Numerical Modeling for Primary Atomization of Liquid Jets

S. G. Chuech,* A. J. Przekwas,† and A. K. Singhal‡
CFD Research Corporation, Huntsville, Alabama 35805

In the proposed numerical model for primary atomization, surface-wave dispersion equations are solved in conjunction with the jet-embedding technique of solving mean flow equations of a liquid jet. Two types of wave models, namely linear and approximate nonlinear models, have been considered. In each case, the dispersion equation is solved over the whole wavelength spectrum. This enables the prediction of drop sizes, frequency, and liquid mass breakup rates from the first principles. Presently, the surrounding gas phase motion is prescribed; in the future, it will be computed simultaneously with the liquid surface and jet equations. The present model has been applied to several low-speed and high-speed jets. For low-speed water jets, predicted intact liquid core lengths and wave growth rates are in excellent agreement with available data. For the high-speed case (the liquid oxygen/gas hydrogen coaxial injection element of the Space Shuttle main engine preburner), predicted drop sizes and liquid breakup rates are in good agreement with the results of the coaxial injection combustion model, which have been calibrated against measured data. The present model limitations and possible extensions are also discussed in this paper.

Nomenclature

a = jet radius
D = jet diameter
d = droplet diameter
I = Bessel function of the first kind
K = Bessel function of the second kind
k = wave number
L = breakup length of liquid jet
ℓ = modified wave number defined by Eq. (3)
m = fluid mass
Oh = Ohnesorge number
t = time
U = mean axial velocity in the z direction
u = axial interface velocity in the z direction
We = Weber number
z = cylindrical coordinate in the axial direction
α = wave frequency or amplitude growth rate
ζ = vertical displacement over the surface
λ = wavelength
ν = kinematic viscosity
ρ = density
σ = surface tension

Subscripts

B = breakup properties
f = liquid phase
g = gas phase
m = index for nonlinear modes
n = index for wavelength
0 = initial or jet exit condition
r = relative quantity

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*Project Engineer; currently Senior Research Engineer, Delavan Inc., West Des Moines, IA. Member AIAA.
†Manager of Research Projects. Member AIAA.
‡President and Technical Director.

Introduction

LIQUID-FUEL jet atomization is a topic of both practical and theoretical interest, encountered in a variety of practical applications, such as gas-turbine combustors, rocket thrust chambers, diesel engines, etc. Many types of atomizing injectors have been developed including air-blast (swirl) atomizers for gas turbines, pressure atomizers for diesel engines, coaxial or impinging injection elements for rocket thrust chambers, etc. Injector designers are facing difficult demands of desired primary atomization length, spatial drop size, and velocity distributions over a wide range of flow rates. Drop sizes have a dominant influence on both combustion efficiency and combustion stability. Fuel injectors are required to yield compact and stable flames with minimum smoke and pollutant formation. Experimental data on atomization characteristics are sparse due to measurement difficulties associated with dense spray zones formed around the liquid jet core. As a result, available empirical correlations have a very narrow range of applicability. The present work is aimed at developing a reliable numerical model of primary atomization from first principles.

Mechanism of Atomization

In a typical liquid-fuel injector configuration, the fuel jet is injected into the oxidizer environment. The freejet surface, initially smooth, becomes unstable, and the disturbances at the liquid-gas interface grow as the jet interacts with the surrounding gas. At low relative velocities, the magnitude of disturbances are on the order of jet size and the large drops separate from the jet tail. This low-speed breakup regime is often called the Rayleigh regime. At higher speeds, the rate of growth of small wavelength disturbances is much faster, and the periodic process of small drop separation from the jet surface takes place. A variety of viscous, inertial, and surface tension mechanisms are important in the breakup process. The complete physics of atomization is complex and not well understood. The surface instabilities are driven by aerodynamic drag, gas and liquid turbulence, boundary-layer/free-layer transition, supply pressure oscillations, or even cavitation. However, experimental observations indicate that the most important mechanism leading to the jet breakup is the growth of unstable mode disturbances on the jet surface. The present paper focuses on the coupled analysis of the mean jet flow and the wave formation and growth on the interface, resulting in droplet separation for both low- and high-speed jets.

Previous Analyses

Past investigations of dense sprays were primarily limited to analyses based on observations near the boundaries of dilute dispersed jets.[1] Detailed information obtained by direct observation and analysis of dense sprays have been reviewed by Faeth,[1,2] Sirignano,[3] Bracco,[4] and Reitz.[5] However, atomization conditions near the injector (i.e., primary breakup from the liquid jet surface) have not been well defined. In the 1960s, Mayer[6] and Adelberg[7,8] predicted mean droplet size and mean breakup rate on primary atomization by using the work of Lamb[9] and Jeffreys.[10] Since then, Mayer's model has been used as a standard method[11] for the evaluation of the liquid propellant rocket engines. This model is limited to coaxial elements and computes the liquid jet stripping rate and median droplet diameter from the semiempirical formulas. The empirical model constants were obtained for specific injection conditions and were "backed-out" from the hot fire engine data. The extension of applicability of the model, for the modern combustion chambers, is questionable.

Recently, Sterling and Sleicher,[12] Reitz and Bracco,[13] and Lin and Kang[14] assumed that atomization is primarily due to aerodynamic interaction between the liquid and the gas leading to unstable wave growth on the liquid jet surface. The stability of liquid surface waves due to initial disturbances was analyzed by using a characteristic equation, which is based on the linear instability theory. The analysis assumed that the mechanism of primary breakup on the jet surface is controlled by the growth of the disturbance wave.

