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Condensation heat transfer coefficient versus wettability

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ABSTRACT

In this paper we show how condensation on substrates can induce wetting behavior that is quite different from that of deposited or impinging drops. We describe surfaces with the same wettability in ambient conditions presenting different wetting behavior and growth of droplets in condensation. The experimental results show a rapid spread of droplets and formation of the film on the copper surface, while droplets on SU-8 surface remains on the regular shape while they grow within the time, without coalescence, as observed for Cu. Although the heat conductivity of SU-8 is much lower, due to a difference in wetting behavior, the heat transfer coefficient (h) is higher for dropwise condensation on Cu with a thin layer of SU-8 than filmwise on the bare copper.

1. Introduction

Understanding the mechanisms governing water condensation on surfaces is crucial to a wide range of applications that have a significant societal and environmental impact, such as energy conversion [1–3], water harvesting [4,5], water desalination [6], thermal management systems [7–11] and environmental control [12].

Likewise, enhancement of heat transfer coefficients for condensation is an active area of research. Conventionally, some of the methods employed to enhance condensation heat transfer coefficients is chemical treatment of the condensation surface, exploiting surface texture to drain the condensate, and adding chemicals to the vapor to affect its interaction with the surface [13–15]. The choice of methods involved to enhance heat transfer depends on the conditions in which condensation takes place.

The interaction of the condensate with the condensation surface is an important factor that controls the heat transfer process [16]. If the condensed fluid quickly coalesces, it forms a thin film and wets the entire surface, film wise condensation (FWC) is said to have taken place [17]. This is a result of high surface energy of the condensation surface and is observed on surfaces which are hydrophilic. On the other hand, drop wise condensation (DWC) occurs in the form of liquid droplets on surfaces which are not fully wetted by the liquid and is a result of low surface energy of the condensation surface; such surfaces are said to be hydrophobic. DWC is characterized by higher drop contact angles of the droplets when compared to that of FWC [17].

Mobility of the condensate on the solid surface also greatly affects the heat transfer. The diameter at which a droplet slides down a vertical surface due to the effect of external forces is called the departure diameter; this typically occurs when the droplet is large. When a condensation surface is washed by a higher frequency of falling droplets, the heat transfer coefficient increases. McCormick and Baer [18] reported that droplet growth and dynamics significantly affected the heat transfer performance.

Thus, droplet mobility becomes an important factor in condensation heat transfer. When a large drop moves away from the point of incipience, the moving drop washes away smaller drops in its path due to the cohesive nature of the liquid [19]. In DWC, droplets can readily be removed from their nucleation sites [20] and, hence, for DWC, heat transfer coefficients have been observed to be up to an order of magnitude higher than FWC [17].

While it is accepted that DWC, which is observed on hydrophobic surfaces, results in high heat transfer coefficients [16], it has been observed that the nucleation rate is larger with hydrophilic surfaces [21]. This is due to the fact that the nucleation rate depends on the free energy barrier of the condensation surface, which in turn is a strong function of surface wettability [22]. The relationship between the nucleation rate and the free energy barrier can be expressed as [21]:

$$J = J_0 e^{-\Delta G/kT} \quad (1)$$

where J is the nucleation rate, J_0 is the kinetic constant, ΔG is the free energy barrier, k is the Boltzmann constant, and T is the absolute temperature.

