High-Fidelity Simulations of High-Viscosity Liquid Jet Atomization in Crossflow

X. Li*, H. Gao, and M. C. Soteriou
United Technologies Research Center
East Hartford, CT 06108 USA

Abstract
Atomization of extremely high viscosity fuel is of interest for applications such as alternative fuels, and altitude relight with extremely cold fuel. In these applications, the fuel-air viscosity-ratio can be orders of magnitude higher than the conventional scenario, outside the applicability of the atomization regimes established in the literature. While detailed atomization measurements usually face grand challenges, high-fidelity numerical simulations offer the advantage to comprehensively explore the atomization details in this new regime. In this work, a previously-validated high-fidelity first-principle simulation code HiMIST is utilized to simulate liquid jet atomization in crossflow in the high viscosity-ratio regime. A Coupled Level Set and Volume-of-Fluid (CLSVOF) interface capturing approach combined with Adaptive Mesh Refinement (AMR) for enhanced simulation efficiencies is used to perform a parametric study in the Ohnesorge number ($Oh$) and Weber number ($We$) space. A wider range of liquid viscosity ($Oh$=0.004 to 2) than literature reports is explored. Direct comparisons between present study and previously published low-viscosity jet in crossflow results are performed. The effects of viscous damping and slowing on jet penetration and ligament formation/breakup are investigated. Near-field decrease and far-field increase in jet penetration with increasing $Oh$ are observed, mostly consistent with the literature reports. The detailed simulations elucidate a distinctive edge-ligament-breakup dominated process with long surviving ligaments for the higher $Oh$ cases, as opposed to a two-stage column-stripping/column-breakup process for the lower $Oh$ counterparts. The trend in the $We$ dependence of penetration is reversed as $Oh$ increases.

*Corresponding author: lixy2@utrc.utc.com
1. Introduction

Atomization of high viscosity liquid fuel in a cross-flowing air stream is of great interest to the operations of future aircraft engines at higher altitude, with the possibility of injecting more viscous alternative fuels at low temperature. While a higher viscosity fuel can perform better in simultaneously serving as the lubricant than the traditional lower viscosity fuel, it may cause issues for fuel injection, since atomization of the high viscosity fuel may be less efficient at higher altitude with very low temperature. Therefore understanding the physics of high viscosity fuel atomization is an important research topic. The knowledge developed for high viscosity liquid atomization may also be applicable to multiple industry communities including aerospace, automotive, pharmaceutical and food industries.

The role of liquid viscosity was investigated by early theoreticians such as Rayleigh [1], Taylor [2] and Tomotika [3], studying the classical problem of capillary breakup of cylindrical threads using analytical approaches. It has been commonly accepted that increasing liquid viscosity not only damps the amplitude of instability waves, but also increases the characteristic length of such waves. Extending such analytical approaches to the complex case of high viscosity liquid jet atomization in crossflow is challenging, and the crossflow atomization problem was previously investigated mostly using experimental approaches [4-12]. Mixtures of different liquids (e.g. water, alcohol, glycerol etc.) at varying ratios were used to achieve a range of liquid viscosity while approximately preserving other fluid properties. The experimental work [4-12] predominantly focused on the impact of liquid viscosity on jet trajectory and penetration and the work was constrained to a relatively small range of liquid viscosity. Other jet breakup behaviors were described only in a qualitative manner due to the limited optical access in the dense atomization region in the experiments. Early work by Reichenbach and Horn [4] reported little sensitivity of jet penetration to viscosity in a range lower than that of water. Schetz et al. [5] investigated a small range of liquid viscosity higher than that of water in the high Weber number shear-breakup dominated regime and observed little impact of liquid viscosity. Nejad and Schetz [6] expanded the range of viscosity (Ohnesorge number $Oh=0.0038$ to 0.0225) and studied the viscosity impact on the jet plume characteristics. They observed an overall increase of jet penetration with increasing viscosity. They also qualitatively described the high viscosity jet breakup process as forming “a very long, thick ligament while continuously shedding smaller sub-ligaments into the cross flow”. Reduced amplitude of surface waves was also observed from the experimental shadow images. In a follow-up work [7], the same authors experimentally measured droplet size and reported an increase in droplet diameter with increasing liquid viscosity. Wu et al. [8] were able to zoom into the near-field and observed an initial penetration decrease (close to the nozzle) and a later-on penetration catch-up (further downstream along the column) as liquid viscosity increases. A recent study of biodiesel jets atomization in crossflow [11] also reported an initial decrease of penetration with increasing viscosity. The observed increase in initial jet bending was explained as due to a lag in the transition from bag to multi-mode breakup at higher liquid viscosity. The perceived inconsistency of literature on the dependence of penetration on liquid viscosity was further clarified by the work of Birouk et al. [10], which was conducted in the widest range of viscosity explored so far ($Oh=0.0027$ to 0.288). They concluded that the impact of liquid viscosity for the initial part of the liquid column is different than for the downstream spray plume. An initial increase in jet bending (or decrease in penetration) with increasing viscosity was explained to be due to an increased drag by a thicker liquid boundary layer on the windward side [8]. The increase in downstream penetration at higher viscosity was attributed to the increased Stokes number due to droplet size increase.

