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Impinging liquid jets on flat fluid interfaces

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Abstract. We study the impact of a liquid jet on a liquid bath in the presence of an external Newtonian liquid. Attention is given to the impact zone where we find a stationary wave-like behavior of the liquid column. We unravel new dynamics, seen at high acquisition frame rates, of the instability of the liquid column at the critical distance between the capillary tip and the surface of the fluid bath. A dominant critical frequency of oscillation is found. Particle Image Velocimetry measurements of the velocity field, in the vicinity of the impact zone, are also performed, with emphasis on the vortex structure that develops near the flat interface.

1. Introduction

Impinging phenomena have always been associated with gas jets. The benchmark problem is that of a gas jet impinging on a flat solid surface. Prior works have shown both their importance in heat transfer enhancement and fundamental knowledge of fluid flow [1-6]. Let us now consider a liquid exiting a nozzle at a constant flow rate. When convective forces overcome surface/interfacial forces, a liquid jet will form. The instability of such liquid columns has been the subject of several past studies due to their implications on fundamental aspects of unstable flows and practical industrial applications [7-9]. If the liquid jet impinges on a fluid bath, a train of standing waves will emerge close to the free surface. The corrugations decay upstream having a velocity equal to that of the impinging jet.

Past studies have shown that predictions given by dispersion relations can be used to describe the wavelength and the decay factor of such waves [10,11]. The addition of a surfactant triggers the appearance of a secondary phenomenon known as the “fluid pipe” phenomenon [12]. So far, the problem of such liquid jets impinging on flat liquid interfaces has received little attention when compared to similar capillary phenomena.

In this paper, we investigate the impact of a water jet, surrounded by another immiscible liquid, on a liquid bath (see figure 1-a). By increasing the distance between the capillary tip and the horizontal interface we obtain the critical distance at which the liquid column starts to oscillate and subsequently break the connection with the interface. For the working two-liquid case, one finds a dominant frequency of oscillation by means of Fourier analysis. PIV measurements in the external flow field are also performed having as primary target the description of the toroidal vortex generated by the impact.

2. Experimental details

The experimental setup consists of a large glass tank filled with sunflower-seed oil and water, as depicted in figure 1-b. A mechanical mechanism was used to handle the position of the capillary. Before injection, the capillary tip is lowered such that it punctures the water-oil interface.



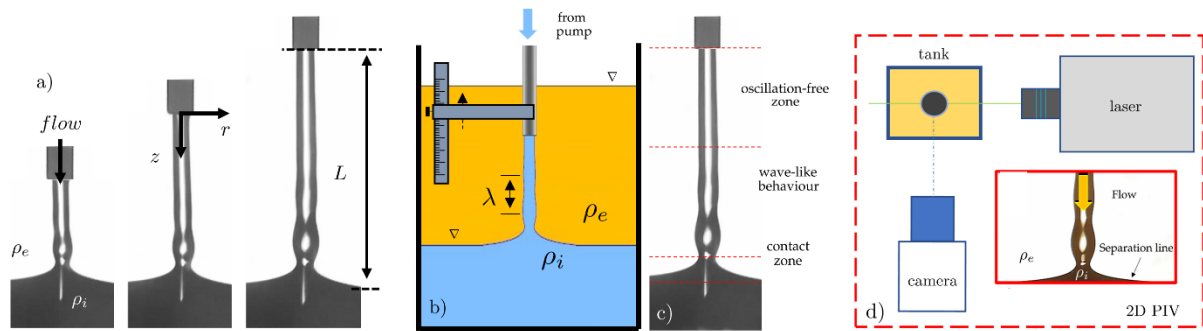


Figure 1. a) Shape of a water jet impinging on a flat liquid interface; oil (ρ_e) and water (ρ_i) system for three different positions of the capillary with respect to the horizontal interface. b) Schematic of the experimental setup; c) Depiction of a plunging liquid jet, at steady state, surrounded by another immiscible liquid (liquid column length below the critical value); d) Schematic representation of the 2D PIV measuring system.

