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Experimental Study of Liquid Sheets Formed in Coaxial Swirl Injectors

K. Ramamurthi* and T. John Tharakan†
Liquid Propulsion Systems Centre, Trivandrum 695 547, India

The shape and disintegration characteristics of swirled annular liquid sheets formed in coaxial injectors are investigated. The effects of ambient pressure and gas flows over the outer and inner surfaces of the liquid sheet are determined. Two general regimes of annular sheets, comprised of a tulip shape and a conical diverging shape, are shown to be formed depending on injector pressure drop, swirl, and orifice size. The transition from the tulip shape to the diverging conical shape occurs when the centrifugal forces at the injector orifice exit exceeds the surface tension forces by about two orders of magnitude. A conical sheet is not formed in annular orifice when the radial clearance of the orifice is of the same order of magnitude as the thickness of the liquid film. The tulip-shaped sheet is very sensitive to small changes in environmental and injection conditions, unlike the diverging conical liquid sheet.

Nomenclature

D = diameter of swirler
d_i = diameter of insert
d_o = diameter of orifice
L = length of orifice
L_s = intact liquid sheet length
l = depth of channel in swirler
N_s = swirl number, Eq. (1)
n = number of helical grooves in swirler
Pa = gaseous nitrogen injection pressure
t = thickness of liquid film in annulus
w = width of channel in swirler
ΔP_{inj} = injection pressure drop
δ = annular gap
ϕ = ratio of air core area to cross-sectional area of flow
ψ = helix angle of grooves in swirler
2α = initial divergence angle of liquid sheet

Subscript
cr = critical condition for transition to conical sheet

Introduction

THE mixture ratio distribution in the combustion chambers of liquid propellant rockets is governed by the shape of the spray fan formed by the injection elements and by the characteristics of atomization. The spray fan comprises the liquid sheet generated by the injection orifices and its subsequent disintegration into droplets. Improved understanding of the characteristics of the liquid sheets formed by different injector configurations under varying operating conditions is required to comprehend the effects of design parameters of the injectors.

Coaxial swirl injectors that produce annular liquid sheets are used in liquid propellant rockets and gas-turbine combustors. The earliest studies of annular liquid sheets were conducted with "water bells," which are primarily unswirled axisymmetric liquid sheets. Taylor[1] identified surface tension forces as being of primary importance in controlling the water bell shape. Parlange[2] extended this work and showed that pressure difference across the liquid sheet is equally important and controls the divergence and penetration characteristics of the liquid sheet. The effect of swirl was explored by Marshall,[3] who distinguished two regimes of swirled annular sheets. A tulip-shaped sheet that "blossomed" into a strong diverging conical sheet was observed when the injection pressure drop exceeded a threshold value. Balakrishnan[4] showed that at low injection pressures, a multiple tulip-shaped sheet was formed that transformed into a single tulip-shaped bulb at higher injection pressures. Camatte et al.[5] showed tulip-shaped sheets to be basically unstable in an environment of high velocity gas flow.[6] The disintegration of tulip-shaped sheets was also seen to be asymmetric in the experiments of Camatte et al.[5]

The strong influence of the pressure variations across the liquid sheet, observed by Parlange,[2] in locally deforming the sheet may be responsible for causing the asymmetric and incipient disintegration of the liquid sheet in the experiments of Camatte et al.[5] The investigation of Li and Tankin[6] demonstrated that recirculatory flows with significant pressure variations across the sheet are possible with the air-assist type of swirl coaxial injectors. However, no systematic variations of the gas velocities, swirl intensities, injector pressure drops, or geometrical configurations of the injector have been done in any investigation to date, with the result that it is not possible to clearly identify the role of the injector and the environmental parameters in controlling the shape and disintegration of the annular sheets. Anomalies in the performance of injectors, when observed, can only be corrected through a laborious series of modifications.

The shape and disintegration characteristics of annular sheets formed by coaxial injectors are investigated in this study as functions of swirl, injection orifice diameter, injection pressure drop, and gas velocity. Variations in these parameters change the forces acting on the liquid sheet and, hence, lead to significant changes in the shape and disintegration behavior. The details of the experiments and results obtained in the study are reported in the following sections.

Experiments

Injector Hardwares

Two types of swirl injectors were used. The first (type A) was comprised of straight-cylindrical orifices, whereas the second (type B) was coannular. Sketches of both configurations are given in Fig. 1. The swirl was generated by a helical swirler of diameter D, with four helical grooves of depth l, width w, and helix angle ψ. The swirler was press-fitted in the injector

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*Group Head, Propulsion Research and Studies Group. Senior Member AIAA.

