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An Experimental Study of the Effects of Liquid Properties on the Breakup of a Two-Dimensional Liquid Sheet

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The breakup of a liquid sheet is of fundamental interest in the atomization of liquid fuels. The present study explores the breakup of a two-dimensional liquid sheet in the presence of co-flow air with emphasis on the extent to which liquid properties affect breakup. Three liquids, selected with varying values of viscosity and surface tension, are introduced through a twin-fluid, two-dimensional nozzle. A pulsed laser imaging system is used to determine the sheet structure at breakup, the distance and time to breakup, and the character of the ligaments and droplets formed. Experiments are conducted at two liquid flow rates with five flow rates of co-flowing air. Liquid properties affect the residence time required to initiate sheet breakup, and alter the time and length scales in the breakup mechanism.

Introduction

Liquid atomization is used for a wide variety of applications, including agricultural sprays, spray coatings, rapid solidification of metals, and combustion and propulsion systems. In many of these systems, a twin-fluid atomizer is employed. In gas turbine engine combustors, for example, the liquid fuel is most often introduced through an annular orifice and exits under relatively low pressure in the form of an annular sheet. High-velocity air is passed along either or both sides of the liquid sheet to produce a shear force at the air-liquid interface. While increasing relative air/liquid velocity has been shown to produce smaller droplets, the mechanism for breakup is not clearly established. The common notion is that (1) the shear causes spanwise waves to form on the surface of the sheet, and (2) the waves grow and separate from the sheet in the form of ligaments, which subsequently fragment into droplets.

The first studies of the instabilities and breakup of liquids were theoretical and focused on jets. Castleman (1930), for example, applied the analysis of Rayleigh (1878) to the breakup of a liquid jet in an air stream, and postulated that the formulation of ligaments was a necessary intermediate in the breakup mechanism. Squire (1953) followed with an analysis of a moving liquid film, in which he determined that two modes of wave instability were possible. The first mode was symmetric about the central plane of the film, and the second mode was axisymmetric. These results have also been verified using nonlinear vortex discretion theory (Rangel and Sirignano, 1988).

In a related theoretical study, Inoue (1989) has applied a three-dimensional vortex method to the growth of a two-dimensional turbulent homogeneous mixing layer. The results show that the streamwise vortices (1) are produced through an amplification of initial disturbances, (2) counterrotate in pairs as a result of the stretching and rotation of the spanwise vortices, and (3) are equal in magnitude to the spanwise vortices.

Because the geometry of an air blast atomizer is somewhat complex, a planar liquid sheet has been used in most of the experiments conducted to study atomization. Researchers at Imperial College, for example, first used fan sprays in quiescent environments to obtain photographs of the breakup of liquid sheets (Fraser, 1956; Dombrowski and Hooper, 1962; Dombrowski and Johns, 1963) and Rizk and Lefebvre (1980) later used a pair of atomizers (Fig. 1) in which a plane sheet of liquid is sheared by air streams on the upper and lower surfaces. The first design is for a prefilming atomizer, while the second design injects a liquid sheet from a wedge surrounded by co-flowing, shearing air streams.

Most sheet disintegration research (Arai and Hashimoto, 1985; Sattelmayer and Wittig, 1986; Beck et al., 1989; Stapper and Samuelsen, 1990) has since been performed on nozzles similar to those of Rizk and Lefebvre (1980). The focus of the research previously cited has been to assess the manner by which the final droplet size distribution is affected by (1) air and liquid properties, and (2) the geometry of the nozzle. The general conclusions are that SMD decreases with increasing relative air/liquid velocity, increasing liquid density, and decreasing surface tension. Viscosity is found to have little or no effect, and sheet thickness, while not playing a role in the prefilming atomizer, can have an effect in the wedge design depending on the relative angle of injection between the liquid and co-flowing air streams. Little emphasis has been placed on the instabilities in the liquid sheet itself, other than to suggest that (1) spanwise waves are the dominant instability, (2) the waves are periodic and a function of air velocity, and (3) the relative strength of the spanwise and streamwise vortical waves

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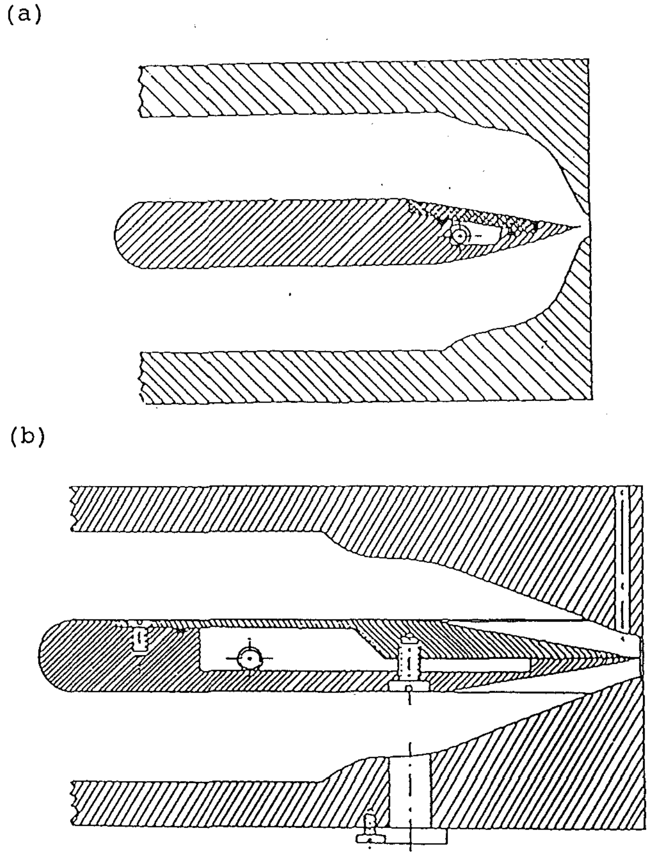