Recent Progress in Computational Models

In recent years, renewed interest in direct and approximate numerical simulation of jet atomization has been observed. The direct simulation of the surface dynamics and jet breakup was recently attempted by Fromm,[15] Childs and Mansour,[16] and Shokoohi and Elrod.[17] All analyses, however, were limited to low-speed, long-wave surface disturbances. The results of Childs and Mansour were limited to initial growth stages of a single disturbance with no breakup. Results of both Fromm[15] and Shokoohi and Elrod[17] predicted the breakup process and successfully demonstrated the possibility of formation of main and satellite drops. These studies show encouraging results; however, due to horrendous computer time requirements, in spite of tremendous growth in computer capabilities, the direct nonlinear simulation of the high-speed, short-wavelength atomization process is not feasible.

The approximate modeling techniques solve for the mean jet flow from nonlinear transport equations and compute the breakup rate from semiempirical formulas. In this category, the volume of fluid (VOF) technique, developed by Hirt and Nichols,[18] has been recently applied by Liang[19] for predicting atomization of a single axisymmetric liquid jet. Two sets of momentum and continuity equations are solved over the entire computational domain. It can resolve the overall jet shape but cannot capture the wave formation and growth on the jet surface. The major limitation of the VOF technique is that it requires very fine grid distribution within the liquid jet and its gaseous neighborhood. Therefore, its use for many practical systems such as rocket combustion chambers with hundreds of injectors is doubtful.

The jet-embedding (JE) technique, proposed by one of the present authors,[20] is an alternative to the VOF for this class of problems. The technique uses the multigrid concept by employing the regular grid for the gas phase, and the embedded, surface-conforming, adaptive grid for the injected liquid jet core. As a result, relative to VOF, it is very economical and flexible (suitable for both single and multi-injector flow analyses). Figure 1 presents sample results obtained with the JE technique for a single coaxial injector reported in a previous publication.[20]

Both of the preceding (VOF and JE) computational approaches require the use of semiempirical formulas for liquid breakup rates and drop sizes. The present work is aimed at eliminating the need for such empirical input by developing an atomization model from first principles.

Proposed Approach

In the present work, the conservation equations describing the liquid jet-core flow are numerically solved on a one-dimensional adaptive, surface-conforming grid based on the JE technique.[20] Gravity and internal viscous effects are neglected, but the viscous friction at the gas-liquid interface is accounted for. The solution of the JE method is coupled with the wave breakup model[21] to compute the wave growth and droplet separation process along the predicted jet-core trajectory. Two formulations (linear and approximate nonlinear) of the wave stability models are considered. For the liquid jet atomization, the drops are assumed to separate from the liquid jet surface due to the growth of surface wave above critical levels. In the following sections, linear and nonlinear approximations for the wave dispersion equation are discussed.

Linear Analysis

The linear analysis examines the stability of a liquid jet surface due to an infinitesimal axisymmetric disturbance with a Fourier form

$$\zeta = \zeta_0 e^{ikz + \alpha t} \tag{1}$$

where ζ_0 is an initial disturbance, k is the wave number, and α is the wave frequency. In the present study, the temporal stability is used, and k is a real wave number for the wavelength $\lambda = 2\pi/k$. The real part of the frequency α determines the degree of wave amplification or damping. It plays a major role in our analysis and is referred to as wave amplitude exponential growth rate α.

By considering the aerodynamic effects with assumptions of incompressible flow and no shear stress[12] at the interface, the governing dispersion equation is obtained from the linearized Navier-Stokes equation using the linear stability theory. Detailed derivation of the dispersion equation is tedious but has been described in detail by Levich.[22] The amplitude growth rate α is governed by the dispersion equation, which can be expressed as

$$\alpha^2 + 2\nu_f k^2 \left[\frac{I_1'(ka)}{I_0(ka)} - \frac{2k\ell}{k^2+\ell^2}\frac{I_1(ka)}{I_0(ka)}\frac{I_1'(\ell a)}{I_1(\ell a)}\right]\alpha$$
$$= \frac{\sigma k}{\rho_f a^2}(1-k^2a^2)\left(\frac{\ell^2-k^2}{\ell^2+k^2}\right)\frac{I_1(ka)}{I_0(ka)}$$
$$+ \frac{\rho_g U_r^2 k^2}{\rho_f}\left(\frac{\ell^2-k^2}{\ell^2+k^2}\right)\frac{I_1(ka)K_0(ka)}{I_0(ka)K_1(ka)} \tag{2}$$

where U_r is the relative velocity, I_0 and I_1 are the zero-order and first-order modified Bessel functions of the first kind, K_0 and K_1 are the zero-order and first-order modified Bessel functions of the second kind, and

$$\ell^2 = k^2 + (\alpha/\nu) \tag{3}$$

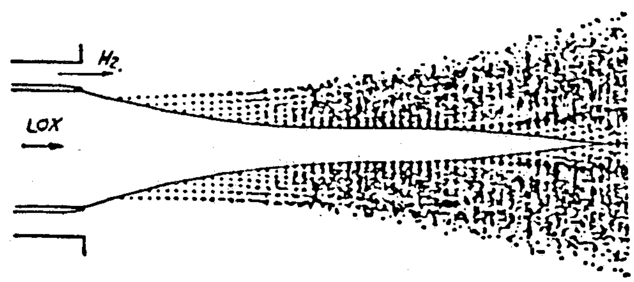


Fig. 1 Sample results of liquid jet atomization for single coaxial injector using JE technique.[20]

By imposing an infinitesimal axisymmetric disturbance with a spectrum of wavelengths, the dispersion equation was solved to obtain the growth rates for the amplitudes of all waves. The growing amplitudes are expressed in Fourier form as shown by Eq. (1) and are applied to determine the primary breakup rates of the liquid.