†Engineer, Propulsion Research and Studies Group.

Table 1 Cylindrical orifice injector

Injector identification	d_o, mm	L, mm	L/d_o	$w \times l$, mm^2	Swirler helical angle, deg	N_s
A-1	0.9	2	2.2	0.2 × 0.75	21	6.38
A-2	2.3	1	2.3	0.1 × 0.52	10.7	101.60
A-3	6.0	15	2.5	0.3 × 1.45	12.3	30.96
A-4	6.0	15	2.5	1.0 × 1.46	13	8.67
A-5	6.0	25	4.1	1.0 × 1.46	13	8.67
A-6	10.0	15	1.5	1.0 × 1.46	13	14.40
A-7	3.0	15	5.0	1.0 × 1.46	13	4.32
A-8	3.0	15	5.0	1.0 × 1.46	13	4.32

Table 2 Annular orifice injector

Injector identification	d_o, mm	L, mm	L/d_o	Range of d_i/d_o	$w \times l$, mm^2	Helix angle, deg	N_s
B-1	2.3	2	0.87	0–0.88	——	——	0
B-2	2.3	2	0.87	0–0.88	0.52 × 0.1	10.65	101.6
B-3	6	15	2.5	0–0.9	1.46 × 1	13	8.7
B-4	6	15	2.5	0–0.9	0.52 × 0.32	12	76.6
B-5	6	25	4.2	0–0.9	1.46 × 1	13	8.7
B-6	10	15	1.5	0–0.9	1.46 × 1	13	14.4

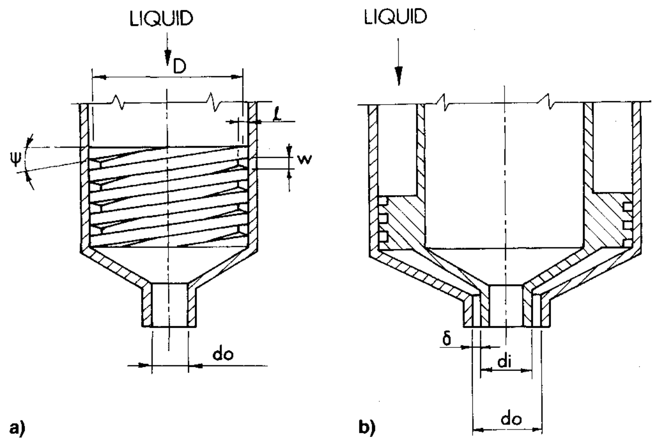


Fig. 1 Injector configuration: a) cylindrical and b) annular orifices.

body to minimize leakage past the swirler. Different combinations of helix angles and flow passage dimensions were used to vary the amount of swirl and the geometrical parameters of the injector. Tables 1 and 2 give the dimensions of the cylindrical and annular orifices and those of the swirler used for the injector. The swirl number N_s for the injector was estimated by the expression of Ruiz and Chigier[7]:

$$N_s = \pi d_o D \cos \psi / 4nwl \tag{1}$$

Cylindrical inserts of varying diameters d_i were used to form different annular gaps δ [$\delta = (d_o - d_i)/2$] for the type B configuration. The diametrical ratio (d_i/d_o) was varied between 0 (no blockage) and 0.9. The components of the injectors were made of stainless steel. The surface finish of the orifices and swirler varied between 1.6–8 μm.

The characteristics of the annular liquid sheets formed in type A and B injectors were evaluated at different injection pressures. The swirl number was varied between 0–102. A swirl number of zero was obtained by removing the swirler in configuration B.

The motivation for investigating the effect of changes of swirl and geometrical parameters in cylindrical and annular configurations of injectors was to obtain basic data for optimally designing coaxial swirl injectors. The coaxial swirl injectors are comprised of an inner cylindrical element surrounded by an outer annular element. During the development of a coaxial injector for a 22-N thrust liquid propellant rocket using monomethyl hydrazine (MMH) for fuel and N_2O_4 for oxidizer, it was found that the walls of the thrust chamber would get overheated in localized zones for injection pressure drops less than 0.7 MPa. The combustion efficiency was also poor. The roughness of combustion exceeded 10% of the mean. It was possible that a nonuniform spray was formed with large variations in mixture ratio profiles across the injector. An understanding of annular liquid sheets formed by the central cylindrical orifice and the outer annular orifice was necessary to select the proper swirl, injector pressure drop, and geometrical parameters of the coaxial injector.

