PRIMARY BREAKUP OF NONTURBULENT ROUND LIQUID JETS IN UNIFORM GASEOUS CROSSFLOWS

K.A. Sallam*, C.Aalburg°, G.M. Faeth°

*Oklahoma State University, Stillwater, Oklahoma, USA
°University of Michigan, Ann Arbor, Michigan, USA

ABSTRACT

An experimental investigation of the primary breakup of round nonturbulent round liquid jets in gaseous crossflows is described. Pulsed shadowgraph and holograph observations of primary breakup regimes, conditions required for the onset of ligament and drop formation, ligament and drop sizes along the liquid surface, drop velocities after breakup, rates of liquid breakup between the onset of drop formation and breakup of the liquid column as a whole, conditions required for the breakup of the liquid column as a whole, and liquid column trajectories were measured for subsonic air crossflows at normal temperature and pressure. The results suggest qualitative similarities between the primary breakup of nonturbulent round liquid jets in gaseous crossflows and the secondary breakup of drops subjected to shock wave disturbances. Phenomenological analyses were effective to help interpret and correlate the new measurements of the primary breakup properties of nonturbulent round liquid jets in gaseous crossflows.

INTRODUCTION

The deformation and primary breakup properties of round nonturbulent liquid jets in gaseous crossflows were studied experimentally, motivated by applications to spray breakup in crossflows in air-breathing propulsion systems, liquid rocket engines, diesel engines, and agricultural sprays, among others. The objective was to extend recent shadowgraph measurements of Mazallon et al. [1] and Wu et al. [2] of some properties of this liquid breakup process to exploit the capabilities of pulsed holography to penetrate dense sprays and observe the detailed properties of both the liquid surface and the primary breakup process at the liquid surface.

Earlier studies of the primary breakup of round nonturbulent liquid jets in gaseous crossflows were recently reviewed by Wu et al. [2]; therefore, the following discussion of past work will be brief. Initial studies of round nonturbulent liquid jets in gaseous crossflows mainly concentrated on lengths of penetration of the liquid jet into the crossflow and the trajectories of the liquid column for various flow conditions [3-14]. Additional details about the properties of round nonturbulent liquid jets in gaseous crossflows were recently obtained by Mazallon et al. [1] and Wu et al. [2], and references cited therein, using pulsed shadowgraphy. These studies reported similarities between the primary breakup regimes of round nonturbulent liquid jets in gaseous crossflows and the secondary breakup of drops due to shock wave disturbances. In particular, both studies observed bag, multimode and shear breakup regimes along the liquid column in crossflow that were qualitatively similar to secondary drop breakup regimes having the same names. Other properties of round nonturbulent liquid column breakup in gaseous crossflows that were observed using pulsed shadowgraphy during these studies were as follows: wavelengths of liquid surface waves along the liquid column, the deformation of the liquid column prior to the onset of breakup along the liquid surface, the conditions for the onset of drop formation along the liquid surface, and the trajectory of the liquid column as it deflects due to crossflow.

The objectives of the present investigation were to extend the studies of Mazallon et al. [1] and Wu et al. [2], using the capabilities pulsed holography to penetrate the dense spray region and observe the liquid breakup process near the surface of the liquid jet. Observations of Mazallon et al. [1] and Wu et al. [2], of conditions for breakup regime transitions, of wavelengths of liquid surface waves along the liquid surface, of the deformation of the liquid column prior to the onset of breakup along the liquid surface, and of the trajectory of the liquid column as it deflects in the crossflow were revisited. In addition, breakup properties at the liquid surface were also observed, as follows: the properties of the liquid surface (surface velocities, the onset of ligament formation and ligament properties), the properties of liquid drops formed by primary breakup along the liquid surface (the onset of drop formation, drop sizes and velocities after primary breakup and rates of drop formation along the liquid surface), and conditions required for the breakup of the liquid jet as a whole (ending the primary breakup process). Finally, phenomenological analyses were used to help interpret the results and correlate the measurements for use by others.