First-principle high-fidelity numerical simulations [13-19] based on direct interface tracking/capturing methodologies [20-24] has demonstrated to be a superior path to quantitatively explore the detailed liquid atomization physics [18, 25, 26], without the optical access and operating condition constraints encountered in experiments. However, due to the various numerical challenges combined with the high cost of liquid atomization simulations, most of the numerical approaches in the literature were verified in simple canonical tests only. High-fidelity crossflow atomization simulations with detailed experimental validation were rare. To the knowledge of the authors, extension of such high-fidelity simulation approaches to study the impact of liquid viscosity on jet atomization in crossflow has not been attempted.

Recently, Li and Soteriou [18] performed high-fidelity simulations of a water jet in crossflow atomization using a coupled level-set and volume-of-fluid (CLSVOF) method [23] combined with an adaptive mesh refinement (AMR) approach [27, 28]. They successfully validated the simulation results against near-field experiment at ambient condition [29]. Detailed column features and droplet formation data matched with the experimental measurements. Complex breakup and flow physics were also analyzed based on the validated simulation results. The jet destabilization and growth of column waves were predominantly attributed to a Rayleigh-Taylor instability mechanism arising from the presence of crossflow pressure gradient. Such first-principle simulation approaches allow evaluation of the impact of various fluid properties including den-
sity, viscosity and surface tension. In a follow-up work, Li and Soteriou [19] applied the same simulation methodology to investigate the impact of density ratio changes associated with operating pressure variations. It has been found that a transition from the Rayleigh-Taylor to the Kelvin-Helmholtz instability mechanisms occurs on the liquid column surface as the density ratio is independently reduced at non-turbulent liquid injection conditions.

In this work, we apply the same approach to perform several simulations of liquid jet in cross flow at different liquid viscosity. The cases were set up based upon several previously validated ambient condition cases [18]. The parameter space of both Weber number and Ohnesorge number are explored. We explore the jet atomization behavior in a wider range of viscosity ($Oh = 0.004$ to $2.0$) expanded beyond previous studies in the literature.

The paper is outlined as follows. The major elements of the numerical framework are briefly described in Section 2. The liquid properties, conditions and numerical configurations are described Section 3. In Section 4, qualitative high viscosity atomization features are first described and compared to corresponding low viscosity behaviors. Jet penetration and spread are quantitatively compared and discussed in the context of previous literature. Column and ligament breakup details at high liquid viscosity is further explored and quantified by leveraging the unique advantage of high fidelity simulations. Finally, summary and conclusions are provided in Section 5.

2. Numerical Methods

The incompressible two-phase flow of liquid and gas can be represented by a single-fluid formulation. The governing equations are

$$\nabla \cdot \mathbf{u} = 0$$

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = -\frac{1}{\rho} \nabla (p + p\mathbf{I}) + \frac{\sigma\nabla \mathbf{H}}{\rho} \quad (2)$$

where $p$ is the pressure, $\rho$ the density, $\mu$ the viscosity, $\mathbf{I}$ the identity tensor, $\mathbf{D}$ the strain rate tensor, $\sigma$ the surface tension, $\kappa$ the local curvature, and $H$ the Heaviside function defined as

$$H(\Phi) = \begin{cases} 1 & \Phi \geq 0 \quad \text{(liquid)} \\ 0 & \Phi < 0 \quad \text{(gas)} \end{cases} \quad (3)$$

Here $\Phi$ is a function that identifies the interface location. The density and viscosity are defined as

$$\rho = \rho_l H(\Phi) + \rho_g [1 - H(\Phi)] \quad (4)$$

$$\mu = \mu_l H(\Phi) + \mu_g [1 - H(\Phi)] \quad (5)$$

where the subscript $l$ and $g$ denote liquid and gas phase, respectively. The motion of the interface follows

$$\frac{\partial \Phi}{\partial t} + \mathbf{u} \cdot \nabla \Phi = 0 . \quad (6)$$