Experimental Procedure

The experiments were conducted with water as the test liquid. The experimental apparatus is shown schematically in Fig. 2. The water was pressurized with nitrogen gas in a run-tank up to 1.6 MPa. The water was admitted into the injector through a series of valves and a 5-μm pleated-disc filter. The liquid sheet was photographed using a still camera with 105-mm zoom lens. A 2000-W light source was used to illuminate the sheet. It was placed at an angle of 60 deg to the camera to provide uniform illumination in the zone of view.

The vacuum chamber in which the experiments were conducted at subatmospheric pressures had a diameter of 1 m and a length of 2 m. Several viewing ports were incorporated in the chamber to observe and photograph the spray.

The initial divergence angle of the liquid sheet as it left the orifice 2α and L_s were measured from the photographic records. The disintegration of the liquid sheet into ligaments and droplets was preceded in some instances by intense undulations on the sheet and formation of a rim at the zone of breakup. Subsequently, the changes in the disintegration pattern are considered. The intact liquid sheet length was taken as the distance between the orifice–exit and the zone at which ligaments and droplets are formed from the liquid sheet.

Repetition of tests demonstrated reproducible data with an accuracy of 2 deg in the divergence angle and 1 mm in the intact liquid sheet length. This corresponds to a measurement accuracy better than 4% in the divergence angle and 2% in the intact liquid sheet length.

The shape and disintegration of the swirled liquid sheets were also studied when nitrogen gas was injected coaxially over the outer surface of the sheet for the injector configuration A-1 (Table 1) and below the inner surface for the injector configuration B-2 (Table 2). The maximum gas velocity was 100 m/s. In coaxial injectors, the liquid sheet is sometimes presented to gas flow before the gas leaves the orifice. The central orifice–port is recessed. This is done to avoid relaxation of the gas-velocity profile and thereby obtain maximum relative velocity between the liquid sheet and the gas. The purpose of experiments with gas flows in the present study is to determine the changes in the shape and disintegration of the swirled liquid sheet for different gas-flow velocities. Recessing was therefore not done in the experiments.

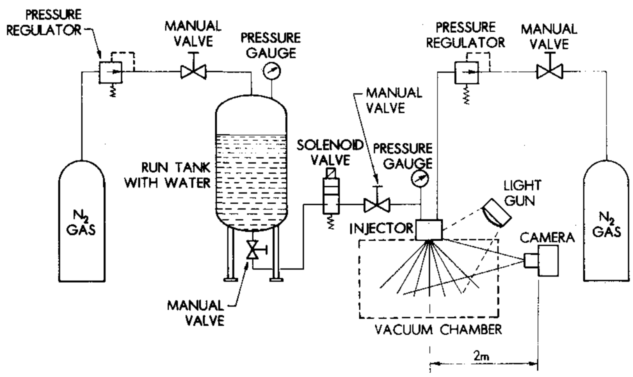


Fig. 2 Schematic of test rig.

Results and Discussion

Swirled Liquid Sheets Formed in Cylindrical Orifices

Figure 3 shows the shape of the swirled annular sheets formed at different injection pressures using injector configuration A-3 of Table 1. At small values of injection pressure drops, typically about 0.04 MPa, multiple tulip-shaped bulbs are formed, as shown in Fig. 3a. When the injection pressure drop is increased to 0.1 MPa, these multiple bulbs merge into a single tulip bulb with a higher divergence angle and increased penetration, shown in Figs. 3b and 3c. When the injection pressure drop is about 0.18 MPa, waves begin to appear in the downstream portion of the tulip and the sheet thickens in a rim where the disintegration of the sheet to droplets takes place, as shown in Fig. 3d.

As the injection pressure drop is further increased to about 0.21 MPa, the liquid sheet diverges further, but the zone of disintegration shifts towards the injector, as shown in Fig. 3e. With further increase in injection pressure, the liquid sheet changes from a bulbous shape to a straight conical sheet. It also disintegrates into droplets without any thickening of the sheet into a rim at the zone of disintegration as shown in Fig. 3f. An increase in injection pressure drop beyond 0.24 MPa does not cause a further increase in the initial divergence angle

