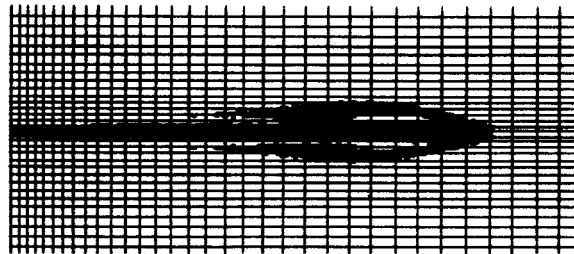


Figure 4. Spray distribution at 4.5 msec.

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