Nonlinear Analysis

The theory of Yuen[23] was used for nonlinear analysis and was applied to only the Rayleigh regime in the present study. The nonlinear theory of Yuen considers the jet as an infinitely long inviscid incompressible liquid cylinder and neglects the effects of surrounding gas ambience. The analysis examines the instability of liquid jet surface due to a third-order disturbance with a form

$$\zeta = \sum_{m=1}^{3} \zeta_0^m \zeta_m = \zeta_0^1 e^{ikz+\alpha_1 t} + \zeta_0^2 \cdot \zeta_2(kz, \alpha_1 t, \alpha_2 t) + \zeta_0^3 \cdot \zeta_3(kz, \alpha_1 t, \alpha_2 t, \alpha_3 t) \tag{4}$$

where ζ_2 and ζ_3 are algebraic functions[23] and α_1, α_2, and α_3 are the growth rates for the first, second, and third modes, respectively. The dispersion equations governing the growth rates α_m are similar to the first-order equation for Rayleigh jets. The readers interested in further details should refer to the original paper of Yuen.[23]

Primary Breakup

In the present model, the ligaments or drops are assumed to separate from the liquid jet surface due to the growth of initial disturbances above critical levels. The criterion for ligaments stripping from the growing waves is based on the assumption that when the wave of wavelength λ_n has grown to an amplitude larger than λ_n, the crest of the wave erupts as a ligament. This criterion can be expressed in the following form

$$\zeta_0 e^{\alpha_n t} \geq \lambda_n \qquad n = 1, 2, 3, \ldots \infty \tag{5}$$

With this assumption, the drop size does not necessarily correspond to the fastest growing wavelength since it is possible for some shorter waves, with less growth rates, to take a shorter amount of time to grow up to their own critical wavelengths. The separated ligament, in the form of a pulsating ring with a cross-sectional diameter equal to $\lambda_n/2$, breaks into a number of drops of similar size, shown in Fig. 2.

After the first drops have been detached, this stripping action must leave smaller ripples on the liquid surface. Therefore, the breakup of other waves of shorter wavelength than λ_n can consequently occur as long as their growth rates α_n are positive. The time needed for each qualified wave to grow to the breakup level can be expressed as

$$t_{B_n} = \frac{\ln(\lambda_n/\zeta_0)}{\alpha_n} \tag{6}$$

and the corresponding stripping mass of a ligament is

$$m_{B_n} = \frac{\rho_f a (\pi \lambda_n)^2}{8} \tag{7}$$

Because of the atomization mass transfer and the acceleration of liquid due to interphase friction, the jet radius diminishes with the downstream distance. When the jet radius decreases, according to the solutions of the dispersion equation, the maximum growth rate shifts to the longer wavelengths. As a result, the drop sizes (proportional to the wavelength) should increase as the downstream distance increases. The drops are separated from the side of the jet. The jet radius is reduced with the downstream distance till the wave amplitude grows to a magnitude greater than the local jet radius. At this point, the drops, of a size comparable to the local jet diameter, are separated from the tail of the liquid jet. The assumption is similar to the hypothesis made by Levich,[22] Rayleigh,[24] and Weber[25] for the low-speed jets.

Coupling Procedure

The main steps of the coupling procedure between the JE technique and wave dynamics model used in the present computational studies are given below.

1) Start with initial jet velocity and radius by assuming no breakup at the nozzle exit.

2) Compute new jet velocity and radius at a downstream section by iterative solution of continuity and momentum equations.

3) Calculate coefficients for the dispersion equation [Eq. (2)] and hence solve for the growth rates of waves with a spectrum of wavelengths by using the new jet radius and relative velocity between gas and liquid phases.

4) Based on Eq. (1), calculate the amplitude of each wave and compare it to its own wavelength to check the onset of the breakup.

5) Calculate the breakup rate and drop size distribution as per the criterion of the breakup.

6) Return to step 2 to start iterative calculations for the next section with present velocity, radius, and breakup rate.

Results and Discussion

Low-Speed Jets

For the present study, the problem considered as baseline analysis is a low-speed jet in the Rayleigh regime. In this regime, past observations[24,25] showed that the large size main

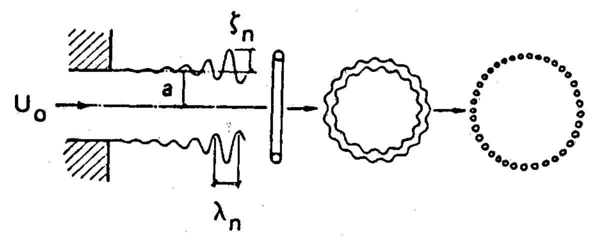


Fig. 2 Postulated mechanism of droplet breakup in the atomization regime.