EXPERIMENTAL METHODS

Apparatus

Observations of liquid breakup along the surface of the liquid jet were carried out using a shock tube apparatus, whereas measurements of the length of the liquid column in the liquid column breakup regime were carried out using a subsonic wind tunnel. The shock tube had a rectangular cross section with a width of 38 mm and a height of 64 mm. The driven section of the shock tube was open to the atmosphere and had windowed side walls in order to provide optical access. The shock tube was sized to provide test times of 17-21 ms in the uniform subsonic flow region behind the shock wave. Crossflow velocities in air of 11-142 m/s were considered for normal temperature and pressure conditions in the crossflow.

The shock tube apparatus did not provide a large enough cross section to observe breakup of the entire liquid column in the liquid column breakup regime for crossflow at normal temperature and pressure conditions; therefore, observation of these properties were carried out in a subsonic wind tunnel having a cross section of 610×610 mm. The wind tunnel had windowed side walls to provide optical access with air crossflow having velocities of 5-15 m/s at normal temperature and pressure.

The nonturbulent round liquid jets were injected vertically downward using a pressure feed system for both the shock tube and wind tunnel arrangements. Round supercavitating nozzles were used to create the round nonturbulent liquid jets; these nozzles had sharp-edged inlets and exits with length-to-diameter ratios smaller than 3. This arrangement yielded uniform nonturbulent round liquid jets as discussed by Wu et al. [15] and Lienhard [16]. Actual liquid diameters at the jet exit were found from shadowgraphs with an experimental uncertainty (95% confidence) less than 10%; these diameters were only 50-70% of the geometrical nozzle exit diameters as discussed by Lienhard [16].

Both test apparatus were evaluated to assure temporally steady crossflows and injector flows, and uniform velocity crossflows. All these requirements of the experiments were satisfied.

Instrumentation

Pulsed shadowgraphy and holography were used for the shock tube experiments to observe the properties of the round liquid jets and the ligaments and drops produced by primary breakup as a function of position along the liquid jet and crossflow conditions. Both measurements used two frequency doubled YAG lasers (Spectra Physics Model GCR-130, 532 nm wavelength, 7 ns pulse duration, and up to 300 mJ optical energy per pulse) that could be fired with pulse separations as small as 100 ns. An off-axis holocamera arrangement was used that provided a 25 mm diameter field of view at the test liquid column location. Reconstruction of the double pulse holograms yielded two images of the flow so that liquid surface and drop velocities could be found given the time of separation of the laser pulses (which was measured using a digital oscilloscope). The same arrangement provided shadowgraph images simply by blocking the reference beam. The hologram reconstruction system was used to analyze the hologram images from the shock tube. The combined holocamera/reconstruction system allowed objects as small as 3000 nm to be seen and the size of objects as small as 10000 nm to be measured with 10% accuracy. The reconstruction system was also used to measure flow properties from shadowgraph photographs with similar accuracy.

Drop sizes and velocities and ligament and liquid surface properties were found similar to past work. Drops generally were spherical and could be represented by an average diameter; ligaments were roughly cylindrical and could also be represented by an average diameter. Drop velocities were found from simple arithmetic averages (because drop velocity distributions were nearly uniform) with experimental uncertainties (95% confidence) less than 10%. Finally, liquid column properties observed using the wind tunnel facility were obtained from single pulse shadowgraphs.

Test Conditions

Test conditions were varied by considering four different liquids (water, ethyl alcohol and glycerol (79 and 84% glycerin by mass), injector passage diameters of 0.5, 1.0 and 2.0 mm, liquid jet velocities of 7-45 m/s and air crossflow velocities of 6-142 m/s at normal temperature and pressure. This yielded the following ranges of test variables: liquid/gas density ratios of 683-1033; actual liquid jet exit diameters, d_j, of 0.34-1.7 mm; liquid jet Reynolds numbers, Re, of 500-59000; crossflow Weber numbers, We, of 0.5-260; liquid/gas momentum flux ratios, q, of 3-450; and liquid jet Ohnesorge numbers, Oh, of 0.003-0.29. Crossflow Mach numbers were smaller than 0.1; therefore, compressibility effects were negligible.

RESULTS AND DISCUSSION

Flow Visualization

First, of all, in the absence of crossflow, We=0, the liquid jet had a round smooth surface with no initiation of surface disturbances or atomization, even though liquid jet Reynolds numbers were large, Re > 10000. This behavior was similar to past observations of supercavitating injectors designed similar to the present arrangement, see Wu et al. [15] and Lienhard [16].

