Simulation of Microbubbles during the Initial Stages of Breakdown in Cyclohexane

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Abstract- The formation of a vapor microbubble has previously been suggested to be the initial mechanism in the process of dielectric failure of dielectric liquids. The bubble is generated by a rapid, highly localized heating of a volume close to a highly stressed electrode, caused by electric currents in the liquid at high voltages. A numerical model is presented in order to investigate the dynamics of a single microbubble in the point-plane geometry in cyclohexane. A condition for the formation of a vapor bubble is discussed. Thereafter, a Computational Fluid Dynamics (CFD) model of two-phase flow with phase transition is used to study the dynamics of the bubble from generation to collapse, under a highly divergent electrostatic field in a subcooled liquid. The amount of subcooling in the simulations is 5 K, and it is found that convergence gets significantly weaker as the amount of subcooling increases. The bubble dynamics is also simulated considering the electrohydrodynamic (EHD) processes in the liquid and vapor phases. Finally, it is shown how the electrostatic forces on the dielectric will cause a bubble to detach from the electrode.

I. INTRODUCTION

Dielectric liquids are commonly used as electrical insulating material in high-voltage devices, such as power transformers. If the liquid fails to maintain the applied voltage between two electrodes, a process referred to as breakdown, the device will normally be damaged or destroyed. Therefore, the understanding of the process leading to breakdown in dielectric liquids is crucial for the design of robust high-voltage systems. During dielectric failure, the dielectric is subjected to both Coulomb and polarization forces [8]. These forces will cause a violent, strongly rotational kind of motion in liquid dielectrics [7]. There are many empirical studies on prebreakdown phenomena in the point-plane geometry in the literature. The tip radius of the needlepoint electrode in these experiments is typically a few micrometers and the distance between the needlepoint and the grounded plane is typically a few millimeters [1, 4]. From these experiments, we know that the prebreakdown process taking place when a large negative potential is applied to the needlepoint is characterized by a series of events. The process starts with a small current pulse with a duration of 10 ns and a peak value of 100 μ A that occurs when the applied voltage is increased to a threshold value [13]. The current pulse is caused by an electron avalanche in the liquid phase [2]. The resulting drift of charge carriers under high electric field causes a rapid, highly localized heating of the liquid close to the needle. The injected energy, which is typically a few nanojoules [1], can result in the formation of a vapor microbubble [1, 2, 13]. After

formation, the bubble expands until it reaches a maximum volume and it thereafter starts to contract and ultimately collapse [2]. The bubble has also been observed to detach from the needlepoint electrode during the contraction phase [4]. The maximum radius of the bubble is typically a few micrometers and the lifetime of the bubble is typically a few microseconds [1].

It has been suggested that “bush like” streamers in liquids grow initially from single bubbles [2]. Thus, the aim of this study is to take the first step towards a numerical model that can simulate this complicated process. A numerical model that can be used for simulation of a single vapor bubble in a highly divergent electric field is presented in this paper. The model is based on Computational Fluid Dynamics (CFD) and the liquid-vapor interface is tracked using the phase-field method which has been modified to take phase transition into account. This model is used to simulate the expansion and subsequent contraction of a single vapor bubble due to local superheating in a liquid subcooled 5 K below the temperature of saturation. Finally, the model is used to simulate a noncondensable bubble detaching from the needlepoint electrode due to electrostatic forces. The simulations presented here were performed for liquid cyclohexane. The presented model is implemented and evaluated using the commercial Finite Element Method (FEM) software COMSOL Multiphysics.

II. SIMULATION MODEL

A. Bubble Formation and Initial Conditions

Experiments on prebreakdown phenomena in dielectric liquids are typically performed at room temperature [1] and the liquid is therefore strongly subcooled. The formation of a single vapor bubble close to a solid boundary due to a heat pulse caused by a current pulse, has previously been studied by Asai in the development of thermal microejectors [5]. A vapor bubble can be formed spontaneously when a pure liquid is subjected to a highly localized heat pulse that rapidly raises the temperature of the liquid. This process is stochastic and normally takes place when the liquid temperature is quickly raised well above the temperature of saturation [5]. Experiments have shown that the formation of the vapor bubble follows the current pulse by a few nanoseconds [2]. Therefore, the two-phase flow simulations presented in this paper assume an initial bubble seed which is small compared to the maximum size of the bubble. The initial bubble seed is assumed to be spherical since the surface tension tends to

minimize the interface area [11]. It is also assumed that the fluids are initially at rest. The density of charge in the liquid phase generated when the voltage is applied to the configuration is estimated by using the model described in [12]. The initial temperature distribution is calculated by solving the heat equation with the Joule heating source term produced by the drift of charge carriers in the liquid phase.

B. Numerical Model

The multiphysics model presented here includes a coupled system of several nonlinear partial differential equations. The velocity field $\vec{u}$ is found from Navier-Stokes equations, the temperature T is found from the heat equation, the electric field $\vec{E}$ is found from Poisson's equation and the distribution of charge ρ is found from the continuity equations for electrons and ions, as described in [12]. The velocity field appears in the convective term of the heat equation and the continuity equations.

