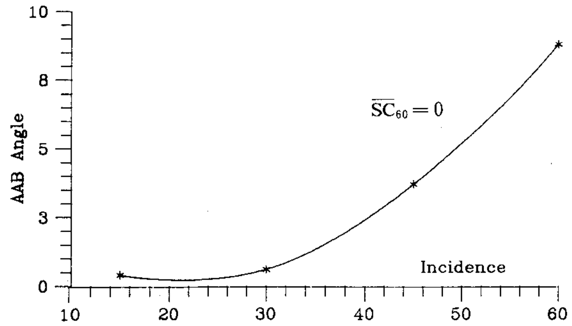

Fig. 3 Relationship between incidence and optimized AAB angle.

mounted near the diffuser entry. This blade could revolve freely around an axis 20 mm behind the leading edge. Installation of the AAB appears to create two inlets. The measurements consisted of static pressure taps along the model walls, measurements of the crossflow velocities and the total pressures at the duct exit at 0-, 5-, 10-, 15-, 30-, 45-, and 60-deg incidences and comparisons with those of no AAB. Details about data processing are described in Ref. 4.

Results and Discussion

The tests in a diffusing S-duct model with the AAB installed showed that the automatically rotating blade experiences no resultant aerodynamic moment at AAB angles of 15 and −12 deg. This physical phenomenon is caused by the bulk vortex because of the flow separation near the inlet and the influence of the blade. Moreover, the swirls at the duct exit have different senses of rotation when the blade is held at these two different angles. The result implies that the large swirl could be reduced only if the AAB is mounted at an angle between these two values.

To find the optimized AAB angle that produces zero swirl, experiments were made at 2.5-deg steps between these two angles. Figures 1 shows that the exit swirl varies with the AAB angle at 60-deg incidence. It is well known that without the AAB the swirl rotates clockwise because of the bulk vortex caused by a large separated flow region near the bottom lip. The results show that the swirl has changed its rotation from clockwise to counterclockwise with increasing AAB angle. The presence of the AAB affects the pressure distribution near the entry, and the bulk swirl could be reduced to the point of elmination at about 7.5-deg AAB angle.

The results also show the static pressure distributions along the model walls at 7.5-deg AAB angle with 60-deg incidence and compared with those of no AAB. It is obvious that both of them are quite similar and that the presence of the AAB does not influence the pressure distribution along the walls. Figures 2 show total pressure coefficient maps at the exit of the curved duct. Clearly, because of the large separated flow near the inlet and the bulk swirl, there is a severely distorted total pressure field at the exit of 60-deg incidence (see Fig. 2a). The low-energy flow region with the lower C_p^* value moves clockwise from the bottom lip at the inlet to the inside wall under the effect of the swirl. The presence of the AAB does not substantially affect this distorted total pressure field, although there is a small drop in the C_p^* value, as shown in Fig. 2b. If this pressure loss is acceptable, the AAB method is an effective means of swirl control in aircraft inlet design.

Figure 3 shows that the relation between the incidence and the optimized AAB angle at which the swirl disappears is nearly an exponential function of the incidence. Hence, the optimized AAB angles for zero swirl coefficient can be determined at any incidence, which may be helpful for aircraft inlet design.

Conclusions

In this Note, a new approach of swirl control in an S-shaped diffuser, called the AAB method, is presented. Several conclusions could be drawn as follows.

1) Two angular positions have been found where the AAB experiences no resultant aerodynamic moment, i.e., 15 and −12 deg.

2) The optimized AAB angle is found between these two positions.

3) The swirl at the duct exit (i.e., the engine face position) can be reduced or eliminated by the AAB method. The relationship between the incidence and the optimized AAB angle at which swirl disappears has been established.

4) The AAB method offers an effective swirl control approach at the expense of an acceptable total pressure loss.

References

[1]Guo, R. W., and Seddon, J., "The Swirl in an S-Duct of Typical Air Intake Proportions," *Aeronautical Quarterly,* Vol. 32, Pt. 2, May 1983, pp. 99–129.

[2]Guo, R. W., and Seddon, J., "Swirl Characteristics of an S-Shaped Air Intake with both Horizontal and Vertical Offsets," *Aeronautical Quarterly,* Vol. 32, Pt. 2, May 1983, pp. 130–146.