The flow rate was adjusted using a Harvard PHD Ultra syringe pump and set at 10 ml/min which ensured the formation of a liquid column. The inner diameter of the capillary is $D_0 = 0.51 \text{ mm}$, much lower than the capillary length of the two-liquid system, $l_c \approx 5.6 \text{ mm}$, a length scale where interfacial forces should dominate. The phenomena are recorded with a high-speed camera working at 5000 fps. Image processing was made with an in-house algorithm implemented in Matlab. The density was determined using a mass per volume method, and the interfacial tension using the pendant drop method. The viscosity of the liquid was measured with a rotational rheometer (Anton Paar Physica) using a cone-plate geometry.

The injected liquid is pure water, with density $\rho_i = 1000 \text{ kg/m}^3$ and viscosity $\eta_i = 1 \text{ mPa s}$, and the external liquid is sunflower-seed oil, with a density of $\rho_e = 920 \text{ kg/m}^3$ and a viscosity 55 times larger than that of water, $\eta_e = 55 \text{ mPa s}$. The interfacial tension was found to be $\gamma = 0.025 \text{ N/m}$.

We start the injection of liquid with the capillary tip in the heavier liquid, which is the same kind as the one being injected. The capillary is then gradually lifted, and the liquid is now injected into the less dense fluid, the horizontal fluid bath suppressing breakup and drop formation. By increasing the distance between the capillary tip and the flat interface, the liquid column reaches a critical height at which the jet starts oscillating. Beyond this critical value, the liquid column breaks near the point of impact. Several measurements are performed in order to quantify this threshold value.

It is important to specify the value of some common dimensionless parameters that describe the flow regime: $We = \rho_i V^2 D_0 / \gamma \approx 13$, $Re = \rho_i V D_0 / \eta_i \approx 408$, $Ca = \eta_i V / \gamma \approx 0.032$, $\alpha = \rho_i / \rho_e \approx 1.08$, $\beta = \eta_i / \eta_e \approx 0.018$, where V is the average flow velocity, We represents the Weber number, Re the Reynolds number, Ca the capillary number, with α and β as the density and the viscosity ratio, respectively.

The velocity field generated by the input flow rate was determined using a PIV (Particle Image Velocimetry) technique. The setup consists of one high-speed camera, SpeedSence VEO 340, having a resolution of 2560×1600 , and a laser sheet of 1 mm in thickness (see figure 1-d). The external liquid was seeded with glass hollow spheres of $1 - 10 \text{ }\mu\text{m}$ in diameter at a density of 6 mg/L . The velocity field is then determined by an Adaptive PIV method implemented by Dantec Dynamics. The method gave less than 2% erroneous velocity vectors. The acquisition frequency was set at 500 Hz . The interrogation area (IA) was set as follows: grid step size 16×16 , width vs. height, minimum IA 32×32 , maximum IA 64×64 . The number of iterations was set at 50.

3. Results

3.1. Critical breakup length

The breakup length of such jets is usually a linear function of the average velocity. For free liquid jets, it has been shown that the breakup length can be written as

$$L_b = C \frac{V}{\omega} \quad (1)$$

where ω is the temporal growth rate of instability given by Tomotika's dispersion relation [13-15] for the current two-liquid system and $C = \ln(R_0/\epsilon_0)$, with R_0 the radius of the capillary and ϵ_0 as the amplitude of some initial random perturbation. Taking ϵ_0 to be 1% of R_0 and $\omega = 394 \text{ s}^{-1}$, we find the critical breakup length to be $L_b \approx 9.35 \text{ mm}$. Measurements of the critical height between the capillary tip and the flat liquid bath reveal poor agreement with theoretical values, $L_b \approx 33 \text{ mm}$ vs 9.35 mm . The comparison between these two similar capillary phenomena, the unbounded liquid jet and the impinging jet, is somewhat misleading since we observe no temporal evolution of the liquid column. Considering a spatially evolving liquid column, one can write

$$R(z) = R_0 + \epsilon_0 \exp(sz) \cos(kz), \quad (2)$$

where s is the spatial growth rate and k the wavenumber. When the critical height is reached $\cos(kL_b) \approx -1$ and $R(L_b) = 0$, which yields

