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Unique shapes of liquid bells as a function of flow parameters: A brief overview and some new results

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HIGHLIGHTS

- Parametric study on liquid bells is conducted.
- Dependence of bell geometry on various factors is studied.
- Gravity, viscosity and surface tension of the liquid affect bell shape.
- Diameter and velocity of the liquid jet affect bell geometry.
- Unique shapes of liquid bell are observed.

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ABSTRACT

The shape of liquid bells formed by thin liquid sheets due to the impingement of jets onto disc shaped objects depends on a large number of parameters. These parameters include physical properties of the liquid like viscosity and surface tension, gravitational acceleration, jet velocity as well as the diameters of the liquid jet and the target disc. In this work the variation of the shape of a liquid bell due to the effect of the above parameters has been investigated based on the governing equations of the bell. It has been observed that for a given impactor diameter a smaller jet diameter results in more symmetrical shapes. Further, the symmetry of the liquid bells increases as $\mathbf{g}$ is reduced. Reduction of surface tension has a dramatic effect on bell shapes. Primarily, the maximum radius and length of the bells increase with decreasing surface tension. For a combination of low surface tension with a non-zero pressure difference across the bell surface, unique shapes are seen to appear. Experiments conducted also confirm the bell shapes predicted by the analysis.

1. Introduction

The dynamics of free liquid sheets has long been a topic of interest for scientists and engineers. Savart was one of the pioneers to initiate the study back in 1833 [1–4]. Due to a wide range of practical applications this problem is still very relevant. The formation of liquid sheets plays an important role in atomization processes [5]. Besides, due to the large surface area of liquid sheets, they are very effective for mass transfer and reaction. Liquid sheets find use in liquid curtains such as those involved in coating techniques or in paper making. Bell shaped water fountains are used for recreation and beautification for their unique aesthetics [6].

Savart considered a cylindrical liquid jet of diameter D_0 traveling with a velocity U_0 and impacting normally on a disc shaped target of diameter D_i in his experiments. According to his observations, if X is the ratio of the diameters D_i and D_0, various phenomena may be observed depending on the value of X, where $X = 0$ deals with the capillary instability of liquid jets and $X \gg 1$ showcases the hydraulic jump phenomenon. The hydraulic jump is a ring like structure forming at a particular radius with the jet at its center due to a sudden thickening of the flow. In the intermediate domain of $X \approx 1$ the fluid spreads radially on the surface of the disc and upon reaching the edge it ejects at a certain angle forming a bell like moving sheet of fluid. This fluid structure has since been known as a liquid bell in the literature. Fig. 1(a) shows a typical liquid bell observed by the present authors in the laboratory. Fig. 1(b) shows a cartoon of the bell along with the geometrical parameters needed for its description.

Since Savart demonstrated the existence of liquid bells, considerable volume of work has been devoted to develop the subject. Re-

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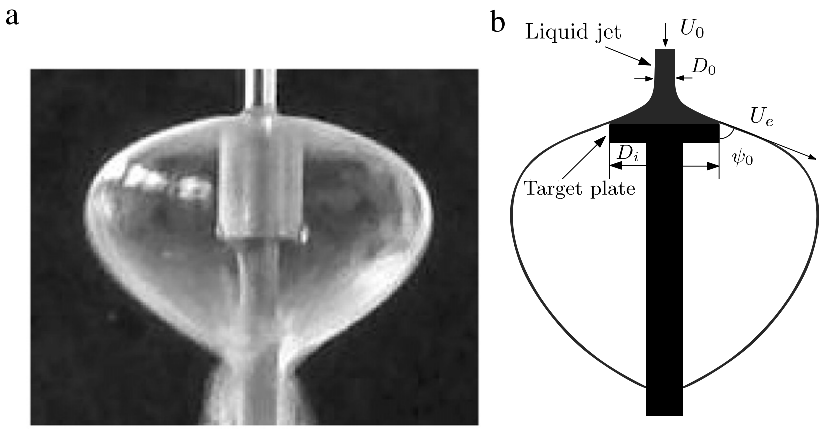

Fig. 1. (a) Photograph of a liquid bell observed for $D_0 = 4.6$ mm, $D_i = 16$ mm, $U_0 = 1.5$ m/s, $\sigma = 0.073$ N/m. (b) Schematic representation of a liquid bell ejected with velocity U_e at an angle ψ_0 at the edge of the impactor.

