

Two instabilities in one liquid sheetSandip Dighe^{1,2,*}, Hrishikesh Gadgil^{2,†} and Tadd Truscott^{1,‡}¹*Mechanical Engineering Program, Physical Science and Engineering Division,
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We present a distinct feature of a fishbone pattern typically observed in the breakup of the liquid sheet formed by the oblique impingement of two liquid jets. The existence of a fishbone structure has been reported in the literature [1–4]. It is attributed to the capillary destabilization of the thick liquid rim that bounds the liquid sheet formed at relatively lower jet velocity. Destabilization of the rim is initiated with the formation of a varicose mode on the rim that forms the localized sites of higher liquid mass. The liquid flowing along the rim has to pass through the curvature. During this passage along the curved rim, the centrifugal force acts preferentially on the localized high liquid masses and these are expelled radially outward. These form the stretched ligaments rooted to the rim and they lag behind their roots due to the resistance of the ambient medium. Although this type of mechanism is invariably present in rim fragmentation, one does not observe this prominently in low-viscosity liquids like water since the ligaments further break before stretching significantly. In the case of high-viscosity liquids (like the glycerol-water mixture used in the present work), the detachment of ligaments from the rim is delayed due to viscous damping and the ligaments stretch and lean backward to produce a structure similar to a fish skeleton. This can easily be verified from Fig. 1 and from the works of Bush and Hasha [1] and Jung *et al.* [2].

The technique of liquid atomization by jet impingement is widely used in liquid rocket engine injectors due to their ability to generate optimal droplet sizes with uniform distribution, enabling efficient fuel-oxidizer mixing and stable combustion [5–9]. These injectors have been integral to major propulsion systems [6,7], including the F-1 engines of the Saturn V heavy launch vehicle [6], and remain common in spacecraft for attitude control and orbital maneuvers. These injectors operate by directing two high-velocity jets to collide at a controlled angle, producing a thin liquid sheet that breaks up via hydrodynamic instabilities into ligaments and droplets [8,10]. Understanding the breakup dynamics in such configurations has direct relevance to liquid propellant rocket injectors, where precise droplet formation control is essential [5–8].

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FIG. 1. A stroboscopic front view shows the breakup of a liquid sheet formed by the orthogonal impact of two liquid jets having a diameter of 1 mm. The front jet is visible in the image, while the second jet, being directly aligned behind it, is obscured from view. Atomization occurs through both rim breakup and wave-driven instabilities on the sheet, with visible perturbations originating at the point of impact. The Weber number of the jet is $We = 338$, and the Reynolds number is $Re = 103$.

In the present experiments, two cylindrical liquid jets having a diameter of 1 mm impinge at 90° on each other, creating a thin liquid sheet bordered by a thick rim, as shown in Fig. 1. The schematic of the experimental setup and optical arrangement for visualization of the liquid sheet is shown in Fig. 2. The impingement length, defined as the distance from the nozzle exit to the impact point, is 5 mm and utmost care has been taken to keep both the jets identical in all aspects. The liquid used is a glycerol-water mixture (80:20 by volume), which has a viscosity and a surface tension of 49.8 mPas and 64.8 mN/m. respectively. The glycerol-water mixture ratio affects key fluid properties such as viscosity and surface tension, which in turn influence the Weber number ($We = \rho V^2 d / \sigma$, where ρ is the liquid density, V the mean jet velocity, d the jet diameter, and σ the surface tension) and the Reynolds number ($Re = \rho V d / \mu$, where μ is the liquid viscosity) governing the breakup dynamics. Viscosity plays a key role in fishbone formation by influencing the rim size, the stability, and the breakup dynamics [1,2]. Fishbones emerge within a moderate viscosity range [1], low enough to permit wave growth yet high enough to suppress rapid rim instability, producing the clearest patterns [1]. Outside this range, sheets either break up irregularly at low viscosities or become overly stabilized at high viscosities. In this study, the 80:20 glycerol-water mixture has a slightly higher viscosity than that of Bush and Hasha [1], providing unprecedented clarity in observing sheet waves as seen in Fig. 1. High-resolution imaging and stroboscopic lighting are employed to visualize the fragmentation of the liquid sheet. Still images of the liquid sheet are captured using a Nikon D7200 digital single-lens reflex (DSLR) camera equipped with a 50-mm lens. The camera is configured with an aperture of f/5.6, an exposure time of 1/400 s, and an ISO sensitivity of 500, enabling the capture of detailed imagery despite the rapid motion of the