[3]Stocks, C. P., and Bussiger, N. C., "The Design and the Development of the Tornado Engine Air Intake," *AGARD Symposium on Aerodynamics of Power Plant Installation,* Paper 10, May 1981.

[4]Weng, P. F., and Guo, R. W., "A New Approach to Swirl Control in an S-Duct," *Proceedings of the First China-USSR Seminar on Aeroengines,* edited by H. Taiping, Nanging Aeronautical Inst., Nanging, PRC, April 1991, pp. 5–10.

[5]Seddon, J., "Understanding and Countering the Swirl in an S-Duct, Testing on the Sensitivity of Swirl to Fence," *Aeronautical Journal,* Vol. 88, No. 874, 1984, pp. 117–127.

[6]Vakili, A. D., Wu, J. M., Liver, P., and Brat, M. K., "Flow Control in a Diffusing S-Duct," AIAA Paper 85-0524, March 1985.

[7]Lin, Q., and Guo, R. W., "Vortex Control Investigation of Swirl in S-Shaped Diffuser," *Astronautica Sinica,* Vol. 10, No. 1, 1989, pp. 35–40.

Breakup of a Liquid Jet in Supersonic Crossflow

H.-S. Li* and A. R. Karagozian†

University of California, Los Angeles,
Los Angeles, California 90024

I. Introduction

CONSIDERABLE attention has been given to the physical process of transverse liquid jet breakup and its role in the control of the rate and/or completeness of combustion.[1-4] The jet-breakup location divides the combustion process into two fundamental stages (see, for example, Fig. 1). Before breakup, the transverse liquid fuel jet evaporates and reacts with the oxidizer in the gas-phase boundary layer at the surface of a coherent, curved liquid column. After breakup, the liquid fuel droplets interact with the gas stream (and, under some circumstances, each other), and burn either as individual particles or as droplet clusters.[5] Thus, the determination of jet-breakup location is a first step in the overall understanding of combustion in the transverse liquid fuel jet.

Schetz et al.[1] first observed that the local sonic point associated with a sharp wave crest is a rather good indicator for the beginning of jet breakup. The liquid jet column fractures shortly behind the local sonic point, where the jet body has

Presented as Paper 91-0689 at the AIAA 29th Aerospace Sciences Meeting, Reno, NV, Jan. 7–10, 1991; received June 26, 1991; revision received Nov. 13, 1991; accepted for publication Nov. 14, 1991.

*Graduate Research Assistant, Department of Mechanical, Aerospace, and Nuclear Engineering.

†Associate Professor, Department of Mechanical, Aerospace, and Nuclear Engineering. Member AIAA.

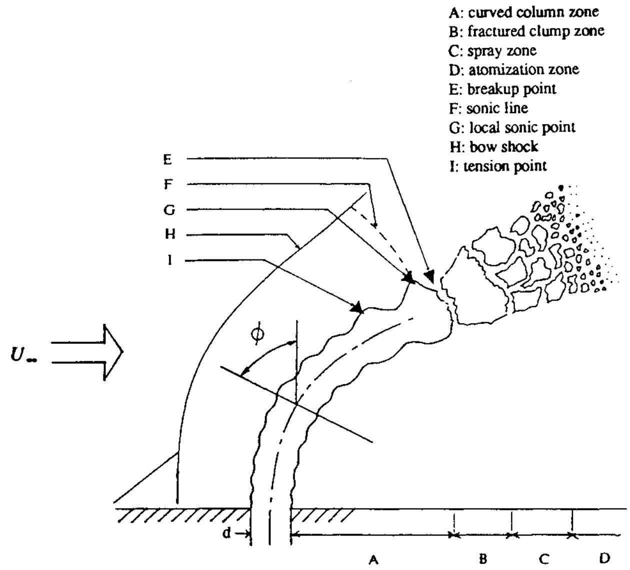

Fig. 1 Schematic of transverse liquid jet-breakup processes.

turned some 25-30 deg from the initial vertical. Another criterion for jet breakup has been proposed which deals with the effects of surface tension and aerodynamic forces[2-4] along the jet. Clark's[2] experimental study of liquid jets in subsonic crossflow reveals that although the surface tension at the liquid interface tends initially to restore the liquid to its original cross-sectional shape, in the later stages of the breakup process, it actually assists the aerodynamic forces in the process of jet disintegration. Other studies[3,4] explore the balance between the effects of viscosity and surface tension as a contribution to transverse liquid jet breakup. We explore both ideas here as alternative breakup criteria.

