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Removal of gas bubbles from highly viscous non-Newtonian fluids using controlled vibration

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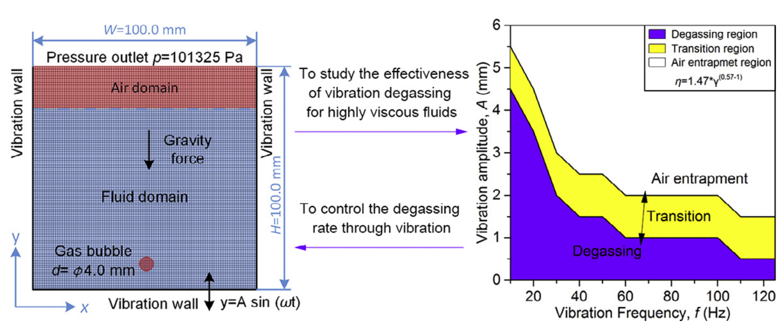
HIGHLIGHTS

- Simulating the motions of gas bubbles in non-Newtonian fluids under vibration.
- Rheological and vibration parameters have great effects on the degassing rate.
- The feasible region of degassing is built with vibration frequency and amplitude.

GRAPHICAL ABSTRACT



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ABSTRACT

Formation of gas bubbles is normal and practically inevitable when fluids are agitated or flow in open containers. The unwanted gas bubbles will damage the product quality, and they are very difficult to be removed from highly viscous fluids. In this paper, the effectiveness of vibration degassing for highly viscous non-Newtonian fluids is investigated using volume of fluid (VOF) model coupled with continuous surface force (CSF) model. The motions of gas bubbles in liquid under vibration are simulated and the effects of various rheological parameters as well as vibration parameters on the degassing rate are studied. The results show that the shear thinning (or thickening) induced by vibration is responsible for the enhancement (or retardation) of degassing rate for non-Newtonian fluids. The more pronounced the non-Newtonian behaviors of fluids are, the greater the effects of vibration on the degassing rate are. The degassing rate is governed by the vibration amplitude and frequency of vibration. However, high frequency or large amplitude vibration may intensify air entrapment and bring new gas bubbles into fluids. Thus, the feasible region of vibration degassing in which the vibration frequency and amplitude don't cause new gas bubbles are further studied. The vibration degassing technology has the added advantage that it does not use intrusive devices to container, nor does it limit the container structure or shape, and thus will find wide applications in laboratory and industrial fields.

1. Introduction

Non-Newtonian fluids are encountered in a vast range of industrial applications, including most multi-phase mixtures, high molecular weight systems and solutions, foods, pharmaceuticals and so on (Deshpande and Barigou, 2001). It is practically inevitable that gas bubbles are dispersed and mixed in fluids when air is included in such processes as mixing, agitation, kneading and dispersion, etc. (Kizito et al., 2009) In addition, the cavitation bubbles are generated in liquids if the alternating pressure exceeds the cavitation threshold (Liu et al., 2015). These unwanted gas bubbles will affect the flow characteristics and compressibility of fluids,

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and even contribute to defect formation and damage the product quality in some industrial processes (Tom and Liu, 2012). Thus, degassing operation is of great importance. However, because of large drag resistance, gas bubbles are very difficult to be removed from highly viscous fluids when they are pushed up by buoyancy only (Alimi et al., 2014; Yu and Louhenkilpi, 2013).

Some widely-used degassing methods include vacuum, heating, ultrasonic and centrifugal ones. The vacuum degassing has low efficiency and often needs the assistance of heating. The heating degassing consumes much energy, and even worse, some fluids will be damaged at high temperature. Although the ultrasonic degassing is fast and environmentally friendly, the ultrasonic intensity tends to decrease exponentially during propagation, as a result of which the degassing effects are limited to a small volume of fluids around the acoustic radiator (Puga et al., 2014).

Vibration may be a new approach to quicken degassing operation. Shoikhedbrod (2016) found that gas bubbles and liquids could be separated or mixed through controlled vibration under reduced gravity conditions. Harold et al. (Howe et al., 2007) proposed a typical low-frequency vibration system for degassing in the range of about 10–100 Hz. However, Sorokin et al. (2012) found that gas bubbles were sucked into the container containing a liquid when it was vibrated in an ambient gas. Hern et al. (2012) found that gas bubbles could behave in unusual ways under vibration, for example, they moved downwards against buoyancy. Improper vibration cannot remove gas bubbles, and even generates gas bubbles due to surface disturbances. Thus, it is important to figure out the mechanism of vibration degassing and explore the possibility of vibration degassing for highly viscous fluids. More detailed work is needed to systematically investigate the roles of vibration parameters and other key rheological parameters in the degassing operation of more complex non-Newtonian fluids.

