PRIMARY BREAKUP AERATED LIQUID JETS IN UNIFORM GASEOUS CROSSFLOWS

K.A. Sallam[*], C.Aalburg°, G.M. Faeth°, K.-C. Lin[†], C.D. Carter[‡], T.A. Jackson[‡]

[*]Oklahoma State University, Stillwater, Oklahoma, USA
°University of Michigan, Ann Arbor, Michigan, USA
[†]Taitech, Inc., Beavercreek, OH, USA
[‡]Air Force Research Laboratory, Wright-Patterson AFB, OH, USA

ABSTRACT

An experimental investigation of the primary breakup of aerated-liquid jets (in the annular flow regime) in supersonic crossflow is described. Single- and double-pulse shadowgraphy and holography were used to study the properties of the liquid sheet as well as outcomes of breakup in the dense spray region near the liquid jet itself that has been inaccessible to past studies using phase Doppler particle analyzers. The results show that the underexpanded internal gas phase forces the liquid sheet into a conical shape upon ejecting from the injector exit passage. Surface breakup along both the downstream and the upstream sides of the jet as well as increased breakup times of the liquid core as compared with pure-liquid jets in subsonic crossflows suggest weak aerodynamic effects of the crossflow near the jet exit. Surface velocities of the liquid sheet were measured and used to develop correlations for the liquid sheet thickness. Sizes of ligaments and drops were measured along the liquid surface and were found to have constant diameters of 0.030 and 0.040 mm, respectively, that were independent of the wide ranges of aeration levels, liquid/gas momentum flux ratios, nozzle diameters and liquid properties considered during the present investigation. Drop size distributions satisfied Simmons' universal root-normal drop-size distribution function with a relatively constant ratio of MMD/SMD=1.07, where MMD = mass median drop diameter and SMD = Sauter mean drop diameter.

INTRODUCTION

Liquid atomization has been studied extensively due to numerous applications for transportation, industrial and agricultural processes. The mixing behavior, combustion efficiency and combustion stability of liquid-fueled air-breathing propulsion systems, for example, depends to a large extent on liquid jet atomization performance. Aerated-liquid jet breakup (also known as effervescent or barbotage breakup) has been popularized by Lefebvre et al. [1] and is of interest due to its demonstrated capabilities to generate finely atomized sprays. These properties are attained by assuring intimate contact between the liquid phase and a gas phase by injecting gas directly into the liquid flow immediately upstream of the injector exit passage. Upon passage of the two-phase mixture through the injector exit passage, the internal gas phase expands to generally yield an annular flow in the injector exit passage, squeezing the liquid into thin sheets and ligaments whose small cross stream dimensions assures a finely atomized spray.

There is a large literature about liquid jets in gaseous crossflows. Studies of pure-liquid jets by Fuller et al. [2] and Wu et al. [3] focused on jet trajectories for various jet exit and crossflow conditions, whereas Mazallon et al. [4] and Sallam et al. [5] mainly investigated the primary breakup properties of round nonturbulent and turbulent liquid jets in uniform gaseous crossflows, including the various breakup modes, drop size distributions and velocities and rates of breakup. The recent work by Lin et al. [6-10] and Mathur et al. [11] considered both pure-liquid and aerated-liquid jets in gaseous crossflows. Their studies generated information about velocity, liquid volume flux and drop size distributions after breakup, showing that aerated-liquid jets can generate smaller droplets with larger velocities and a more uniform volume flux at lower injection pressures than conventional jets within a relatively short distance after injection. In addition, the spray penetration height and the cross-sectional area of the spray plume for an aerated-liquid jet are larger than those of a pure-liquid jet under the same ambient and liquid flow conditions. These investigations were based on shadowgraph and phase-Doppler particle anemometry measurements. In order to avoid problems of large drop number densities and large liquid volume fractions, however, these measurements had to be performed at some distance from the initial breakup location. As a result, characteristics of the spray breakup in the near-injector field, and the driving mechanism behind the effervescent induced breakup remain unknown.

The objectives of the present investigation were to measure the properties of aerated-liquid jet breakup in supersonic crossflow by emphasizing the outcomes of breakup in the dense spray region extending right up to the liquid jet itself. Pulsed shadowgraphy and holography were employed in order to consider spray cone angles, the location of the end of the liquid core and drop size and velocity distributions after breakup, seeking to quantify effects of aeration levels, momentum flux, nozzle diameters and liquid properties on the breakup properties of aerated-liquid jets in supersonic crossflows.

EXPERIMENTAL METHODS

Apparatus

The experiments were carried out inside a supersonic wind tunnel in Test Cell 19 of the Air Force Research Laboratory, Wright-Patterson Air Force Base. This facility is a continuous-run, open-loop, rectangular wind tunnel with a test section having a 12.7 cm height, a 15.2 cm width and a 76.2 cm length. The flow Mach number was constant at M=1.94 yielding crossflow velocities behind a normal shock wave in the range u_∞=195-263 m/s, depending on the stagnation temperature of the air in the wind tunnel. Air pressure and temperatures were measured using strain gauges and k-type thermocouples with uncertainties less than 1%.