$$L_b = \frac{\ln\left(\frac{R_0}{\epsilon_0}\right)}{s}. \quad (3)$$

For the current water-oil system, the value of the spatial growth rate was found to be $s = 139.55 \text{ m}^{-1}$, considering $L_b = 33 \text{ mm}$ and $\epsilon_0 = 1\% R_0$. Also, since the cosine must reach negative one for instability to occur, its argument must be an odd function of π

$$kL_b = (2n - 1) \pi, \quad (4)$$

Measurement of the distance between the last two successive peaks gives the value of the wavelength of the dominant spatial perturbation and its corresponding wavenumber $\lambda = 2\pi/k \approx 3.4 \text{ mm}$. The value is also close to the wavelength of the fastest-growing mode given by Tomotika's dispersion relation [13]. For $n = 10$ one finds the critical length to be $L_b = 32.2 \text{ mm}$, which is close to the measured value.

3.2. Dominant frequency of oscillation

Below the critical threshold value, the liquid column is characterized by three zones, as depicted in figure 1-c. Near the capillary tip, we observe an oscillation-free zone followed by a varicose zone indicating wave-like behavior, and the contact zone where the liquid column merges with the liquid bath. When the distance between the capillary tip and the liquid bath reaches a critical length, the liquid column starts to oscillate. Figure 2-b shows the time evolution of the diameter of the liquid column for several heights Z_i above the liquid bath (see figure 2-a). They all show the same periodic behavior. The Fourier amplitude spectrum of the data shows a dominant frequency of 24 Hz (see figure 2-c). Figure 2-d also shows that the difference between the maximum and minimum value of the amplitude increases with height.

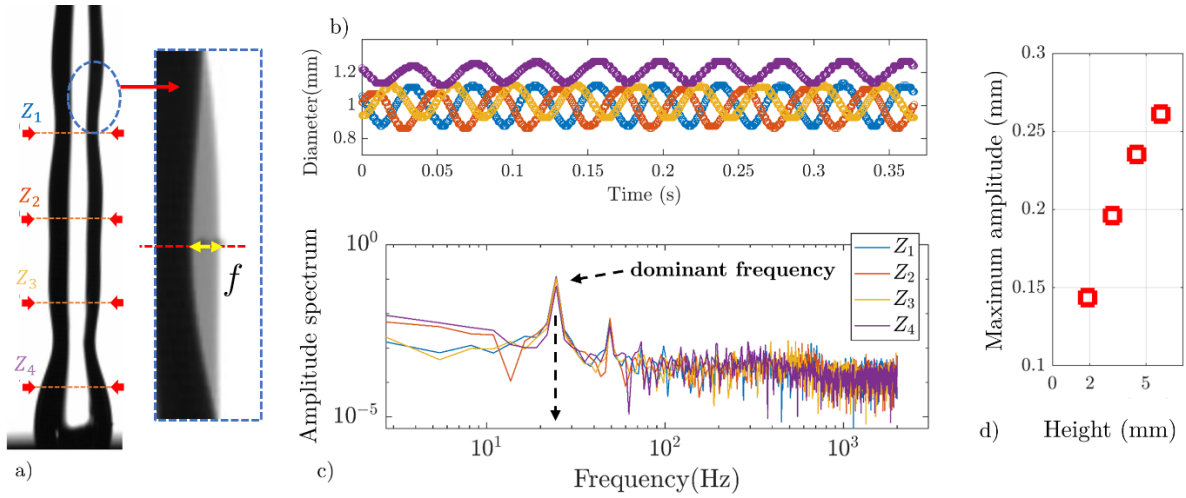


Figure 2. Oscillations of the diameter of the liquid column (b) characteristic to four different heights above the liquid bath, as depicted in (a). The link is made via color-coding. c) Fourier amplitude spectrum showing a dominant frequency of approximately 24 Hz. d) Maximum oscillation amplitude of four characteristic cross-sections. as depicted in (a), as a function of the height above the liquid bath. The characteristic dimensionless parameters of the two-liquid system are: $We \approx 13$, $Re \approx 408$, $Ca \approx 0.032$, $\alpha \approx 1.08$, and $\beta \approx 0.018$.