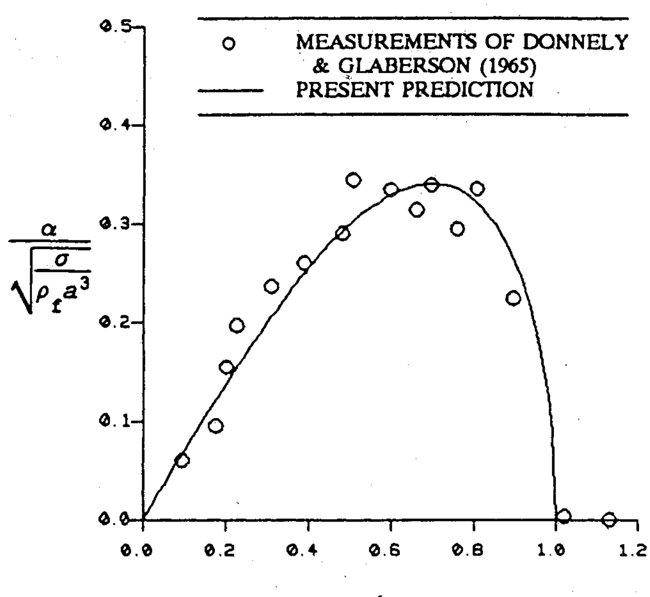


Fig. 3 Variations of nondimensional wave growth rate with wave numbers for low-speed liquid jets.

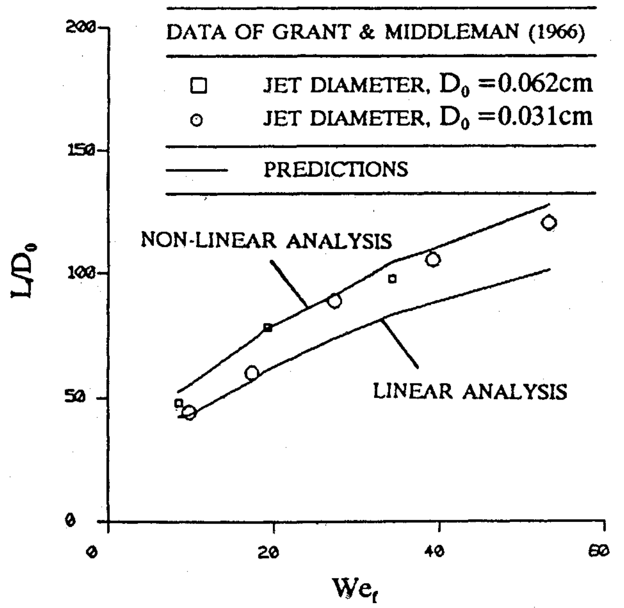


Fig. 4 Variations of intact length of low-speed water jets in stagnant air.

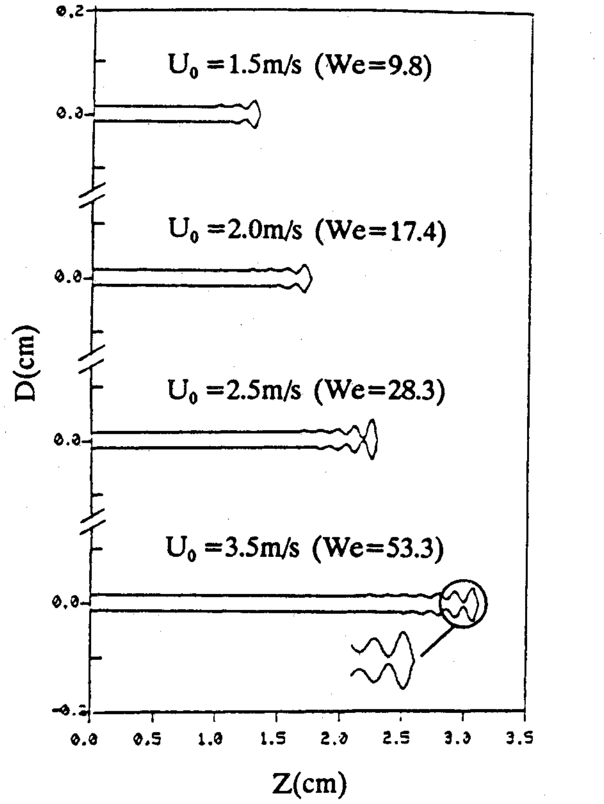


Fig. 5 Predicted shapes of low-speed water jets in stagnant air with linear analysis.

drops are formed at the tail of the jet and small spherules are formed between the main drops. It is generally recognized that the small "satellite" drop formation is due to a nonlinear behavior. Therefore, in the present study, both the linear and nonlinear theories have been considered for the analysis of low-speed jets.

Linear Analysis Results

The dispersion equation [Eq. (2)], which is based on the linear theory, has been solved for the Rayleigh regime. Note that the present prediction accounts for the viscous term in Eq. (2), which has been neglected in the past.[5,24] Figure 3 presents the calculated dimensionless wave growth rate as a function of the normalized wave number; for comparison, the measured data of Donnely and Glaberson[26] are also shown. These results show that 1) for the long waves ($\lambda > 2\pi a$), the growth rate α is positive, and hence the long waves can grow; and 2) for the short waves ($\lambda < 2\pi a$), the growth rate α is negative, and therefore the short waves do not grow.

