Numerical study of bubble growth and collapse dynamics, near the rigid wall

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ABSTRACT

In this study, the dynamics of bubble growth and collapse near a rigid wall is investigated using the modified volume of fluid method and the improved compressible interfoam solver in the OpenFoam open-source code. The research results indicate that the dimensionless gamma number has the most significant impact on the growth and collapse of the bubble near the wall. This study examined two gamma number 0.8 and 1.3. It was found that with a 60% increase in the gamma number, the maximum shear stress on the wall decreased by 37%, while the maximum absolute temperature inside the bubble increased by 12%.Additionally, as the gamma number increases, the area affected by the jet impact due to the bubble collapse increases. Within the scope of the present research, the initial pressure parameter of the bubble has the most significant impact on the maximum temperature inside the bubble. In the range of considered initial pressures, a 50% increase in the initial pressure results in a 6% decrease in the maximum temperature of the bubble. However, the values of other studied parameters, such as shear stress, change by less than one percent.

KEYWORDS

Cavitation, microbubble, bubble collapse, microjet, rigid wall

1. Introduction

The phenomenon of cavitation and bubble collapse is crucial in industrial and medical applications. New approaches are being explored to utilize this phenomenon in solving various problems, including cancer treatment and surface cleaning. Recent studies indicate that the type of wall has a significant impact on the collapse of bubbles near the wall. Many studies have explored the dynamics of bubble collapse under various conditions, including next to an elastic wall [1], next to a rigid wall [2], and next to the free surface [3]. Based on previous research, it has been determined that when examining the dynamics of bubble collapse near a wall, the parameters of the gamma number, type of wall, and initial pressure have the most significant impact on flow parameters. The primary research gap in the study of bubble collapse is the investigation of the combined effects of the dimensionless gamma number and the initial pressure of the bubble on changes in bubble temperature, shear stress on the wall, and jet velocity resulting from the collapse.Therefore, the impact of the dimensionless gamma number and initial bubble pressure on flow parameters during bubble collapse near a solid wall is investigated in this research. The goal is to address a research gap and propose a new method to enhance the power of the resulting jet during bubble collapse.

In summary, the innovations of this work can be outlined as follows

1- Development of a compressible two-phase solver by improving the discontinuity caused by interface tracking.

2- Examination of the impact of dimensionless gamma numbers 0.8 and 1.3 on temperature, pressure, shear stress, and jet velocity parameters.

3- Exploration of the effect of the initial pressure of the bubble on the energy released from the collapse of the bubble near the rigid wall and its impact on velocity, stress, and temperature in a constant gamma.

2. Methodology

To investigate the phenomenon of bubble collapse using the modified volume of fluid method, mass conservation equations, momentum, liquid phase volume fraction equation, and energy equation are utilized in the form of equations (1) to (4).

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho U) = 0 \qquad (1)$$

$$\frac{\partial \rho U}{\partial t} + \nabla.(\rho UU) = \nabla.\tau_{\mu} - \nabla p + \sigma\kappa\nabla\alpha \qquad (2)$$

$$\frac{\partial \alpha}{\partial t} + \nabla.(\alpha U) + \nabla.(U_r \alpha(1-\alpha)) = \alpha(1-\alpha)\left(\frac{1}{\rho_g}\frac{d\rho_g}{d\rho_l} - \frac{1}{\rho_l}\frac{d\rho_l}{dt}\right) + \alpha\nabla.U \qquad (3)$$

$$\left[\frac{\partial(\rho T)}{\partial t} + \nabla.(\rho TU)\right] + \left(\frac{\alpha_l}{C_{p,l}} + \frac{\alpha_g}{C_{p,g}}\right)\left[\frac{\partial(\rho k)}{\partial t} + \nabla.(\rho kU)\right] = \left(\frac{\alpha_l}{C_{p,l}} + \frac{\alpha_g}{C_{p,g}}\right)\left[\frac{\partial p}{\partial t} + \nabla.(\tau.U)\right] + \left(\frac{\alpha_l \beta_l}{C_{p,l}} + \frac{\alpha_g \beta_g}{C_{p,g}}\right)(\nabla^2 T) \qquad (4)$$

In equations (1) and (2), U represents the velocity field, t represents time, ρ represents density, α represents the volume fraction of the liquid phase, p represents pressure, σ represents the surface tension coefficient, and κ represents the curvature of the interface. In equation (2), the last term on the left expresses the viscous stress. In equation (3), U_r represents the relative speed of two phases. In equation (4), C_p represents the specific heat coefficient at constant pressure, β represents the conductive heat transfer coefficient, T represents the temperature, and k represents the kinetic energy.