Fig. 1 Two-dimensional air blast atomizers: (*a*) prefilming atomizer, (*b*) fixed sheet thickness atomizer (Rizk and Lefebvre, 1980)

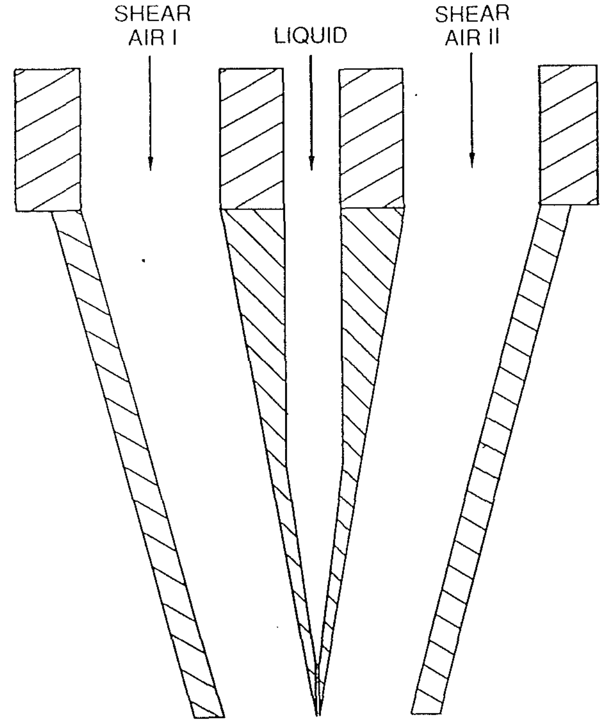


Fig. 2 Two-dimensional parallel flow plane sheet atomizer

in the sheet is a controlling factor in the breakup mechanism (Sattelmayer and Wittig, 1986; Stapper and Samuelsen, 1990; Hagerty and Shea, 1955; Asare et al., 1981).

Even less attention has been directed to the transitional breakup regime of the spray beginning with the formation of ligaments and ending with their breakup. To explore this area of interest, we have recently examined the role of air and liquid velocities on the formation, size, and lifetime of ligaments using water as the test liquid (Stapper and Samuelsen, 1990). This study revealed that (1) the relative air/liquid velocity is a primary factor in the ligament formation and breakup, (2) the breakup is a complex three-dimensional interaction of spanwise and streamwise waves, between which are stretched thin film membranes, (3) the relative velocity establishes the relative importance of the spanwise and streamwise waves, and (4) an increase in relative velocity leads to further stretching of both the liquid membranes and streamwise ligaments, both of which lead to smaller droplets and, hence, lower SMDs. The present paper addresses the effects of liquid properties on the mechanisms of breakup.

Approach

Three liquids were selected that would demonstrate the differences in viscosity and surface tension effects on the breakup mechanisms. A two-dimensional nozzle was employed in combination with a nonintrusive pulsed laser imaging system to obtain images of the spray elements in sharp focus. Emphasis was placed on the breakup mechanisms of the liquid sheet at the various conditions, and the time required for the sheet to break up into ligaments.

Experimental Apparatus

The experimental apparatus, described in detail elsewhere (Stapper and Samuelsen, 1990), consists of a test fixture and a supporting facility. By way of summary, the test fixture is a two-dimensional parallel flow plane sheet nozzle, similar to the second design of Rizk and Lefebvre (1980). As shown in Fig. 2, the nozzle consists of a pair of triangular wedges, which are separated by shims to achieve the desired thickness for the liquid sheet. The sheet that is produced is 4.7 cm wide and 508 μm thick. A plexiglass plenum surrounds the wedges to contain the shear air as it passes on either side of the sheet. The air plenum converges slightly as it approaches the nozzle tip to maintain straight flow.

The flow preparation upstream of the injection can affect the vorticity generated by the liquid feed in the nozzle. The liquid enters the nozzle in a central reservoir from which it is forced under pressure to the injection plane of the nozzle. The liquid passes through a section of constant channel height for a distance of 13 channel heights before exiting the nozzle. To assess the effect of boundary conditions internal to the nozzle on the results, tests were conducted for a wide range of surface roughness, and a variety of screens in the central reservoir. No effect on the results reported was observed. For the results reported here, screens were not used and the internal surfaces were unpolished.

The nozzle is down-fired and the liquid is driven through the system by a gear pump with a maximum capacity of 157 g/s at 1.72 MPa. The two shear air lines can each deliver 0.126 kg/s.

