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Three-dimensional LBE simulations of a decay of liquid dielectrics with a solute gas into the system of gas–vapor channels under the action of strong electric fields☆

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ABSTRACT

The three-dimensional simulations of an anisotropic decay of binary mixtures of a dielectric liquid with solute gas in a strong electric field are carried out. The Lattice Boltzmann Equation method (LBE) is exploited for computer simulations of the evolution of such systems with the newly arising interfaces between vapor and liquid phases. The parallel implementation of the LBE algorithm is realized on a large number of cores in the GPU. For the GPU programming, the CUDA technology is used.

It is important that new regions of the low-density phase appear as thin quasi-cylindrical gas–vapor channels oriented along the electric field. The gas–vapor channels expand because of the diffusion of the solute gas from the mixture, evaporation of liquid into the channels and also due to the coalescence of channels with each other. The critical values of electric field necessary for such decay of a binary mixture are considerably lower than the critical electric field for pure dielectric liquids. Hence, if we take into account a solute gas, the electric fields for which the anisotropic mechanism of streamer channels generation and growth is operated, become considerably lower.

Thus, at a breakdown of dielectric liquids in a strong electric field, the anisotropic instability is possibly the key mechanism of the generation of a gas phase, inception of conducting streamer structures, their fast growth in the form of thin filamentary channels, as well as branching of streamer structures during propagation.

1. Introduction

The main features of the well-known phenomenon of breakdown of liquid dielectrics are tree- or bush-like shapes of conductive structures (streamers), a cylindrical form of channel segments, and ultra-fast propagation of streamer tips in a strong electric field with a velocity of up to 300 km/s [1,2]. However, the mechanisms of a streamer inception and a fast propagation of streamer filaments were not revealed till now. Since the electric strength of a liquid phase is very high, the electric breakdown can occur initially in a low-density phase (vapor). For dielectric liquids with nonlinear density dependence of permittivity, the new mechanism of anisotropic decay of an initially uniform fluid being in a stable liquid state into the liquid and gaseous phases under the action of strong electric fields was proposed in works [3,4]. It is important

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that new segments of the low-density phase appear in the form of thin filamentary channels oriented on average along the electric field. The mechanism of the anisotropic decay allows one to explain easily the major part of the experimentally observed phenomena at liquid dielectric breakdowns [5] (an ultra-fast propagation of streamer tips, an occurrence of a fan of dark thin radial channels of low density near the tip of the electrode and a further breakdown of the gas phase in one or several of these channels, the cylindrical shape of segments of channels and also their branching during propagation). The authors of experimental work [5] explained their results on the breakdown of liquid dielectrics based on our model of streamer inception and growth according to the mechanism of anisotropic decay of liquid dielectrics in a high electric field proposed in [3,6]. However, the first study was carried out only for pure dielectric liquids. In this case, the anisotropic decay can occur for electric fields of the magnitudes of the order of tens of MV/cm. On the other hand, the actual electric fields in most experiments on electrical breakdowns were much lower (in the range from several tenths to several MV/cm). Moreover, the first computer simulations were carried out only in the two-dimensional case.

In the present study, the three-dimensional simulations of anisotropic decay of binary mixtures of a dielectric liquid with solute gas in a strong electric field were carried out. For binary mixtures of a dielectric liquid and a solute gas, the value of the critical electric field turned out to be considerably lower than for the pure dielectric liquids. At the breakdown of dielectric liquids in a strong electric field, this anisotropic instability is possibly the key mechanism of generation of a gas phase, inception of conducting streamer structures, their fast growth in the form of thin filamentary channels and the branching of streamer structures during propagation.

The Lattice Boltzmann Equation (LBE) method was used for three-dimensional computer simulations of the evolution of such binary systems in strong electric fields with the newly arising interfaces between vapor and liquid phases. This method has been widely exploited in simulations of multiphase and multicomponent flows.

The several LBE models are known to simulate multiphase flows (including the color-fluid model [7], the free energy model [8], the model with interparticle interaction forces [9], and the pseudopotential model [10]). The major disadvantage of the color-fluid model is that it does not include any equation of state. Hence, this model cannot describe the phase transitions, the origination of new interfaces, condensation and evaporation. The free energy model ensures the constant interface thickness. However, this model is more complicated, needs corrections of equilibrium distribution functions to improve the Galilean invariance, does not describe the correct temperature dependence of the surface tension and cannot simulate the liquid–vapor interfaces with a high density ratio.

The model exploited in the present paper was firstly proposed in 2005–2007 [11–13]. It was based on two models. The main one was the pseudopotential model proposed by Qian [10]. We exploited this approach, because it allows one to incorporate easily an arbitrary form of EOS. However, the part of the finite difference isotropic approximation of the gradient of the pseudopotential was very close to the model of interparticle interaction [9].

The idea to introduce the total force acting on a node instead of interparticle forces was proposed in the work [10]. The total force should be a gradient of a pseudopotential $\mathbf{F} = -\nabla U$, where $U(\rho) = P(\rho) - \rho\theta$. Later, this approach was extended to the equation of state given in the form $P(\rho, T)$ [14]. In [11–13], the special function $\Phi = \sqrt{-U}$ was introduced that allowed us to propose a new isotropic finite difference approximation of the gradient of the pseudopotential.

Later, in 2011, the same model was published in [15]. If one redefines the free coefficients of this model, their main equations exactly coincide with the equations proposed earlier in [11–13].

A modern Graphics Processing Unit (GPU) consists of a large number of cores that allows one to realize parallel computations. For the first time, a GPU was used for LBE simulations in the work [16]. For simple variants of LBE without phase transitions, the parallel computations using one or several GPU were exploited in [16–20]. Multiphase lattice Boltzmann simulations of fluid flows were carried out in [21,22].

This paper is organized as follows. In Section 2, the macroscopic equations are given that describe the hydrodynamics of the problem and the electric field distribution. In Section 3, the algorithm of the LBE method for simulation of a fluid with a possible liquid–vapor phase transition in accordance with the given equation of state is described. Section 4 is devoted to parallel computations on Graphics Processing Units (GPU). Section 5 is devoted to the simulations of spinodal decomposition using the lattice Boltzmann equation method. In Section 6, the simulations of a decay of binary mixtures in strong electric fields are described. Some concluding remarks are given in Section 7.

2. Macroscopic equations

The well-known macroscopic equations of hydrodynamics for a viscous compressible fluid are the continuity equation

$$\frac{\partial \rho}{\partial t} + \nabla(\rho \mathbf{u}) = 0 \tag{1}$$

and the Navier–Stokes equation

$$\frac{\partial(\rho u_i)}{\partial t} + \frac{\partial \Pi_{ij}^{(0)}}{\partial x_j} = \rho a_i + \frac{\partial}{\partial x_j}\left(\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right) + \frac{\partial}{\partial x_j}\left(\left(\lambda - \frac{2}{3}\mu\right)\delta_{ij}\frac{\partial u_k}{\partial x_k}\right). \tag{2}$$

Here, ρ is the density, $\mathbf{u}$ is the velocity, μ and λ are the dynamic and second viscosities, and $\Pi_{ij}^{(0)} = P(\rho, T)\delta_{ij} + \rho u_i u_j$ is the non-viscous part of the momentum flux tensor. The acceleration $\mathbf{a}$ is defined by the total body force $\mathbf{F} = \rho\mathbf{a}$. The equation