Since the numerical methods adopted in this paper have been comprehensively described in our previous work [16-18, 30], only a brief highlight is provided here for the completeness of the paper. Our computational code HiMIST is based on the Coupled Level-Set and Volume Of Fluid (CLSVOF) method [23] to capture the liquid-gas interface. The method capitalizes on the advantages of both the accurate geometric interface representation in level set method and the volume-preserving properties in the volume of fluid method. The CLSVOF interface tracking method is implemented under the framework of a block structured adaptive mesh refinement (AMR) [27, 28]. The flow solver features a two-fluid advection approach to avoid artificial smearing of velocity field across the interface. The pressure projection equation is solved using a Multi-Grid Preconditioned Conjugate Gradient method (MGPCG). The method is augmented by a ghost fluid (GF) treatment for pressure, density and viscosity jump conditions to achieve stable and fast solution.

3. Physical Parameters and Numerical Setup

The controlling parameters for the problem of interest include the viscosity ratio $r_\mu = \mu_l / \mu_g$, the momentum flux ratio $q = \rho_l \mu_l^2 / \rho_g \mu_g^2$, the gaseous Weber number $We = \rho_g \mu_g^2 d_0 / \sigma$, and the Ohnesorge number

$$Oh = \frac{\mu_l}{\sqrt{\rho_l \sigma d_0}} , \quad \text{where} \quad d_0 \quad \text{is the diameter of injection orifice. To provide direct comparisons of liquid atomization between the high viscosity and the low viscosity regime, the simulations in this work were configured in a similar fashion as those in the low viscosity work by Li and Soteriou [18], as shown in Table 1 and 2. While the liquid density $\rho_l$, gas density $\rho_g$, gas viscosity $\mu_g$, surface tension $\sigma$, jet diameter $d_0$, and liquid/gas inlet velocities are kept the same as in [18], the liquid viscosity $\mu_l$ is varied from a lower value for water to higher values (the highest being close to that of approximately 97% glycerol water solution). In this way, the Ohnesorge number $Oh$ (hence the viscosity ratio $r_\mu$) will be varied while the density ratio $r_\rho$, the momentum flux ratio $q$ and Weber number $We$ will be kept the same as before. Two cases with increasingly higher viscosity (case 3b and case 3) are simulated. For case 3, the viscosity ratio ($r_\mu=25554$) and Ohnesorge number ($Oh=2$) are significantly higher than the values of case 3a in [18]. At the highest viscosity, the gaseous Weber number $We$ is also varied from 10 to 160 (case 1, 2 and 3) as in the corresponding low viscosity cases (case 1a, 2a, 3a) [18]. It has been shown that this range of $We$ covers several breakup regimes for the low viscosity cases, where $We=10$ corresponds to bag breakup, $We=40$ multimode breakup, and $We=160$ shear breakup. In Fig. 1, all the simulation cases are mapped...
onto a regime diagram as suggested in Ref. [29, 31, 32]. It was suggested that a drastic change in droplet breakup regime may occur at high $Oh$ [31]. Whether similar change in breakup regime occurs for the corresponding liquid jet atomization cases will be explored in this work.

The simulations are performed in a rectangular domain with dimension of $5.0 \times 2.0 \times 5.0$ cm. The liquid jet is injected in the positive z direction while the crossflow is imposed in the positive x direction. The injection orifice is located at 0.2 cm downstream of the domain inlet boundary. No-slip wall boundary condition is imposed at the z=0 boundary except for the liquid injection orifice. Uniform inflow velocities are specified for both the crossflow airstream at the x=0 boundary and the liquid jet at the injection orifice. Effects of inlet turbulence are excluded in this work as in the low viscosity study [18]. Outflow boundary conditions are applied for the remaining boundaries.