To image the atomization of the liquid sheet properly, a nonintrusive method for measuring the dimensions of the spray elements was created. A pulsed nitrogen laser (PRA Model LN1000) was used to backlight the sheet. The short duration of the laser pulse (1 ns) allows the rapidly moving small structures in the breakup mechanism to be visualized in sharp focus, a marked benefit in comparison to previously reported exposure times (e.g., 0.8 μs; Arai and Hashimoto, 1985). The UV laser pulse was expanded and directed to impinge on a sheet of paper behind the liquid sheet. The fluorescence of the paper created visible backlighting. The results were documented using a 35 mm camera (Pentax Superprogram) and

Table 1 Liquid properties

Liquid	Viscosity ($mN \cdot s/m^2$)	Surface Tension (mN/m)	Density (kg/m^3)	Re_{ch}
Water (H_2O)	0.89	72	998	561
Ethanol (C_2H_6O)	1.39	22	789	284
Ethylene Glycol ($C_2H_6O_2$)	14.72	48	1114	38

Table 2 Experimental test matrix

Case	Velocity (m/sec)		
	Liquid	Air I	Air II
11	5	0	0
12	5	20	20
13	5	30	30
14	5	40	40
15	5	50	50
16	5	60	60
21	1	0	0
22	1	20	20
23	1	30	30
24	1	40	40
25	1	50	50
26	1	60	60

Professional Ektachrome film (P800/1600). Developing was pushed two stops.

Test Matrix

The properties of the liquids used for the evaluation of the viscosity and surface tension effects on ligament formation and breakup are given in Table 1. Three different liquids with widely varying physical properties (e.g., viscosity and surface tension) were chosen to examine the influence of liquid properties on sheet breakup. The Reynolds number based on the channel height of the nozzle exit is given for the liquids at 1 m/s.

The test matrix for the experiment is given in Table 2. The shear air velocity of the sheet was varied from 0 to 60 m/s, with the same velocity on both sides of the sheet. The liquid velocity was set at one of two values: 1 or 5 m/s.

Results

Liquid Sheet Breakup. An example is first provided to describe the general behavior and structure of the liquid sheet for a representative operating condition. This is followed by a description of the two mechanisms observed for breakup. A schematic of the face and side views of the structures that form during the breakup of a sheet is provided in Fig. 3 to assist the reader in the interpretation of the figures.

Example. An example of a water sheet with no co-flow air (Case 11) is shown in Fig. 4(*a*). Spanwise vorticity is generated as a result of the shear between the liquid velocity and quiescent surroundings. The spanwise vortical waves extend to the edges of the sheet and propagate in the streamwise direction. Less

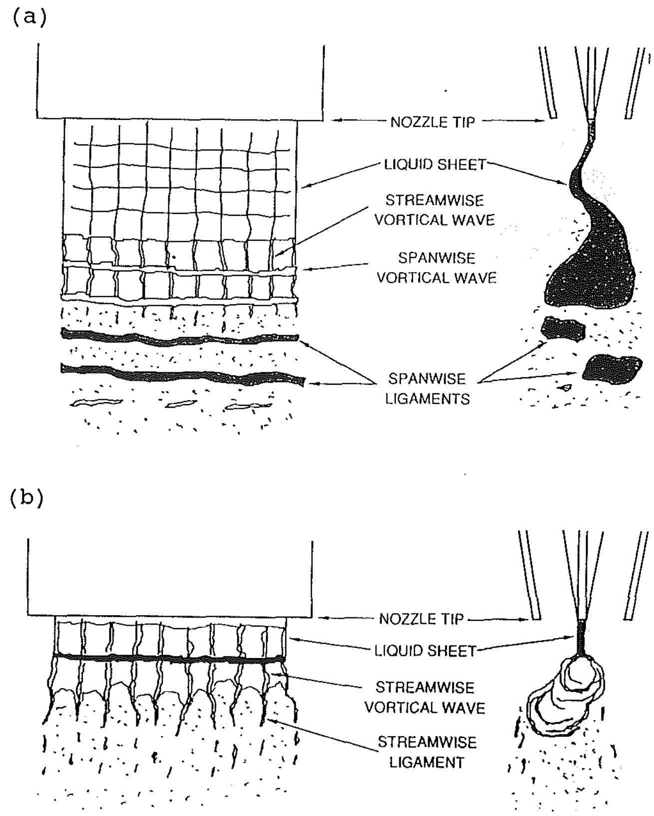


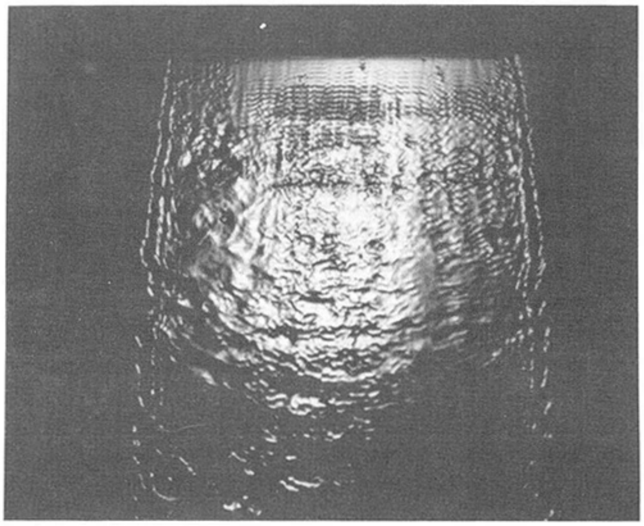
Fig. 3 Schematic of face and side views detailing the structures in the breakup of a liquid sheet for (*a*) cellular breakup, and (*b*) stretched streamwise ligament breakup (Stapper and Samuelsen, 1990)

noticeable on the liquid sheet, but important to the eventual breakup, are streamwise waves that are present at the nozzle tip and extend through the length of the sheet at a fixed spanwise location. These streamwise striations are attributed to counterrotating streamwise vortices generated by background disturbances and amplified by the close coupling with the spanwise vortices as described by Inoue (1989).