For present conditions, where effects of liquid viscosity were small (Oh ≤ 0.3), four regimes of primary breakup of the liquid jets were observed for fixed liquid jet exit conditions as the crossflow velocity (characterized by the crossflow Weber number, We) was increased, as follows: column breakup, bag breakup, multimode (or bag/shear) breakup, and shear breakup. Transition crossflow We to these breakup regimes were independent of the Ohnesorge number for the present small Ohnesorge number conditions. See Mazallon et al. [1] for shadowgraphs of the appearance of these breakup regimes. For small crossflow velocities, We ≤ 4, the process was in the column breakup regime where the liquid jet is deflected in the cross stream direction and breaks up into large drops. As crossflow velocities increase, the next primary breakup regime that is observed is bag breakup for We = 4-30; this type of breakup looks very similar to the familiar bag breakup regime seen for secondary breakup of drops. Shifting to the largest gross flow velocities considered during the investigation, the shear breakup regime is observed for We > 110. This regime is also similar to shear breakup of drops and involves the formation of ligaments from the periphery of the liquid column with drops formed at the tips of ligaments along the downstream side of the liquid column. Finally, for We in the range 30-100, there is a regime that involves characteristics of both bag and shear breakup, which is called the multimode breakup regime. This regime is also observed for secondary drop breakup.

Primary Breakup Regimes

Exploiting the similarities between the primary breakup regimes of round nonturbulent liquid jets in crossflow, and the secondary breakup of drops subjected to shock wave disturbances, the breakup regimes of round nonturbulent liquid jets in crossflow were correlated in terms of crossflow Weber and Ohnesorge numbers, as first proposed by Hinze [17] for the secondary breakup of drops exposed to shock wave disturbances at large liquid/gas density ratio conditions similar to present observations. The present breakup regime map was generally in agreement with earlier observations of Mazallon et al. [1], except for the onset of multimode breakup which is difficult to identify. This map was also qualitatively in agreement with similar maps for the secondary breakup of drops exposed to shock wave disturbances as proposed by Hinze [17].

Liquid Surface Waves

The properties of peripheral waves that formed along the liquid surface were studied finding results similar to Mazallon et al. [1]. Column breakup was observed when wavelength/column-diameter ratio, L/d > 1, bag breakup involved L/d ≈ 1, shear breakup involved L/d < 0.1 and multimode breakup involved L/d in the range 0.1-1.0.

Liquid Surface Velocities

Liquid surface velocities were found by measuring the motion of small disturbances on the surface of the liquid jet using double-pulse shadowgraphs. It was found that the streamwise velocity remained equal to the jet exit velocity for the length of the jet. Cross stream velocities of the liquid around the periphery of the jet were comparable to the characteristic liquid velocity of Ranger and Nicholls [18] for the secondary breakup of drops.

Onset of Breakup

Measurements of the onset of breakup was limited to the shear breakup regime. A successful correlation for onset of breakup along the liquid surface was obtained by equating the momentum of the viscous liquid layer flowing along the periphery of the liquid jet to the surface tension force that must be overcome to form a ligament having a given diameter. This results in a simple expression where the ratio of the ligament/liquid-jet diameter was inversely proportional to the cross stream Weber number. These results also showed that there were two regimes of drop formation along the liquid surface, one where initial drop sizes increased with distance along the liquid jet as the thickness of the shear layer grows by viscous action from the crossflow, and a fully developed regime where the viscous layer is a fixed fraction of the liquid jet diameter. The measurements then showed that the ratio of drop/ligament diameters at onset was a constant, indicating drop formation was by Rayleigh breakup. Extending these results yielded a good correlation for onset of drop formation along the jet.