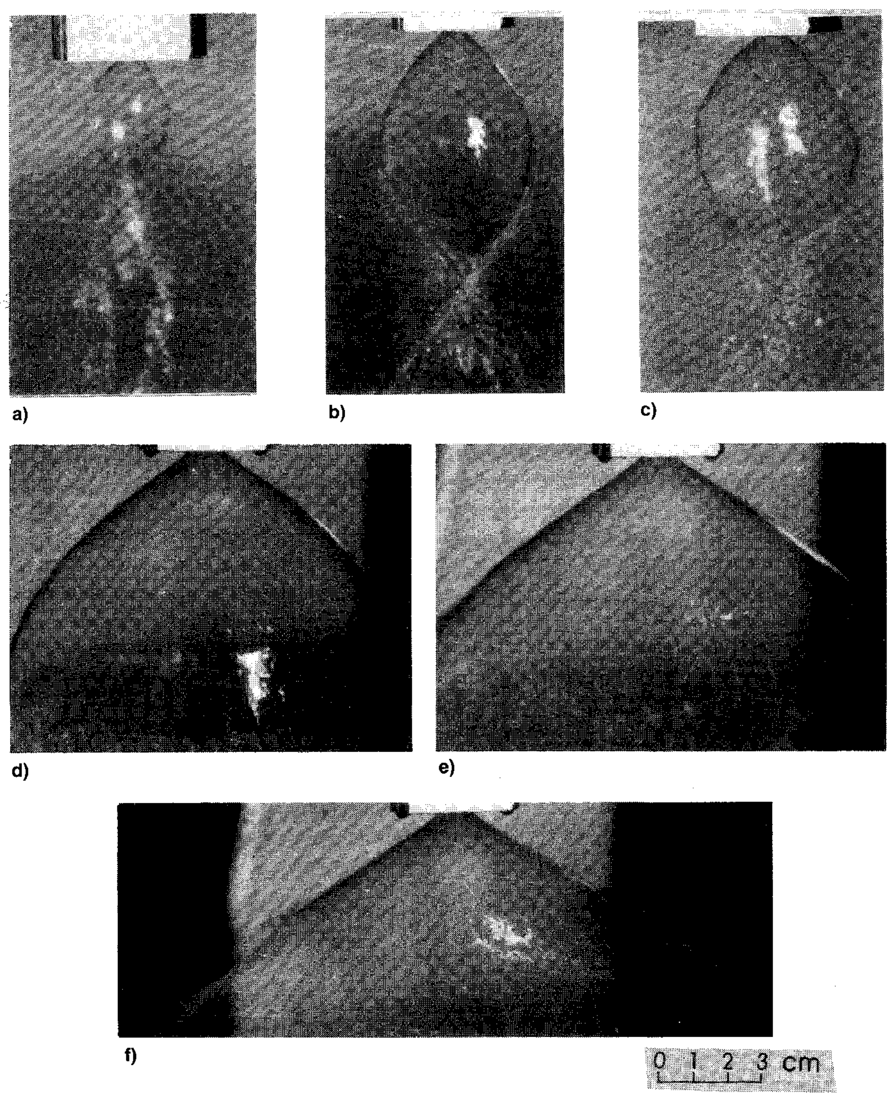


Fig. 3 Different shapes of swirled liquid sheet shapes: a) multiple tulip shape, b) single tulip shape, c) disintegration of tulip-shaped sheet, d) disintegration in upper portion of tulip, e) transition to conical shape, and f) straight diverging conical sheet.

of the sheet. However, the disturbances on the surface get intensified and the zone of disintegration progressively shifts towards the injector.

Experiments conducted with different orifice diameters and swirl show similar evolution in the shape of the liquid sheet when the injection pressure drop is increased. Above a threshold value of injection pressure drop, the shape of the liquid sheet changes from a tulip shape to a diverging conical shape. The value of the threshold pressure depends on the swirl and the orifice diameter used in the injectors.

Figures 4 and 5 show the intact liquid length and the initial divergence angle measured in the different experiments. The intact liquid sheet length is expressed as a fraction of the injection orifice diameter in Fig. 4 and is plotted as functions of injection pressure drops for injectors A-1, A-3, and A-4 given in Table 1. It decreases for higher injection pressure drops due to the increased shear at the liquid–gas interface for larger values of liquid sheet velocities. The result is in agreement with the computations of Chuech,[8] who observed a monotonic decrease of sheet penetration as injection velocity is increased.

The initial divergence angle of the sheet, plotted in Fig. 5, increases with increasing values of injection pressure drop. It attains a maximum when the injection pressure drop reaches the threshold pressure at which the liquid sheet changes to the conical diverging shape. The threshold injection pressure drop $\Delta P_{\mathrm{inj,cr}}$ decreases as N_s and d_o are increased as shown in Fig. 6.

Considering the forces acting on the sheet, the centrifugal force causes the liquid sheet to diverge, whereas the surface tension force causes the sheet to collapse. The surface tension force varies inversely with radius and becomes dominant when the radius of the sheet is small. The centrifugal force increases with swirl and radius and is significant for the larger values of sheet radius and swirl number. The annular sheet is dominated by the centrifugal force for the larger swirl numbers and larger injection orifice diameters and diverges readily even when the values of the injection pressure drops are small.