II. Prediction of Jet Breakup

The model used in the present calculations is described in detail in Heister et al.[6] for the nonreacting liquid jet in supersonic crossflow. In this study, the jet trajectory and the external flow structure (bow shock) are predicted and compared with experimental data. The primary assumption employed is that the jet behavior may be determined by examining the dynamics of locally two-dimensional slices of the liquid jet, taken perpendicular to its centerline. Slices of the liquid jet are represented by the elliptical cross section of a vortex pair recirculation cell, consistent with experimental observations[7] of a kidney-shaped jet cross section. For supersonic crossflow, a locally two-dimensional shock wave dominates the airflow about the jet cross section. In taking a slice of the transverse liquid fuel jet, the external flow approaches the jet at a local Mach number $M_n = M_\infty \sin(\phi)$, where M_∞ is the freestream Mach number and ϕ is the inclination angle of the jet slice (see Fig. 1). Numerical simulation of the flow about the elliptical cross section (after Godunov et al.[8]) allows evaluation of the pressure distribution, velocity distribution, and the bow shock shape about the cross section.[6] Incorporation of this information into mass and momentum balances along the jet then allows estimation of the global gas properties for the entire (three-dimensional) flowfield.

A. Sonic Point Criterion

In attempting to provide a reliable prediction for the breakup location in supersonic crossflow, we first consider the simple criterion that the liquid jet column fractures shortly behind the local sonic point.[1] This criterion concerns only the properties of the inviscid external gas flow, and does not deal directly with complicated wave phenomena and surface instabilities in the liquid flowfield. Consistent with the observations of Schetz et al.,[1] the axial velocity component to be used in the sonic point calculation is that in the vicinity of the stagnation region of the jet trajectory. Because the component of velocity tangential to the bow shock (in the plane of the jet) is conserved, it is reasonable to approximate the local axial velocity of the gas just outside the jet as $v = U_\infty \cos\phi$. Experiments also indicate that the bow shock and jet trajectory are roughly parallel for crossflow Mach numbers $M_\infty > 2$. Using this approach, we then compute the resultant Mach number in each grid cell along the jet by coupling the solution of the jet orientation to the numerical compressible flow solution.

Figures 2a and 2b show the location of the local sonic point on the liquid fuel jet, as an indication of the breakup location, at different values of freestream Mach number M_∞ and jet-to-crossflow momentum flux ratio $R^2 \equiv \rho_j U_j^2/\rho_\infty U_\infty^2$. The sonic point on the liquid jet occurs further downstream with increasing momentum flux ratio and decreasing freestream Mach number. These correlations agree with previous investigators' observations,[1,9] particularly in that the breakup occurs at roughly ten jet diameters downstream of injection for typical flow conditions, as shown in Fig. 2b. This correspondence with experimental observation is indicated further by computing the local angle ϕ corresponding to the sonic point as a function of M_∞, shown in Fig. 3. The angle ϕ corresponding to the sonic point ranges from about 50 deg (for $M_\infty = 1.5$) to about 75 deg (for $M_\infty = 3.5$), which is consistent with experimental observations that breakup occurs in the flow regime studies when ϕ is roughly 60-65 deg.[1]

B. Stress Balance/Tension Point Criterion

The importance of the balance of stresses to the jet-breakup process can be examined as an alternative criterion to determine the breakup location. Some experimental studies [2-4] indi-

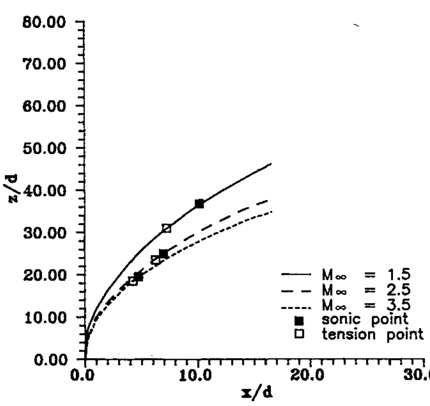

Fig. 2a Computed local sonic point and "tension point" on the liquid jet trajectory for $R^2 = 5$. Trajectory coordinates are x (downstream distance measured from jet orifice) and z (distance from injection wall).