In the analysis, it is assumed that axisymmetric, exponentially growing disturbances disintegrate the jet when its amplitude becomes equal to the jet radius. Thus, the initial disturbance ζ_0, of the most unstable wave, which is at the peak of the curve shown in Fig. 3 (i.e., at $ka \simeq 0.7$), will first grow to a magnitude of the jet radius. This explains the phenomenon of large main drops occurring at the tail of liquid jets in the Rayleigh regime.

Figure 4 shows the dimensionless intact length vs Weber number for low-speed water jets. Experimental data have been reported by Grant and Middleman[27] for two jet diameters (0.062 and 0.031 cm). The prediction of the linear theory exhibits the proportional behavior along the curve, which is a typical feature in the Rayleigh regime. It should be noticed that the present analysis considers the jet viscosity with low exit velocity where ambient effects are small and neglected.

In order to observe the growth of jet surface waves, four cases are selected from Fig. 4. The shape predictions of selected cases (i.e., water jet velocities of 1.5, 2, 2.5, and 3.5 m/s and stagnant surrounding air) are shown in Fig. 5. It can be seen that large main drops form at the end of the jet when the wave amplitude grows and becomes equal to the jet radius. Figure 5 shows the proportionality of the jet intact length with the jet velocity. However, the approach with the first-order (linear) theory is unable to predict satellite drops. The nonlinear analysis results are discussed below.

Nonlinear Analysis Results

The current nonlinear analysis, which has been coupled with the JE technique, is based on a third-order theory by Yuen.[23] As discussed in Ref. 23 for the same initial disturbance, the wave is found to have a maximum growth rate at $ka = 0.7$ in agreement with the linear theory. Based on the breakup criterion and flow conditions as used for the linear analysis, the nonlinear prediction for the jet breakup length shows a better agreement with the measurements (see Fig. 4). The reason for this is that the linear theory does not conserve the mass[23] and momentum[22] when the disturbance becomes large.

The nonlinear analysis can also predict the satellite drop formation for the liquid jet in the Rayleigh regime. Figure 6 shows predictions of the jet shapes with satellite formation. The four cases used in Fig. 6 are exactly the same as those for linear analysis shown in Fig. 5. It can be seen, in Fig. 6, that a satellite drop is forming at the neck between main drops of the jet tail. This cannot be observed from the linear analysis results, shown in Fig. 5. In both Figs. 5 and 6, the jet tail of the case with $U_0 = 3.5$ m/s has been magnified for a detailed comparison about the formation of the satellite drop.

In order to obtain a further assessment of the nonlinear model's capability of predicting satellite drops, another case was considered for which Taub[28] has reported shape measurements, using the laser shadowgraphy. Figure 7 shows that the shape prediction agrees qualitatively with the jet shape photographs obtained from an oscilloscope tracer.

High-Speed Jets

The validation of the present approach for low-speed jets (Rayleigh regime) provided a good basis for modeling primary breakup of high-speed jets (atomization regime). When the relative velocity between liquid and gas phases increases significantly, the effects of aerodynamic forces should be considered along with the effects of capillary forces. Consequently, in the wind-induced regimes (i.e., first and second) and the atomization regime, the relative velocity becomes a controlling parameter. It should be noted that only the linear theory was applied for these regimes, and secondary breakup, coalescence, turbulence, and vaporization effects are not considered in the present study.

Instability Analysis

The solutions of the dispersion equation [Eq. (2)] are first examined and discussed here by considering a water jet into a gas stream.

Figure 8 shows that with the increase in relative velocity, the maximum growth rate occurs in the range of shorter wavelengths, i.e., larger wave numbers ($ka \gg 1$). This implies that in the atomization regime, smaller droplet sizes may exist in the primary breakup region. The case of low relative velocity, $U_r = 1$ m/s, shows a result similar to the Rayleigh case shown in Fig. 3, but slightly shifted toward the short wave region where $ka > 1$.

For the cases of $U_r = 30$ and 100 m/s, the growth rates α are positive in both long and short wave regions (i.e., $ka < 1$ and $ka > 1$, respectively). This leads both long and short waves to grow on the jet surface. Therefore, in the atomization regime, due to aerodynamic effects, both short and long waves are unstable, and their amplitudes grow exponentially in time. The growth in amplitude of short waves leads to the separation of small droplets and to atomization of the liquid jet. The instability of long waves leads to the appearance of significant wave formation along the jet surface.

Because of the complexity of the full dispersion equation, considerably useful information can also be obtained by analyzing the solutions of two limiting cases,[22] namely, $ka \gg 1$ for the short wave region, and $ka \ll 1$ for the long wave region. Therefore, the approximate equations of two limiting cases for the atomization regime have also been solved. Figure 9