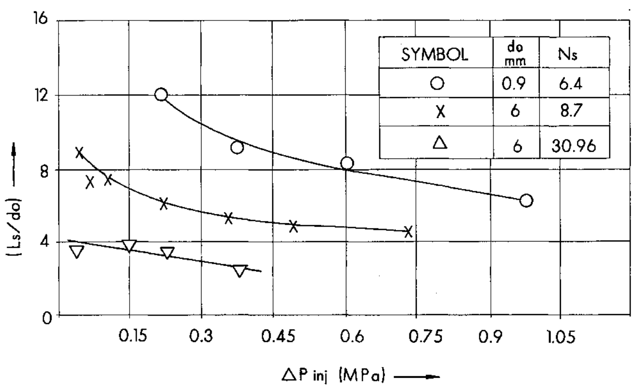


Fig. 4 Intact liquid sheet length at different injection pressure drops.

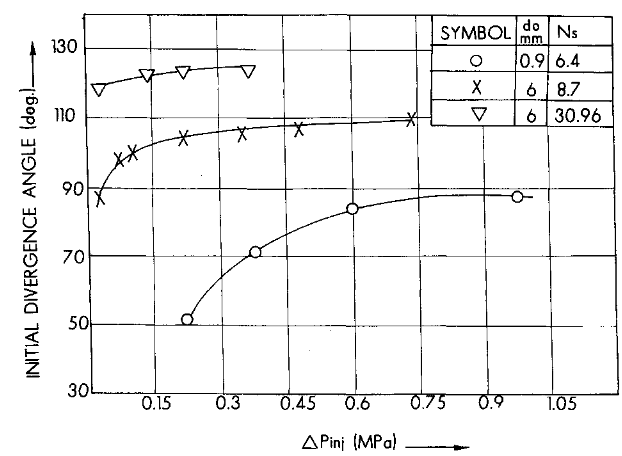


Fig. 5 Initial divergence angle at different injection pressure drops.

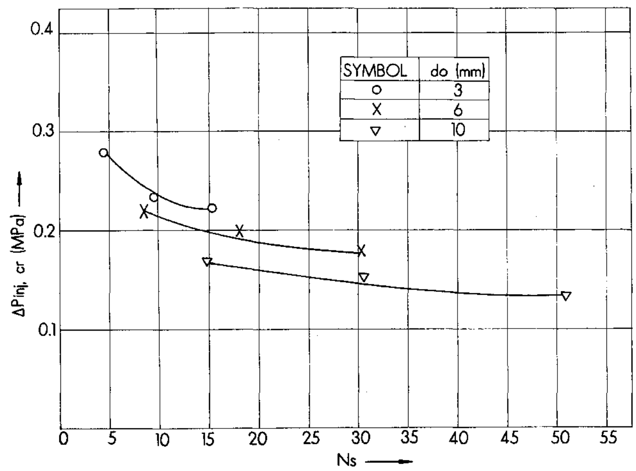


Fig. 6 Influence of swirl number and orifice dimensions on threshold injection pressure drop.

A nondimensional plot of initial divergence angles of the sheet obtained in the multiple experiments as functions of the ratio of centrifugal and surface tension forces evaluated at the injector orifice exit is given in Fig. 7. The initial divergence angle is nondimensionalized with respect to ψ and the ratio of the length scale associated with the flow passage in the swirler $[(l \times w)^{0.5}]$ and D. The centrifugal force F_c is calculated from the computed rotational velocities of the liquid sheet at the exit of the injection orifice. The contribution of the meridional component to the centrifugal force is neglected. The plot in Fig. 7 shows that smaller divergence angles, corresponding to the tulip-shaped sheet, are obtained when the ratio of centrifugal forces and surface tension forces are less than about 80.

The Reynolds number based on orifice diameter varied in the experiments between 1.5×10^4 and 8×10^4. The flow through the injector orifice was generally turbulent and the changes in the shape of the liquid sheet are not associated with transition of laminar flow to turbulent flow.

Experiments were also conducted with changes in the length/diameter ratio L/d_o of the injection exit orifices. Over the range of L/d_o of the orifices (1.5–4.1) used in this study (Table 1), there was no perceptible change in the initial divergence angle of the sheet or its disintegration behavior. This aspect is considered later.