A plain-orifice aerated-liquid injector, consisting of an internal tube for the aerating gas flow and an external tube for the liquid flow was flush-mounted at the bottom surface of the wind tunnel. The aerating gas flowed through the internal tube and passed through several 0.10 mm orifices located at the end of the tube, which is 25 mm upstream of the entrance to the injector exit passage. This allows the aerating gas to fully mix with the liquid to form the two-phase annular flow in the injector exit passage. Two injector exit passages with a length/diameter ratio of 20 and passage diameters of 0.5 and 1.0 mm were used to inject three different liquids, i.e. water, alcohol and glycerol, vertically upward into the crossflow. The aerating gas was nitrogen.

The injection system consisted of a liquid tank with an internal volume of 0.144 cu-m to insure a constant liquid supply. Test liquids were filled into the tank and pressurized with high-pressure nitrogen before each experiment. The pressure was varied to provide various liquid velocities at the exit of the injector. Both the liquid and the aerating gas volumetric flow rates were controlled by pressure regulators and measured by flow meters, respectively. Gas/liquid mass ratios (GLR) between 2-10% were used, ensuring that the internal multiphase flow within the injector exit passage was in the annular flow regime (see Kim and Lee [12]). The flow meters were calibrated to an uncertainty of less than 2%. More details about the wind tunnel and the spray injection system can be found in Lin et al. [6,7] and references cited therein.

Instrumentation

Single- and double-pulse shadowgraphy and holography were used to observe the properties of the aerated-liquid jets and the ligaments and drops produced by primary breakup. Two frequency-doubled Nd:YAG lasers with a wavelength of 532 nm and a pulse duration of 7 ns were used as the light source to expose the pictures. The pulse duration was short enough to essentially freeze the flow. Both an off-axis holocamera arrangement and regular shadowgraphy (provided by blocking the reference beam) were used to observe the flow. Reconstruction of double-pulse holograms and shadowgraph pictures yielded two images of the flow so that liquid surface and drop velocities could be found given the known time of separation between the two pulses (as short as 100 ns).

The hologram reconstruction system involved a helium-neon laser with the reconstructed image observed using a CCD camera. The optics yielded a magnified view of the image on the monitor equivalent to a 0.7×0.8 mm region of the flow. The optical data was obtained using a frame grabber (Data Translation DT2851) and processed using Media Cybernetics Image-Pro Plus Software. Various locations of the hologram reconstruction were observed by transversing the hologram in two directions, and the video camera in the third direction using stepping motor-driven linear traversing systems (Velmex, Model VP9000) having 0.001 mm positioning accuracies. The combined holocamera/reconstruction system allowed objects as small as 0.002 mm to be seen and the size of objects as small as 0.010 mm to be measured with 10% accuracy. The reconstruction system was also used to measure flow properties from shadowgraph photographs with the photographs placed in the hologram holder for two-dimensional traversing as before.

Pictures of reference objects (needles) having known dimensions were used to correlate measurements on the monitor of ligaments and drop sizes as well as drop velocities (from double-pulse exposures) to real dimensions. Drops generally were spherical and could be represented by an average diameter. Experimental uncertainties for drop diameters larger than 0.010 mm were less than 10%, increasing inversely to the drop diameter for smaller sized drops.

Test Conditions

The test conditions were varied by considering three different liquids, water, ethyl alcohol and glycerol, ejecting through round injector exit passages having 0.5 and 1.0 mm diameters for liquid jet velocities of 17-54 m/s based on no aerating gas flow (GLR=0). Properties of each test liquid were measured before the experiments were conducted. Liquid densities were measured using a hydrometer having an accuracy of 0.5 kg/cu-m. Cannon/Fenske viscometers were used to measure liquid viscosities with an uncertainty of less than 0.3%. The liquid surface tension in air was measured using a ring tensiometer which has an accuracy of 5E-04 N/m.

The freestream total pressure was 0.21 Mpa and the gas/liquid mass flow ratio was varied in the range GLR=0-10%. The liquid/air momentum flux ratio was found from the liquid flow rate and the diameter of the nozzle orifice under the assumption that no gas was present inside the nozzle, i.e. GLR=0, throughout the experiments. According to this definition, the momentum flux ratio was in the range q=1-15 during the present investigation. It should be noted, however, that the actual momentum flux ratio for the aerated jet is larger due to the reduced effective nozzle area for the liquid, which is caused by the presence of the gas phase inside the nozzle. For a given liquid flow rate, the presence of the internal gas phase therefore has the effect of increasing liquid velocities.