The computational domain is covered with a uniform base grid of $320 \times 128 \times 320$, yielding a resolution of 156 $\mu$m. Two levels of refinements are applied in the vicinity of the liquid/gas interface, yielding a finest resolution $\Delta x_{\text{refine}} = 39$ $\mu$m, the same as in [18]. Since the liquid/gas inlet turbulence is excluded in the simulations, the smallest relevant flow scales are generated at the liquid-gas interface by multiphase flow breakup. Events at very small scales such as liquid pinch-off do occur in reality. However, we postulate here that the smaller-scale physics has little impact on the larger-scale flow. Previous validations [18] have shown that when the grid resolution is smaller than the ligament or droplet size observed in the experiment, the simulation can resolve physics down to the experimentally measured scales and the under-resolved flow and pinch-off physics do not have a significant impact on the atomization features of interest at the measurement scales. Since it has been reported in experiment that increasing liquid viscosity tends to increase the droplet size [7], the grid size as required by the baseline low viscosity cases [18] is deemed to be sufficient for capturing the atomization processes for the higher viscosity cases here.

The time stepping for all the simulations is defined by three criteria: CFL criterion, surface tension criterion and viscous criterion [23]:

$$
\Delta t < \min \left( \frac{1}{2} \frac{\Delta x}{U_{\text{max}}}, \frac{1}{2} \sqrt[3]{\frac{\rho_{l}}{8\pi\sigma}} \frac{1}{2} \frac{\Delta x^{2}}{\nu_{\text{max}}} \right)
$$

where $U_{\text{max}}$ is the maximum velocity in the domain and $\nu_{\text{max}}$ is the maximum kinematic viscosity in the domain. Flow-through time can be estimated based on the gaseous velocity $u_{g}$ as listed in Table 2 and the domain size $L_{x}=5$cm in streamwise x-direction. The simulations were performed for physical time of 10ms, 5.0ms, and 2.5ms for case 1, 2, and 3, respectively, which accounts for more than 5 flow-through times. At this stage, the jet atomization simulations have reached stationary state, with a total grid count of $\sim$30 million. The total cost for one simulation is around 10 days using $\sim$400 processors.

4. Results and Discussions

4.1. Qualitative Comparisons of Atomization Processes

In Fig. 2-7, the atomization features of the liquid jet are qualitatively compared at different $Oh$ and $We$ conditions. Fig. 2 and 3 focus on the impact of $Oh$ ($Oh=0.004$ to 2) while keeping other parameters constant ($We=160$, $q=88.2$). In Fig. 4-7, the Weber number sensitivity of the jet behavior at different $Oh$ ($Oh=0.004$ and 2) is illustrated by showing atomization details at lower Weber numbers ($We=40$ and 10). The low viscosity ($Oh=0.004$) results obtained from previous work [18] are shown here as the benchmark for comparisons.

Fig. 2 demonstrates the differences in jet atomization process at different liquid viscosities. As the jets penetrate into the crossflow, they all bend towards the direction of the crossflowing stream. At the same momentum flux ratio, the jets show different penetrations, which is related to the differences in the breakup process. As discussed in previous work [18], at low viscosity ($Oh=0.004$), Rayleigh-Taylor instability waves are formed on the windward surface of the column. The instability promotes intensive stripping of droplets on the edges of the column (Fig. 2(f)) and the column is depleted in a large degree before reaching the column fracture point. The Stokes number for droplets generated by the ligament stripping mechanism is small and therefore the droplets have a large drag/inertia ratio and penetrate much less in the positive z direction (Fig. 2(c)). As the viscosity is increased ($Oh=0.4$), the windward instability waves seem to be significantly damped out (Fig. 2(e)). The breakup due to droplet stripping from the column edge also seems to be delayed (Fig. 2(b)). The column survives longer as it penetrates into the crossflow, leading to a higher jet penetration (Fig. 2(b)). As the viscosity is further increased ($Oh=2$), edge stripping/breakup seems to be further delayed and its rate is also reduced. An even smoother windward surface is observed. Wavy perturbations are found at the edge of the column only. The growth of such surface perturbations leads to the formation of ligaments, which are further pulled from the column edge. These ligaments are long, forming pronounced “finger” structures along the column. The reduced tendency of breakup for such long ligaments is probably due to the increased wavelength for capillary pinch-off of liquid thread at higher viscosity [3]. Despite the large differences in breakup details for cases at different $Oh$, the overall transverse spread when viewed from the top (Fig. 2(g)-(i)) does not change much with $Oh$. 
The cross-section shapes of jets at different heights (z=5 to 15 mm) are compared in Fig. 3 to better illustrate the differences in column deformation and breakup at different Oh. At the z=5mm plane, column stripping/breakup has not started and the degree of column flattening is similar although Oh is different. At an increased height z=10mm, the column is further deformed into a crescent shape. For the low viscosity case (Oh=0.004), the more intensive column stripping/breakup at the edge of the crescent leads to reduced width in the transverse y direction than the higher viscosity case (Oh=0.4 and 2). The larger column width or windward surface area exposed to the crossflow at higher viscosity (compare Fig. 3(d) with Fig. 3(e) and (f)) probably leads to larger column drag and stronger column bending as shown in Fig. 2 (a) compared to Fig. 2(b) and (c). Because of column liquid depletion for the low viscosity case (Oh=0.004), the contiguous column cannot reach the z=15mm plane. For the higher viscosity cases (Oh=0.4 and 2), the column width decreases as the height is increased from z=10mm to 15mm, due to ligament breakup on the edge and column liquid depletion.

