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Evaporation condensation-induced bubble motion after temperature gradient set-up

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ABSTRACT

Thermocapillary (Marangoni) motion of a gas bubble (or a liquid drop) under a temperature gradient can hardly be present in a one-component fluid. Indeed, in such a pure system, the vapor–liquid interface is always isothermal (at saturation temperature). However, evaporation on the hot side and condensation on the cold side can occur and displace the bubble. We have observed such a phenomenon in two different fluids submitted to a temperature gradient under reduced gravity: hydrogen under magnetic compensation of gravity in the HYLDE facility at CEA-Grenoble and water in the DECLIC facility onboard the ISS. The experiments and the subsequent analysis are performed in the vicinity of the vapor–liquid critical point to benefit from critical universality. In order to better understand the phenomena, a 1D numerical simulation has been performed. After the temperature gradient is imposed, two regimes can be evidenced. At early times, the temperatures in the bubble and the surrounding liquid become different thanks to their different compressibility and the "piston effect" mechanism, i.e. the fast adiabatic bulk thermalization induced by the expansion of the thermal boundary layers. The difference in local temperature gradients at the vapor–liquid interface results in an unbalanced evaporation/condensation phenomenon that makes the shape of the bubble vary and provoke its motion. At long times, a steady temperature gradient progressively forms in the liquid (but not in the bubble) and induces steady bubble motion towards the hot end. We evaluate the bubble velocity and compare with existing theories.

1. Introduction

Classically, when a bubble of gas (radius R) is immersed in a liquid and subjected to a temperature gradient, a bubble drift along the gradient is observed when the gravity effects are negligible. This motion is classically attributed to a thermocapillary (Marangoni) convection, the temperature gradient inducing a surface tension gradient that drives the flow. The bubble velocity in a steady gradient is given by the expression [1]

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$$\vec{v}_M = -\frac{2}{2\eta_L + 3\eta_G}\frac{d\sigma}{dT}\frac{R}{2 + \lambda_G/\lambda_L}\nabla T \quad (1)$$

Here T is temperature, ∇T is the temperature gradient, σ is surface tension, η_L and η_G are the liquid and gas shear viscosities and λ_L and λ_G are the liquid and gas thermal conductivities, respectively. Depending on the sign of $d\sigma/dT$, the gas bubble will move parallel or antiparallel to the thermal gradient. When both liquid and gas are the same substance, the gas corresponds to the pure vapor in equilibrium with its liquid. The vapor–liquid interface is at the saturation temperature. Any interface temperature change then leads to evaporation or condensation and will thus be immediately counterbalanced by the latent heat effect [2]. The thermocapillary motion is thus hardly possible. However, another reason for the bubble motion can exist.

A simple 1D model where the gradient is directed along the z direction shows that evaporation, which adds the vapor to the hot side of the bubble, and condensation, which removes it from the cold side, corresponds to a bubble drift with an (apparent) velocity v_D equal to the evaporation (condensation) interface velocity. The rate of evaporation dm/dt, where m is mass, t is time, S is the interface area perpendicular to z and L is the latent heat can be expressed as

$$\frac{dm}{dt} = L v_D S \rho_L = \lambda_L S \frac{dT}{dz}. \quad (2)$$

Here ρ_L and ρ_V are the liquid and the vapor density, respectively. This gives the interface velocity

$$v_D = \frac{\lambda_L}{\rho_L L}\frac{dT}{dz}. \quad (3)$$

A similar reasoning applied to a 3D model (see Appendix A) results in a factor 3,

$$v_D = \frac{3\lambda_L}{\rho_L L}\frac{dT}{dz}. \quad (4)$$

In contrast to thermocapillary migration, the bubble always moves in the direction of the temperature gradient, with a constant speed independent of its radius. This approach was followed by Mok et al. [3] when analyzing their experiments in hydrogen H_2. The thermal gradient was used there to compensate buoyancy.

A further study was performed by Onuki and Kanatani [4] in the framework of a dynamic van der Waals theory starting with entropy and energy functional with gradient contributions [5]. The resultant hydrodynamic equations contain the stress arising from the density gradient. It provides a general scheme of two-phase hydrodynamics involving the vapor–liquid transition at non-uniform temperature. Accounting also for evaporation and condensation, the vapor bubble velocity v_D was found to be

$$v_D = \frac{\hat{\eta} + \left[(1 + \hat{\eta}/2)\right]\hat{\rho}}{(1/3 + \hat{\eta}/2)\,\rho_V L}\lambda_L \nabla T \quad (5)$$

where $\hat{\eta} = \eta_V/\eta_L$ and $\hat{\rho} = \rho_V/\rho_L$. Far from T_c ($\hat{\eta} \to 0$), this expression reduces to Eq. (4), which neglects however the hydrodynamic flow induced by the phase change. Note that close to T_c, where $\hat{\eta} \sim 1$ Eq. (5) yields exactly the same expression as $\hat{\rho} \sim 1$ in numerator and $\rho_V \sim \rho_L$ in denominator. This shows that the hydrodynamic flows caused by the phase transition have only a small impact on this phenomenon. They will be neglected in the theoretical part of the present article. The flow can however be important in constrained geometries (where the moving bubble size is comparable to the vessel size), as it will be discussed later on.

In this paper, we report preliminary experiments performed (i) with a H_2 vapor bubble in liquid H_2 under magnetic compensation of gravity near its critical point and (ii) in liquid–vapor water at saturation very near its critical point under weightlessness. The data are analyzed in the framework of a 1D model that ignores hydrodynamic effects, but captures the main characteristics of the problem, including phase change, release of latent heat and compressibility (piston effect). A realistic temperature distribution in the fluid is calculated. The bubble displacement caused by the evaporation/condensation process is evaluated, in particular at short times after temperature has been changed at the boundary, and late times when a steady gradient has taken place.

2. Experiment

2.1. Hydrogen under magnetic compensation of gravity

Gravity forces can be compensated by magnetic forces that are the strongest near the end of a solenoid. The HYLDE (HYdrogen Levitation DEvice) facility has been set up at CEA–Grenoble to work with hydrogen. Details can be found in [6]. It can be shown [7] that a perfect homogeneous acceleration field cannot be obtained in the whole volume. In practice, a zero value of effective gravity g^* is achieved at one or several points in space and can be made as small as needed within a finite volume by configuring the magnetic field [8]. When the condition $g^* = 0$ is achieved at some point, the spatial distribution of g^* is called "residual gravity". The residual gravity is directed upward (downward) at the upper (lower) part of the cell, corresponding to bubble attraction to the cell center (i.e. to the stable position for bubble levitation at