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Simulation and validation of the dynamics of liquid films evaporating on horizontal heater surfaces

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HIGHLIGHTS

► Liquid film dynamics under thermal influence is simulated.
► Long wave theory and minimum free energy theory are applied.
► Impacts of heat flux and surface wettability on film dynamics are investigated.
► A correlation is developed to predict the critical thickness of film rupture.

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ABSTRACT

In this study a non-linear governing equation based on lubrication theory is employed to model the thinning process of an evaporating liquid film and ultimately predict the critical thickness of the film rupture under impacts of various forces resulting from mass loss, surface tension, gravity, vapor recoil and thermo-capillary. It is found that the thinning process in the experiment is well reproduced by the simulation. The film rupture is caught by the simulation as well, but it underestimates the measured critical thickness at the film rupture. The reason may be that the water wettability of the heater surfaces is not taken into account in the model. Thus, the minimum free energy criterion is used to obtain a correlation which combines the contact angle (reflection of wettability) with the critical thickness from the simulation. The critical thicknesses predicted by the correlation have a good agreement with the experimental data (the maximum deviation is less than 10%).

1. Introduction

Liquid films spreading over and evaporating on solid surfaces are commonly encountered in daily life and industrial applications that involve processes such as cooling (e.g., condensation), heating (e.g., boiling), coating, cleaning and lubrication. Studies on liquid film dynamics are of paramount importance to achieve an efficient and safe operation of the related equipments. For instance, the instability of a liquid film will affect the coating quality, while the rupture of a near-wall liquid film (e.g., macrolayer in boiling) will deteriorate heat transfer and lead to safety issues (destruction of heater surface due to burnout) in power plants.

In our previous work, a novel experimental method using a confocal optical sensor was developed to measure the thickness evolution of an evaporating liquid film, and first-of-a-kind data about the thinning and rupture process of a thin liquid film on a horizontal surface heated from below was obtained [1,2]. It was observed that a liquid film ruptures when it was thinning to a threshold value (called critical thickness). The critical thickness of the liquid films performed in the tests was found to increase with increasing heat flux, and within the range of 60–150 μm for water films and 150–250 μm for ethanol films. In addition, the film instability was greatly affected by the properties of heater surfaces. Wettability of the surfaces proves to have a profound influence on film stability, and the critical thickness decreases with the reduction in contact angle. The wettability (contact angle) alone, however, could not explain all the effects of material properties and surface conditions on film instability. Thermal–physical properties of the heater surfaces also manifest themselves through the onset of liquid film instability. For instance, given two surfaces with a comparable contact angle, the one (e.g., copper or aluminum) with a high thermal conductivity exhibited a thinner critical film than the one with a low thermal conductivity (e.g., stainless steel or titanium). For the essentially wetting case (contact angle near zero) of a hexane film formed on an aged titanium surface, the liquid film was found resilient to rupture, and instability was not detected

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