The impact of viscosity on liquid breakup is also assessed at two lower Weber numbers We=40 and We=10 in Fig. 4 and 5 respectively. In Fig. 4, for the high viscosity case (Oh=2) at We=40, no discernible windward surface waves are observed. Wavy perturbations are formed on the transverse edge and the growth rate of such waves is reduced compared to the corresponding case at We=160 (Fig. 2(d)). Ligament formation is delayed along the column and ligament fingers also seem to survive longer before breaking up into droplets. In contrast to the corresponding low viscosity case (Oh=0.004, We=40), the penetration is significantly higher and the flattening of the column is much less. As the Weber number is further reduced to We=10 in Fig. 5, for the high viscosity case (Oh=2), the windward column surface is smooth and wavy structures are again observed on the column edge only, with an increase in wavelength. However, ligament formation and breakup does not occur until the jet reaching a very large height. In the end, the breakup of the column predominantly follows a ligament stretching-breakup mechanism (Inset of Fig. 5(a)(c)), instead of the bag breakup mechanism [18] observed for the corresponding low viscosity case (Fig. 5(d)). Larger contrast in penetration and flattening is observed between the higher and lower viscosity cases. Note that such ligament-breakup dominated process at higher Oh is consistent with the qualitative description in an earlier experimental work by Nejad and Schetz [6].

The cross-section shapes of jets at different Weber number is shown in Fig. 6 at Oh=0.004, as compared to those in Fig. 7 at Oh=2. As discussed in previous low viscosity work [18], the range of Weber number explored covers several breakup regimes from shear breakup at We=160 to bag breakup at We=10. In these regimes, the early deformation of the column is largely insensitive to the Weber number (Fig. 6 (a)-(c)). The difference in column shape in the later stage can be attributed to the more intensive column-stripping at higher We. As a result, the column width is smaller at higher We (Fig. 6 (d)-(f)) and the reduced drag leads to reduced jet bending. For the corresponding cases at higher liquid viscosity (Oh=2) in Fig. 7, the column deformation decreases with decreasing We. Decreased column deformation has been observed for the low viscosity jet under capillary column breakup at very low Weber numbers [9, 29, 32]. Part of the effects of liquid viscosity here can be viewed as inhibiting the breakup process to hold the jet together, analogous to the effects of increased surface tension at low We. In this sense, high viscosity effects are explained in a similar way as in [11] (liquid viscosity causing a lag in the transition to higher We breakup regimes). As shown in Fig. 7, at higher liquid viscosity, the decreased column deformation at lower We leads to reduced flattening and less drag on the column. Therefore, less bending is observed for the lower We case at Oh=2 (Fig. 5(a)), in contrast to the more bending observed at lower We case at Oh=0.004 (Fig. 5(b)).

4.2. Comparisons of Jet Plume Boundaries

The boundaries for the jet plume were quantitatively extracted from the simulation data for all the cases and compared in Fig. 8. The boundaries were defined as the minimum and maximum y and z locations of liquid surfaces for each x-bin. The bin size was set to be 0.5 mm. Too small bin size leads to large oscillations of data due to the limited number of samples while too large bin size fails to capture the local variations of plume boundary. In Fig. 8, the data were extracted by averaging over 50 snapshots for each case. Note that only the z boundaries were investigated in the previous experimental work [4-12] due to the constraints in the optical setup.

