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Viscosity Effect on regular bubble entrapment during drop impact into a deep pool

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HIGHLIGHTS

- Viscosity effect on regular bubble entrapment was presented.
- Viscosity effect on critical cone angle, pressure and velocity was investigated.
- Viscosity effect on regular bubble entrapment region was conducted.
- A scaling model for limits of the regular bubble entrapment region was proposed.
- Viscosity effect on bubble size distribution was studied.

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ABSTRACT

Viscosity plays an important role in regular bubble entrapment during drop impact into a deep pool. In this paper, the volume of fluid (VOF) model in conjunction with the continuum surface force (CSF) model is used to investigate the dynamics of regular bubble entrapment in fluids with a range of viscosities (η=0.1–10.0 × 10^{-3} Pa s). Time evolutions of the crater profiles and crater depths in different viscous fluids are compared. Numerical results show that the damping effect of the viscosity on capillary wave propagation leads to an increase in the lower limit of the regular bubble entrapment region, whereas the damping effect on crater cusp reversal dynamics leads to an increase in the upper limit. Based on the timing estimate, a scaling model for the effect of viscosity on the limits of the regular bubble entrapment region is provided. Finally, the distribution of bubble size as a function of the capillary number is investigated.

1. Introduction

The phenomenon of a drop impacting a dry solid or liquid surface, a very familiar scene observed during rainfall, is not only esthetically interesting and beautiful but also of great practical importance in many technical applications, including underwater noise during rains, material erosion, meteorology, spray coating, the formation of nucleation sites during boiling, fire suppression systems, medical technology and the design of gas–liquid separation units (Prosperetti and Oguz, 1993; Rein, 1993; R. Davidson, 2002; Yarin, 2006; Lunkad et al., 2007; Rein and Delplanque, 2008; Khan et al., 2011). Regular bubble entrapment is one of the fantastic phenomena that occur when a drop impacts a pool. During the heat-transfer process, the entrapped bubble can provide boiling nucleation sites for the target fluid and enhance heat transfer (Manzello et al., 2003; Thoroddsen et al., 2003). However, in the cell-encapsulation process, the quality of the capsule surface is adversely affected by the bubble, and the capsule is vulnerable to attack by the immune system (Deng et al., 2007, 2009). In chemical reaction system, the entrapped bubble will increase chemical exchanges considerably or result in material erosion, due to the increase of the contact area between gas and liquid (Martin, 2002). Thus, it is important to clearly understand the transitional mechanisms of the regular bubble entrapment region to obtain optimal design parameters and operating conditions.

The study of drop impact into a pool is an important topic of research, and many experimental and theoretical investigations in this direction have been performed over the past years (Charles and Mason, 1960; Pumphrey and Walton, 1988; Rein, 1996; Thoroddsen and Takehara, 2000; Zeff et al., 2000; Wang and Fedorchenko, 2004; Okawa et al., 2008; Gekle and Gordillo, 2010). Five types of flow patterns can generally be observed as the impact velocity of a drop increases (Engel, 1966; Hsiao et al., 1988; Rein, 1996; Leng, 2001; Zhao et al., 2011): (i) coalescence, (ii) regular bubble entrapment, (iii) thick jet, (iv) splashing and (v) canopy

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formation. The critical transition from coalescence to regular bubble entrapment is always named as the lower limit of the regular bubble entrapment region while the critical transition from regular bubble entrapment to the thick jet is defined as the upper limit of regular bubble entrapment region. The physical forces involved in drop impact are primarily surface tension, gravity, inertia, gas pressure (Xu et al., 2005, 2007) and viscous damping. For liquids with low viscosities, such as water, the viscosity effect has usually been neglected in previous studies and the impact outcomes are primarily governed by the two dimensionless parameters *We* and *Fr*, which are defined as follows:

$$We = \frac{\rho D_0 U^2}{\sigma}, \; Fr = \frac{U^2}{g D_0}, \tag{1}$$

where U is the impact velocity, D_0 is the drop diameter, σ is the surface tension, ρ is the density and g is the acceleration due to gravity.

In general, three types of bubbles could be observed after drop impact onto liquid surface: Mesler entrainment, irregular entrapment, regular bubble entrapment. Detailed characteristic regimes, based on drop diameter and impact velocity on the *U–D*-map, could be found in recent literature by Wang et al. (2013). Esmailizadeh and Mesler (1986) provided first series of images showing possibly thousands of microbubbles ($<50\,\mu$m). The experiments by Sigler and Mesler (1990) show that the microbubbles origins from the destruction of a thin film between the drop and surface. Thoroddsen et al. (2003) observed the breakup of thin films in liquid–liquid films and could only detect the formation of microbubbles at low Weber numeber ($We<22$). Another bubble region on the *U–D*-map is the irregular regime, where one could not predict whether a bubble will be entrained or not based on drop diameter and impact velocity (Pumphrey and Elmore, 1990). As depicted by Wang et al. (2013), irregular bubble entrapment occurs when the drop diameter is approximately larger than 5 mm. It is likely caused by various interactions of the moving cavity with small satellite drops or the collapse of a water column (Pumphrey and Elmore, 1990; Tomita et al., 2007). One of the most well-known phenomena on the *U–D*-map is regular bubble entrapment and it presents in the region of $D_0=1.0$ mm$\sim$4.0 mm and $U=1.1$–3.0 m/s. Pumphrey and Elmore (1990) were the first to report a single air bubble entrapped at a crater bottom during collapse of the crater and defined the event as regular bubble entrapment because it is reproducible. Furthermore, Wang et al. (2013) suggests that regular bubble entrapment could be commonly classified into two regimes: small bubble regime (below 1 mm) and large bubble region (5–10 mm). The large bubble region is very narrow, and in this paper, we focused on regular bubble entrapment phenomenon in the small bubble regime.