Figure 4(*b*) shows the water sheet with 40 m/s co-flow shear air (Case 14). In this case, spanwise waves again form on the sheet due to the relative velocity of the air and liquid flows, but the presence and role of the streamwise striations become more pronounced. In particular, the combination of the streamwise and spanwise vortical waves produces a cellular structure embodied by thin film membranes. The sheet is stretched by the shear air until the membranes burst into relatively small droplets, and the waves separate as ligaments. These ligaments then become unstable and fragment into droplets.

Sheet Breakup Mechanisms. Two mechanisms of sheet breakup have been identified in the experiments conducted to data (Stapper and Samuelsen, 1990). The first of these, labeled in this study as "cellular breakup," occurs at higher relative air-to-liquid velocities, but where the breakup is well displaced from the nozzle tip. This breakup mechanism, illustrated in Fig. 4(*b*), is characterized by the presence of spanwise vortical waves that are approximately equal in strength to the streamwise vortical waves. As the sheet is extruded by the shearing action of the air, the membranes stretch between the spanwise and streamwise vortical waves, forming cell-like structures. Eventually, the sheet is stretched to the point where (1) the streamwise vortical waves and connecting membranes burst, and (2) the spanwise vortical waves separate into spanwise ligaments. The small droplets in the resultant spray distribution originate from the bursting membranes. Larger droplets are

(a)



(b)

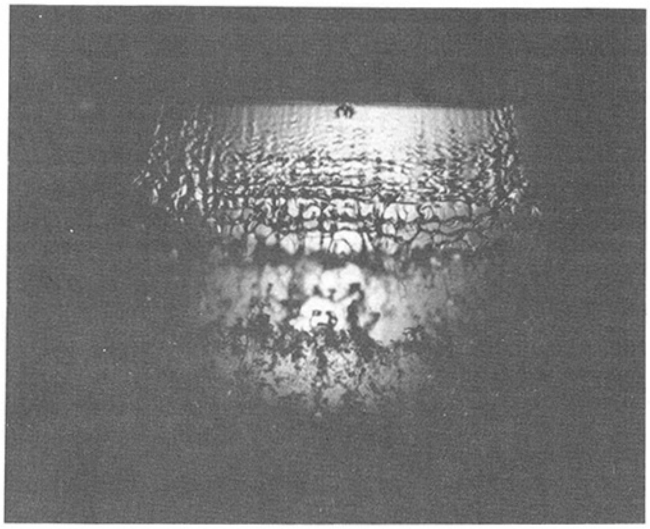
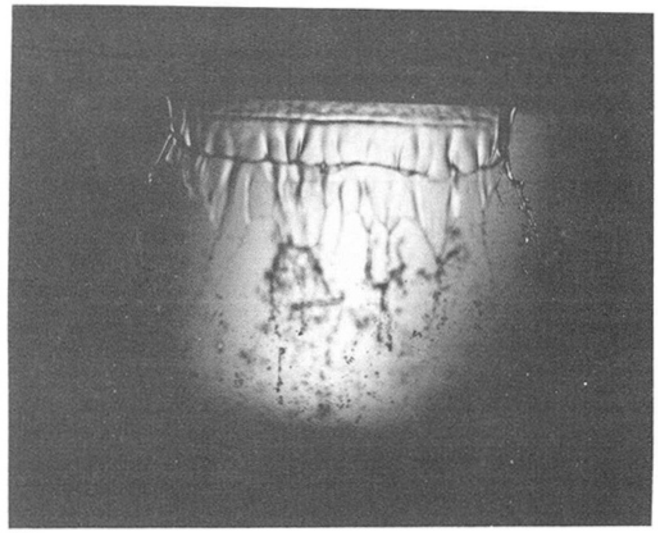


Fig. 4 "Cellular breakup" (Stapper and Samuelsen, 1990): water sheet at 5 m/s with (*a*) no co-flow air, (*b*) 40 m/s co-flow air

(a)



(b)

