International Journal of Heat and Fluid Flow 70 (2018) 104–113

Contents lists available at ScienceDirect

International Journal of Heat and Fluid Flow

journal homepage: www.elsevier.com/locate/ijhff

Numerical investigation of the evolution and breakup of an evaporating liquid film on a structured wall

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ARTICLE INFO

Keywords:
Film flow
Evaporation
Structured wall
Long-wave theory

ABSTRACT

This paper examines the evolution and rupture of a thin liquid film evaporating on a structured wall and the concomitant heat and mass transport. The heat is supplied either from the side of the wall or from the hot ambient gas. An evolution equation for the film thickness is derived in the framework of the long-wave theory under the assumption that the film thickness is small compared to the length scale of film deformation. The resulting fourth order partial differential equation is solved numerically employing a finite difference scheme using a MATLAB code. The results show that, in the case of a hot wall, the film breakup may occur even in the absence of evaporation. The reason for this breakup is Marangoni convection driven by uneven temperature distribution at the liquid-gas interface due to the wall structure. With increasing evaporation rate the rupture time decreases and the position at which the rupture occurs is shifted towards the crests of the wall topography. Additionally, it is found that the wave length of the wall structure has a non-monotonous effect on rupture time. If the film is heated by the ambient gas, the liquid-gas interface tends to follow the wall topography shape.

1. Introduction

Thin liquid films evaporating on structured surfaces can be found in many industrial applications. Depending on the application, the film can either be heated from the wall or from the ambient gas phase. Diesel and gasoline fuels, for example, are known to form films on the cylinder surface after injection from where they evaporate in the ambient gas phase (Drake et al., 2003; Schintzel, 2005; Zhao et al., 1999). Deposits, which have a negative effect on the combustion process as shown by Güralp et al. (2013), can be formed from those films. It can be assumed that deposits form preferably in the vicinity of three-phase contact lines during dewetting. This behavior has been observed for many multi-component systems, for example by Brack (2016) for urea-water systems. Thus, it is necessary to understand the impact of influencing factors on film topology and stability, as well as heat and mass transfer to prevent deposit formation. This behavior makes it important to understand how the deposit structure on the wall and the evaporation of the film influence film instability and breakup.

Furthermore, the deposits significantly contribute to the wall roughness. If the liquid film evaporates from a wall on which a deposit layer already exists, the film evolution and rupture depends on the topography of the deposit.

One of the most widespread methods for theoretical and numerical description of liquid film dynamics and stability is the long-wave theory (Oron et al., 1997; Craster and Matar, 2009), which is based on an assumption that the average film thickness is very small in comparison to the characteristic wave length of the film thickness variation. Evaporating films on plane walls have been first considered in the context of long-wave theory by Burelbach et al. (1988). Inclusion of terms describing the so called Derjaguin pressure (Israelachvili, 1992) into the long-wave evolution equation allows predicting the dynamics, stability, as well as heat and mass transfer in film flows, including an evaporating three-phase contact-line for the cases of perfect wetting (Klentzman and Ajaev, 2009) and partial wetting (Oron and Bankoff, 1999; Ajaev et al., 2010; 2011). In all these works, it is assumed that the liquid evaporates into a pure vapor environment.

Evaporation of a liquid film into a mixture of a vapor and an additional non-condensable component in the gas phase has been studied numerically by Haut and Colinet (2005). The evaporation rate, in this case, is limited by the diffusive transport of vapor in the gas phase. It has been shown that the presence of the non-condensable component leads to instabilities driven by gradients of surface tension (Marangoni effect).

Kabova et al. (2014) developed a model to describe film dynamics as well as heat and mass transfer in a gas-driven film flow in a microchannel with local heating. The film flow has been modeled using lubrication approximation, and the convective transport, which is usually neglected in long-wave models, has been taken into account in both

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https://doi.org/10.1016/j.ijheatfluidflow.2018.01.013
Received 29 September 2017; Received in revised form 23 January 2018; Accepted 31 January 2018

liquid film and gas phase. The development of thermal and concentration boundary layers in the gas phase and their influence on evaporation rate and Marangoni stresses has been described. The influence of the Marangoni effect and evaporation on film deformation has been quantified.

Several works have been devoted to theoretical and numerical investigation of the stability, dynamics, heat transfer and evaporation of liquid films on structured walls. Gambaryan-Roisman and Stephan (2003) used long-wave-theory (LWT) to show that grooves in flow direction have a stabilizing effect on a falling film flow. Additionally, they investigated the evaporation of falling film flowing along the grooved wall. Evaporation into the pure vapor environment was considered. If the mass flow rate is low enough, the grooves are only partially filled with liquid, so that the groove crests remain dry. In this case, the overall heat transfer is substantially enhanced by evaporation in the vicinity of the three-phase contact lines (micro region evaporation). A similar investigation has been performed by Helbig et al. (2005) for the case of the film driven by the gas flow along grooved surfaces.