Fig. 8(a) and (b) compare the plume boundaries for different Oh at the same Weber number (We=160). The upper boundaries (solid lines) in Fig. 8(a) represent the penetrations of the jets. Previous experimental [29] and simulation [18] work on low viscosity jet in crossflow suggest that momentum flux ratio q is the most dominant factor in determining the spray penetration. In Fig. 8(a), a strong correlation between liquid viscosity and jet penetration is observed. Consistent with the trends observed in [10], the liquid viscosity affects the initial part of the column differently from the far stream in the spray plume. The penetration initially decreases with increasing Oh. As explained in section 4.1, the reduced column stripping/breakup at higher Oh leads to wider cross-section area exposed to the crossflow (Fig. 3(d))
and therefore larger drag on the column, causing larger deflection. However, a reversed trend in penetrations (penetration increases with increasing Oh) is observed further downstream. This is related to the earlier depletion of liquid and earlier column breakup at lower Oh. The sharp turning of liquid trajectory at x/d_0=5 in Fig. 8(a) is caused by the column facture after which the contiguous liquid column no longer exists. The droplets resulted from jet breakup have small Stokes number and tend to penetrate less into the crossflow. As the Oh increases, the jet breakup is delayed and the contiguous jet column penetrates more into the crossflow. In Fig. 8(a), the lower boundaries (dashed lines) of jet plume follow a non-monotonic variation with Oh. The phenomenon is not easy to explain and may be linked with differences in the recirculating flow behind the jet. In Fig. 8(b), the transverse spread of the liquid jet when viewed from the top (Fig. 2(g)-(i)) does not seem to be very sensitive to the liquid viscosity. However, it should be noted that the results in Fig. 8(b) combine the behavior of liquids at different heights. For cases with different liquid viscosity, liquid droplets may reach the same transverse spread at different heights (Fig. 2(d)-(f)).

Fig. 8(c) and (d) compare the plume boundaries for different We at the same high viscosity (Oh=2). As the Weber number decreases, both the upper and lower boundaries of the jet plume increase to larger heights. The increase in penetration with decreasing We is due to the reduction in column deformation (Fig. 7), which leads to the reduction in drag on the column. It is interesting to note that the opposite trend was found for the low viscosity counterpart [18]. At Oh=0.004, the initial jet penetration increases as We decrease, because of the reduced stripping at the edge of similarly deformed columns (Fig. 6) and increased column drag at lower We. In Fig. 8(c), the lower plume boundary also increase in height as We decreases, mostly due to the delayed ligament breakup process along the column at lower We (Fig. 5(c)). The delayed ligament breakup also leads to the reduction of overall transverse liquid spread in Fig. 8(d) as the We decreases.

4.3. Quantitative Comparison of Near Field Breakup Properties

In Fig. 9, several near-field breakup properties for high viscosity liquid jet in crossflow are compared with the data for the low viscosity counterpart [18]. The correlations obtained from the low viscosity measurements [29] are also plotted.

The location for the onset of breakup is shown in Fig. 9(a). It is identified by collecting the position of the first ligament that is pulled off the column to form droplets. The experimental correlation [29] is

$$\frac{t_b}{t_v} = 0.0004 \left( \frac{\mu_i / \mu_0}{We_g} \right)$$

where \( t_b \) is the time needed to travel the distance from the orifice to the onset of breakup, and \( t_v \) the viscous time scale calculated as \( t_v = L^2 \left( \frac{\mu_i}{\rho_i} \right) \). The correlation was developed based on a viscous stripping phenomenological model. The ligament is viewed to originate from a viscous shear layer in the liquid beginning at the upstream crossflow stagnation point and the diameter of the ligament is proportional to the thickness of the shear-layer. At the onset of ligament breakup, the surface tension force cannot balance the momentum of the liquid shear layer. It has been shown [18] that the simulated data for the low viscosity jets (Oh=0.004) match well with the correlation Eq. (8). Since liquid viscosity is taken into account in the phenomenological stripping model, for the higher viscosity jets (Oh=2 and 0.4), the predicted onset locations are also in reasonable agreement with the correlation.

Figure 9(b) shows the deformation of the liquid jets at the breakup onset location. The deformation is defined as the ratio of the initial jet diameter \( d_0 \) to the minimum column thickness \( d_i \) in the crossflow direction at the onset of breakup. The experimental correlation [29]

$$\frac{d_0}{d_i} = \begin{cases} 
2, & 4 < We_g < 30 \\
\frac{12 We_g^{0.53}}{30}, & 30 \leq We_g \leq 110 \\
1, & We_g > 110
\end{cases}$$

developed for low viscosity jets is also plotted. At small Ohnesorge number (Oh=0.004), it has been reported [18] that the deformation compares well with the correlation for We=40 and 160. The discrepancy for the We=10 case was attributed to the possible inaccuracy in experimentally quantifying the column thickness due to optical constraints [29]. At large Ohnesorge number (Oh=2) in contrast, the deformation is approximately independent of Weber number, following \( d_0/d_i \approx 2.3 \). As the Oh increases at constant We (We=160), the column deformation \( d_i \) decreases.