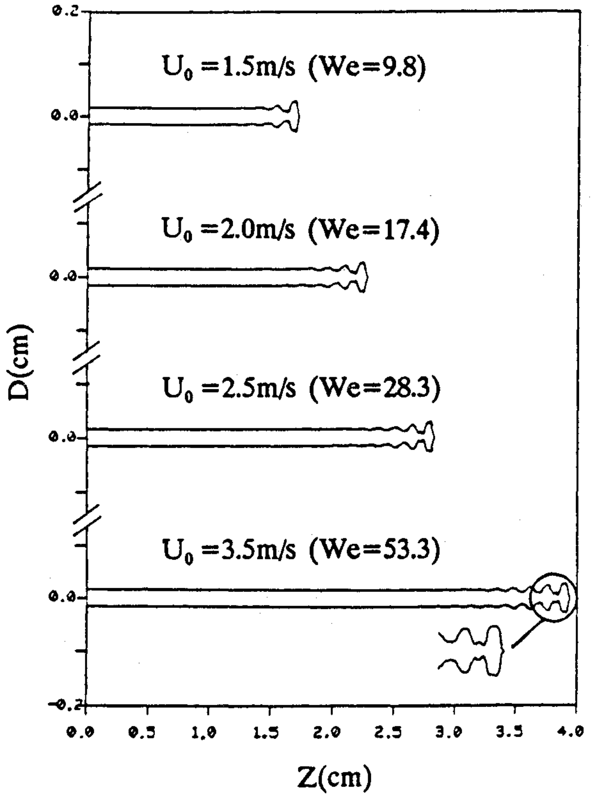
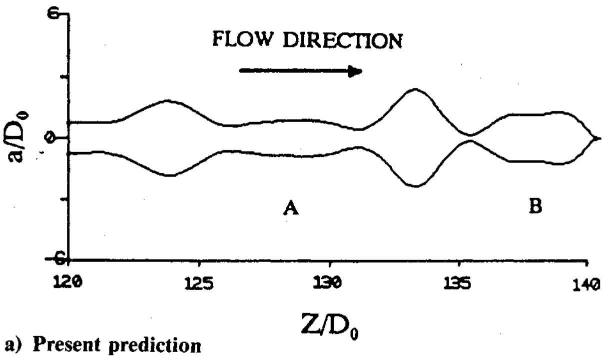
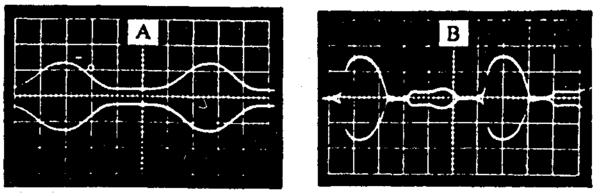


Fig. 6 Predicted shapes of low-speed water jets in stagnant air with nonlinear analysis.



a) Present prediction



b) Photographs by Taub (1976)

Fig. 7 Satellite drop formation.

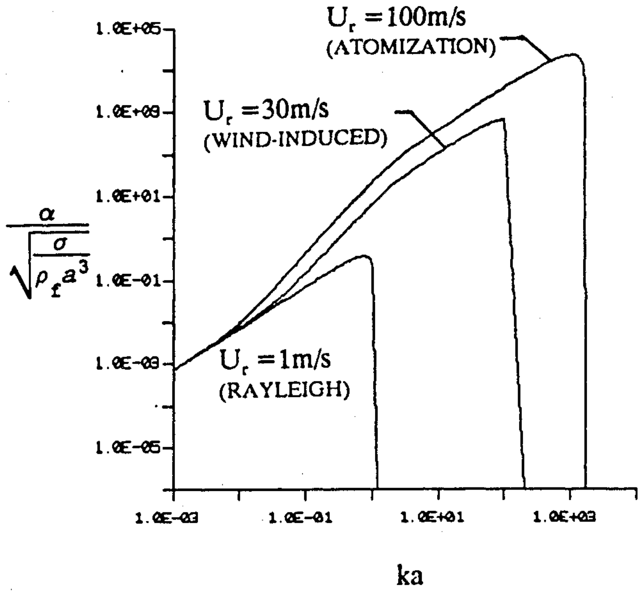


Fig. 8 Variations of nondimensional wave growth rate with wave numbers for high-speed water jets of 1-cm radius.

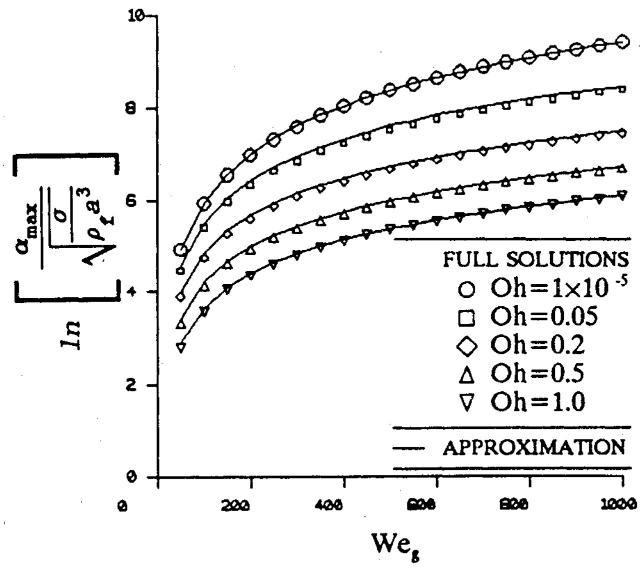


Fig. 9 Variations of nondimensional wave growth rate with Weber numbers for liquid jets at various Ohnesorge numbers.

