THE REBOUND OF A BUBBLE WITH A SOLID SURFACE: SURFACE WAVES AS AN ADDITIONAL DISSIPATION MECHANISM

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Summary We have studied the motion of bubbles colliding with solid walls both numerically and experimentally. The simulations were performed considering a VOF method of the JADIM code that permits to reproduce accurately motion bubbles for a wide range Morton numbers. To be able to compare with the numerical results, the experiments were carried out using silicon oils, for which the interface remains clean under ordinary laboratory conditions. By measuring the approach and rebound velocities, we calculated the coefficient of restitution of the collision, ϵ, which was found to scale as $-\log \epsilon \sim (Ca/St)^{1/2}$, as suggested by Zenit and Legendre[1] (where Ca is the capillary number and St is the Stokes number). Since the numerical results were validated (through direct comparisons with experiments), we conducted a vast parametric study of coefficient of restitution, varying all the fluid properties in an independent manner. We found that the coefficient of restitution reaches a maximum value for intermediate values of the ratio Ca/St; highly energetic collisions induce the formation of surface waves, which in turn dissipate some energy, reducing the bubble rebound velocity.

INTRODUCTION

Particulate two-phase flows are common in many practical engineering applications, such as reactors, mineral processing, and oil extraction. Particularly, contact of particles, fluid or solid, is relevant in many applications and in some cases these interactions have a significant effect in the global behavior of the mixture. For instance, the collision of solid particles determines the rate of erosion in the transport of solid-liquid mixtures; in flotation processes, the contact of bubbles with particles is a necessary condition. We are interested in understanding the conditions for which one can expect contact and a rebound, as opposed to a gentle arrest or deposition, when a bubble approaches a wall. Zenit and Legendre[1] showed that the coefficient of restitution, ϵ, defined as the ratio of the rebound to the approaching velocities, scaled as:

$$\log(\epsilon) \sim \sqrt{\frac{Ca}{St}}$$

where $Ca = U_o\mu/\sigma$ and $St = \rho^* U_o d_{eq}/(9\mu)$ are the capillary and Stokes numbers, respectively. μ and σ are the fluid viscosity and surface tensions, respectively. U_o is the bubble velocity and d_{eq} is the bubble equivalent diameter. $\rho^* = \rho_g + C_{AM}\rho_f$ is the effective bubble velocity, which account for both the gas and liquids densities and the added mass effect.

These experiments clearly showed that the evolution of the coefficient of restitution is significantly different from that observed for solid particles. However, some uncertainty remained because the fluids used were not 'clean' (water-based solution). Surface contamination has been shown to cause significant variations in the terminal velocities of bubbles. Therefore, it is expected that their influence will be important for the case of bouncing bubbles and droplets.

EXPERIMENTAL CONDITIONS AND NUMERICAL SCHEME

To measure the bubble trajectory and deformation through out the collision process, we used the same experimental setup used by Zenit and Legendre[1], but used low viscosity silicon oils such as those used by Zenit and Magnaudet[2]. With these liquids, the interphase remains clean under standard laboratory conditions. The liquids used in this study are listed in table 1.

Liquid	ρ, kg/m^3	μ, mPa s	σ, mN/m	Mo=g$\mu^4/(\rho\sigma^3)$
water	1000	1.00	72.86	2.5×10^{-11}
DMS-T02	873	1.75	18.7	1.6×10^{-8}
DMS-T05	918	4.59	19.7	6.2×10^{-7}
DMS-T11	935	9.35	20.1	9.9×10^{-6}

Table 1. Properties of the liquids used in the experiment: ρ is the density, μ the dynamic viscosity and σ the surface tension. The properties of pure water are also shown for reference.

To complement our study, we conducted numerical simulations using the JADIM code. This second order (space and time) 3D unsteady Navier-Stokes solver uses a Volume of Fluid (VoF) method, with no interface reconstruction (FCT scheme).