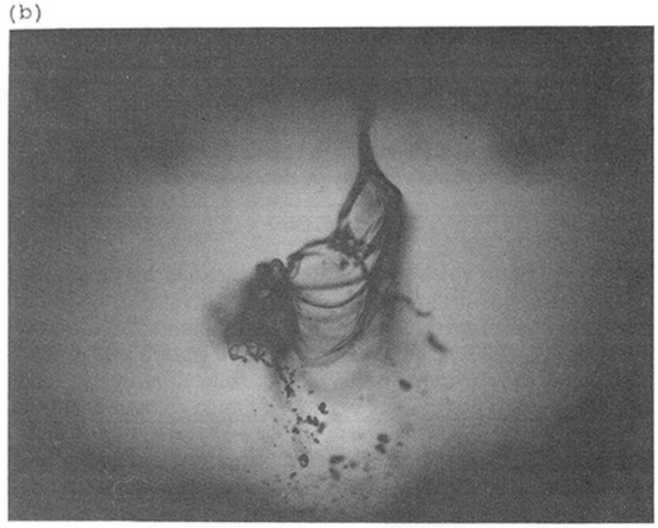


Fig. 5 "Stretched streamwise ligament breakup" (Stapper and Samuelsen, 1990): water sheet at 1 m/s with 20 m/s co-flow air: (*a*) face view, (*b*) side view

associated with the breakup of the streamwise waves. The largest droplets are associated with the fragmentation of the spanwise ligaments.

The second breakup mechanism, referred to as "stretched streamwise ligament breakup," occurs at low liquid velocities. As shown in Fig. 5(*a*) for Case 22, this mechanism is dominated by the streamwise vortical waves in the breakup process. As the sheet is stretched by the co-flowing air, the streamwise vortices amplify with thin liquid membranes stretched between. The sheet is a corrugated structure with the membranes stretched sinusoidally about the plane of the sheet. A side view of this process is presented in Fig. 5(*b*). As a result, the membranes are stretched by the counterrotation of the bounding vortices. When the membranes burst, the liquid film forms small drops, while the vortical waves form streamwise ligaments. These ligaments are then stretched by the shearing action of the air and transition to higher rotating velocities, and finally fragment into relatively large drops when the surface tension forces can no longer keep the ligaments intact.

Liquid Property Effects. The variation in the liquid properties considered did not alter the general character of the two breakup mechanisms. However, the change in liquid properties had a pronounced effect on the time and length scales. Results are presented first for the influence of liquid properties on sheet breakup length and sheet breakup time. This provides a global perspective. Secondly, an examination of the effect of liquid properties is presented for both the cellular breakup, and for the stretched streamwise ligament breakup mechanisms. For the latter, select conditions are presented where the photographs are most illustrative of the effects.

Although the liquid properties of the three liquids vary, the liquids were selected for their substantial variation in viscosity and surface tension: Water has relatively high surface tension and relatively low viscosity, ethanol has a threefold lower surface tension and a slightly higher viscosity (~ 50 percent) than water, and ethylene glycol has a viscosity much greater than water while its surface tension is slightly lower (~ 30 percent).

While it is likely that the liquid property effects presented are dominated by the differences in surface tension and viscosity, the variation in other physical properties and the limited number of fluids considered preclude an unequivocal determination of the precise role of viscosity and surface tension. As a consequence, the results are presented in terms of the generic names of the liquids with a parenthetical note of the relative values of surface tension and viscosity.

Sheet Breakup Time. Measurements were made of the length from the nozzle tip to the point at which the thin film membranes fragment. The results, presented in Fig. 6(*a*), reveal

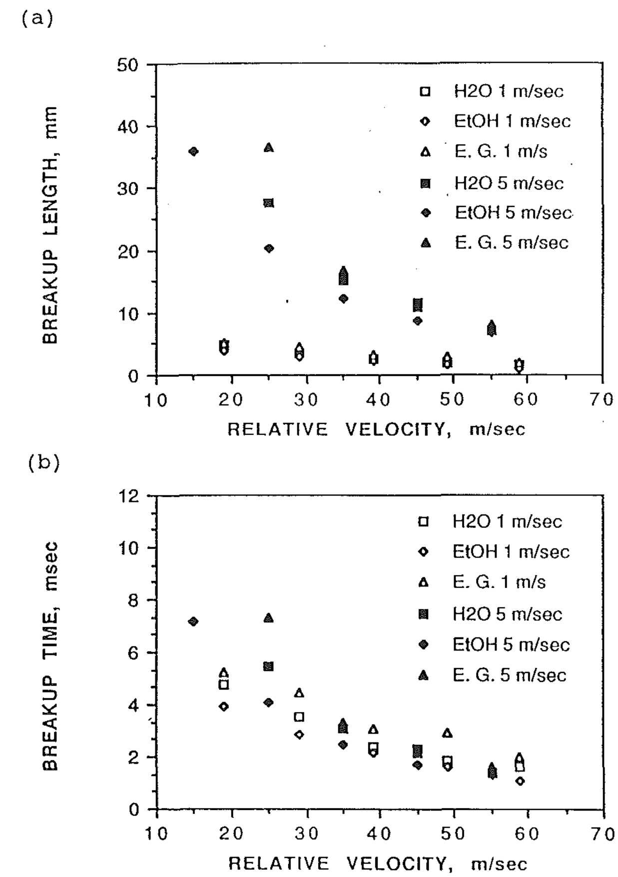


Fig. 6 Effect of relative velocity on: (*a*) sheet breakup length, (*b*) sheet breakup time

that the higher liquid velocity leads to longer sheet breakup lengths. The breakup lengths were strongly correlated with the liquid sheet-air residence time of interaction. In Fig. 6(*b*), the data are replotted in terms of interaction time and air-to-liquid relative velocity, where interaction time is defined as the breakup length divided by the liquid velocity at the nozzle tip. Based on these data, it is apparent that the liquid properties have a notable effect on the required air-liquid interaction time to breakup. The required interaction time of the ethanol is the shortest, while the ethylene glycol generally has the longest required time. The former is the lowest in surface tension of the three liquids, while the latter is the highest in viscosity. It should also be noted that the sheet breakup time correlates well with the liquid density as would be expected due to conservation of momentum. The lowest density liquid (ethanol) has the shortest breakup time, while the highest density liquid (ethylene glycol) has the longest.