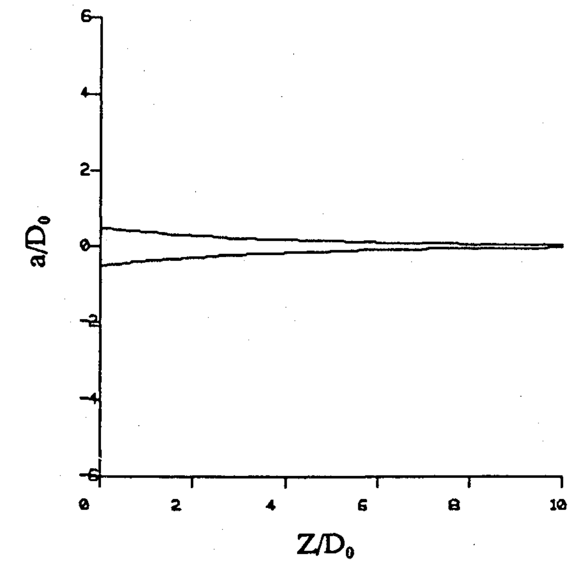


Fig. 10 Predicted shape of liquid oxygen jet into a constant-speed hydrogen stream.

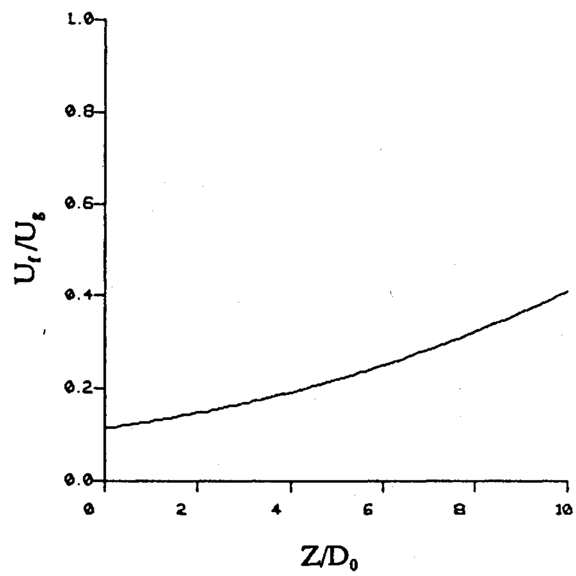


Fig. 11 Variations of axial velocity of liquid oxygen jet into a constant-speed hydrogen stream.

shows the comparisons of results from approximate and full equations for different cases of the Ohnesorge number, which is defined as $Oh = \mu_f/\sqrt{\rho_f a \sigma}$. The dimensionless maximum growth rates are plotted as a function of the ambient Weber number, which indicates the ratio of inertia force and surface tension. The ambient Weber number is defined as $We = \rho_g U_r^2 a/\sigma$. From Fig. 9, it is evident that approximate equations can provide an acceptable accuracy up to $Oh = 1$. Therefore, for economic computation, the approximate equations can be employed to the following analyses.

Coaxial Injection Element Simulation

For the practical demonstration of the present technique, an analysis of the single injection element of the Space Shuttle main engine (SSME) preburner has been performed. A coaxial injection element, with a liquid oxygen jet surrounded by an annular hydrogen gas stream, is considered. Strictly speaking, the liquid oxygen (LOX) is under supercritical pressure but subcritical temperature condition; therefore, in this analysis (in the proximity of the injector tip), LOX is treated as liquid. Table 1 provides flow conditions[29,30] used in the analysis. The calculated jet shape and the intact-core length are shown in

Table 1 Summary of test parameters

	Oxidizer	Fuel hydrogen gas
Temperature, K	106	69.4
Flow rate, kg/s	0.1498	0.1806
Density, kg/m^3	1122	91
Velocity, m/s	24.4	213
Diameter, m	2.64×10^{-3} (inner)	4.34×10^{-3} (outer)
Surface tension,[30] N/m	9.252×10^{-3}	

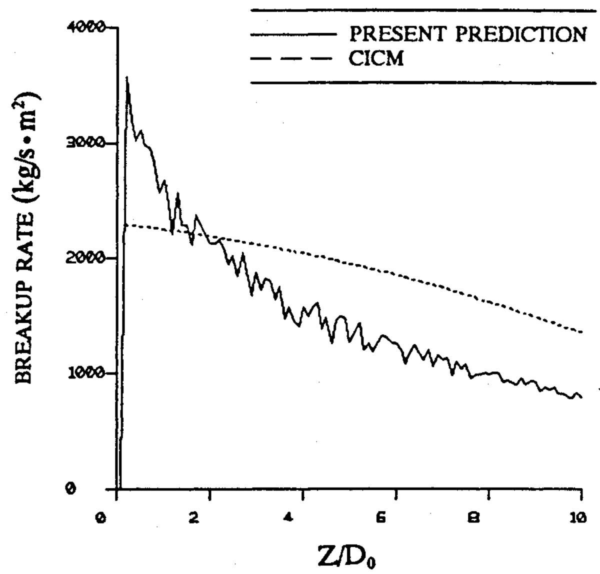


Fig. 12 Variations of primary breakup of liquid oxygen jet into a constant-speed hydrogen stream.