Over the past two decades, many studies have focused on understanding the mechanism of regular bubble entrapment. Pumphrey and Elmore (1990) observed a capillary wave traveling down the inner sidewall of a crater. According to experimental observations, the authors proposed that the crest of the capillary wave closed in from all sides after it reached the crater base, thus trapping a bubble. Capillary wave propagation has been confirmed by other authors (Rein, 1996; Elmore et al., 2001; Leng, 2001; Cole, 2007; Liow and Cole, 2007; Deng et al., 2009). These studies indicate that the capillary wave distorts the crater shape and plays a dominant role in regular bubble entrapment. Oguz and Prosperetti (1990) stated that “whether a bubble is entrapped or not is determined by a delicate balance between the times at which the outward motion of crater walls is reversed at different positions”. Based on this presumption, the authors derived the lower limit of the regular bubble entrapment region as $We\sim Fr^{1/5}$ by comparing the time of the capillary wave at the crater base with the time of the crater to maximum growth. Furthermore, Oguz and Prosperetti (1990) postulated that the crater collapses simultaneously at all points on the crater walls, and thus, no bubble can be entrapped when the drop material spreads over the entire surface of the crater. From a force-balance analysis of the energy available for the drop to spread and the force retarding this spread, the upper limit of the regular bubble entrapment region was determined to be $We\sim Fr^{1/4}$. Through a systematic experimental study, Leng (2001) determined the lower limit for regular bubble entrapment to be $We=36.2Fr^{0.186}$ and the upper limit to be approximately $We=48.3Fr^{0.247}$.

With advancements in numerical simulation techniques and computing power, computational fluid dynamics (CFD) has become a very effective tool for exploring drop impact behavior. Several numerical simulations of regular bubble entrapment have been conducted in recent years (Oguz and Prosperetti, 1990; Morton et al., 2000; Berberović et al., 2011; Fest-Santini et al., 2011; Ray et al., 2012). Most numerical simulations (Morton et al., 2000; Berberović et al., 2011; Fest-Santini et al., 2011; Ray et al., 2012) have applied the simple but powerful volume of fluid (VOF) model based on the concept of a fractional volume of fluid to treat the complex gas–liquid surface. The flow regimes resulting from the impact of a 2.9-mm water drop diameter were investigated by Morton et al. (2000). Time evolution studies of the minimum radius during the final bubble pinch-off stage have been conducted by Ray et al. (2012). The results of these studies indicate that the phenomenon of regular bubble entrapment can be reliably predicted using the VOF model.

Most of the previous studies on regular bubble entrapment have been carried out using pure water as the medium, and the role of viscosity on regular bubble entrapment dynamics is always neglected. However, Deng et al. (2007) proposed that the limits of the regular bubble entrapment region is affected by viscosity. The authors also indicated that the phenomenon of regular bubble entrapment disappears when the impact capillary number is greater than approximately 0.6. To further understand regular bubble entrapment, the role of viscosity remains to be elucidated in more detail. In addition, viscosity effect on the transitional limits of the regular bubble entrapment region need to be investigated further.

In this study, the VOF method is used to investigate the role of viscosity on regular bubble entrapment during the impact of a drop into a deep pool. The continuous surface tension model and a sharper interface resolution are incorporated into the VOF method. Based on the numerical results, we attempt to investigate viscosity effect on regular bubble entrapment and establish a scaling model of the lower and upper limits of the regular bubble entrapment region in viscous fluids. Furthermore, the effect of viscosity on the bubble size distribution will also be investigated.

2. Mathematical model

2.1. Governing equations

In this section, a mathematical model and a strategy for conducting viscous fluid flow simulations are introduced. The system consists of two incompressible and immiscible fluids, represented as liquid and air phases. There are several competitive effects influencing the flow field during impact, such as gravity, inertia, viscosity, gas pressure and surface tension. The governing equations for such unsteady, incompressible, viscous, immiscible two-phase flows are as follows (Delnoij et al., 1997; van Sint Annaland et al., 2005; Lunkad et al., 2007; Rabha and Buwa, 2010):

$$\nabla \cdot u = 0, \tag{2}$$