The locations for the liquid column fracture are shown in Fig. 9(c). Experimental measurements [29] with Oh<0.3 give the correlation:

$$\begin{align*}
\frac{x_b}{d_0} &= 8 \\
\frac{z_b}{(d_0 q)^{0.5}} &= 2.5
\end{align*}$$

which compares reasonably well with prediction of low viscosity jet simulations [18]. For high viscosity jets (Oh=2), however, column breakup is significantly delayed (2-4 times longer in x-direction and 1.2-2 times longer in the z-direction), probably due to the combined effects of the reduced rate of liquid depletion at the column edge and the damped out windward column waves. Moreover, due to enhanced column edge breakup with increasing We, earlier column breakup is
observed at higher \( \text{We} \) for both the high viscosity and low viscosity liquid jets (the latter being less prominent).

The wavelength of surface instabilities is quantified in Fig. 9(d). For the low viscosity case (\( \text{Oh}=0.004 \)), surface waves were identified on the windward side of the liquid jet and extracted from previous simulations \([18]\) for the case of \( \text{We}=10 \) and 40. In Fig. 9(d), the wavelength data were in good agreement with the correlation \([29]\)

\[ \frac{\lambda_s}{d_0} = 3.4 \text{We}_g^{-0.45} \]  

(11)

For the high viscosity cases (\( \text{Oh}=2 \)), instability perturbations and waves are formed at the column edge (inset of Fig. 9(d)), instead of the windward surface. The wavelength extracted on the edge is plotted in Fig. 9(d), in comparison with the windward surface wavelength for the low viscosity cases. Apparently, the power-law exponent (-0.45) developed for the low viscosity (\( \text{Oh}=0.004 \)) windward waves no longer holds for the high viscosity (\( \text{Oh}=2 \)) edge waves. A simple linear regression model

\[ \frac{\lambda_s}{d_0} = 1.3 \text{We}_g^{-0.17} \]  

(12)

can be developed for the edge waves, as displayed by the dashed line in Fig. 9(d).

5. Summary and Conclusions

High-fidelity simulations of liquid jet atomization in crossflow at high liquid viscosity (up to \( \text{Oh}=2 \)) have been performed and the results are compared with the low viscosity (\( \text{Oh}=0.004 \)) counterparts. The coupled level-set and volume-of-fluid method together with the block-structured adaptive mesh refinement technique was used to accurately capture the liquid/gas interface in such complex multiphase flows. The numerical study probed the details of atomization processes and revealed distinctive breakup behaviors, which are difficult to observe and measure through experimental approaches. The major conclusions are as follows:

a) Increasing liquid viscosity damps out the windward column waves and delays the breakup process at the column edge. A distinctive edge-ligament-breakup dominated process was observed at high liquid viscosity. Long ligaments can survive as a result of the increased characteristic wavelength for the capillary instability for liquid threads.

b) Jet penetration initially decreases with increasing liquid viscosity, then increases, both because of the delay in the breakup process: reduced ligament breakup causing increased jet bending; reduced column depletion causing delayed column fracture and further penetration of the contiguous column.

c) In contrast to the low viscosity jets, a reversed trend in the dependence of penetration on \( \text{We} \) was found for the high viscosity jets: penetration increases with decreasing \( \text{We} \) due to the reduced column deformation at lower \( \text{We} \).

d) The instability wavelength at the edge of column decreases as the \( \text{We} \) increases.

Acknowledgements

The authors would like to acknowledge the funding support from United Technologies Corp. Valuable technical discussions with Dr. Zhongtao Dai and Dr. Jeffrey Cohen at United Technologies Research Center are gratefully acknowledged.

