Noncoalescence in the Oblique Collision of Fluid Jets

Navish Wadhwa, ¹,* Pavlos Vlachos, ² and Sungwan Jung¹,†

¹Department of Engineering Science and Mechanics, Virginia Tech, Blacksburg, Virginia 24060, USA
²Department of Mechanical Engineering, Virginia Tech, Blacksburg, Virginia 24060, USA

(Received 31 October 2012; revised manuscript received 8 February 2013; published 20 March 2013)

When two jets of fluid collide, they can “bounce” off each other, due to a thin film of air which keeps them separated. We describe the phenomenon of stable noncoalescence between two jets of the same fluid, colliding obliquely with each other. Using a simple experimental setup, we carry out a parametric study of the bouncing jets by varying the jet diameter, velocity, angle of inclination, and fluid viscosity, which suggests that the contact time of bouncing jets scales as the square root of the normal Weber number We. A dimensionless parameter $K = (\text{We} \sqrt{\text{Re} / \sin \alpha})^{1/2}$, where Re is the normal Reynolds number and $\alpha$ the angle of inclination of the jets, quantitatively captures the transition of colliding jets from bouncing to coalescence. This parameter draws parallels between jet coalescence and droplet splashing and indicates that the transition is governed by a surface instability. Stable and continuous noncoalescence between fluid jets makes it a good platform for experimental studies of the interaction between fluid interfaces and the properties of the interfacial air films.

DOI: 10.1103/PhysRevLett.110.124502

PACS numbers: 47.55.df, 47.15.—x, 47.55.N–

While intuition tells us that two streams of fluid colliding with each other will mix together into one stream, that is not always the case. Contrary to the expectation, two jets of fluid can undergo stable noncoalescence and thus bounce off each other upon collision [Fig. 1(a)]. Understanding the interaction between two fluid interfaces is central to a variety of industrial and everyday processes, such as raindrop formation [1], spray coating [2], inkjet printing [3], and metallurgical processes [4]. In 1878, Lord Rayleigh [5,6] was the first to point out that drops emerging from them lie in the same vertical plane and collide with each other obliquely. Needles with interfacial air films. These oils have kinematic viscosity $\nu = 4.37, 8.52, 17.9, \text{and} 46.6 \text{cSt}$, surface tension $\sigma = 19.7, 20.1, 20.6, \text{and} 20.8 \text{mN/m}$, and density $\rho = 918, 935, 950, \text{and} 960 \text{kg/m}^3$, respectively. A few experiments with glycerol solution in water (75% by weight, $\sigma = 66.1 \text{mN/m}$, $\nu = 22.44 \text{cSt}$, and $\rho = 1195 \text{kg/m}^3$) are conducted to explore the role of surface tension. Two blunt tip stainless steel needles with a circular cross section are fitted on three-axis translation stages and arranged such that the jets emerging from them lie in the same vertical plane and collide with each other obliquely. Needles with internal diameter $D = 0.58, 0.65, 0.81, 0.97, \text{and} 1.35 \text{mm}$ are used in this study. The needles are supplied with fluid from two glass syringes using a syringe pump, whose flow rates could be precisely adjusted to control the velocity of the colliding jets. Flow rates ranging from 400 to 2900 ml/hr are used in the experiments. The collision region is imaged using a digital SLR camera, from a direction perpendicular to the plane containing the jets.

Figure 1(a) shows an example of two silicone oil jets bouncing off each other upon collision. The jets drag along air into the collision region where it is squeezed in a thin film. Since the thickness of the air film is much smaller than the other dimensions, lubrication approximation is applicable [20], which results in high magnitude forces keeping the jets apart. When the jet velocity $V$ is increased beyond a threshold, the jets undergo coalescence, as shown in Fig. 1(b).

Silicone oils (Clearco Products Co., Inc.) are used for most experiments in order to avoid any surface contamination. These oils have kinematic viscosity $\nu = 4.37, 8.52, 17.9, \text{and} 46.6 \text{cSt}$, surface tension $\sigma = 19.7, 20.1, 20.6, \text{and} 20.8 \text{mN/m}$, and density $\rho = 918, 935, 950, \text{and} 960 \text{kg/m}^3$, respectively. A few experiments with glycerol solution in water (75% by weight, $\sigma = 66.1 \text{mN/m}$, $\nu = 22.44 \text{cSt}$, and $\rho = 1195 \text{kg/m}^3$) are conducted to explore the role of surface tension. Two blunt tip stainless steel needles with a circular cross section are fitted on three-axis translation stages and arranged such that the jets emerging from them lie in the same vertical plane and collide with each other obliquely. Needles with internal diameter $D = 0.58, 0.65, 0.81, 0.97, \text{and} 1.35 \text{mm}$ are used in this study. The needles are supplied with fluid from two glass syringes using a syringe pump, whose flow rates could be precisely adjusted to control the velocity of the colliding jets. Flow rates ranging from 400 to 2900 ml/hr are used in the experiments. The collision region is imaged using a digital SLR camera, from a direction perpendicular to the plane containing the jets.

We measure the contact length $L$ and the jet angle $\alpha$ of bouncing jets from the images for various combinations of $V$ and $D$ for different fluid viscosities [inset in Fig. 2(a)]. We then calculate the contact time $T$ by dividing $L$ with the
vertical component of the jet velocity, such that $T = L/V \cos \alpha$. Assuming that the rebound of the jets is inertial, $T$ can be derived from a scaling analysis by considering a balance between the kinetic and surface energies at maximal deformation. If the kinetic energy due to velocity normal to the collision plane (of the order of $\rho (V \sin \alpha)^2 D^3$, with $V \sim \delta/T$ where $\delta$ is the change in diameter of the jet during the collision) is balanced with surface energy (of the order of $\sigma \delta^2$), then we get $T \sim (\rho D^3 \sin^2 \alpha / \sigma)^{1/2}$. In a dimensionless form, this scaling can be written as $T \times V/D \sim (We)^{1/2}$, where $We$ is the normal Weber number, defined as $We = \rho (V \sin \alpha)^2 D / \sigma$.

