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Analysis of bubble growth on a hot plate during decompression in microgravity

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The focus of the present work is the modeling of bubble growth on a hot plate during decompression (depressurization) of a volatile liquid at temperatures close to saturation and in the presence of dissolved gas. In particular, this work presents an organized attempt to analyze data obtained from an experiment under microgravity conditions. In this respect, a bubble growth mathematical model is developed and solved at three stages, all realistic under certain conditions but of increasing physical and mathematical complexity: At the first stage, the temperature variation both in time and space is ignored leading to a new semi-analytical solution for the bubble growth problem. At the second stage, the assumption of spatial uniformity of temperature is relaxed and instead a steady linear temperature profile is assumed in the liquid surrounding the bubble from base to apex. The semi-analytical solution is extended to account for the two-dimensionality of the problem. As the predictions of the above models are not in agreement with the experimental data, at the third stage an inverse heat transfer problem is set up. The third stage model considers an arbitrary average bubble temperature time profile and it is solved numerically using a specifically designed numerical technique. The unknown bubble temperature temporal profile is estimated by matching theoretical and experimental bubble growth curves. A discussion follows on the physical mechanisms that may explain the evolution of the average bubble temperature in time.

1. Introduction

Bubble formation, growth and detachment in liquids including dissolved gases when the ambient pressure decreases is a very important process in diverse scientific fields, e.g. in cavitating turbines and pumps [1]; in carbonated drinks [2], in liquid waste treatment by dissolved air flotation [3]. In the past, *liquid degassing* focused mainly on the mechanisms of nucleation rather than bubble dynamics, e.g. see [4]. Therefore, tests were conducted at low temperatures where the role of liquid vapor pressure is negligible. In addition, most of those experiments strived to avoid thermal gradients in the system. However, even at moderate temperatures the presence of temperature gradients is inevitable due to appreciable liquid evaporation at the gas/liquid interface. A relevant case with particular technological significance is that of a liquid which depressurizes in the presence of dissolved non-condensable gases close to its saturation temperature. Such experiments are complicated to investigate under terrestrial conditions because gravity yields natural convection currents and makes the bubbles to distort from their spherical shape and depart when they are still small. A microgravity environment would circumvent these effects and would further allow considerably large bubbles to be examined where the capacity of optical diagnostics is higher.

Pool boiling experiments in presence of non-condensable gas have been performed in the SOURCE experimental setup which has flown in the sounding rocket Maser 11 attaining microgravity conditions for several minutes. The SOURCE experimental set-up consists of a small cylindrical reservoir of 60 mm diameter and 271 mm long partly filled with a liquid refrigerant HFE7000 pressurized by gaseous nitrogen. The experiment has been described in detail in [5]. At the tank bottom, a heated plate of 1 cm^2 is located to study nucleate boiling regimes in microgravity (see Fig. 2). This plate is equipped with a thermocouple and a flux-meter (uncertainty ± 80 W/m^2) to measure the wall heat transfer. Before the launch of the rocket, the reservoir is overheated and pressurized with Nitrogen at a pressure of 3 bar. The sequence of the

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experiment is described in Fig. 1:

- after take-off (time t = 0s) the rocket accelerates during the ascent,
- at t = 50s the microgravity period starts,
- from t = 65s to t = 88s, the tank is filled with the refrigerant HFE7000 at 25 °C,
- from t = 88s to t = 190s, the free surface stabilizes, the refrigerant evaporates in the wall vicinity, then the concentration of the HFE7000 vapour in the gas phase increases close to the tank wall. The non-uniformity of HFE7000 vapour concentration in the gas phase along the interface leads to a strong Marangoni convection.
- At t = 190s, the tank pressure is reduced from P = 3.35 bar–1.82 bar to initiate nucleate boiling.
- From t = 200s to t = 263s, the small plate is heated and nucleate boiling takes plate in subcooled condition. The liquid temperature is smaller than saturation temperature.
- At t = 263s, the tank pressure is reduced from 1.93 bar to 1.23 bar.
- From t = 320s–380s, heat transfer and bubble size evolution in saturated boiling condition is investigated. The results obtained in subcooled and saturated boiling conditions have been reported in [6].

Pictures of the different steps of the experiments are shown in Fig. 2.

In the present paper, we focus on investigating the depressurization phase between t = 263s and 324s, which is a period lying between the sub-cooled and the saturated boiling phases. During this phase, the wall heat flux is kept constant and equal to 1.36 W/cm^2 and the wall temperature T_0 is equal to 51 °C. In this phase of the experiment, a bubble remaining on the heated plate after the end of the subcooled boiling period continues to grow. This is a result of different contributions such as volume expansion due to depressurization, desorption of dissolved non-condensable gas, rise of vapour pressure. The evolution of the radius of the large bubble during the depressurization is measured by image processing. At t = 263s, the bubble radius is equal to R_o = 4.18 mm. While the pressure decreases by a factor of 1.57, the bubble radius increases by a factor of 3.05.