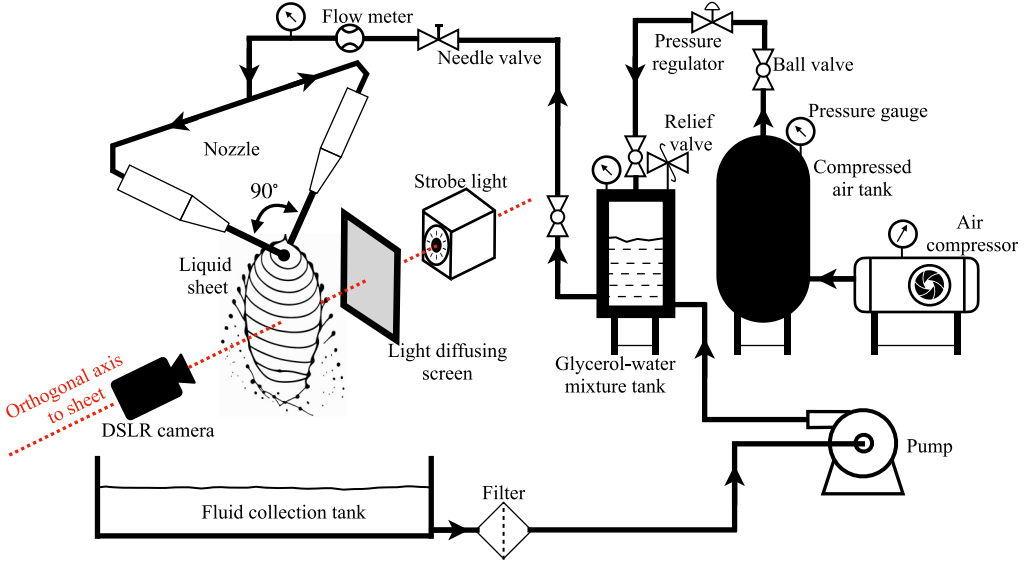


FIG. 2. Schematic of the experimental setup and optical arrangement for liquid sheet visualization. The glycerol-water mixture is stored in a pressurized tank, with high-pressure air used to maintain the required driving pressure. The pressurized fluid is supplied through a single feed line, which is then split into two identical branches feeding the nozzles. The lengths of both branches are kept equal to ensure the same pressure drop across each nozzle. Flow to the nozzles is monitored using a flow meter and regulated via a needle valve. For imaging, the camera, the light diffusing screen, and the strobe light are aligned along a single optical axis, oriented orthogonally to the plane of the liquid sheet.

liquid sheet. The DSLR provides a maximum image resolution of 6000×4000 pixels, enabling visualization of the minute details of fragmentation of a liquid sheet. To freeze the motion of the liquid during the experiments, a stroboscope (Sugawara, model: PS-250D) is employed, operating at a frequency of 440 Hz and a flash duration of $50 \mu\text{s}$. The intense and regular pulsing of the strobe light enhances the contrast and clarity of the captured images by intermittently illuminating the fast-moving liquid sheet, allowing clear observation of intricate liquid breakup characteristics.

Figure 1 depicts the formation of a classical fishbone pattern producing two well-defined vertical rows of bigger droplets accompanied by the smaller droplets resulting from the necking of the stretched ligaments. One major difference between fishbones reported in the literature [1,2] and the picture in Fig. 1 is that the surface of the liquid sheet has a wavy pattern that starts near the point of impact. The sheet surface has periodic waves and the rim has uniformly placed ligaments. A careful observation of fishbones in Bush and Hasha [1] shows that the sheet surface in those patterns is typically smooth and unperturbed. In fact, Bush and Hasha [1] mention that the formation of surface waves and the formation of radial ligaments seem to potentially synchronize with each other but they did not capture strong photographic evidence of the phenomena. Although these features have been predicted, capturing the coexistence of both instabilities with the clarity presented in Fig. 1 is worthy of highlighting. Thus, we classify the fishbone instability phenomena into (i) stable sheet fishbone [1] and (ii) unstable sheet fishbone as in Fig. 1.