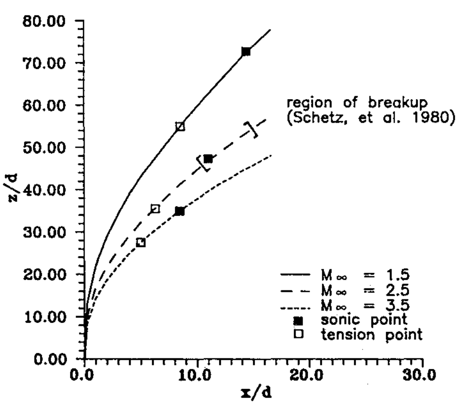

Fig. 2b Computed local sonic point and "tension point" on the liquid jet for $R^2 = 8$. Trajectory coordinates are x (downstream distance measured from jet orifice) and z (distance from injection wall).

cate that the breakup of a transverse liquid jet can be deduced from a consideration of the internal and external forces acting at the liquid interface. The tangential component of stress, in particular, becomes very large further downstream of the injection point. Hence as a zeroth-order estimate, the location where the aerodynamic forces due to shear stress and the surface tension are of the same order can be used as a criterion for determining the breakup location.[3,4]

In the present model, axial shear stresses at the liquid-gas interface along the jet trajectory are evaluated at the jet's local stagnation point, where the stresses are the most severe. This calculation requires solution of the local gas- and liquid-phase velocity profiles simultaneously along the jet trajectory. In view of solving for the axial shear stresses at the interface, this mathematical model serves well in simplifying the vector space and reasonably reproducing the most severe conditions for shear-stress distribution.

The two-dimensional, steady momentum equations describing flow in the liquid- and gas-phase boundary layers in the axial direction are first nondimensionalized with respect to the initial liquid velocity at the injection point and the semiminor axis of the elliptical jet cross section. The pressure distribution at the stagnation point along the jet trajectory is derived from shock dynamics[10] and can be written as

$$p = p_\infty (1 + 0.2M^2)^{3.5} (1.167M^2 - 0.167)^{-2.5} [(1/1.2M^2) + 0.167]^{-3.5}$$

where the local effective Mach number upstream of the bow shock, M, is given by $M = M_\infty \cos\phi$. By using backward discretization based on the Crank-Nicholson scheme, the governing differential equations can be transformed into tridiagonal difference equations. The critical part of this numerical procedure involves handling the interface conditions, which is accomplished by introducing imaginary points into the opposite phase layer for both gas-phase and liquid-phase flow at the interface. Specific details of this evaluation can be found in Ref. 11.

An iterative solution procedure is then used to obtain the local velocity profiles of the liquid- and gas-phase boundary layers in the stagnation region along the jet trajectory. The velocity profiles indicate that the shear stress increases significantly and monotonically along the jet trajectory due to the increase in mass loss from the liquid surface.

This alternative criterion for transverse jet breakup can be examined using the computed shear stress acting at the liquid interface together with the effective surface tension. The location at which both stresses are of the same order (the so called "tension point") may indicate the beginning of the breakup process.[3,4] Figures 2a and 2b display this tension point together with the previously determined sonic point along the jet trajectory. For higher momentum flux ratios ($R^2 = 8$), the tension point tends to occur a few diameters upstream of the sonic point, which lies closer to the actual breakup locations indicated by Schetz et al.[1] The tension point also does not appear to vary significantly with momentum flux ratio, and changes very little with crossflow Mach number, since the shear-stress distribution does not vary significantly with M_∞ and R^2. The estimation of the sonic point, however, inherently includes an alteration in the jet trajectory with different input values of M_∞ and R^2, so that the sonic point varies more significantly with these input variables.

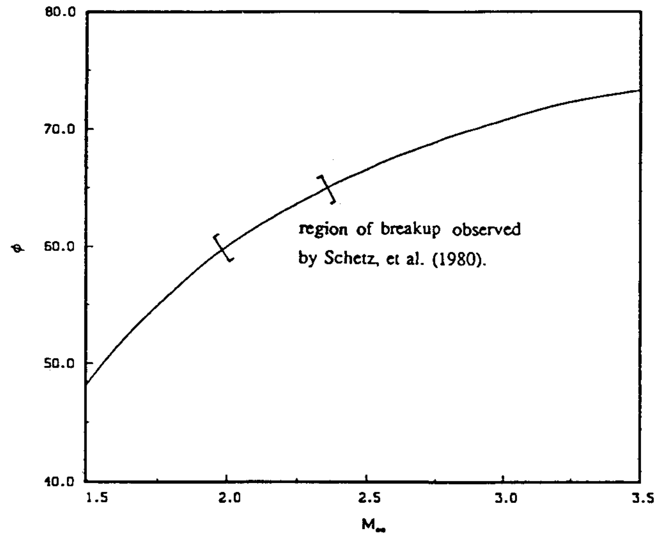

Fig. 3 Computed angular location of the sonic point as a function of Mach number.