References


### Table 1. Material properties in present study and in Li & Soteriou (2014).

<table>
<thead>
<tr>
<th>Cases</th>
<th>( \rho_1 ) (kg/m(^3))</th>
<th>( \rho_g ) (kg/m(^3))</th>
<th>( \mu_1 ) (kg/m·s)</th>
<th>( \mu_g ) (kg/m·s)</th>
<th>( \sigma ) (N/m)</th>
<th>( d_0 ) (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>997</td>
<td>1.18</td>
<td>0.4753</td>
<td>1.86e-5</td>
<td>7.08e-2</td>
<td>8e-4</td>
</tr>
<tr>
<td>2</td>
<td>997</td>
<td>1.18</td>
<td>0.4753</td>
<td>1.86e-5</td>
<td>7.08e-2</td>
<td>8e-4</td>
</tr>
<tr>
<td>3</td>
<td>997</td>
<td>1.18</td>
<td>0.4753</td>
<td>1.86e-5</td>
<td>7.08e-2</td>
<td>8e-4</td>
</tr>
<tr>
<td>3b</td>
<td>997</td>
<td>1.18</td>
<td>8.94e-2</td>
<td>1.86e-5</td>
<td>7.08e-2</td>
<td>8e-4</td>
</tr>
<tr>
<td>1a</td>
<td>997</td>
<td>1.18</td>
<td>8.94e-4</td>
<td>1.86e-5</td>
<td>7.08e-2</td>
<td>8e-4</td>
</tr>
<tr>
<td>2a</td>
<td>997</td>
<td>1.18</td>
<td>8.94e-4</td>
<td>1.86e-5</td>
<td>7.08e-2</td>
<td>8e-4</td>
</tr>
<tr>
<td>3a</td>
<td>997</td>
<td>1.18</td>
<td>8.94e-4</td>
<td>1.86e-5</td>
<td>7.08e-2</td>
<td>8e-4</td>
</tr>
</tbody>
</table>

### Table 2. Conditions of present study and of Li & Soteriou (2014).

<table>
<thead>
<tr>
<th>Cases</th>
<th>( U_l ) (m/s)</th>
<th>( U_g ) (m/s)</th>
<th>q</th>
<th>( \text{We}_g )</th>
<th>( \lambda_\mu )</th>
<th>Oh</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8.9</td>
<td>27.4</td>
<td>88.2</td>
<td>10</td>
<td>25554</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>17.7</td>
<td>54.8</td>
<td>88.2</td>
<td>40</td>
<td>25554</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>35.4</td>
<td>109.6</td>
<td>88.2</td>
<td>160</td>
<td>25554</td>
<td>2</td>
</tr>
<tr>
<td>3b</td>
<td>35.4</td>
<td>109.6</td>
<td>88.2</td>
<td>160</td>
<td>4800</td>
<td>0.4</td>
</tr>
<tr>
<td>1a</td>
<td>8.9</td>
<td>27.4</td>
<td>88.2</td>
<td>10</td>
<td>48</td>
<td>0.004</td>
</tr>
<tr>
<td>2a</td>
<td>17.7</td>
<td>54.8</td>
<td>88.2</td>
<td>40</td>
<td>48</td>
<td>0.004</td>
</tr>
<tr>
<td>3a</td>
<td>35.4</td>
<td>109.6</td>
<td>88.2</td>
<td>160</td>
<td>48</td>
<td>0.004</td>
</tr>
</tbody>
</table>
Figure 1. Simulation cases mapped onto breakup regime diagram in terms of gaseous Weber number ($We$) and Ohnesorge number ($Oh$).
Figure 2. Instantaneous snapshots of liquid jet breakup in crossflow at the same Weber number ($We=160$) and different Ohnesorge number ($Oh = 2$ to 0.004).
Figure 3. Comparison of jet column shape in several XY plane cross-sections at the same Weber number ($We=160$) and different Ohnesorge number ($Oh = 2$ to $0.004$).
Figure 4. Instantaneous snapshots of liquid jet breakup in crossflow at the same Weber number ($We=40$) and different Ohnesorge number ($Oh = 2$ and $0.004$).
Figure 5. Instantaneous snapshots of liquid jet breakup in crossflow at the same Weber number ($We=10$) and different Ohnesorge number ($Oh = 2$ and 0.004). The inset of (a) and (c) shows the breakup details further downstream along the column.
Figure 6. Comparison of jet column shape in several XY plane cross-sections at the same Ohnesorge number (Oh=0.004) and different Weber number (We=160 to 10).
Figure 7. Comparison of jet column shape in several XY plane cross-sections at the same Ohnesorge number ($Oh=2$) and different Weber number ($We=160$ to 10).
Figure 8. Comparison of liquid jet plume boundaries at different conditions.
Figure 9. Quantitative comparison of near-field column metrics for current high viscosity cases against previous low viscosity simulation and experimental data. (a) Onset of ligament breakup, (b) column deformation at the onset of breakup, (c) column breakup location and (d) wavelength for instabilities formed at the column edge.