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The Rupture of Thin Liquid Films Placed on Solid and Liquid Substrates in Gravity Body Forces

A. L. Kupershtokh[1,2,*], E. V. Ermanyuk[1,3] and N. V. Gavrilov[1]

[1] *Lavrentyev Institute of Hydrodynamics SB RAS, Novosibirsk 630090, Russia.*
[2] *National Research Novosibirsk State University, Novosibirsk 630090, Russia.*
[3] *Laboratoire de physique ENS de Lyon, France.*

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Abstract. This paper presents a numerical and experimental study on hydrodynamic behavior of thin liquid films in rectangular domains. Three-dimensional computer simulations were performed using the lattice Boltzmann equation method (LBM). The liquid films laying on solid and liquid substrates are considered. The rupture of liquid films in computations is initiated via the thermocapillary (Marangoni) effect by applying an initial spatially localized temperature perturbation. The rupture scenario is found to depend on the shape of the temperature distribution and on the wettability of the solid substrate. For a wettable solid substrate, complete rupture does not occur: a residual thin liquid film remains at the substrate in the region of pseudo-rupture. For a non-wettable solid substrate, a sharp-peaked axisymmetric temperature distribution induces the rupture at the center of symmetry where the temperature is maximal. Axisymmetric temperature distribution with a flat-peaked temperature profile initiates rupture of the liquid film along a circle at some distance from the center of symmetry. The outer boundary of the rupture expands, while the inner liquid disk transforms into a toroidal figure and ultimately into an oscillating droplet.

We also apply the LBM to simulations of an evolution of one or two holes in liquid films for two-layer systems of immiscible fluids in a rectangular cell. The computed patterns are successfully compared against the results of experimental visualizations. Both the experiments and the simulations demonstrate that the initially circular holes evolved in the rectangular cell undergoing drastic changes of their shape under the effects of the surface tension and gravity. In the case of two interacting holes, the disruption of the liquid bridge separating two holes is experimentally observed and numerically simulated.

AMS subject classifications: 76M28, 76T30, 76M25, 65Z05

Key words: Lattice Boltzmann equation method, phase transition, liquid films, dynamics of multiphase media, Marangoni effect, computer simulations.

*Corresponding author. *Email addresses:* `skn@hydro.nsc.ru` (A. L. Kupershtokh), `ermanyuk@gmail.com` (E. V. Ermanyuk), `gavrilov@hydro.nsc.ru` (N. V. Gavrilov)

1 Introduction

The mechanism for rupture of thin liquid films is of importance for colloid science, foam mechanics, ecological problems and many engineering applications. The films can be freely hanging as well as laying on solid or liquid substrates. The theory of the critical thickness of rupture of free thin liquid films was proposed by Scheludko et al. in [1–3]. There exists extensive literature on rupture of thin liquid films on solid substrates including structured surfaces (see review [4]). The systems consisting of thin liquid films on liquid substrates are widely present in nature and technology (see review [5]). One of the first experiments on the hydrodynamic behavior of thin films on liquid substrate after rupture was carried out in work [6], where the authors used a round cell and considered an axisymmetric problem of expansion and further evolution of a hole in the film.

Our earlier work [7] was devoted to three-dimensional computer LBM simulations of the dynamics of thin freely hanging liquid films with no gravity under the action of a radially symmetric temperature distribution with a maximum at the center. This temperature distribution can initiate a rupture of the film due to the thermocapillary effect. Depending on the shape of the temperature distribution in the vicinity of the symmetry axis (maximum of temperature), the film ruptured either with the formation of a central round hole or an annular hole. In the latter case, a liquid disk was formed that later evolved into a droplet in the center of the round hole.

The present study is focused on the hydrodynamic aspects of the rupture of thin liquid films on liquid and solid substrates in a rectangular cell. The evolution of one or two holes in liquid films on a liquid substrate is investigated in experiments and is simulated for two-layer systems of immiscible fluids.

The three-dimensional computer simulations are performed using the lattice Boltzmann equation method. The phase transitions in the LBM are simulated by introducing attractive forces acting on the matter at the nodes of the computation grid. The pseudopotential method proposed in [8, 9] describes the fluids with an arbitrary equation of state (pressure as a function of density and temperature) and simulates the interfaces between vapor and liquid phases with a surface tension. Here we use the pseudopotential model considerably improved in works [10–12]. For liquid films and liquid substrates we use the model van der Waals equation of state for which the surface tension decreases with temperature and tends to zero near the critical point. The effect of solid walls on fluids is simulated by special forces acting between the nodes representing the solid boundaries and the nodes belonging to the liquid or vapor phases.

2 Lattice Boltzmann Equation method

Simulations of hydrodynamic flows with the interfaces between liquids and gases are of vivid interest in scientific and industrial applications. We use the lattice Boltzmann equation method in computer simulations because it does not require tracking of the