We now turn our attention to the surface waves on the unstable sheet fishbone. One might argue that the waves are formed by aerodynamic interactions between the liquid sheet and the ambient medium (aka Kelvin-Helmholtz instability). However, if we increase the velocity of the impinging jets (i.e., increase sheet velocity) as shown in Figs. 3(a)–3(e), respectively, the sheet transitions from smooth (a), to wavy (b), to smooth (c), to wavy (d), and back to smooth (e). This behavior is not typical for increasing velocities within the Kelvin-Helmholtz instability. Thus, the

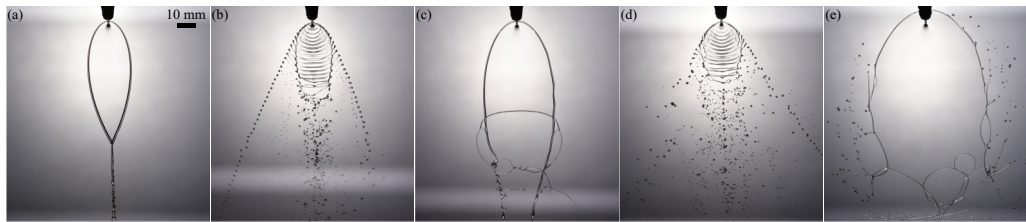


FIG. 3. Various regimes of the liquid sheet with the same experimental arrangement except an increasing jet velocity from panel (a) to panel (e): (a) closed rim ($We = 187$), (b) first unstable sheet fishbone ($We = 338$), (c) open rim or disintegrating sheet ($We = 401$), (d) second unstable sheet fishbone ($We = 446$), and (e) disintegrating sheet ($We = 795$).

wavy nature of the sheet seen in Fig. 1 may not be the consequence of the Kelvin-Helmholtz instability. Moreover, in contrast to typical convective instabilities [8,11–16], where infinitesimal disturbances grow gradually as they travel downstream and become observable only near the bottom edge of the sheet, the waves in our observations appear with significant amplitude right from the point of jet impingement, as clearly seen in Fig. 1, suggesting a fundamentally different underlying mechanism.

In addition, Jung *et al.* [2] proposed the necessity of asymmetry in colliding jet lengths for the existence of the stable sheet fishbone instability. Each of their impinging jets is a different length, with a ratio of 0.54 ($l_1/l_2 = 3.5 \text{ mm}/6.5 \text{ mm}$). Our jets are the same length; thus, asymmetry is not the source of the unstable sheet fishbones.

We now turn to the Weber number and Reynolds number to understand the sheet stability. The Reynolds number compares inertial to viscous forces and indicates how easily disturbances and turbulence develop within the jets and the resulting sheet, a higher Re generally produces more turbulent jets [5,17], leading to irregular sheet breakup, and violent sheet flapping [1,5], while a lower Re allows viscosity to dampen turbulence, leading to laminar jets [15,17] which stabilize the sheet. In the present study, the liquid jets are in the laminar regime, so turbulence effects are minimized, and disturbances in the sheet arise primarily from the impingement dynamics. The Weber number compares inertial to surface tension forces and governs whether the sheet remains intact or breaks up, a higher We leads to earlier breakup [5] and finer droplets [5], while a lower We favors a more stable sheet [1,5,8]. Together, Re and We determine the breakup mode [1,2,8,10] and the resulting droplet size distribution [5,8].

Our Weber number and our Reynolds number corresponding to the liquid sheet shown in Fig. 1 are $We = 338$ and $Re = 103$, which places our Reynolds number near the lower end of the Reynolds number range reported by Jung *et al.* [2] ($49 \leq We \leq 100$ and $100 \leq Re \leq 280$), while the Weber number lies significantly above the Jung *et al.* [2] range and well within the regime identified by Bush and Hasha [1] ($169 \leq We \leq 900$ and $180 \leq Re \leq 760$). The presence of asymmetry might be the reason why Jung *et al.* [2] could trigger the fishbone at lower Reynolds and Weber numbers. Additionally, their study used long nozzles with an internal length-to-diameter ratio of 30, whereas the present study employs short nozzles with a ratio of 5. This difference in nozzle geometry can lead to distinct velocity profiles at the jet exit [18], which in turn influence the Reynolds and Weber number thresholds for transitions between liquid sheet regimes, including fishbones. These discrepancies highlight that the Weber and Reynolds numbers associated with the fishbone instability differ considerably across studies and are also influenced by the nozzle properties, indicating that these parameters alone are insufficient to reliably predict its onset.

