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Research Paper

Evaporation and boiling in narrow gap

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HIGHLIGHTS

- Evaporation dynamics is visualized for test liquid sandwiched between glass plates.
- Flash boiling pushes up the top plate, energetics of which is discussed.
- Vertical oscillation of the top plate at a later stage is caused by incomplete condensation.
- Surface roughness and dissolved gas affect the dynamics.

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ABSTRACT

In order to investigate a washing process of liquid-immersed laminated plates with solvent vapor, we have done visualization experiments of liquid confined between solid plates. Ethanol is used as test liquid, which is sandwiched between horizontally placed glass plates in a vacuum chamber with a reduced pressure of typically 3 kPa at room temperature. When the plates are clamped, evaporation proceeds from the plate edges and complicated branching patterns appear with occasional rapid motions of liquid front. To study this quasi two-dimensional flash boiling in more detail, we carried out similar experiments with unclamped plates. At the earlier stage, several isolated jumps of the top plate were observed, which correspond to the flash boiling. Rough energetic analysis indicates that the flash boiling has only a limited contribution to the whole evaporation process. As the evaporation proceeds, jumps change into regular oscillations, which can be explained by incomplete condensation of vapor. These behaviors of isolated jumps and oscillations are strongly affected by surface roughness and dissolved gas.

1. Introduction

This study has a fairly practical goal, which is to understand the cleansing mechanism of laminated plates. Metal plates are widely used as iron cores in various types of electric transformers. The cores are normally immersed in insulating mineral oils. On their disposal, it requires much time and cost to wash the remaining oil away. Until 1970s, polychlorinated biphenyls (PCBs) were widely used as an ingredient, the use of which is now strictly banned due to their high toxicity [1]. Thus the ways of safe and cost-effective disposal process are demanded.

Among several technologies, vapor washing with organic solvents seems promising [2–4]; under sufficiently high temperature (typically 100–200 °C, depending on the type of insulating oil) and reduced pressure conditions, the oil containing PCBs between the core plates is gradually replaced by the solvent vapor and easily washed away after a certain time. To understand the mechanism and optimize the working conditions, it is essential to investigate the fluid dynamics in such narrow gaps in more details. Flows with phase change in various types of micro channels have been widely studied in thermal science and engineering [5], the target of which is to achieve a better heat exchanger. Their experimental approaches as well as theoretical modellings are closely related to our goal, but the situations are rather different.

To achieve our goal of understanding fluid phase change in thin gaps, we have tried to visualize the fluid behavior using model systems [6–8]. Most of our recent results with a model system are described in Ref. [9], and briefly summarized as follows:

1. The model system uses ethanol, water, and several organic liquids (other than insulating oils for technical reasons), which are sandwiched between clamped glass plates.
2. We use sand-blasted (or ground) glass, which enables us to distinguish between wet (i.e., liquid-filled gap) region and dry one because the dried sand-blasted glass scatters incident light.

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3. The plates are placed in a vacuum chamber; detailed description of the conditions will be given in the next section.
4. As the evaporation proceeds, complicated patterns of dry region usually appear.

Some examples of "patterns" are shown in Fig. 1; while ethanol and organic liquids (acetone, heptane, and octane) show branching patterns which resembles "cracks" in liquid, evaporation in water starts from many tiny spots, which are probably cavitation caused by dissolved gas. Detailed analyses are given in Ref. [9].

We also found another interesting phenomenon. During the evaporation, we occasionally observed abrupt and rapid deformation of the wet region, as shown in Fig. 2. This is supposed to be flash boiling in quasi two dimensions. During the "boiling", the region boundary propagates as fast as 50 mm/s, in contrast to the typical evaporating speed (i.e., propagation of branching pattern) of 0.1–1 mm/s. This phenomenon of rapid phase change may play an important role in the oil retrieve process in transformer core treatments. In this paper, we focus on the flash boiling and investigate it from a different viewpoint.

2. Experimental setup

2.1. Visualization system

The essential part of the system is similar to that used in Ref. [9]; a schematical setup is shown in Fig. 3. The inner size of the transparent acrylic resin vacuum chamber is $200 \times 200 \times 200\,\mathrm{mm}^3$, inside which glass plates sandwiching test liquid are horizontally placed with a simple zig. The glass plates are not clamped, so the top plate will be pushed up when flash boiling occurs; by analyzing the plate motion, we expect to obtain some information on the boiling phenomenon.

The chamber is depressurized with a rotary vacuum pump (TASCO, 48 L/min). The inside pressure is monitored with a digital differential pressure gauge, the uncertainty of which is 0.1 kPa. All experiments were done at room temperature, without any active temperature control. We record the temperature outside the chamber with a digital thermometer and the glass plate temperature with a K type thermocouple, the uncertainty of which is $\pm 0.1\,^\circ\mathrm{C}$. In general, the temperature variation during the evaporation is less than $1\,^\circ\mathrm{C}$ since the heat capacity of the glass plates is much larger than that of test liquid.

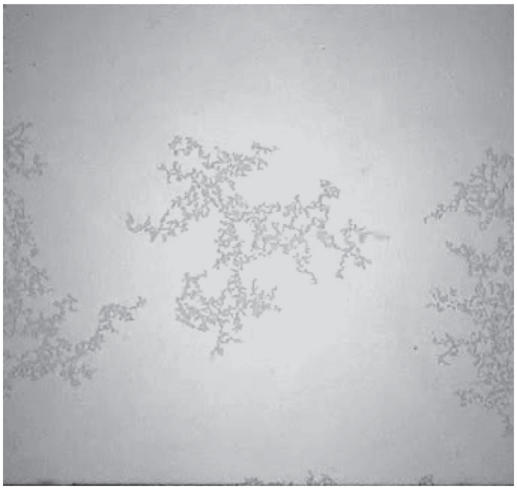
The area size of the glass plate is $100 \times 100\ \mathrm{mm}^2$ with 5 mm thickness. The plates are illuminated with a white-type LED light source. A photo-sensing unit and a shutter are utilized to synchronize the digital camera and the pressure measurement.

2.2. Model system

We use ethanol (99.5%) as the test liquid, which is colorless and sufficiently volatile, instead of insulating oils which are hard to evaporate at room temperature.

Two types of commercially available glass plates are used; one is float glass with smooth surface, and another is ground (sand-blasted) glass. The surface image of the latter taken with an optical microscope is shown in Fig. 4. The roughness of the sand-blasted plate is measured with a surface measurement instrument to be $\sim 40\,\mu\mathrm{m}$, which is coincidentally the same order of magnitude as typical metal plates used in transformers. The sand-blasted glass is more wettable than the float glass; the contact angle on float glass is $\sim 18^\circ$, while that on sand-blasted one is almost zero. Relevant properties of ethanol are summarized in Table 1.

When the chamber pressure is sufficiently reduced under the saturated vapor pressure p_s which is solely determined by the



(a) Ethanol at 55 s

(b) Heptane at 60 s

(c) Water at 100 s

Fig. 1. Examples of appearing patterns during evaporation of test liquids sandwiched between clamped glass plates. Brighter area indicates the liquid-filled region. The size is about $100 \times 100\,\mathrm{mm}^2$. Detailed conditions are described in Ref. [9].