Given that the accuracy of the volume of fluid method relies heavily on how well the interface is tracked, the lafaurie filter is employed to improve the precision of this method (40). To implement this filter, equations (5) and (6) is used [4].

$$\kappa = \nabla.\left(\frac{\nabla\tilde{\alpha}}{|\nabla\tilde{\alpha}|}\right) \qquad (5)$$

$$\tilde{\alpha}_P = \frac{\sum_{f=1}^{n} \alpha_f S_f}{\sum_{f=1}^{n} S_f} \qquad (6)$$

In order to solve the governing equations, it is important to establish the relationship between the equations using an appropriate solver and solve the equations throughout the entire computational domain at each time step. The solver utilized in this study is the compressible interFoam solver in the OpenFOAM-extend 4.1.

3. Discussion and Results

The phenomenon of bubble collapse near a rigid wall is simulated in this study. The simulation geometry, as shown in Figure 1, consists of a 5-degree segment of a cylinder with a radius of 50 mm and a height of 50 mm. Figure 1 provides details of the dimensions, boundary conditions, and the meshing approach used for addressing the problem.

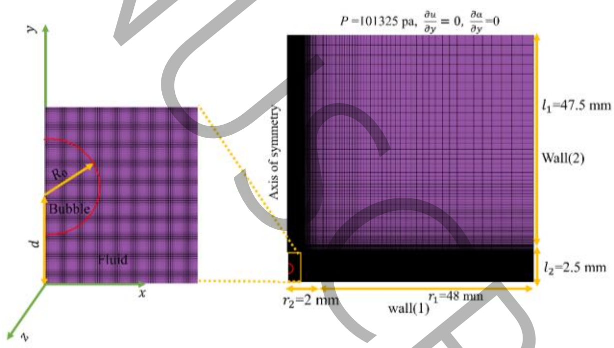

Figure 1: Geometry used in single bubble collapse near a rigid wall.

According to the results obtained for the problem of bubble collapse near the solid boundary, it can be concluded that the dimensionless gamma number plays the most important role in the physics of bubble collapse. The shear stress distribution on wall 1 when the jet reaches it is shown in Figure 2 for two different gamma values: 0.8 and 1.3. The maximum shear stress value decreased from 39 kPa to 25 kPa when the gamma number increased from 0.8 to 1.3. Additionally, the location of the maximum shear stress moved from 0.15 mm to 0.28 mm from the coordinate axis as the gamma number increased. For larger gamma values, a longer length of wall 1 is affected by fracture and the resulting shear stress, as shown in Figure 2.

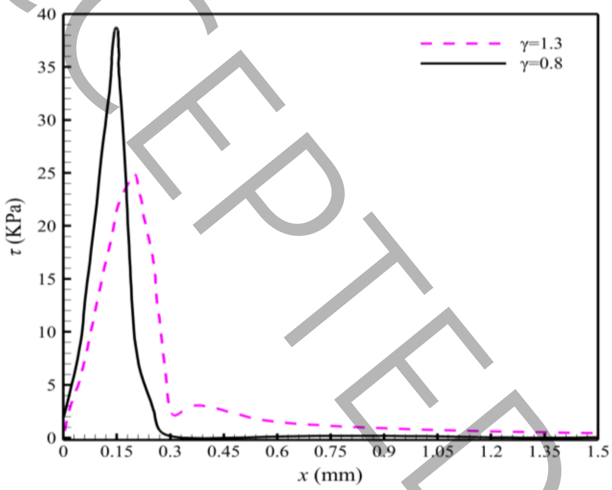

Figure 2: Geometry used in single bubble collapse near a rigid wall.

Based on the parametric study conducted on the initial pressure of the bubble, it can be inferred that an increase in the initial pressure of the bubble has a negligible effect on the amount of shear stress and pressure on the wall when the thickness of the liquid layer between the bubble and the wall remains unchanged at high pressures. However, this parameter has a significant effect on the minimum radius and time of bubble collapse. It is advisable to use a higher initial pressure to reduce the maximum temperature inside the bubble for applications such as drug delivery to vulnerable tissues.

4. Conclusions

The results of this research can be summarized as follows:

1. The dimensionless gamma number has the greatest impact on the growth and collapse dynamics of a bubble near a rigid wall. As the gamma number increases due to the thicker fluid layer between the bubble and the wall, the energy dissipation from the bubble collapse increases. Consequently, the shear stress caused by the collapsing bubble's impact on the wall will be lower at higher gamma numbers.

2. In the examination of heat transfer between fluid and gas phases in the bubble collapse problem, the parameters of jet velocity, bubble collapse time, and maximum bubble compression during the volume reduction stage are of paramount importance. An increase in the dimensionless gamma number leads to a rise in the maximum temperature inside the bubble, a factor of considerable significance in applications such as drug delivery.

3. In larger gamma values, although the shear stress created on the solid wall is smaller, the area affected by the impact of the jet caused by the bubble on the wall is larger. Increasing the initial pressure of the bubble also increases the area affected by bubble collapse. Therefore, when considering the use of the shear stress caused by the bubble collapse for medical applications such as destroying the brain's defense barrier or treating kidney stones, it is essential to set the parameters of the dimensionless gamma number and the initial pressure of the bubble according to the intended goal.

5. References

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