One other possible source of the unstable sheet fishbone could be periodic perturbations within the nozzle that propagate to the impingement point (e.g., a Helmholtz resonator [19]). As the velocity of the jet increases, the unstable sheet fishbone occurs in Fig. 3(b) and then goes away in Fig. 3(c) and reoccurs in Fig. 3(d), similar to acoustic harmonics. We note that when we performed

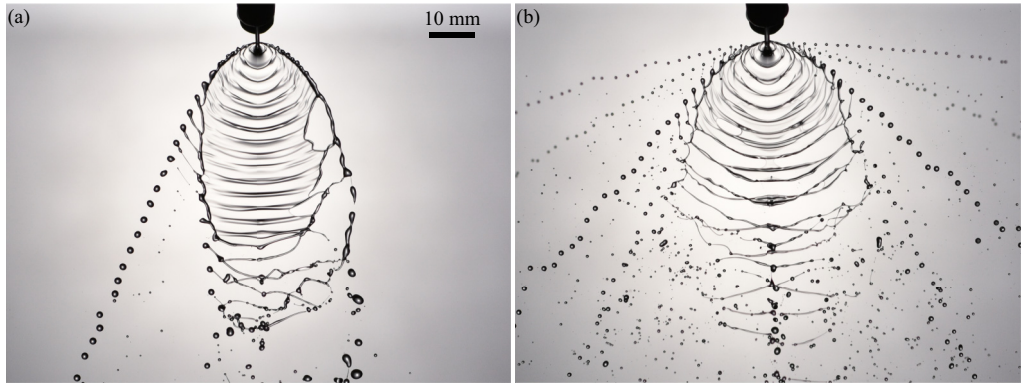


FIG. 4. Transition of the unstable sheet fishbone structure into (a) an asymmetric sheet or (b) a sheet with multiple droplet trails emanating from the rim. The Weber number and the Reynolds number of the jet are the same as in Fig. 1, showing how small perturbations in the jet flow can alter the behavior of the phenomenon.

the experiments there was a distinct noise produced only when the unstable sheet regimes appeared. While this hypothesis is compelling, a definitive conclusion requires further investigation and a more detailed stability analysis.

Figure 3 illustrates other well known regimes of the stable sheet fishbone that emerge with increasing jet velocity, including the closed rim [Fig. 3(a)], the open rim [Fig. 3(c)], and the disintegrating sheet [Fig. 3(e)]. Further, the fishbone structure observed in the present study is very sensitive to small flow fluctuations in the nozzle (similar to what others report [2]). This is evident from instances where the sheet transitions into an asymmetric shape [Fig. 4(a)] or breaks violently, producing multiple (three or four) droplet trails from the rim, as shown in Fig. 4(b).

This study offers a detailed visual and conceptual exploration of two distinct instabilities: rim fragmentation (fishbone) and surface wave formation coexisting within a single liquid sheet formed by the orthogonal impingement of two jets. While the classical fishbone pattern (aka stable sheet fishbone) has been previously associated with capillary breakup of the sheet rim, our observations reveal an additional and previously underdocumented wavelike disturbance on the sheet surface, initiating directly at the point of impact (aka unstable sheet fishbone). The wavy sheet pattern cannot be easily explained by conventional aerodynamic (Kelvin-Helmholtz) or convective instabilities, suggesting a more complex or intrinsic mechanism at play. Through careful experimentation and high-resolution imaging, we show that the instability is highly sensitive to flow velocity, flow fluctuations, nozzle geometry, and potentially even acoustic resonances within the nozzle system. These findings not only highlight nuances in the breakup mechanisms of liquid sheets but also raise important questions about the role of internal jet dynamics in driving such patterns. Future work is aimed at isolating these influences through stability analysis and controlled perturbations to provide a more complete understanding of these phenomena.

Data availability. The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

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