Single drop impact onto a deep pool: experimental observations and theoretical model for the crater evolution

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Abstract

An experimental investigation on the crater formed by the impact of a millimetric drop onto a semi-infinite liquid target has been performed using high-speed imaging and image processing. Then, a theoretical model for the crater evolution has been developed, which is able to predict the temporal variation of the crater depth for high Weber, Froude and Reynolds numbers. The flow around the crater is approximated by an irrotational velocity field past a moving and expanding sphere. The equations of propagation of the surface of the crater have been obtained from the balance of stresses at the crater interface, accounting for inertia, gravity, surface tension and viscosity. The temporal evolution of the crater depth has been calculated by numerical solution of the equations of motion. The model has been validated against experimental data. The agreement is rather good.

Introduction

The subject of this study is the investigation of the temporal evolution of the crater formed by drop impact onto a deep liquid pool. It is motivated mainly by the modeling of spray/wall interaction and spray cooling. In order to model these phenomena, in particular the interaction of neighboring drop impacts through the liquid film, an accurate prediction of the typical size of the crater and the characteristic time of its formation and collapse is necessary. Moreover, a model for the liquid flow generated by drop impact is required in order to model the heat transfer associated with spray cooling.

Most of the models present in literature [1, 2, 3, 4, 5, 6, 7, 8, 9, 10], usually based on the consideration of the energy balance, deal with predictions of the maximum crater depth. All the models are based on the assumption of a hemispherical shape for the crater, centered on the impact point and do not predict crater temporal evolution during both the expansion and receding phases.

Experimental investigation

The impact of drops onto a pool of the same liquid has been experimentally studied by means of a digital high-speed camera and image analysis. Measurements were then performed on the crater, whose shape, in addition to dimensions, was also investigated. All the measurements used similar image processing steps, consisting of edge detection and feature recognition. Edge detection was performed with a Laplacian of a Gaussian detector, in order to prevent the position of an edge to depend on a threshold value and to always obtain closed boundaries. The connected pixels forming each edge were filled and labeled, obtaining image regions where properties were measured. Although the code was automatic, analysis were run together with a graphical interface showing frame by frame the edges of the detected features superimposed onto the original image and allowing user visual control.

After edge detection, the points forming the crater profile have been interpolated with a circle and its center has been tracked on the images. During the initial growing phase its center moves downward along the symmetry axis, then it is almost fixed a little below the surface and subsequently it moves upwards during the receding phase

Model development

The model is based on the assumption of an irrotational velocity field around the crater, associated with a moving and expanding sphere. Such a velocity field is a good approximation near the crater bottom. The pressure field in the target liquid is then obtained from the instationary Bernoulli equation, which accounts for the liquid velocity and acceleration, and gravity. The equations of motion of the crater are obtained from a balance of stresses at the crater bottom, accounting for gravity, surface tension and viscosity.

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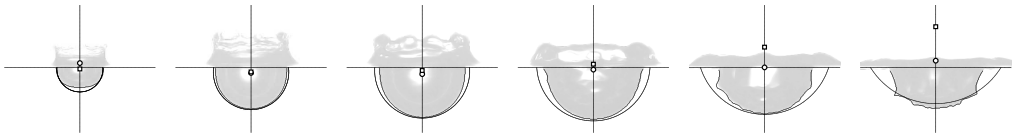

(a) $\tau = 3.02$ (b) $\tau = 9.72$ (c) $\tau = 17.54$ (d) $\tau = 27.60$ (e) $\tau = 37.65$ (f) $\tau = 42.12$

Figure 1. Superposition of the theoretical model and the recorded images. The round point represents the center of the circle fitting the crater edge. The square point represents the center of the modeled crater. Luminosity of the images has been increased for better visualization. τ is the dimensionless time, where the drop diameter D and impact velocity V have been used as length and velocity scales. (Water, $D = 2.8\,\mathrm{mm}$, $V = 4.2\,\mathrm{m/s}$, $We = 683$, $Fr = 620$, $Re = 14\,638$)

The following evolution equations for the crater expansion are obtained from the model:

$$\ddot{\alpha} = -\frac{3}{2}\frac{\dot{\alpha}^2}{\alpha} - \frac{2}{\alpha^2 We} - \frac{1}{Fr}\frac{\zeta}{\alpha} + \frac{7}{4}\frac{\dot{\zeta}^2}{\alpha} - \frac{4\dot{\alpha}}{\alpha^2 Re}, \tag{1a}$$

$$\ddot{\zeta} = -3\frac{\dot{\alpha}\dot{\zeta}}{\alpha} - \frac{9}{2}\frac{\dot{\zeta}^2}{\alpha} - \frac{2}{Fr} - \frac{12\dot{\zeta}}{\alpha^2 Re}. \tag{1b}$$

where $We = \rho V^2 D/\sigma$, $Fr = V^2/(gD)$ and $Re = \rho V D/\mu$ are the Weber, Froude and Reynolds numbers, ρ, σ, μ are the fluid density, viscosity, surface tension, D is the drop diameter and V the impact velocity. α and ζ are the crater radius and the z-position of its center, non-dimensionalised with the drop diameter. The z-axis is the symmetry axis with the origin at the impact point and it is positive below the target surface. Dots indicate derivation in time, which is non-dimensionalized using drop diameter D and impact velocity V. Eq. (1) is a system of ordinary differential equations, which is solved numerically, using initial conditions obtained from experimental data and theoretical predictions. The solution yields the the evolution in time of the dimensionless crater depth $\Delta = \zeta + \alpha$.

Results and Discussion

Figure 1 shows a superposition of the crater predicted by the theoretical model to a case from the experimental data. The agreement between the theoretical predictions and the experimental shape of the cavity is rather good at the bottom region of the crater, where the model is valid. The model has the capability to predict also the maximum depth, the time of maximum depth and a general receding phase. The difference between experimental data and predicted values increases at the last part of the receding phase because of the influence on the crater shape of the propagation of the capillary waves (not considered in the theory) and by the crater deformation at the bottom part, leading to the formation of the central jet.

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