Ligament and Drop Sizes Along the Liquid Surface

In order to consider ligament and drop sizes along the liquid surface, times required to reach specific distances along the liquid surface were found from the convection approximation. A second limitation was to consider ligament and drop formation only in the shear breakup regime as opposed to the more complex bag and multimode breakup regimes; fortunately, shear breakup tends to dominate practical applications. Finally, velocities associated with the formation of ligaments were assumed to be from the shear layer as given by the shear layer approximation. Then, similar to observations concerning the onset of ligament formation, the variation of ligament size along the surface was assumed to involve a transient regime where the thickness of the shear layer grows as a function of distance, and a quasi-steady regime where the shear layer thickness becomes a fixed fraction of the liquid jet diameter which in turn is taken to be proportional to the initial liquid jet diameter. This approach gave an excellent correlation of the variation (increase) of ligament diameter as a function of distance along the liquid surface. This information was readily converted to the variation of drop diameter as a function of distance along the surface, after noting the drop formation occurred by Rayleigh breakup of ligaments, as before.

Drop Velocity Properties

Drop velocities after breakup were measured and successfully correlated. Streamwise drop velocities were found to be proportional to the streamwise jet velocity whereas cross stream drop velocities were found to be proportional to the Ranger and Nicholls [18] characteristic liquid velocity in the cross stream direction.

Liquid Column Breakup

Breakup of the liquid column as a whole was measured and successfully correlated. The correlation was found by analogy to the secondary breakup of drops as a function of time, assuming that sections of the liquid jet do not interact. The present measurements yielded the ratio of the time of breakup, TB, to the Ranger and Nicholls [18] crossflow characteristic time, TC, as follows: TB/TC = 2.6. This is comparable but somewhat smaller than TB/TC = 6.0 for the secondary breakup of drops.

Liquid Breakup Rates

The flux of liquid drops relative to the liquid surface was measured as a function of distance along the liquid column. These results were correlated in terms of a liquid surface breakup efficiency factor defined as the actual flux of drops relative to the projected cross-sectional area, MA, of the liquid jet normal to the crossflow direction to the theoretical maximum liquid flux, MT, in the crossflow direction assuming drops were formed uniformly over the projected area and moved away at the crossflow drop velocity, i.e., E = MA/MT. The measurements indicated that E was very small at the onset of drop formation and reached values on the order of unity where breakup of the liquid column as a whole occurred.

Liquid Column Trajectories

Liquid column trajectories were measured and successfully correlated based on phenomenological analysis.

CONCLUSIONS

The major conclusions of the study were as follows:

1) There is a useful general analogy between the primary breakup of round nonturbulent liquid jets in crossflow and the secondary breakup of drops subjected to shock wave disturbances which suggests modest streamwise interactions of the liquid jets, e.g., liquid breakup properties were not strongly affected by the liquid/gas momentum ratio for values smaller than 8000, which was the largest value considered during the present and earlier investigations.
2) Transitions between the various breakup regimes are not influenced significantly by liquid viscosities for $Oh < 0.3$ and by liquid jet exit velocities for $q < 8000$. Transitions to bag, multimode and shear breakup occurred at $We = 4$, 30 and 110 which were in reasonably good agreement with earlier results for round nonturbulent liquid jets in crossflow from Mazallon et al. [1]
3) There were two regimes for both the onset of ligament formation along the liquid surface and for the variation of ligament diameter as a function of distance along the liquid surface: (i) an initial transient regime associated with the growth of a shear layer near the liquid surface which supplies liquid to the base of ligaments, and (ii) a quasi-steady regime where the shear layer reaches its maximum possible growth within the confines of the round liquid jet and has a thickness that is a fixed fraction of the liquid jet diameter.
4) In both regimes of ligament growth, drops formed at the tips of ligaments were a fixed multiple of the ligament diameter; thus, this behavior generally supports drop formation at the tips of ligaments by the classical Rayleigh breakup mechanism.
5) Drop velocity distributions after breakup were relatively independent of drop size and approximated the liquid jet velocity in the streamwise direction but were somewhat larger than the characteristic liquid-phase velocity in the cross stream direction due to drag on the drops by the crossflowing gas as the drops are formed.
6) Breakup of the liquid column as a whole in the bag, multimode and shear breakup regimes approximated the total times of breakup of drops subjected to shock wave disturbances in the bag, multimode and shear breakup regimes, yielding $TB/TC = 2.5$.
7) The mean drop mass flux over the downstream projected area of the liquid column due to nonturbulent primary breakup at the liquid surface could be correlated by the dimensionless length along the liquid column. Quite plausibly, the surface efficiency factor was small near the onset of drop formation due to nonturbulent primary breakup but reached values on the order of unity as the end of the liquid jet was approached.