Cellular Breakup. The effect of liquid properties on the cellular breakup mechanism is presented in Fig. 7(*a*) by comparing the face view of sheets of water and ethanol for Case 13. Spanwise vortical waves are formed closer to the injector inlet for ethanol (the lower surface tension liquid), and the cellular structures that form are smaller than those of water. It is also noteworthy that the streamwise ligaments fragment into droplets at the point the spanwise ligament breaks off, while in the case of water, the streamwise ligaments persist well downstream of the sheet breakup. The rapid breakup of the ethanol is illustrated effectively by a side view of sheets of water and ethanol (Fig. 7*b*, Case 26).

Figure 7(*c*) demonstrates the characteristics of ethylene glycol relative to the cellular breakup mechanism (Case 14). The high viscosity of the ethylene glycol dampens out the small-scale structures in the sheet that are generated by the shear layer instabilities. The spanwise vortical waves develop in a

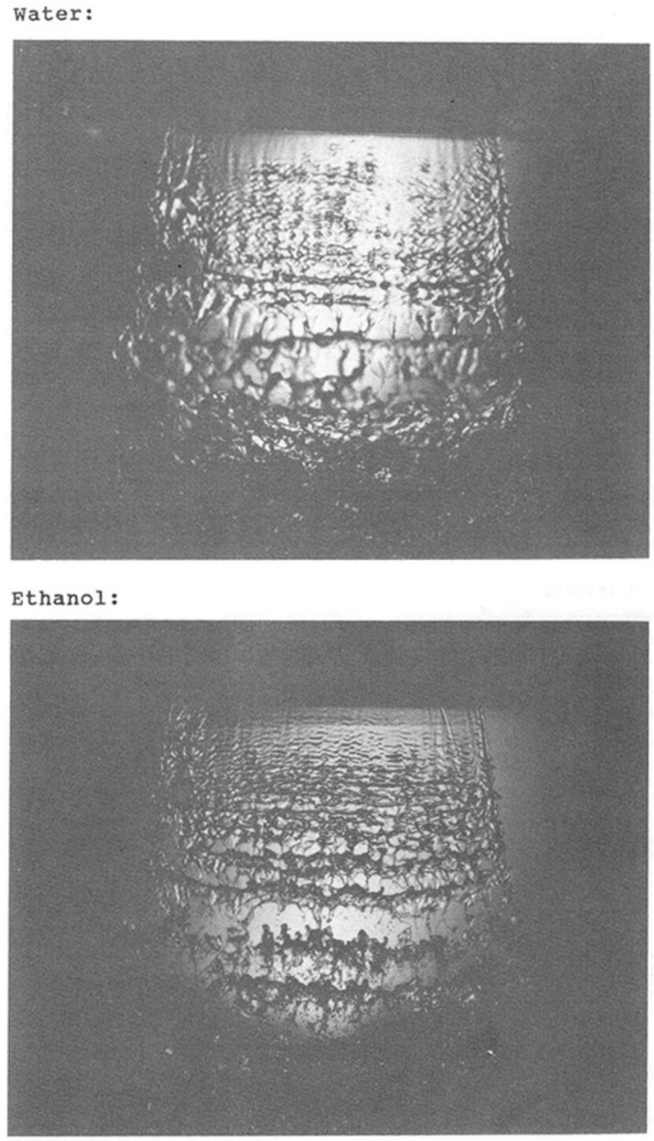


Fig. 7(*a*) Effect of liquid properties on "cellular breakup": face view, water and ethanol (Case 13)

shorter time, and appear more dominant than the streamwise vortical waves. The cellular structure in the ethylene glycol sheet is not as uniform as in the water sheet. After the spanwise ligaments break off the sheet, the streamwise ligaments formed by the ethylene glycol (higher viscosity fluid) remain intact for a longer time than those formed by the water.

Stretched Streamwise Ligament Breakup. The stretched streamwise ligament breakup mechanism is also affected by the liquid properties. Figure 8 is a face view of the three liquids at a low liquid flow condition (Case 22). The membrane formed between the streamwise vortical waves is broken up rapidly into small drops in the case of the lower surface tension liquid (ethanol). The streamwise ligaments of the water break off and form globules and then break up farther downstream into drops. The ethylene glycol stretches farther and the streamwise ligaments persist longer than those for either water or ethanol.