The experiments show that the diverging conical liquid sheets are formed when the centrifugal force of the swirled liquid at the exit of the injection orifice dominates over the surface tension force by about two orders of magnitude. For large orifice diameters ($d_o > 6$ mm), the divergent liquid sheet is formed at relatively lower values of injection pressure drops (0.15–0.2 MPa) in view of the enhanced centrifugal forces associated with the larger radius of the sheet. Injectors using small orifices need to improvise larger levels of swirl if diverging conical sheets are desired. The conventional methods recommended for predicting the divergence angle of swirl injectors[9] do not consider the tulip-shaped sheets that are formed when the swirl numbers, injection pressure drops, and orifice dimensions are reduced.

Swirled Liquid Sheets Formed in Annular Orifices

Figure 8 shows initial divergence angles of liquid sheets measured at different injection pressure drops for the injector configuration B-3 of Table 2. As injection pressure drop in-

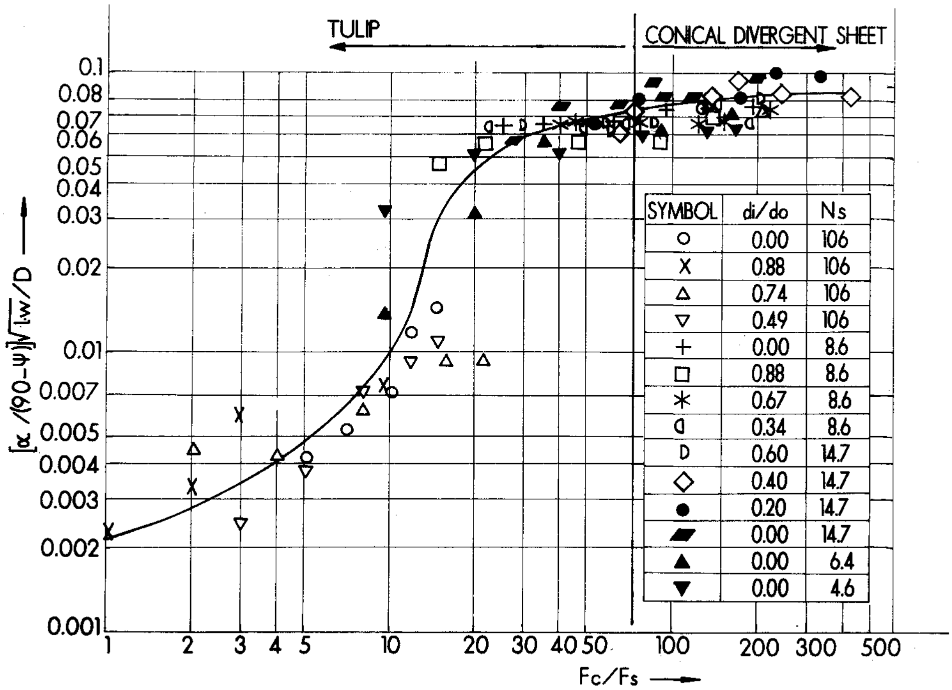


Fig. 7 Nondimensional plot of initial divergence angle.

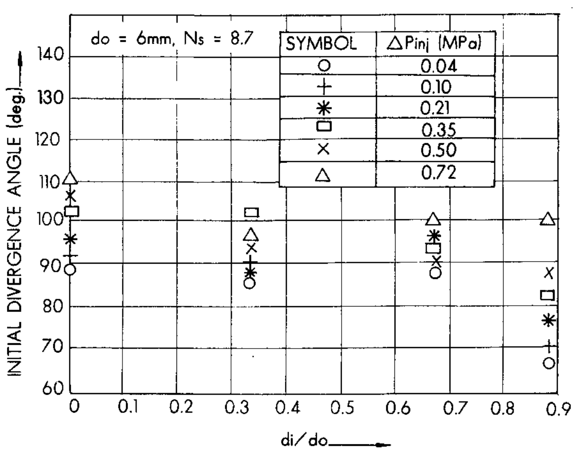


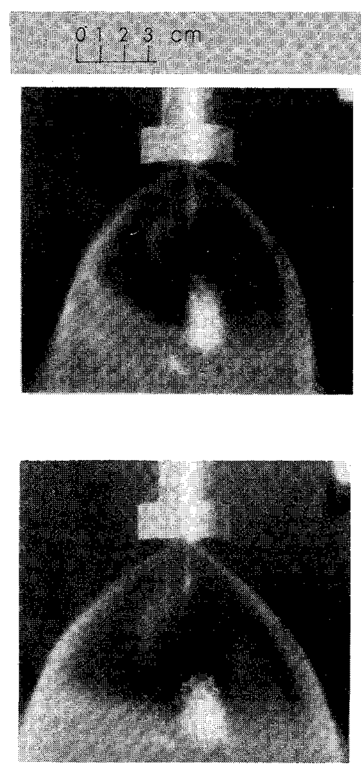
Fig. 8 Initial divergence angle for different diametrical ratios.

creases, the initial divergence angle of the liquid sheet increases. For increased diametrical ratios of the annular orifice (i.e., small annular gap), such that $d_i/d_o > 0.8$, Fig. 8 shows a sharp reduction in the initial divergence angles, especially for lower injection pressure drops. A reduction of the swirl number also caused a rapid decrease of the divergence angle, especially for diametrical ratios exceeding 0.8. These results were determined by using the injector configurations B-2 and B-4 in Table 2.