Acknowledgments

This research was sponsored by the Air Force Office of Scientific Research, Grant Nos. F49620-99-1-0083 and F49620-02-1-0007, under the technical management of J.M. Tishkoff. The assistance of R. Jolly and D. Ma under the Undergraduate Research Opportunity Program (UROP) of the University of Michigan is gratefully acknowledged. The U.S. Government is authorized to make copies of this article for governmental purposes notwithstanding any copyright notation thereon.

REFERENCES

1. J. Mazallon, Z. Dai and G.M. Faeth, Primary Breakup of Nonturbulent Round Liquid Jets in Gas Crossflows, *Atom. Sprays*, vol. 9, pp. 291-311, 1999.
2. P.-K. Wu, K.A. Kirkendall, R.P. Fuller and A.S. Nejad, Breakup Processes of Liquid Jets in Subsonic Crossflows, *J. Prop. Power*,vol. 13, pp. 64-73, 1997.
3. E.L. Geary and M.J. Margettes, Penetration of a High Velocity Gas Stream by a Water Jet, *J. Spacecraft*, vol. 6, pp. 79-81, 1969.
4. P.R. Reichenbach and K.P. Horn, Investigation of Injectant Properties in Jet Penetration in a Supersonic Stream, *AIAA J.*, vol. 9, pp. 469-471, 1971.
5, E.A. Kush and J.A. Schetz, Liquid Jet Injection into a Supersonic Flow, *AIAA J.*, vol. 11, pp. 1223-1224, 1979.
6. JA. Schetz and A. Paddye, Penetration of a Liquid Jet in Subsonic Airstreams, *AIAA J.* vol. 15, pp. 1385-1390, 1977.
7. J.A. Schetz, E.A. Kush and P.B. Joshi, Wave Phenomena in Liquid Jet Breakup in a Supersonic Crossflow, *AIAA J.*, vol. 15, pp. 774-778, 1979.
8. A.S.Nejad and JA. Schetz, Effects of Properties and Locations in the Plume or Droplet Diameter for Injection in a Supersonic Stream, *AIAA J.*, vol. 21, pp. 956-961, 1983.

9. A.S.Nejad and J.A. Schetz, Effects of Viscosity and Surface Tension on a Jet Plume in Supersonic Cross-Flow, *AIAA J.*, vol. 22, pp. 458-459, 1984.
10. D.M. Less and J.A. Schetz, Transient Behavior of Liquid Jets Injected Normal to a High-Velocity Gas Stream, *AIAA J.*, vol. 24, pp. 1979-1985, 1986.
11. Y. Kitamura and T. Takahashi, Stability of a Liquid Jet in Air Flow Normal to the Jet Axis, *J. Chem. Engr. Japan*, vol. 9, pp. 282-286, 1976.
12. T.T. Nguyen and A.R. Karagozian, Liquid Fuel Jet in a Subsonic Crossflow, *J. Prop. Power*, vol. 8, pp. 21-29, 1992.
13. A.R. Karagozian, An Analytical Model for the Vorticity Associated with a Transverse Jet, *AIAA J.*, vol. 24, pp. 429-436, 1986.
14. F.J. Higuera and M. Martinez, An Incompressible Jet in a Weak Crossflow, *J. Fluid Mech.*, vol. 249, pp. 73-97, 1993.
15. P.-K. Wu, R.F. Miranda and G.M. Faeth, Effects of Initial Flow Conditions on Primary Breakup of Nonturbulent and Turbulent Round Liquid Jets, *Atom. Sprays*, vol. 5, pp. 175-196, 1995.
16. J.H. Lienhard, Velocity Coefficients for Free Jets from Sharp-Edged Orifices, *J. Fluids Engr.*, vol. 106, pp. 13-17, 1984.
17. J.O. Hinze, Fundamentals of the Hydrodynamic Mechanism of Splitting in Dispersion Processes, *AIChE J.*, vol. 1, pp. 289-295, 1955.
18. A.A. Ranger and J.A. Nicholls, The Aerodynamic Shattering of Liquid Drops, *AIAA J.*, vol. 7, pp. 285-290, 1969.