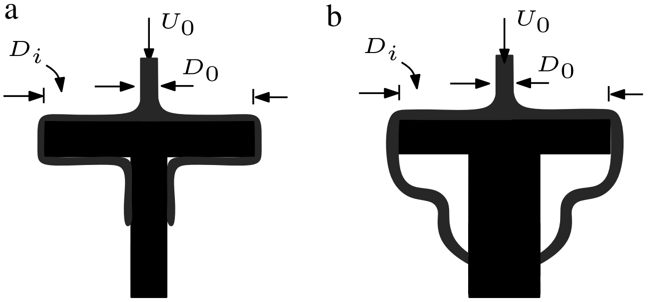

Fig. 2. At low velocities liquid does not detach from impactor but sticks to it.

searchers have devised various other experimental arrangements to obtain liquid bells. Taylor and Howarth [7] constructed perfectly closed symmetrical liquid bells with a horizontally aimed jet hitting a cone. Clanet et al. [8] designed a setup in which a liquid bell is formed below an overflowing circular dish of a certain radius which is supplied with liquid at constant rate. However, they report that in this case, low viscosity liquids such as water cannot form liquid bells as the liquid sheet always breaks. When silicone oil which is 200 times more viscous than water is used, stable bells are obtained.

A new class of liquid bells were observed by Jameson et al. [9,10] where the liquid jet is fired in the upward direction to hit the underside of a large horizontal plate. After impact the liquid spreads radially to an abrupt point where it detaches from the surface of the plate and falls as a curtain to form a liquid bell. This is very unlike the liquid bell obtained by Savart where fluid detaches from the impactor at its edge. A large number of shapes are seen to exist when the flow rate of the jet is altered.

Bark et al. [11] were the first to investigate the problem of swirling liquid bells. These liquid bells are axisymmetric in nature but they are not closed structures. They reopen after reaching a certain distance which is dictated by the conservation of angular momentum. In specific situations, the shape of swirling liquid bells exhibits periodic behavior along the axis of rotation. Gasser and Marty [12] conducted further studies on the topic by closing the bells with a bottom surface.

A unique type of liquid sheet formation is observed when a drop of liquid or a solid object impinges on the free surface of a liquid. This results in the formation of an ejecta i.e. a thin sheet of liquid which is thrown outward in the vertical plane making an angle with the free surface [13,14]. According to Clanet [15], the axisymmetric structure of the ejecta looks very much like an inverted liquid bell and thus he terms this as a reverse bell. Aristoff and Bush [16] have reported the existence of a splash curtain resulting due to the normal impact of hydrophobic spheres on a water surface. They have considered the splash curtain to be an axisymmetric liquid sheet, the evolution of which results in a closed bell. The shape of the splash curtain is calculated using water bell equations.

Liquid bells are closed structures exhibiting remarkable stability. Stability is ensured by a balance between forces of inertia, gravity and surface tension. The radial flow of the liquid on the impactor surface is strongly influenced by viscosity [17]. But in the suspended part of the bell, dissipation is zero as the shear stress with the surrounding air is negligible. However around sharp sheet curvatures this does not hold.

Experiments reveal that the formation and shape of liquid bells depend on a number of operational and geometrical parameters of which the three parameters D_i, U_0 and D_0 are crucial. According to Clanet [18], for a fixed value of the jet diameter (D_0) and jet velocity (U_0), varying the diameter (D_i) of the circular target, a bell may be observed only when $X = (D_i/D_0)$ reaches a critical value X^- given by $62/We$, where $We = \rho U_0^2 D_0/\sigma$ is the Weber number. Below this value the fluid does not detach but surrounds the whole impactor and flows along its surfaces (as shown in Fig. 2). As D_i is gradually increased bells are observed until X reaches another critical value X^+ given by the implicit relation [18]

$$17.6\frac{X^+}{Re^{1/3}}\left(1 + 3.51\left(\frac{X^+}{Re^{1/3}}\right)^3\right) = \frac{We}{Re^{1/3}} \qquad (1)$$

where $Re = U_0 D_0/\nu$ is the Reynolds number. Beyond X^+ for some values of D_i the liquid film remains attached to the impactor and further increasing of D_i leads to the hydraulic jump phenomenon.

Acceleration due to gravity as well as liquid properties like surface tension and viscosity have been found to affect the shape of liquid bells. Apart from the shape depicted in Fig. 1(a), other unique shapes may also be observed due to the effect of the parameters stated above. A non-zero pressure difference that might occur between the inside and outside of liquid bells can affect their stability and hence their shape and size. It will not be out of place to mention that shape and size of the liquid bells are of great interest as they determine the interfacial area available for mass transfer, reaction or other transport processes. Atomization due to capillary instability is also dependent on bell shape.

Since the number of parameters affecting the shape of the bell is large, carrying out a systematic experimental study by varying all of them is laborious and difficult. Although earlier researchers have analyzed the effect of some of the parameters, a comprehensive study is yet to be carried out. The aim of the present work is to carry out a thorough theoretical investigation to study the dependence of bell shape on the different parameters mentioned above.