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"Acoustic Bubble Removal from Boiling Surfaces"

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The object of the study was the investigation of the forces generated by standing acoustic waves on vapor bubbles, both far and near boundaries.

In order to accomplish this objective, in view of the scarcity of publications on the topic, it has been necessary to build an edifice of knowledge about vapor bubbles in sound and flow fields from the ground up, as it were. We have addressed problems of gradually greater difficulty as follows:

1. In the first place, the physics of an stationary isolated bubble subject to a sound field in an unbounded liquid was addressed;
2. The case of bubbles translating in a stationary pressure field was then considered;
3. This was followed by a study of the combined effects of sound and translation,
4. And of a neighboring boundary
5. Finally, a new method to deal with nonspherical bubbles was developed.

In addition to the work on vapor bubbles, some studies on gas bubbles were conducted in view of NASA's interest in the phenomenon of sonoluminescence.

This work has led to the following papers, copies of which are attached:

1. Hao, Y. and Prosperetti, A., The dynamics of vapor bubbles in acoustic pressure fields, *Phys. Fluids* **11**, 2008-2019, 1999.
2. Hao, Y. and Prosperetti, A. The Collapse of Vapor Bubbles in a Spatially Non-Uniform Flow, *Int. J. Heat Mass Transfer* **43**, 3539-3550, 2000.
3. Hao, Y., Oğuz, H.N. and Prosperetti, A. The Action of Pressure-Radiation Forces on Pulsating Vapor Bubbles, *Phys. Fluids* **13**, 1167-1177, 2001.
4. A. Prosperetti and Y. Hao, Vapor Bubbles in Flow and Acoustic Fields, in *Free-Surface Flows*, edited by A.C. King and Y. Shikhmurzaev, Kluwer, pp. 249-256, 2001.
5. Prosperetti, A. and Hao, Y., Modeling of spherical gas bubble oscillations and sonoluminescence, *Philos. Trans. R. Soc. London* **A 357**, 203-223, 1999.
6. Hao, Y. and Prosperetti, A., The effect of viscosity on the spherical stability of oscillating gas bubbles, *Phys. Fluids* **11**, 1309-1317, 1999.

Highlights of the work (described in the attached papers) are the following:

1. Bubbles containing either a permanent gas or a condensible vapor owe their finite lifetime to diffusion processes in the liquid – of dissolved gas in the former case and of heat in the latter. In spite of this fundamental similarity, the facts that the diffusivities for mass and heat typically differ by nearly two orders of magnitude, and that the capacity for heat absorption in a liquid is vastly greater than that for dissolved gas, have the effect that in practice the two entities behave very differently: gas bubbles have a relatively long lifetime and, for certain purposes, may be thought to possess an equilibrium radius. On the contrary, vapor bubbles are much less persistent and the notion of an equilibrium radius is of limited usefulness. These crucial differences required a detailed study of the physics of oscillating vapor bubbles, which was carried out numerically and substantiated by physical arguments.

2. The fate of vapor bubbles depends critically on heat transfer, which is of course greatly affected by translation. Since pressure gradients act differently on liquid particles and suspended bubbles, they are capable of inducing a relative motion between the phases even when no relative velocity initially exists. As a consequence of the enhanced heat transfer in the presence of convection, this fact may have a major impact on the evolution of a vapor bubble. The effect is particularly strong in the case of a collapsing bubble for which, due to the conservation of the system's impulse, the induced relative velocity tends to be magnified when the bubble volume shrinks. A practical application could be, for instance, the enhancement of the condensation rate of bubbles downstream of a heated region thereby reducing the quality of a flowing liquid-vapor mixture. These processes are of particular importance in microgravity where it is necessary to replace to some extent the gravitational pressure gradient.

3. In addition to pressure fields, convection in the neighborhood of a vapor bubble can also be the result of the presence of boundaries. When these are combined with a sound field, the situation becomes rather complex. For sufficiently large bubbles, a plane solid boundary can be replaced by an image bubble, which requires the ability to simulate bubble-bubble interactions in the presence of a sound field. A numerical method for this purpose has been developed. The results show that, when the acoustic wavefronts are parallel to the surface, the bubble remains trapped due to secondary Bjerknes force caused by the image bubble. When the wavefronts are perpendicular to the surface, on the other hand, the bubble can be made to slide laterally and, in this way, removed.

4. All of the previous work was carried out assuming the bubble to remain spherical. The last fraction of the time was spent in the search of a method capable of dealing with deformable bubbles. It was realized that the available methods were not sufficient as they gave an inaccurate representation of the temperature field near the bubble surface, which is of course crucial for the determination of the vapor mass fluxes at the bubble surface. A new method has been developed but, for the time being, it is limited to the adiabatic case. It does however seem possible to extend it to the heat transfer problem.

5. The bubble models investigated so far only included vapor, with no incondensible gases. In practice, unless one works with cryogenic liquids, the presence of incondensibles is unavoidable and it is therefore desirable to extend the models to this case. We have started to work on the formulation and numerical implementation of a gas-vapor diffusion model.

6. A small portion of the effort was devoted to the study of the effect of viscosity on the spherical stability of oscillating gas bubbles. The objective here was to compare experimental data (obtained by Holt and Gaitan under NASA sponsorship) with our theory developed earlier. A paper on this subject has been accepted for publication in The Physics of Fluids.

Personnel

Over the duration of this grant, in addition to the PI, this work has involved the following personnel:

1. Dr. Hasan N. Oğuz, Associate Research Professor
2. Dr. He Yuan, Research Scientist
3. Dr. Emmanuel Ory, post-doctoral fellow
4. Dr. Jan Wei Qi, post-doctoral fellow
5. Mr. Yue Hao, doctoral student