The temperature of the gas inside the bubble is also measured at different locations (Fig. 3). An array of 5 thermocouples is placed above the heated plate. Thermocouple T_{14}, T_{16} and T_{17} are located 1.59, 4.27, 8.69 mm above the heated wall, respectively. The liquid bulk temperature T_L measured above the bubble and the saturation

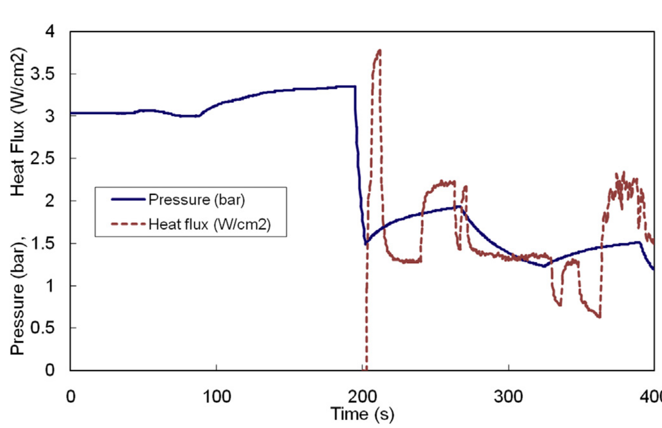

Fig. 1. Sequence of the experiment Source.

temperature at the tank pressure T_{sat} are also plotted in Fig. 3. Temperature measurements are quite noisy but although absolute values are within thermocouple uncertainty (±0.1 °C) the observed fluctuations (sensitivity) are real and reflect the dynamic nature of the observed phenomena. In particular, thermocouple T_{16} shows a marginal increasing trend in temperature evolution. A temperature rise of 1 °C during the decompression period is recorded by thermocouple T_{17} but the measurement noise prevents to recognize the exact time evolution of this rise. Finally, the thermocouple T_{14} undergoes a temperature increase of 3 °C with most of it occurring sharply at t = 305s which appears to be the moment at which the thermocouple pierces the bubble. The thermocouples T_{14}, T_{16} and T_{17} are located inside the large bubble for a significant part of the depressurization. Then a gradient of temperature inside the gas phase can be evaluated at a value around 2 K/cm. T_{17} measures an average temperature of 33.8 °C, which corresponds to a partial pressure of HFE7000 vapour P_v = 0.96 bar, whereas T_{14} which measures an average temperature of 35.8 °C, corresponding to P_v = 1.03 bar. These temperatures are almost unchanged during the end of the depressurization after t = 300s.

A direct modeling approach is extremely difficult since the problem is a combination of degassing and evaporation [7,8]. The plate in contact with the bubble is heated and this creates a temperature distribution in the liquid. As the system pressure decreases it is possible that the temperature of the solid in contact with the bubble gets close or even exceeds the boiling temperature of the liquid. However, the average temperature of the bubble remains colder than the one of its base and this average temperature governs bubble growth. In any case, all the complexities associated with microlayer evaporation may be present. The information given by the measured temperatures in the liquid is limited since the temperature profile in the liquid can be very complex and the connection between the fixed in space thermocouples and the actual average bubble temperature is rather weak.

In addition to the effort needed to deal with the heat transfer problem, the mass transfer equations for the dissolved gas in the liquid domain must be solved. In particular, handling of Marangoni motion for a growing bubble requires a big computational effort [9]. So detailed modeling of the process requires state of the art elaborate computational tools and it is out of the scope of the present work. The alternative approach followed here is to build step by step simplified models incorporating basic aspects of the process and compare to the experimental curve in order to assess the phenomena determining the bubble growth. In this respect, the first step is to develop an isothermal 1-D bubble growth model for which an approximate analytical solution can be derived (i.e. assuming as bubble temperature the time average value of thermocouples measurements). The second step is to extend the analytical solution in order to account for the 2-D nature of the liquid domain (due to existence of the hot plate) and for a steady linear temperature profile in liquid. The above scenarios yield results that can not explain the experimental curve so a time variation of the average bubble temperature is considered, next. A numerical technique for the corresponding non-isothermal 1-D bubble growth problem is developed. Finally, an inverse problem of computing the average bubble temperature evolution corresponding to the experimental growth curve is set up and solved.

2. Formulation of 1-D radial symmetric model for isothermal bubble growth

The mathematical model which describes the depressurization stage of bubble growth in the present experiment refers to the growth of a pre-existing gas bubble inside a volatile liquid during the reduction of the external (with respect to the bubble) pressure