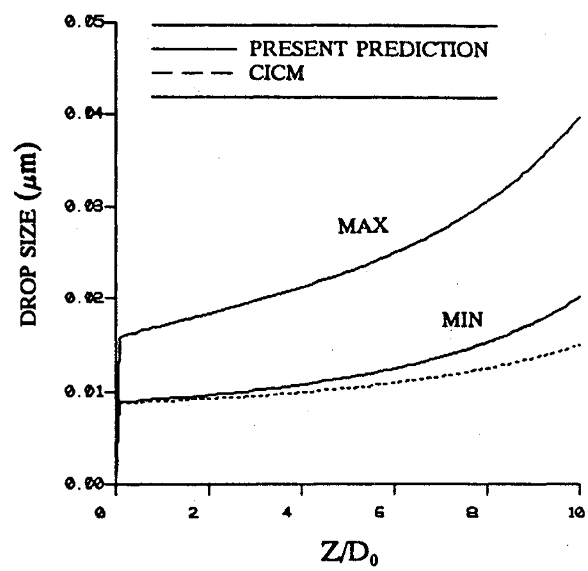


Fig. 13 Drop size range of primary breakup of liquid oxygen jet into a constant-speed hydrogen stream.

Fig. 10. The predicted intact-core length is about 10 injector diameters. The radius decreases monotonically with the distance from the injector. Results of other reported studies[19,20] indicate a more nonuniform jet radius variation. The difference can be attributed to the present assumption of nonreactive constant-velocity hydrogen gas flow. In the other computations, direct coupling between the atomization correlations and gas phase hydrodynamics was accounted for. Figure 11 presents the predicted liquid jet core velocity variation along the axial distance. A monotonic jet velocity increase up to 40% of the gas velocity is observed.

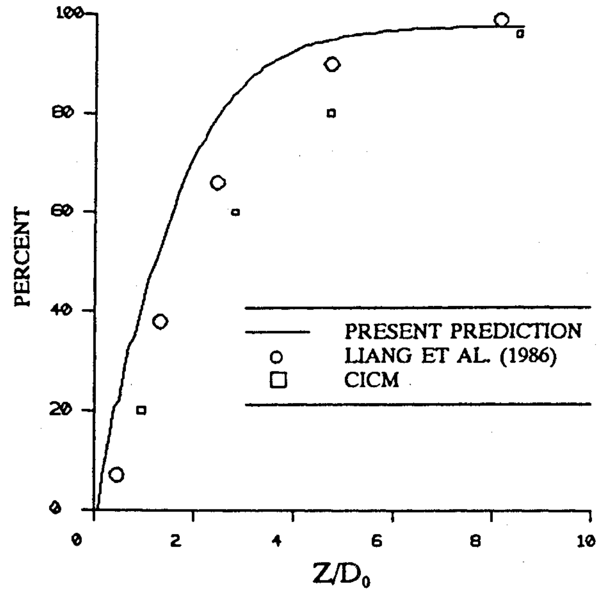


Fig. 14 Atomized mass percentages of liquid oxygen jet into a constant-speed hydrogen stream.

Figures 12 and 13 show the calculated primary breakup rate per unit area and the maximum and minimum drop size variation along the axial direction and their comparison with results of the coaxial injection combustion model (CICM).[11] The comparison between present predictions and CICM results shows reasonable good agreement. The CICM formulas have been calibrated for LOX/H_2 flow experiments. The fluctuations along the curve are caused by the inadequate spectral resolution (discrete wavelength $\Delta\lambda$) in the solution of the dispersion equation over the whole wavelength spectrum.

Figure 14 presents the comparison of the predicted breakup rate between the CICM formula,[11] Liang model,[29] and present results. Note that the results of Liang are based on the use of the semi-empirical formula of CICM for atomization. Present results show a pretty good agreement, but slight overprediction of the breakup rate along the jet length. This is due to the overprescribed gas velocity at some injector diameters downstream. The assumed constant gas velocity, used in the reported computations, does not adequately represent the complex reactive flow pattern in the vicinity of the injector. Coupling of the present model with a computational fluid dynamics (CFD) code to provide simultaneous solutions of liquid core, surface waves, and gas phase motion (with dispersed drops) is the next planned step.

Conclusions

Major conclusions of the present study can be summarized as follows.

1) The coupling of the JE technique and surface-wave dynamics is feasible for the analysis of atomization.

2) For the low-speed (Rayleigh regime) jets, only the large waves grow and form drops at the tail of the jet. The predicted intact core lengths and surface shapes agree very well with experimental studies reported in the literature.

3) Nonlinear theory of the wave dynamics provides more accurate predictions for the breakup length of liquid jets and also predicts the formation of satellite drops.

4) For high-speed jets, small waves grow at the liquid gas interface and provide continuous liquid stripping. For the SSME preburner injector, good agreement was obtained with the results of the CICM code (anchored on experimental data).

The present study shows encouraging results and good potential for predictions of liquid jet atomization from first principles. There are, however, several areas for further model improvement. The weak elements and assumptions of the current model can be summarized as follows.

1) A local quasiequilibrium assumption is used in the wave-dispersion model, i.e., the wave-dispersion equation uses only local relative velocity and does not directly take account of convection.

2) The wave-dispersion equation for the atomization regime is based on the linear small perturbation theory and cannot predict jet breakup due to larger (e.g., turbulence generated) perturbations.

3) In the present study, the JE technique was formulated for the one-dimensional mean flow equations for axisymmetric jets.

4) The gas phase flowfield was prescribed by a uniform or constant-velocity profile. This assumption had an important impact on the "realism" of the predicted results. In the future, gas fluid dynamics and atomization calculations should be fully coupled.

5) Liquid breakup criteria need further study and refinements.

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