An increase of the length of annular orifice, obtained by using injectors B-3 and B-5 in Table 2, did not reveal any significant change in the initial divergence angle and the intact liquid sheet length. Experiments of Yapici et al.[10] suggest negligible dissipation of swirl in the annulus for the values of L/d_o considered. The L/d_o of orifices used in coaxial injectors is smaller than unity and the changes in the values would not significantly influence the shape and disintegration.

Experiments also showed that the disintegration becomes asymmetrical when d_i/d_o is increased, especially at the lower injection pressures. The asymmetry is particularly severe when a tulip-shaped sheet is formed. This is illustrated in Fig. 9.

The thickness of the swirling liquid film in the orifice was estimated from the measured flow rates and compared with



a) b)

Fig. 9 Asymmetric collapse of tulip-shaped sheet in annular orifice. P_{inj} = a) 0.1 and b) 0.21 MPa.

the annular gap of the orifice. The conservation of mass and momentum was solved to give t as

$$t = d_o(1 + \sqrt{\phi})/2 \tag{2}$$

The value of ϕ was determined by solving the Bernoulli equation for flow in the orifice.[9] The initial divergence angle of the sheet measured at different values of d_i/d_o is plotted in Fig. 8 as functions of the ratio of δ and t. For $\delta/t < 10$, the initial divergence angle of the liquid sheet is significantly influenced by changes in injection pressure drop and the injector configuration. The shape of the sheet is in the form of a tulip. When $\delta/t > 10$, the changes in the divergence angle are small (Fig. 10) and the sheet is conical in shape.

Unswirled Liquid Sheets

Experiments with annular orifices (type B) given in Table 2 showed that a uniform axisymmetric liquid sheet was not formed in the absence of swirl except at very low injection pressure drops less than 0.01 MPa. The liquid sheet, when formed, was full of longitudinal corrugations. It is likely that the flow of liquid without swirl separates from the wall in the entrance region of the injection orifice giving rise to cavitation of the liquid.[11] The disturbances induced by the cavitating liquid may be responsible for breaking up the liquid sheet spontaneously and asymmetrically.

Effect of Ambient Pressure

The swirled liquid sheets were also evaluated for the effect of environmental pressure changes in a vacuum chamber. As the ambient pressure was decreased, the initial divergence angle and the intact liquid sheet length increased. The surface of the sheet was also smoother. Waves were observed to develop on the sheet prior to disintegration.

Figure 11 shows the initial divergence angle of the liquid sheet measured at subatmospheric pressures for injector configurations A-3 and A-4 of Table 1. At low injection pressure drops (<0.5 MPa) for which a tulip-shaped sheet was formed, a reduction in the ambient pressure led to a very significant increase of the initial divergence angle. A less pronounced change was observed for the sheets formed with liquid injection pressures exceeding about 0.50 MPa. The threshold value of injection pressure drop, at which the liquid sheet changed from a tulip shape to a diverging conical shape, did not vary at the different vacuum pressures at which experiments were conducted.

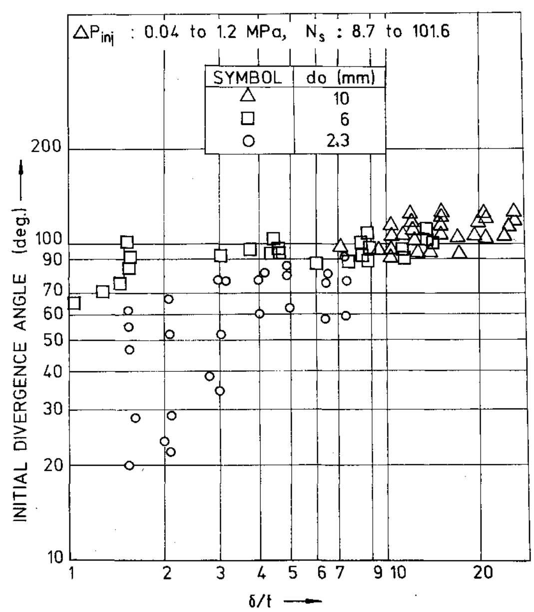


Fig. 10 Variation of initial divergence angle with ratio of annular gap.