Conclusions

The breakup of a liquid sheet in a field of co-flow shearing air, and the effects of liquid properties on the breakup have been studied in a two-dimensional nozzle. Two mechanisms of breakup are identified. The first, termed "cellular breakup," exhibits vortical waves of equal strength in the streamwise and

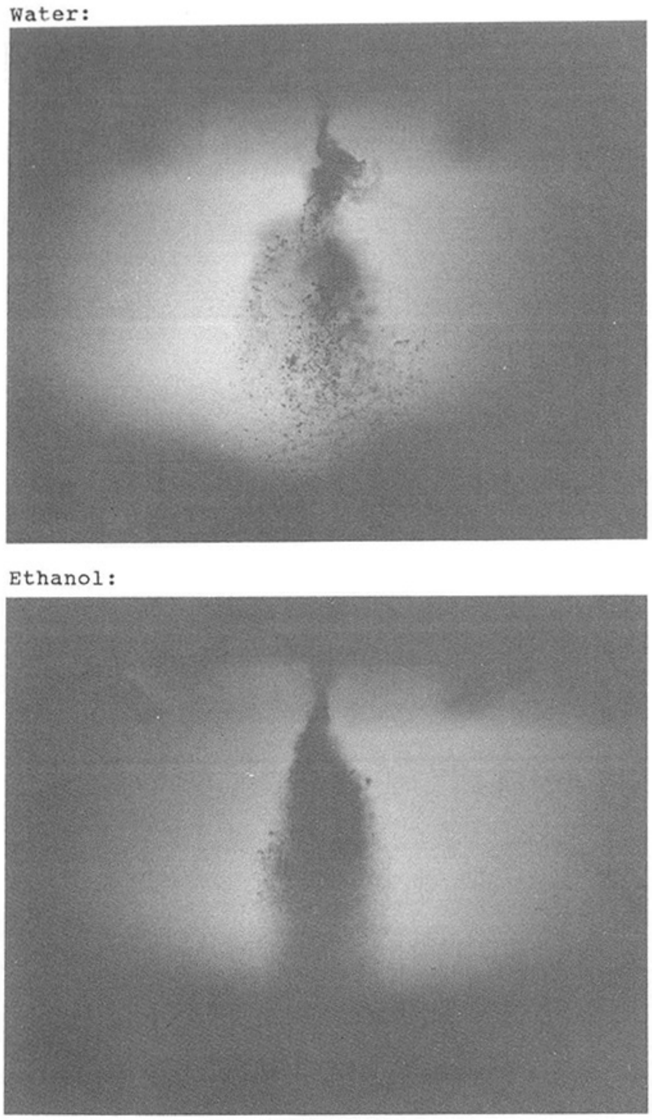


Fig. 7(*b*) Effect of liquid properties on "cellular breakup": side view, water and ethanol (Case 26)

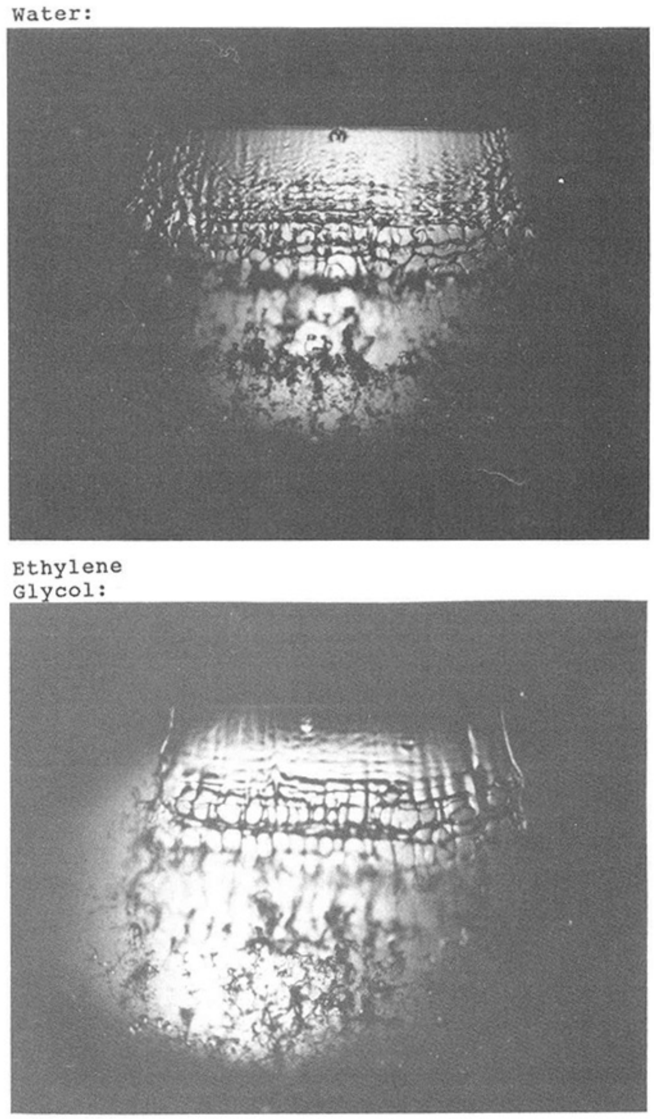


Fig. 7(*c*) Effect of liquid properties on "cellular breakup": face view, water and ethylene glycol (Case 14)

spanwise directions, with membranes stretched between. In this case, the streamwise vortical waves are broken off the sheet, forming spanwise ligaments downstream of the sheet. The second, termed "streamwise ligament stretching breakup," occurs at low liquid and air flow conditions. It is dominated by streamwise ligaments with thin membranes of liquid stretched between.