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It considers the procedure proposed by Brackbill *et. al* [3] to consider the capillary contribution. The performance of this code has been widely validated [4, 5]

RESULTS

Figure 1 shows the measurements of the coefficient of restitution as a function of the ratio Ca/St for the three fluids considered in this study. Clearly, ϵ decreases as the ration Ca/St increases, in good agreement with [1]. However, the value of the coefficient of restitution is generally higher with respect to the previous measurements. Therefore, it can be argued that surface contamination tends to reduce the bouncing capacity of bubbles. Also, noteworthy, is the excellent agreement between the numerical and experimental results.

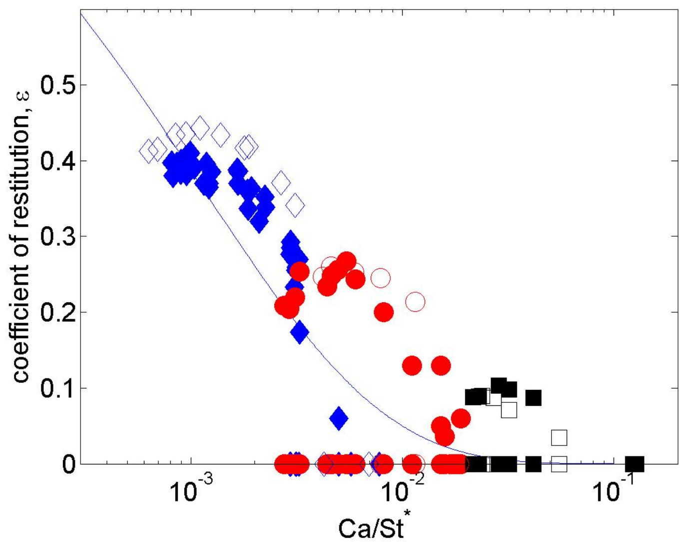

Figure 1. Coefficient of restitution as a function of Ca/St for bubbles colliding against a horizontal plate. The filled and empty symbols show the experimental and numerical results, respectively. The solid line shows the experimental fit from [1]. The different symbols show the experiments conducted for the three fluids used in this study (Table 1).

One of the most interesting features of the results shown in the figure is the fact that, for a given fluid, the coefficient of restitution seems to reach a maximum value for an intermediate Ca/St. We have noted that for fast collisions (small values of Ca/St) waves can be observe to develop across the surface of the bubble during the collision. For collisions with large values of Ca/St, the bubble is deformed during the interaction but no waves are observed. Clearly, some part of the bubble kinetic energy is being transferred to the surface and it is dissipated through vibration modes. We currently developing a model that accounts for these feature, that can predict that the coefficient of restitution reaches a maximum for a certain range of physical parameters.

CONCLUSIONS

We have conducted experiments and numerical simulations to investigate the process of rebound of bubbles against a solid wall. We have considered the case of clean bubbles: the bubble surface is free of surface active agents. A good agreement was found with previous measurements. The coefficient of restitution was observed to decrease as the ratio Ca/St increases. We found also that the coefficient of restitution reaches a maximum value for intermediate values of Ca/St. We argue that when the available kinetic energy excess a certain amount, surface waves can be produced on the bubble. These surface waves act as an additional energy dissipation mechanism, reducing the bouncing capacity of bubbles.

References

[1] Zenit R. , Legendre D.: The coefficient of restitution for air bubbles colliding against solid walls in viscous liquids. *Phys. Fluids* **21**: 083306, 2009.

[2] Zenit R. , Magnaudet J.: Path instability of rising spheroidal air bubbles: A shape-controlled process. *Phys. Fluids* **20**: 061702, 2008.

[3] Brackbill J.U., Kothe D.B, Zemach, C. : A numerical methods for modelling surface tension. *J.Comp. Phys.* **100**: 335-354, 1992.

[4] Bonometti T., Magnaudet J.: An interface-capturing method for incompressible two-phase flows. Validation and application to bubble dynamics. *Int. J. Multiphase Flow* **33**: 109Ű133, 2007.

[5] Dupond J.B., Legendre D.: Numerical simulation of static and sliding drop with contact angle hysteresis. *J.Comp. Phys.* **229**: 2453-2478, 2010.