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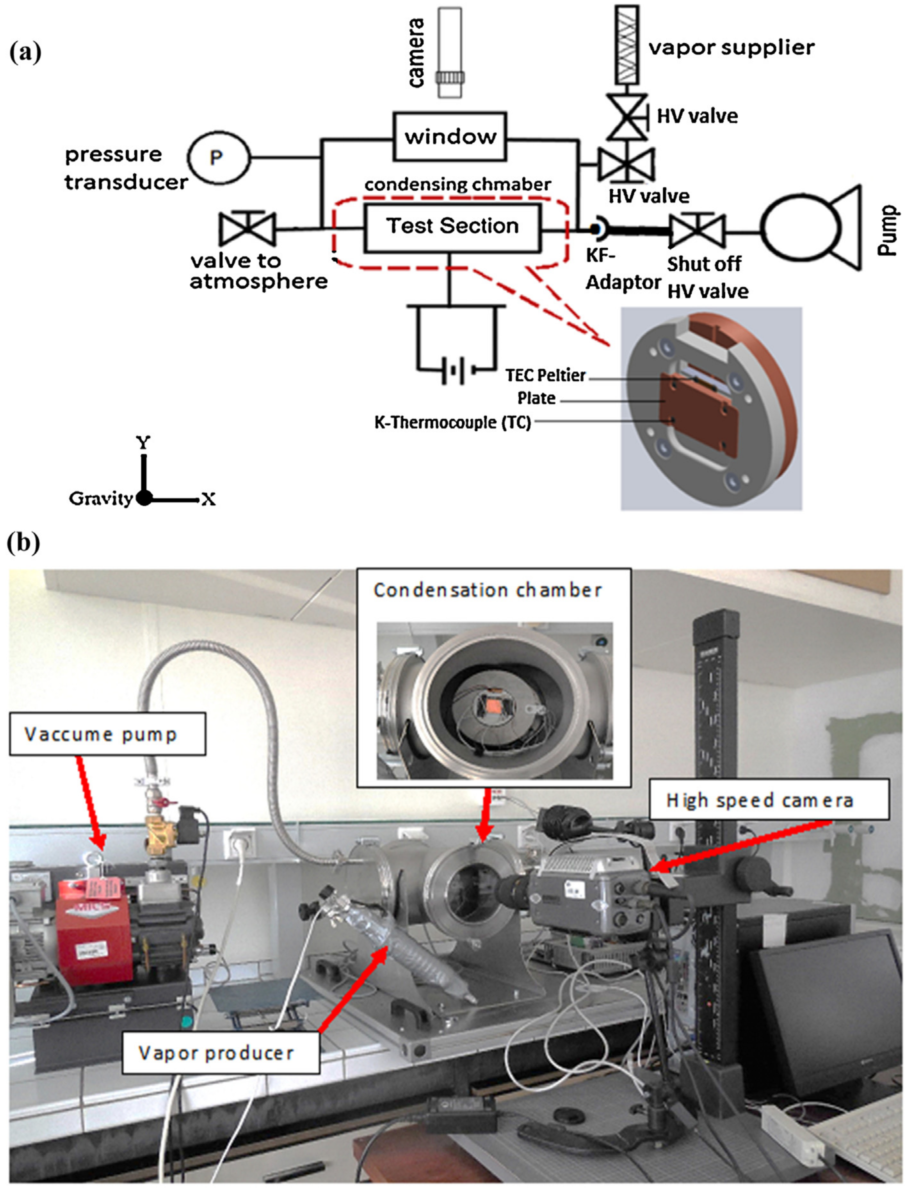

Fig. 1. (a) and (b) Schematic of the test condensation and, the measurement setup, respectively.

Since hydrophilic surfaces have a smaller free energy barrier when compared to hydrophobic surfaces, they have higher rates of nucleation, as can be concluded from Eq. (1) and is discussed by Varanasi et al. [21]. Thus, it is inferred that, while hydrophobic surface is necessary for DWC and high heat transfer coefficient, a hydrophilic surface is necessary to achieve high condensation rate.

Although many studies have been devoted to the wetting behavior of drops deposited on a surface [23], very few have delved into the condensation process even though it is a key phenomenon in both fundamental and applied studies. Condensation on substrates can indeed induce wetting behavior that is quite different from that of deposited or impinging drops [24–26] since during condensation, hot steam from boiling water is used in contact with supercooled surfaces. The surface tension of water and the surface energy of the considered surfaces change with temperature, due to this fact, wettability in condensation is different from the one measured in environmental situation such as deposition and pinning.

On the other hand, the drops grow on all surfaces of the substrate and the drops coalesce with each other. This drop–drop interaction and the fact that the drop sizes cover a broad range of length scales make the condensation situation quite different from the generally considered case of drop deposition. In this paper, we investigate the main features of water condensation on the surfaces with similar contact angle in ambient conditions, whereas quite unexpected phenomena are observed. This can be generalized to other surfaces and could lead to interesting applications or developments.

2. Materials and methods

2.1. Experimental set up

Visualization of the condensation behavior is performed inside an aluminum condensation chamber with one viewing window (Fig. 1).

A stainless steel tube line is fed into the chamber via a KF adapter port that serves as the flow line for the incoming water vapor supplied from a heated steel water reservoir. The vapor reservoir is wrapped with a rope heater and insulated to limit heat loss to the environment. The access tube is welded to the vapor reservoir with valves.