The liquid properties in the range evaluated do not change the breakup mechanisms, but do contribute to an altered form of the breakup in terms of the time and length scales. The ethanol (lower surface tension compared to water and ethylene glycol) displays smaller scale structures on the sheet, and a greater tendency to break up into droplets rather than form streamwise ligaments. The ethylene glycol (higher viscosity compared to water and ethanol) stretches farther before breakup, which results in the streamwise ligaments reaching smaller diameters before fragmenting into drops.

The breakup time of the sheet is dependent on liquid properties and relative velocity of the liquid and air. The ethanol (lower surface tension and density) demonstrates decreased breakup time, while the ethylene glycol (higher viscosity and density) exhibits increased breakup time relative to water.

The relationship of these events to the ultimate distribution of the droplets formed is the subject of present inquiry.

For the conditions and liquid properties examined, the following conclusions can be made:

- Liquid properties, especially excursions in surface tension and viscosity, do not appreciably change the basic mechanisms of cellular and stretched streamwise ligament breakup.
- Liquid properties can affect, however, the structural details of the sheet, leading to a notable change in the characteristic time and length scales associated with breakup.

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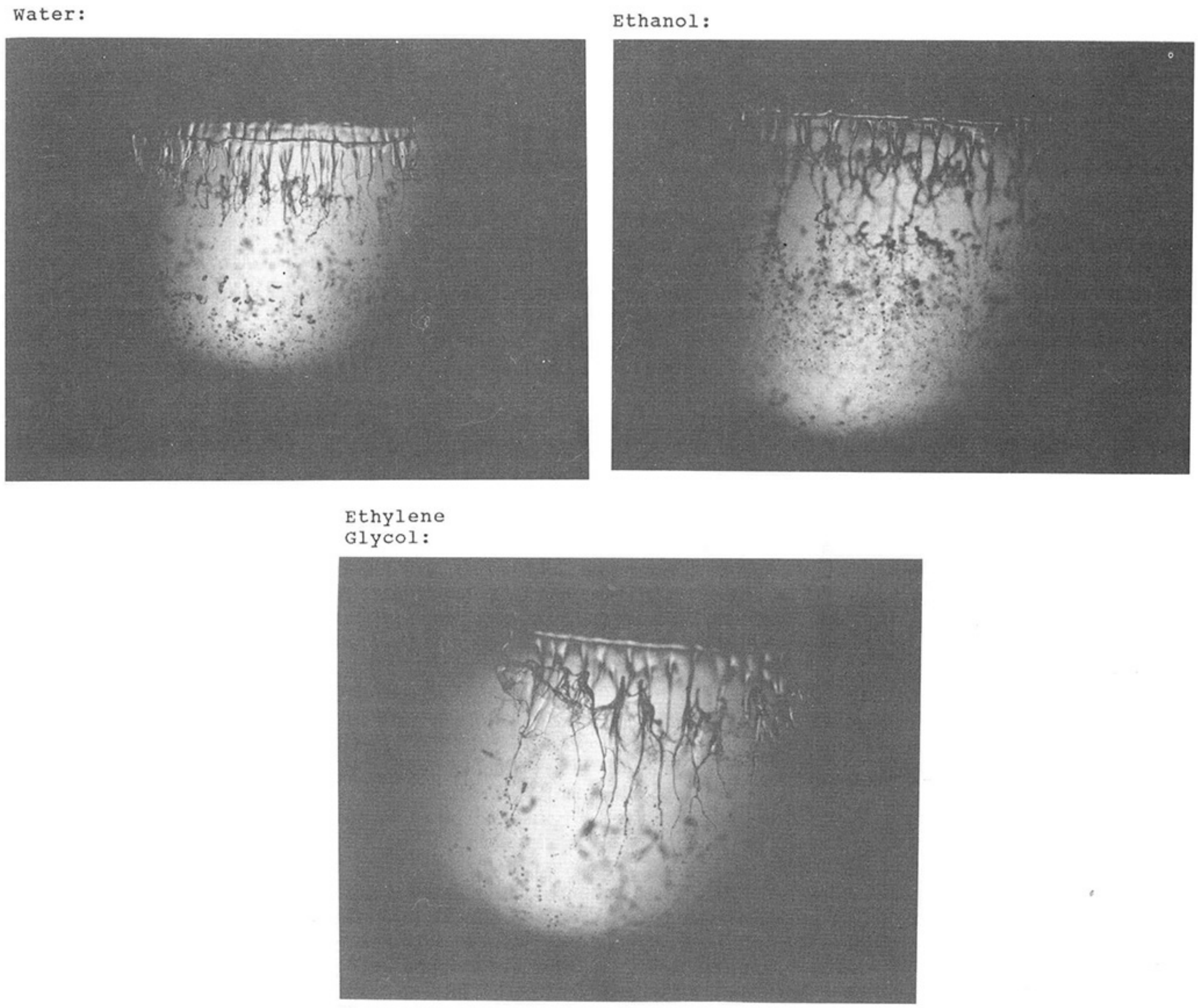

Fig. 8 Effect of liquid properties on "stretched streamwise ligament breakup" (Case 22): (*a*) water, (*b*) ethanol, (*c*) ethylene glycol

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