In recent years, the rise and deformation of a single bubble in liquids have been widely studied. The computational fluid dynamics (CFD) is effective for exploring the behaviors of gas bubbles (Krishna and Van Baten, 1999; Carvajal et al., 2015). In most numerical simulations; the volume of fluid (VOF) model (Yoon and Shin, 2016; Chakraborty et al., 2013) is employed. The VOF method is more suitable for the simulation of gas-liquid interfaces with large deformations because of its inherent mass conservation property and reduced computational costs (Ma et al., 2012). Klostermann et al. (2013) presented a numerical model based on the VOF method with surface compression to deal with the bubble rising problem, which demonstrated the good capabilities of the numerical model with regard to the preservation of sharp interfaces, boundedness, mass conservation and low computational time. Jeon et al. (2011) investigated the behaviors of condensing bubbles using the VOF model in the FLUENT code and the simulation results agreed well with the experimental data. Gollakota and Kishore (2015) proposed a numerical study on flow and drag phenomena of spheroid bubbles in Newtonian and shear-thinning power-law fluids. Cano-Pleite et al. (2015) numerically investigated the size and motion of isolated bubbles in a vertically-vibrated fluidized bed with a two-fluid model. These studies indicated that the CFD model is capable of simulating the dynamics of gas bubbles in viscous liquids. However, theoretical or numerical investigations focused on vibration degassing are rarely reported, so further researches are needed to develop some basic theories about vibration degassing and gas bubble behaviors under controlled vibration.

This study is focused on the effectiveness of vibration degassing for highly viscous non-Newtonian fluids. The two-dimensional VOF method is used to simulate the motions of gas bubbles in the liquid under vibration and the continuum surface force (CSF) model is employed to account for the surface tension effects. The effects of various rheological parameters as well as vibration parameters on the degassing rate are studied. The feasible region of vibration degassing is further discussed and plotted with vibration frequency and amplitude. This study can provide a physical understanding of the vibration degassing phenomenon and show qualitative behavior related to gas removal with vibration.

2. Numerical simulation

2.1. Physical model and materials

Two dimensional (2D) domain is used to study the flow of a single bubble in a container. The container basically has a height of H = 100 mm and a width of W = 100 mm to form a rectangular domain and is filled with liquid and air. The height of liquid is 80 mm and the remainder is air. A single gas bubble with a diameter of d = 4.0 mm is used to simplify calculations, while bubble breakup and coalescence are ignored. It is assumed that the gas bubble is far enough from any wall of the container so that the interactions between the gas bubble and the container walls can be neglected. The physical model and the boundary conditions of vibration degassing are presented in Fig. 1.

The container is rigidly fixed on a moving platform of a shake table and is subjected to vibration. Fig. 1 illustrates the computational geometry, mesh and boundary conditions for this study. In order to improve the calculation efficiency, a two-dimensional numerical transient model is employed. The bottom and side of

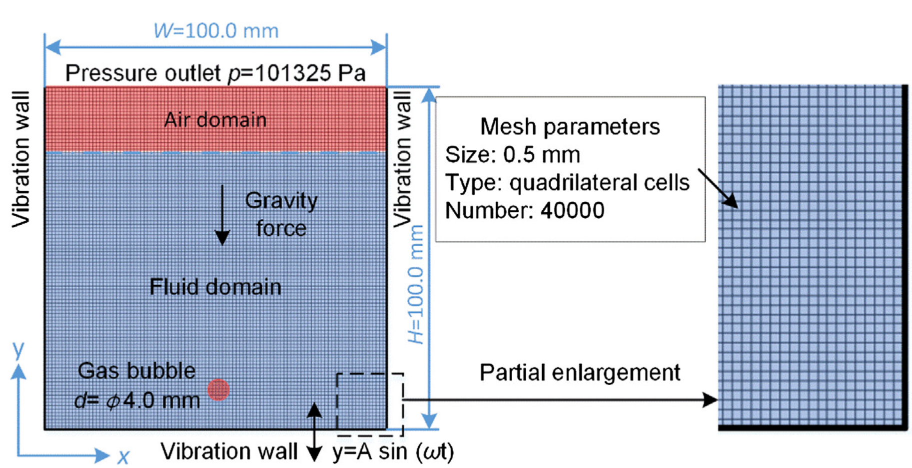

Fig. 1. The physical model, meshes and boundary conditions of vibration degassing.