III. Conclusions

The current approach compares two transverse liquid jet-breakup criteria: the local sonic point criterion and the "tension point" criterion. Our findings indicate that the sonic point criterion is more accurate as a predictor of breakup. Of course, inherent to the calculation of the local sonic point is the assumption that the actual jet trajectory after breakup is not significantly different from that which would occur without breakup. As indicated in Heister et al.,[6] after breakup occurs, the experimentally observed trajectories do tend to lie 10–15% below the jet trajectories predicted using the assumption of a coherent liquid jet column. This difference in trajectory shape is not large enough to make a significant difference in the location of the sonic point. We might add that a reduced degree of penetration of the jet after breakup is consistent with the fact that the effective drag on the set of droplets comprising the jet cross section is greater than the drag on the single jet column. Although the present approach utilizing the local sonic point certainly is not the "final word" in the study of liquid transverse jet breakup in a supersonic stream, it does provide a simple, computationally inexpensive means of estimating breakup.

Acknowledgments

This work has been supported by NASA Ames/Dryden Flight Research Center under Grant NCC 2-374 and by the U.S. Department of Energy under Grant DE-FG03-88-ER13910.

References

[1]Schetz, J. A., Kush, E. A., and Joshi, P. B., "Wave Phenomena in Liquid Jet Breakup in a Supersonic Crossflow," *AIAA Journal*, Vol. 18, No. 7, 1980, pp. 774–778.

[2]Clark, B. J., "Breakup of a Liquid Jet in a Transverse Flow of Gas," NASA TN D-2424, Feb. 1964.

[3]Sherman, A., And Schetz, J. A., "Breakup of Liquid Sheets and Jets in a Supersonic Gas Stream," *AIAA Journal*, Vol. 9, No. 4, 1971, pp. 666–673.

[4]Nejad, A., and Schetz, J. A., "Effects of Viscosity and Surface Tension of Liquid Injectants on the Structure Characteristics of the Plume in Supersonic Airstream," AIAA Paper 82-0253, Jan. 1982.

[5]Faeth, G. M., "Current Status of Droplet and Liquid Combustion," *Progress in Energy and Combustion Science*, Vol. 3, No. 4, 1977, pp. 191–224.

[6]Heister, S. D., Nguyen, T. T., and Karagozian, A. R., "Modeling of Liquid Jets Injected Transversely into a Supersonic Crossflow," *AIAA Journal*, Vol. 27, No. 12, 1989, pp. 1727–1734.

[7]Forde, J. M., Molder, S., and Szpiro, E. J., "Secondary Liquid Injection into a Supersonic Airstream," *Journal of Spacecraft and Rockets*, Vol. 3, No. 8, 1966, pp. 1172–1176.

[8]Godunov, S. K., Zabrodin, A. V., and Prokopov, G. P., "A Computational Scheme for Two-Dimensional Non-Stationary Problems of Gas Dynamics and Calculation of the Flow from a Shock Wave Approaching a Steady State," U.S.S.R. Computational Mathematics and Math Physics, May 1961.

[9]Less, D. M., and Schjetz, J. A., "Transient Behavior of Liquid Jet Injected Normal to a High-Velocity Gas Stream," *AIAA Journal*, Vol. 24, No. 12, 1986, pp. 1979–1986.

[10]Anderson, J. D., *Modern Compressible Flow with Historical Perspective*, 2nd ed., McGraw-Hill, New York, 1990, Chap. 3.

[11]Li, H.-S., "Transverse Liquid Fuel Jet Breakup, Burning, and Ignition," M.S. Dissertation, Dept. of Mechanical, Aerospace, and Nuclear Engineering, Univ. of California, Los Angeles, CA, 1990.