Gambaryan-Roisman et al. (2005), Kabova et al. (2005) and Kabova et al. (2006) have used the long-wave theory to study Marangoni-induced deformation and rupture of thin liquid films resting on a structured heated wall. The non-uniform thickness of a liquid film covering a structured surface leads to non-uniform temperature distribution at the liquid-gas interface. The local temperature maxima correspond to the locations of the structure crests, and the minima correspond to the locations of the structure troughs. Since the surface tension decreases with increasing temperature, the interface temperature non-uniformity induces interfacial forces acting in the direction of decreasing temperature (or increasing film thickness). These forces result in appearance of flow patterns (Marangoni convection) and in film deformation. Depending on the parameters of the surface structure (wave length and amplitude of the sinus-shaped grooves) and on the values of governing parameters, which reflect the relative influence of Marangoni stresses, surface tension and gravity, the evolution equation possesses stable stationary solutions or describes the local film thinning and rupture.

In Gambaryan-Roisman and Stephan (2006), the stability of an evaporating falling liquid film on a grooved surface has been studied using the long-wave theory. The authors considered evaporation of liquid into the mixture of the vapor and a non-condensable gas. It was assumed that the heat transfer between the liquid and the ambient gas is determined by a constant heat transfer coefficient. In addition, the dynamics of evaporating film at rest has been simulated in the limit of small ratio between the groove amplitude and the average initial film thickness. It has been shown that the film dynamics are dominated either by evaporation or by the Marangoni effect at different stages of the film thinning. During the Marangoni-governed stages the amplitude of the film deformation increases. The work of Gambaryan-Roisman and Stephan (2006) is devoted to the cases where the major film rupture mechanism is the Marangoni effect.

Gaskell et al. (2006) investigated the flow of an evaporating two-component film down an inclined plane. The analytical model of Eres et al. (1999) was extended to study the effect of structured walls by using a numerical method. The solvent evaporates from the liquid film with a prescribed evaporation rate leading to a thinning of the film and changes in species concentration. The viscosity of the liquid changes with the solvent concentration and may lead to deformations of the free surface, while the surface tension was kept constant. It was shown that wall topography leads to an uneven distribution of the volatile component.

In spite of the increasing interest in liquid film evaporation and in controlling the Marangoni effect (Gambaryan-Roisman, 2015), the simultaneous influence of evaporation and the Marangoni effect on film dynamics and time to rupture on a structured wall has not been completely understood and predicted. The role of the Marangoni effect on evaporating film dynamics in the case where the film is heated by the ambient gas has, to the best of our knowledge, never been treated numerically.

In this work, the effect of evaporation and wall structure on the development of thin liquid films and the resulting heat and mass transfer is examined. Temperature gradients develop at the liquid-gas interface and lead to Marangoni convection. Film evaporation and the unequal heating of the liquid due to the structure affect the film stability. Long-wave theory (Oron et al., 1997; Craster and Matar, 2009) is used to reduce the complexity of the problem and obtain an evolution equation for the film thickness. The influence of evaporation rate and wall structure on film development and rupture time as well as heat and mass transfer within the film is discussed.

The rest of this paper is structured as follows: in Section 2 the problem is formulated, the relevant governing equations are given, and the evolution equation for the film thickness is derived. The numerical scheme is described in Section 3. The results are presented and a discussion of the results is given in Section 4. Finally, concluding remarks can be found in Section 5.

2. Formulation

2.1. Problem definition

A sketch of the two-dimensional problem under consideration is shown in Fig. 1. A film of thickness h and length c rests on a structured wall with variable thickness $l(x)$. The film is thick enough, so that the van der Waals forces do not play a role, but so thin that buoyancy can be neglected. The lower side of the wall is kept at a constant temperature T_w, and the gas phase far from the interface is at a constant temperature T_∞. The liquid evaporates into the gas phase, so that the film thickness decreases with time.

The evaporation can happen into a pure vapor atmosphere or into a mixture of vapor and an ambient non-condensable gas. In the case of a pure vapor atmosphere, the molecular-kinetic resistance at the liquid-vapor interface is small leading to high Biot numbers (compare Gambaryan-Roisman and Stephan, 2006). If the liquid is evaporating into a vapor-gas mixture, the evaporation rate is governed by convective and diffusive transport of vapor in the gas phase. In this case, the Biot number is determined by effective heat and mass transfer coefficients.

Temperature gradients arise through uneven heating of the liquid from the structured wall. These temperature gradients give rise to Marangoni convection and may lead to film instability. However, the temperature differences are small enough so that the material properties, except for the temperature-dependent surface tension, can be

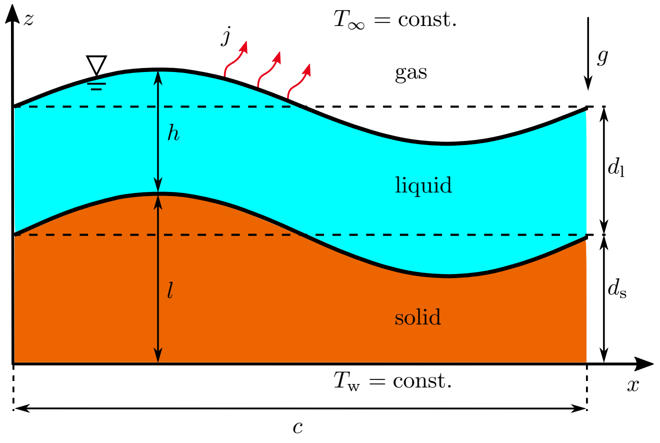

Fig. 1. Sketch of the two-dimensional problem. The thin film evaporates on a structured wall with constant wall temperature.