In order to qualitatively describe this frequency, we seek analogy with stationary waves on a string. The frequency of such waves is given by

$$f = \frac{n}{2L} \sqrt{\frac{T}{\rho_l}}, \quad (5)$$

where T is the tension in the string and ρ_l its linear density. Considering T in this case as being surface tension, for $n = 2$ one can rewrite the above equation as

$$f = \frac{1}{L_b} \sqrt{\frac{4\gamma L_b}{\pi D_m^2 \rho}}, \quad (6)$$

where $\rho = (\rho_i + \rho_e)/2$ and $D_m \approx 1 \text{ mm}$ is the average diameter of the column. The theoretical prediction of equation (6) is approximately 31 Hz which is close to the experimental value, 24 Hz.

The value of the Weber number suggests the formation of liquid jets which is indeed what we observe. On the other hand, the low value of the capillary number shows that interfacial forces are dominant compared to viscous dissipation inside the liquid column. Significant dissipative action may come from the external liquid which is 55 times more viscous than the injected one. PIV measurements reveal the formation of a large toroidal vortex near the water-oil interface (see figure 3). The velocity distribution outside the liquid column is depicted in figure 3-a where we capture and observe the alleged axial symmetry of the phenomenon. This can also be seen in the computed vorticity field as shown in figure 3-b. Negative values of the vorticity field suggest the presence of counter-rotating vortices. A toroidal-type vortex is the rationalized since we consider axial symmetry. Vorticity is concentrated near interfaces (near the jet or the water-oil interface) and rapidly decays in the radial direction.

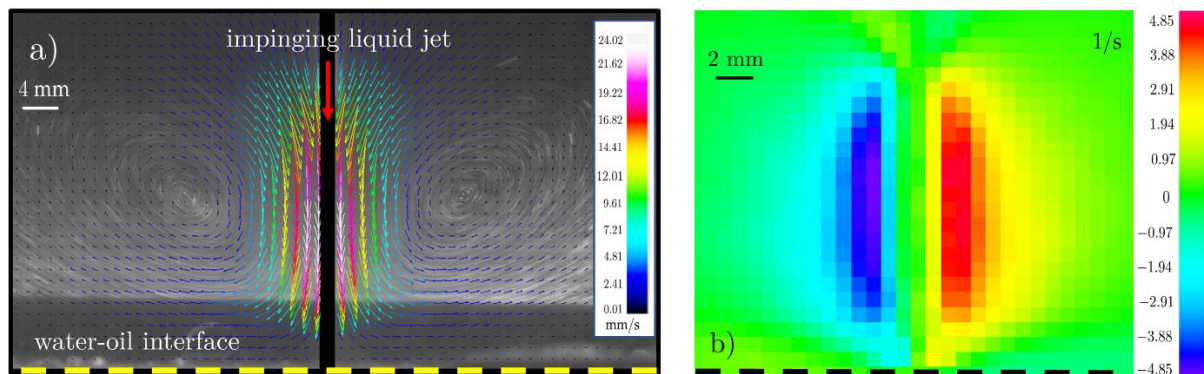


Figure 3. Depiction of the large vortex structure near the flat interface and the computed velocity field (a), superposed over an instantaneous picture of the flow, together with the vorticity field (b).

4. Conclusions

In this paper, we study the problem of a liquid jet impinging on a liquid bath in the presence of a viscous outer immiscible liquid. For a water-oil system, $\beta = 0.018$ with $We = 13$, a dominant critical frequency of 24 Hz was found when the distance between the capillary tip and the horizontal surface reaches the threshold limit. Stationary wave theory was found to qualitatively describe the observed value of the dominant frequency. The spatial growth rate of the liquid column was found to be approximately 139.55 m^{-1} . The difference between the maximum and minimum value of the diameter of the oscillating liquid jet increases with the height from the horizontal liquid interface. This observation will be further analysed to determine if this is indeed the signature of travelling or a stationary wave-like behavior. PIV measurements reveal a large toroidal vortex structure residing near the horizontal surface, with vorticity decaying rapidly in the radial direction. The use of the vorticity field is indeed a fast way to visualize vortices but seldom used to identify vortices, for which more appropriate methods are used [16-17].

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