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GRAVITY- AND SHEAR-DRIVEN THIN FILMS FLOW ON HEATED MICROSTRUCTURED WALLS

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Summary A model describing the behaviour of the gravity- and shear-driven liquid films on heated microstructured walls is developed. The hydrodynamic stability of the film flow is investigated using the long-wave theory. It is shown that the longitudinal grooves stabilize the film flow both when the wall is completely or only partially covered by the film. The influence of the thermocapillarity on the film shape and velocity field has been analyzed in the framework of the long-wave theory and numerically using the volume of fluid method.

INTRODUCTION

Thin falling films and shear-driven films are used for cooling of electronic devices and other components, for powders production and for other technological processes. Using microstructured wall surfaces improves the performance of the device and prevents the film dryout. Smooth films flowing down vertical walls are hydrodynamically unstable. The small disturbances are developed into waves, which in many cases possess a three-dimensional structure. Normally, the pure shear-driven flows with linear velocity profile are stable to long-wave disturbances. However, when the gravity- and shear-driven flows are superimposed, the long-wave film instability may appear, leading to development of waves showing a very complicated behaviour [1]. The film waviness drastically changes the heat and mass transfer characteristics of the film. The effect of thermocapillarity (surface tension dependence on temperature) is in many cases a primary reason for the film rupture.

The wall topography may cause the film deformation [2]. It has been shown [3] that, if the wall is completely covered with the liquid, the longitudinal grooves stabilize the isothermal falling film flow.

This work is aimed at investigation of the combined effect of the gravity and the shear stress on long-wave stability of thin liquid films on grooved walls. Another goal of this work is to qualify the effect of the wall structure on the flow induced by thermocapillarity.

FILM STABILITY ANALYSIS

We consider a film flowing down an inclined grooved plate. The grooves axes are oriented in parallel with the gravity-induced flow. The shear stress due to a gas flow over the film acts in the same or opposite direction. The wall temperature is constant and above the gas temperature. The liquid is assumed to be nonvolatile. We assume that the characteristic film thickness h^* is much smaller than the characteristic length of the thickness variation, and the same is applicable to the variation of the wall topography. We also assume that the Reynolds number of the flow is moderate. Under the above assumptions the film dynamics can be described in the framework of the long-wave theory [4]. The film flows under the influence of the gravity, constant shear stress and the surface tension (including the thermocapillarity). We neglect the effect of the film wavyness on the gas pressure and the shear stress.

To perform the film stability analysis, we first determine the shape of an unperturbed film. Then simple harmonic disturbances with small amplitude are applied to this basic state. This disturbed solution is substituted into the evolution equation, which is linearized. The resulting eigenvalue problem is solved to determine the disturbance growth rate and the wave speed depending on the wave number.

SIMULATION OF FILM DYNAMICS

Since the validity conditions of the long-wave theory are rather restrictive, the CFD simulation methods are required. We develop a numerical model for the solution of two-dimensional flow of a liquid film characterized by the gas-liquid interface over a structured wall. The incompressible Navier-Stokes equations are solved for the liquid and gaseous phases, while the free surface is modeled with the Volume of Fluid (VOF) technique. The energy equation is also included into the numerical model allowing calculations of temperature distributions within the film. We use the numerical model to investigate flow of a liquid on a structured wall, when it is caused by a temperature drop between the wall and the ambient gas. This calculation is the first step toward the modeling of a three-dimensional flow of a falling film on a wall with longitudinal grooves.

RESULTS

We have quantified the combined effect of the gravity, the interface shear stress and the groove geometry on the stability characteristics of a film fully covering a wall surface. We have found that in this case, as in the case of falling

films, the grooves have a stabilizing effect on the film flow. The co-current shear stress destabilizes the film, and the counter-current shear stress stabilizes it.
The stability characteristics of the flow with a contact line is illustrated in an example of a flow down a vertical wall in a rectangular groove with a contact angle equal to $\pi/2$. This angle is assumed to be between the receding and the advancing contact angles, so that the contact line is immobile. Figure 1 shows the dependence of the disturbance growth rate, ω, on the wave number, k, values of the groove width, d. The disturbance growth rate on the grooved wall is smaller than that on the smooth wall, which points out at the stabilizing effect of the grooves. Moreover, starting from some value of h^*/d, the film becomes stable for any small disturbance. This behaviour is qualitatively different from that of the thin films on smooth walls.
If the temperature of the wall is higher than that of the gas, the wall structure causes the temperature gradients on the liquid-gas interface. As a result, a thermocapillary flow develops even in the undisturbed state. The interface deforms in such a way, that the liquid tends to accumulate inside the groove. We have shown that, if the grooves are deep enough, dry patches may appear even at moderate temperature drops. But, unlike the case of smooth wall, the location of these dry patches is well defined and corresponds to the grooves crests. The appearance of these dry patches may even improve the heat transfer characteristics [3].
Figure 2 illustrates the thermocapillarity-induced velocity field in a single groove with a depth of 0.5 mm. The calculations have been performed using the VOF method. The temperature drop between the wall and the gas is 10 K. The deformations of the liquid-gas interface are small. The maximal liquid velocity at the interface reaches 1.6 mm/s. The main feature of the velocity field is a vortex in the counter-clockwise direction. This vortex provides an additional mixing of the liquid and may increase the heat transfer rate.

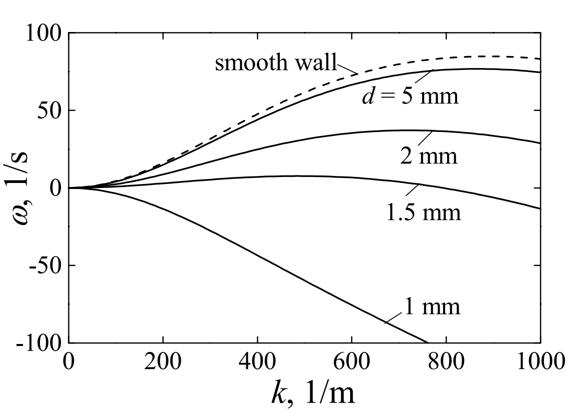

Figure 1. Disturbance growth rate for a film on vertical wall with rectangular grooves. Water, h^*=200 μm, shear stress 1 N/m^2.

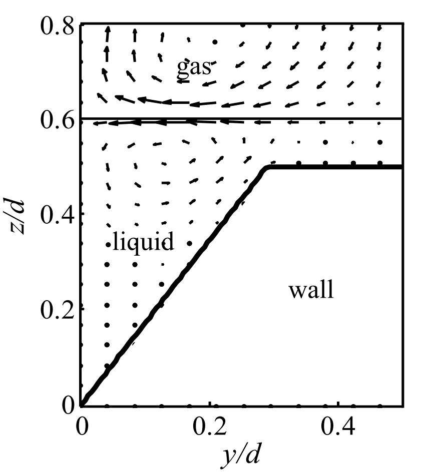

Figure 2. Thermocapillarity-induced velocity field in a film on a grooved wall.

CONCLUSIONS

The foundations for modelling the wavy motion of the gravity- and shear-driven liquid films on structured heated walls have been established. It has been shown that in the case when the wall is completely covered by the liquid the longitudinal grooves have a stabilizing effect on the film flow. The stabilization tendency is also predicted for the cases where the grooves are partly covered by the liquid, and the contact angle is finite.
The thermocapillarity-induced velocity field and liquid-gas interface deformations on the microgrooved wall have been studied in the framework of the long-wave theory and numerically using the VOF method. The thetmocapillary flow pattern is determined by the wall microstructure.

References

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