The liquid-vapor interface is tracked using the phase field method. The equations governing the interface dynamics of a two-phase flow can be described by the Cahn-Hilliard equation. This equation can be modified to allow for the change of phase [6]

$$\begin{aligned} \frac{\partial \Phi}{\partial t} + \vec{u} \cdot \nabla \Phi - \dot{m} \delta \left(\frac{V_{f,v}}{\rho_v} + \frac{V_{f,l}}{\rho_l} \right) \\ = \nabla \cdot \frac{\gamma \lambda}{\varepsilon^2} \nabla (\nabla \cdot \varepsilon^2 \Phi + (\Phi^2 - 1) \Phi) \end{aligned} \quad (1)$$

where Φ is the dimensionless phase field variable, λ is the mixing energy density (N), ε is a stability parameter (m) that is used to scale the thickness of the interface and finally, ρ_L and ρ_V are the mass densities of the liquid and vapor phases respectively. The vapor volume fraction variable $V_{f,v} \in [0,1]$ equals 1 in the vapor phase and 0 in the liquid phase. Similarly, the liquid volume fraction variable $V_{f,l} \in [0,1]$ equals 1 in the liquid phase and 0 in the vapor phase. Both volume fraction variables are calculated from the phase field variable Φ . All material parameters are evaluated as a function of position $(\vec{r})$ using the volume of fraction variables. The mobility γ determines the time scale of the Cahn-Hilliard diffusion. The mobility is implemented as $\gamma = \varepsilon \chi^2$ where χ is a stability parameter (mskg^{-1}). A rule of thumb is to take ε equal to $0.5h$, where h is the maximum size of a mesh element in the region where the interface passes, and to take χ close to unity [9]. The velocity of the bubble interface has never exceeded $0.1c$, where c is the speed of sound in the liquid, in the bubble dynamics experiments performed by Jomni *et al* [1]. Compressibility effects are therefore negligible and the flow can be considered to be incompressible [10]. The incompressibility condition is modified to account for phase transition [6]

$$\nabla \cdot \vec{u} = \dot{m} \delta (\rho_v^{-1} - \rho_l^{-1}) \quad (2)$$

where δ is the interface delta function. The rate of vaporization $\dot{m}$ is estimated as

$$\dot{m} = C \rho_L \frac{T - T_{sat}}{T_{sat}} \quad (3)$$

where T_{sat} is the temperature of saturation and C is a stabilization parameter that should be chosen large enough for the interface to remain at saturation temperature, but small enough to prevent numerical instability. The rate of vaporization $\dot{m}$ appears as a heat sink

$$Q_s = -L \dot{m} \delta \quad (4)$$

in the heat equation, where L is the latent heat of vaporization. The heat equation is given by

$$\frac{\partial T}{\partial t} + \vec{u} \cdot \nabla T = \frac{1}{\rho_m c} (k_T \nabla^2 T + \vec{E} \cdot \vec{J} + Q_s) \quad (5)$$

Where ρ_m is the mass density, c is the specific heat, k_T is the thermal conductivity and $\vec{J}$ is the current density.

C. Volume Force

The volume force in a dielectric can be expressed as

$$\vec{f} = \rho \vec{E} - \frac{|\vec{E}|^2}{2} \nabla \varepsilon_r \varepsilon_0 + \frac{1}{2} \nabla \left(|\vec{E}|^2 \rho_m \frac{\partial \varepsilon_r \varepsilon_0}{\partial \rho_m} \right) + \rho_m \vec{g} \quad (6)$$

where the first and last terms are the Coulomb and gravitational forces respectively. The second term is the dielectrophoretic term which arises due to polarization [7]. The third term is the electrostrictive term, taking into account the elastic deformation of a dielectric under an electrostatic field [8] and can be neglected since the flow is assumed to be incompressible.

D. Boundary Conditions

The point-plane geometry used in [13] is used in this simulation. The radius of the needle tip is $1 \mu\text{m}$ and the distance between the electrodes is 0.5 mm . The grounded plane is set to zero potential while the needle electrode is set to the applied voltage V_a . The temperature boundary condition for all boundaries but the needle tip is the constant temperature, and the zero heat flux condition is used for the needle tip.