RESULTS AND DISCUSSION

Spray Visualization

For present conditions with GLR=0, visualization of the spray near the exit of the injector showed that breakup was similar to the breakup of round nonturbulent liquid jets in gas crossflows as reported by Sallam et al. [13]. In this case, the aerodynamic force of the freestream air, along with instabilities along the liquid column, breaks the column into ligaments and drops on its downwind side. For GLR ≥ 2%, however, the liquid forms an annular flow inside the injector exit passage and the corresponding annular sheet expands to a conical shape immediately upon leaving the injector exit passage. This expansion is caused by the internal gas phase flow which is choked and underexpanded at the injector exit. With increasing vertical distance from the nozzle exit, the outer dimension of the liquid cone expands to more than 3 times the initial jet diameter before aerodynamic forces of the crossflow turn the upstream side of the cone upwards toward the vertical direction and later toward the crossflow direction. Unlike the pure-liquid jet, which shows ligament and drop formation only on the downstream side of the jet, the aerated-liquid jet displays primary breakup at the liquid surface even on its upstream side, suggesting considerable influence of the internal underexpanded gas jet on the primary breakup mechanism of the liquid sheet. As the aeration level is further increased, the cone angle near the nozzle increases. As a result, effects of the crossflow are further reduced and the area penetrated by the spray increases. Larger aeration levels also enhance the primary breakup at the liquid surface both on the upstream and the downstream sides of the jet.

Properties of the Liquid Sheet

The angles of the conical liquid sheet on its upwind and downwind sides, relative to the initial axis of the spray, are approximately equal for GLR ≥ 2%. The progressive increase of these angles with increasing GLR, and thus increasing degrees of underexpansion of the choked gas flow at the jet exit, is predicted very well by the theoretical Prandtl-Meyer expansion angle that is driven by the static pressure difference between the crossflowing ambient air and the underexpanded gas at the exit of the injector passage.

Velocities of the liquid sheet were relatively independent of distance from the injector exit. In addition, these velocities were in good agreement with predictions assuming a static pressure drop in the injector exit passage from its inlet pressure to the static pressure of the sonic flow at the passage exit, combined with a velocity coefficient of 0.84. Given this velocity, the thickness of the liquid sheet at the nozzle exit could be estimated.

Analogous to the breakup of round pure-liquid jets, aerated-liquid jets disintegrate into drop-like segments at the end of the liquid core. These drops subsequently are subject to secondary drop breakup. Locations of the completion of the primary breakup process in the direction of the liquid jet flow were measured from the present experiments and normalized by the characteristic liquid breakup time due to Ranger and Nicholls [14]. For the present measurements, the dimension of the liquid phase was taken to be the hydraulic diameter of the initial liquid sheet, whereas the velocity and density of the gas phase corresponded to the condition of the crossflowing freestream behind a normal shock wave. For pure-liquid jets (GLR=0%), the present results for breakup times of liquid columns in supersonic crossflows are in excellent agreement with the measurements of Sallam et al. [13] for the breakup times of round nonturbulent liquid jets in subsonic crossflows. When the round liquid jets are aerated by injecting gas into the liquid flow prior to the nozzle exit orifice, however, breakup times of the liquid core undergo a transition to roughly twice as long a breakup time as a pure liquid jet for GLR at or above 2%. These results suggest that the effect of the crossflow on the primary breakup of aerated liquid jets in the annular flow regime is somewhat reduced as compared to the primary breakup of round pure-liquid jets. Full understanding of the breakup of aerated liquid jets, however, requires further study of the effect of the internal underexpanded gas jet on the surrounding liquid sheet.

Structure of the Dense Spray

Ligament diameters, and drop diameters after breakup of ligaments, were measured along the surface of the liquid sheet for GLR $\geq$ 2%. Remarkably, for the entire test range of the present investigation, ligament diameters had an average of 0.029 mm whereas the SMD of the drops was 0.041 mm. Thus the drop/ligament diameter ratio was 1.9 which is typical of expectations if drop formation occurs by Rayleigh breakup at the end of ligaments [13]. The findings concerning drop SMD are in excellent agreement with observations of Kim and Lee [12] who found that drop SMD approached 0.040 mm as GLR reached values larger than 2%. Finally, present measurements indicated that drop size distributions satisfied the university root normal distribution with the ratio of the mass median diameter, MMD, to the SMD equal to 1.07 which suggests a nearly monodisperse drop size distribution.

CONCLUSIONS

Major conclusions of the study were as follows:

1. Cone angles and surface breakup properties along both the upstream and downstream sides of the jet suggest weak aerodynamic effects due to the crossflow near the jet exit.
2. The average discharge velocity of the liquid sheet is related to the difference between the liquid stagnation pressure and the static pressure of the choked gas flow inside the nozzle orifice.
3. Breakup times of aerated liquid jets (the liquid sheet) can be correlated with a constant normalized breakup time, analogous to, but somewhat larger than, the primary breakup time of a pure-liquid jet in a subsonic crossflow.
4. Ligament and drop sizes after primary breakup are relatively constant and independent of the final jet exit passage diameter, aeration level (GLR), liquid/gas momentum flux and the liquid properties considered during the present investigation. The average drop diameter was 40 μm.
5. Drop size distributions in the dense spray region (the universal region) near the liquid surface satisfied root-normal distribution function, with MMD/SMD=1.07

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