Plotted against $We$ on a logarithmic scale, the dimensionless contact time $T \times V/D$ is seen to scale with $We$, as shown in Fig. 2(a). The best fit line has a slope of 0.49 ($\text{rmse} = 0.12$, $R^2 = 0.82$), suggesting a square root scaling. The plot includes data for five different values of $V$ and four different values of $\nu$, for various jet angles (see Supplemental Material [21] for the data points corresponding to different angles). Two data points for glycerol solution (which has a much higher surface tension than silicone oil) also fall on top of the silicone oil data, thus confirming the scaling. By rearranging the terms in this scaling, we get $T/D^{3/2} \sin \alpha \sim (\rho / \sigma)^{1/2}$. For the experiments with different silicone oils, which all have almost the same value of surface tension and density, $T/D^{3/2} \sin \alpha$ should be independent of $V$ and roughly constant. Figure 2(b) shows $T/D^{3/2} \sin \alpha$ plotted against $V$, and it shows no significant trend with $V$ (see Supplemental Material [21] for a plot highlighting the effect of diameter).

These results are in good agreement with the previous studies involving drops bouncing on hydrophobic surfaces [22], beads bouncing on elastic membranes [23], and drops bouncing on soap films [17]. The rebound of the jets is caused by surface tension acting like a compressed spring during the collision. Bouncing jets thus act like a classic inertial spring system, for which the time period is proportional to the square root of the ratio of inertia to the spring constant. Surface tension acts as the spring constant and the ratio of inertia to the surface tension is given by $We$. The contact time is, therefore, found to scale with the square root of $We$, within experimental error.

We investigate the transition of colliding jets from bouncing to coalescence in another set of experiments. In the coalescence state, no bouncing is observed in the jets upon collision. In contrast, the bouncing state is bistable; the jets can coalesce due to dirt or perturbation and stay coalesced. In order to distinguish between such events of coalescence and true transition to coalescence, we employ the following method. Starting with two coalesced jets, bouncing is initiated by perturbing them with a needle and the time elapsed from the beginning of bouncing to recoalescence is measured. This is repeated 20 times and median bouncing life-time of the jets decreases monotonically with an increase in velocity, as shown in the inset in Fig. 3(a).
Beyond a threshold velocity, no bouncing is observed in 20 trials and the median bouncing life-time thus dropped down to 0. This velocity is termed as the transition velocity \( V_{cr} \) for the given set of fluid properties, jet diameter, and angle. For fixed \( \nu/C_{23} \), the transition velocity decreases both with an increase in \( D \) and in \( \nu/C_{11} \) [Fig. 3(a)]. We thus determined \( V_{cr} \) for various combinations of \( \nu/C_{23}, D, \) and \( \nu/C_{11} \).

A unifying criterion for transition from bouncing to coalescence is found in terms of the parameter \( K \), defined as \( K = (Wef^{\sqrt{\text{Re}}}/\sin \alpha)^{1/2} \), where \( Wef \) is the normal Weber number as defined earlier, and \( \text{Re} \) the normal Reynolds number defined as \( \text{Re} = V \sin \alpha \times D/\nu \). This is graphically shown in Fig. 3(b), which shows \( K \) for observations from experiments with four different jet diameters and three different viscosities, with solid symbols representing coalescence and open symbols representing bouncing. The solid, horizontal line represents the average critical value of \( K \), termed \( K_{cr} \), which is found to be 6.1. When the transition velocity \( V_{cr} \) is backcalculated from \( K_{cr} = 6.1 \), it matches very well with the observed transition velocity [dashed lines in Fig. 3(a)].

The parameter \( K \) has previously been reported in the literature, albeit without the \( \sin \alpha \) in the denominator [24–26]. In the phenomenon of drop impact on a solid surface, it has been shown to be responsible for the transition between depositing and crown formation in the impacting drop. We infer that the transition to coalescence in colliding jets is governed by a similar instability as that in the crowning or splashing of drops. During the collision of the jets, at higher velocities, the fluid interface has a tendency to become unstable due to the high value of inertia dominating the surface tension forces. Further, the size of these instabilities or lamellae is dictated by the momentum boundary layer thickness, as argued in the droplet splashing studies [24,27,28]. The balance between inertia and surface tension, combined with the length scale proportionality to the momentum boundary layer thickness, results in the combination of dimensionless numbers denoted as the parameter \( K \).

Another possible explanation for the transition from bouncing to coalescence is the thinning of the air film separating the jets, to a critical thickness required for...
Bouncing jets is a rich system to study; while we focused on the collision of jets with identical properties, one could have different hydrodynamic and physical properties in the two colliding jets, with a different set of dimensionless parameters for each of the jets. We also observed bouncing in three colliding jets for two different configurations, one in which jets were in the same vertical plane and another in which they were in three different planes (see Supplemental Material [21] for images). We hope that the stable and continuous noncoalescence in bouncing jets can be useful in gaining a better understanding of fluid-fluid noncoalescence and interfacial dynamics.

Authors wish to thank Tomas Bohr and Anders Andersen for useful discussions. Acknowledgment is made to the donors of American Chemical Society Petroleum Research Fund No. (PRF# 52332-DNI9) for support of this research.

*Present address: Department of Physics, Technical University of Denmark, 2800 Kongens Lyngby, Denmark.
†sunnyjsh@vt.edu