III. RESULTS

A. Bubble Expansion and Contraction

The expansion and subsequent contraction of a vapor bubble is simulated in cyclohexane subcooled by 5 K. The hydrostatic pressure in this simulation is set to one atmosphere. The electrostatic forces are not considered in this simulation and the slip condition is used for the sake of simplicity. The slip condition allows the fluid to flow tangent to the needle boundary but not through it. The initial temperature is obtained from (5) and reaches 490 K in a small region close to the needle tip for an injected energy $W_i = 4 \cdot 10^{-10}$ J. This maximum temperature is well above the temperature of saturation while being below the critical temperature. The liquid is thus strongly superheated and vapor microbubbles may be formed due to spontaneous vaporization. The initial bubble seed is assumed to have a radius of $r_0 = 0.5 \mu\text{m}$, as shown in Fig. 1. The color scale in this figure is chosen such that the liquid phase is white, and the vapor phase is red. The mesh is approximately uniform with the maximum mesh element length $h = 18 \text{ nm}$ in a circular region close to the bubble. The stability parameter C was chosen to be 1 m/s. In order to find a convergent solution, the required values for the stability parameters ε and χ were 100 nm and 250 mskg^{-1} respectively. Although these values are small enough for the liquid-vapor interface to be relatively thin, and to prevent excessive Cahn-Hilliard diffusion, they are significantly larger than the values suggested for this kind of calculations [9]. The calculated bubble size as a function of time is shown in Fig. 2. Note that the obtained maximum radius is in good agreement with the value of $3.5 \mu\text{m}$ obtained by the relationship $R_{\text{max}}^{\text{measured}} \approx 0.85k(W_i/p_\infty)^{1/3}$ [3] with $k=0.258$ for cyclohexane [1].

It is found that convergence becomes significantly weaker as the amount of subcooling increases. Numerical experiments have shown that the solution in this case is convergent only until the onset of condensation, i.e. when $\dot{m}$ first takes negative values. The contraction of the bubble due to condensation causes a rapid drop of the pressure in the liquid phase outside the liquid-vapor interface. Hence, it is found that the pressure can drop suddenly by more than 50 kPa in the liquid outside the bubble. This large pressure gradient is likely what is causing the convergence issue. Furthermore, it appears that this convergence issue is almost independent of both temporal and spatial discretization.

B. Effects of Hydrostatic Pressure on the Maximum Radius

The relation between hydrostatic pressure p_∞ and maximum radius r_{max} is found from a parametric sweep. The results from this simulation are presented in Fig. 3. This result can now be compared with a simple thermodynamic model where the relation is estimated as $r_{\text{max}} \propto p_\infty^{-1/3}$ [3]. It has been found that the relation $r_{\text{max}} \propto p_\infty^{-2/3}$ fits better with the simulation results over a wide pressure range. Fig. 3 shows

that there is no significant bubble expansion over 1 MPa, which agrees with experiments where bubbles are not detected for hydrostatic pressures over 1 MPa [13].

Fig. 1. Initial bubble seed attached to the needlepoint electrode. This is a volume fraction plot where the vapor phase is red and the liquid phase is white. The computational domain is axisymmetric and the boundaries visible in this figure are the axis of symmetry and the needlepoint electrode.

Fig. 2. Simulated relation between bubble radius (m) and time (s) for 5 K subcooling. It can be seen in this figure that the bubble with initial radius of $0.5 \mu\text{m}$ expands to a maximum radius around $3 \mu\text{m}$ before it starts to implode.

Fig 3. Calculated maximum bubble radius as a function of hydrostatic pressure. The radius of the initial bubble seed is $r_0 = 0.5 \mu\text{m}$.

Fig. 4. A noncondensable microbubble detaching from the needlepoint electrode due to dielectrophoretic and Coulomb forces. This is a volume fraction plot where the gaseous phase is red and the liquid phase is white.

C. Bubble Detachment

The EHD motion of a noncondensable bubble is simulated in order to study the detachment of a single bubble. The initial bubble is attached to the needle (Fig. 4) and the initial radius of the bubble is set to 1 μm . The no-slip condition is used for the needle boundary. There is a negative distribution of charge closest to the needle after the initial current pulse. This initial distribution of charge is estimated using the model described in [12]. Consequently, the Coulomb force tends to accelerate the dielectric closest to the needle in the downwards direction in Fig. 4. The polarization forces will also accelerate the bubble in this direction due to the dielectrophoretic term in (6) which is acting on the liquid-vapor interface. These two forces can consequently cause the bubble to detach from the needle. The detachment is simulated and presented in the sequence of volume fraction plots presented in Fig. 4.

V. DISCUSSION AND CONCLUSION

A simulation model based on the phase-field method is suggested for studying of the dynamics of microbubbles during the initial stages of breakdown in cyclohexane. The expansion and contraction of a vapor microbubble in a liquid subcooled by 5 K is simulated. The simulated relation between hydrostatic pressure and maximum radius is found to be $r_{\text{max}} \propto p_{\infty}^{-2/3}$ rather than $r_{\text{max}} \propto p_{\infty}^{-1/3}$ which has previously been suggested. It is also shown that the detachment of a single microbubble, which has previously been observed in the experiment by Lesaint *et al* [4], is caused by polarization and Coulomb forces.

It is found that the stability parameters required for finding convergent solutions are significantly larger than the values suggested in [9]. It is also found that the model can be used for simulations close to saturation temperature, but the Finite Element Method fails to produce convergent solutions as the

amount of subcooling increases. This convergence issue does not appear to be dependent on the spatial or temporal discretization. To the author's knowledge, there are no simulations of bubble dynamics in strongly subcooled liquids in the literature. In fact, simulations on bubble dynamics in subcooled liquids are typically performed with only 5 K subcooling [14]. Therefore, it seems that further advances are required in order to develop a multiphysics model that can be used to study the dynamics of microbubbles formed in a liquid at room temperature.

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