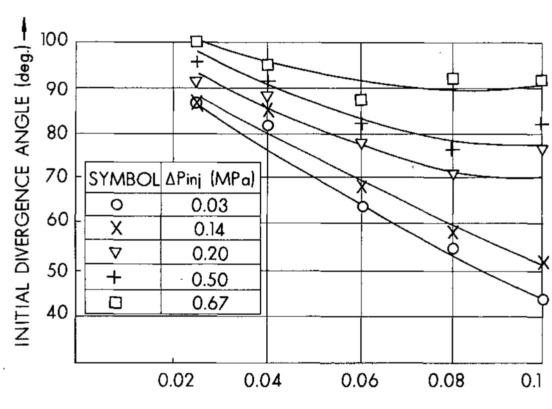


Fig. 11 Initial divergence angle variations with ambient pressure.

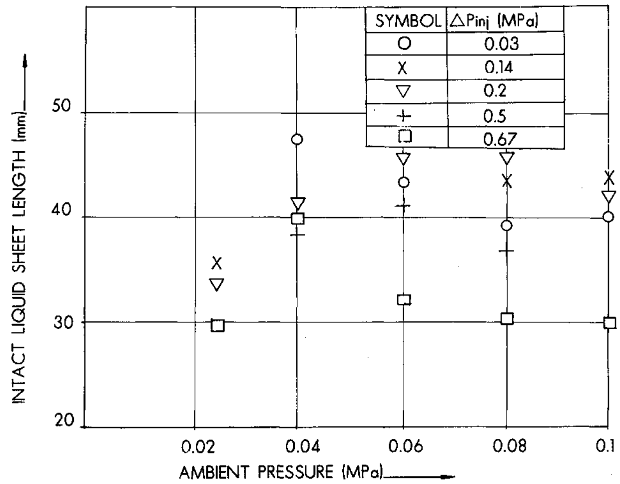


Fig. 12 Intact liquid sheet length at subatmospheric pressures.

The reduced shear at the gas–liquid interface delays the onset and intensification of wave motion for the lower subatmospheric pressures and increases the intact liquid sheet length as shown in Fig. 12. However, for the tulip-shaped sheet, the intact liquid sheet length decreases at subatmospheric pressures less than 0.04 MPa. The increase of divergence angle at the lower subatmospheric pressure causes the sheet to become thin and thereby disintegrate.

Influence of Gas Flow on the Outer and Inner Surface of the Liquid Sheets

The variations in the shape of the liquid sheet and the intact liquid length were determined for various liquid injection pressure drops when nitrogen gas was injected at velocities up to 100 m/s over the outer surface. For gas velocities exceeding 90 m/s, disintegration took place at the injector outlet orifice. Changes in the velocity of the gas brought about rapid changes in the intact liquid sheet length for smaller liquid injection pressures at which a tulip-shaped sheet was formed. Relatively small changes in the intact liquid sheet length were observed at higher liquid injection pressures. The disintegration was very symmetric for all injection pressures. Asymmetric disintegration reported by Camatte et al.[5] was not observed.

The effect of gas flowing over the liquid sheet was opposite to the trends observed as the ambient pressure was reduced. This is understandable since the flow of gas over the liquid sheet increases the shear force at the liquid–gas interface. A decrease of the ambient pressure reduces the shear.

The flow of gas below the inner surface of the liquid sheet was not as effective in disintegrating the sheet as the flow of gas over its outer surface. When the gas flows over the outer surface of the liquid sheet the reduced pressure on the outer surface results in a net positive overpressure on the inside surface of the sheet. This destabilizes the sheet,[2] helping it to disintegrate.

Conclusions

Experimental results obtained in this study reveal the influence of the injection parameters and ambient pressure on the shape and disintegration characteristics of swirled annular liquid sheets. The tulip-shaped liquid sheets are formed in the region of lower injection pressures when the ratio of the centrifugal and surface tension forces is typically less than about 80. The tulip-shaped sheets are also formed for high injection pressures in annular orifices when the ratio of the annular gap to the liquid sheet thickness δ/t is less than about 10. The tulip-shaped sheet is sensitive to small changes in injection pressures, gas velocities over the sheet, and the environmental pressures unlike the diverging conical liquid sheets.

Coaxial swirl injectors should be designed with large annular clearances and high centrifugal forces to ensure the formation of annular sheets in the regime of the diverging conical shape, which is fairly insensitive to small changes in the injection and environmental conditions.

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