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Simulation of Hydrodynamic Behavior of a Conductive Drop Under an Electric Field

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ABSTRACT: In this research, the effect of an electric field on the deformation and phase change of a perfect conductive drop suspended in a perfect dielectric fluid is studied. Basic equations are the incompressible flow and energy equations. Electric field effect appears as normal stresses at interface which are taken into account in solving flow equations. The level-set method is used for interface tracking. Discontinuities at interface are imposed using the ghost fluid method. In the first step, the effect of an electric field on the hydrodynamic of a drop is studied. A good agreement between the simulation and experimental results is observed. Due to electric stresses, drop deforms in the direction of electric field. The drop deformation increases with the electric capillary number. If the electric capillary number exceeds the critical value, deformation will be unsteady. Novelty of this research is related to the study of electric field effect on the drop evaporation. Based on the results, drop evaporation rate is enhanced in the presence of an electric field. If the electric capillary number exceeds a specific value (evaporation critical electric capillary number), drop evaporation will increase considerably. This critical value is introduced in this research, for the first time.

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1- Introduction

Many industrial processes are associated with heat and mass transfer. An important challenge is the use of techniques for increase of heat and mass transfer. One of this methods is using high-voltage electric field.

Paknemat et al. [1] studied drop deformation under an electric field. They used the level set method along with the ghost fluid method for interface modeling. Using a new technique in implementation of the ghost fluid method, the applied tangential stresses at the interface for a leaky dielectric drop successfully. Karyappa et al. [2] conducted a detailed experimental and numerical analysis of the drop Axisymmetric Shape Prior to Breakup (ASPB). They explained that there are three different kinds of ASPB modes: formation of lobes, pointed ends and non-pointed ends. In their work, an intermediate mode of non-pointed ends was observed between the ASPB modes of lobes and pointed ends. Tomar et al. [3] numerically studied effect of an electric field on the growth of the bubble and heat transfer in saturated film boiling using a coupled level set and volume of fluid methods. They observed that the space and time average Nusselt number and bubble release frequency increases by an increase in the electric field strength.

Previous studies are mainly concentrated on the hydrodynamic of drops in the presence of an electric field. There are a few works about the effect of the electric field on the phase change phenomenon which are related to the film boiling phenomenon. Previuosly, one of the authors studied the electric field effect on the deformation and breakup of drops [1]. In this research, by solving energy equation in conjunction with the flow and electrostatic equations, hydrodynamic behavior of a conductive drop with phase change under an electric field is simulated.

2- Methodology

In this study, droplet impact on a surface is simulated. Fig.1 shows the computational domain and boundary conditions. R_0, H, ψ, and E_0 are drop radius, domain height, electric potential and electric field strength, respectively. Governing equations are incompressible continuity and momentum equations in axisymmetric case. Appropriate jump conditions are imposed

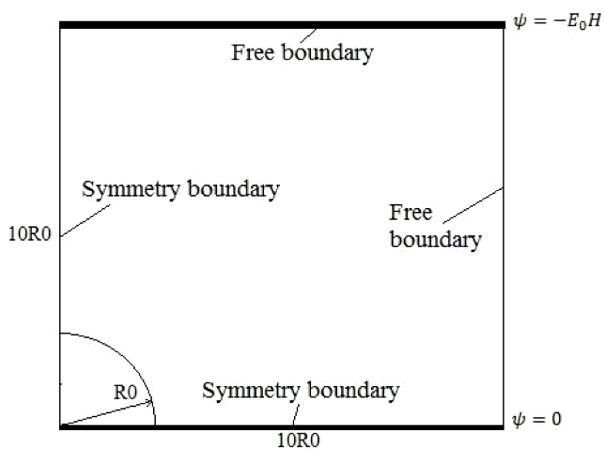

Fig. 1. Schematic of the problem

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at the interface, when governing equations are solved.

Flow equations are solved using the projection method [4]. The 3rd order TVD Runge-Kutta method is used for temporal discretization. Convective and diffusion terms are discretized using WENO and central approximation, respectively [4]. The level set method is employed for interface tracking [4]. In this method, interface is considered as zero level set of a smooth scalar function. Using the ghost fluid method, appropriate jump conditions are imposed at the interface [4].

3- Results and Discussion

First, the simulation results for a deionized water drop suspended into silicon oil are presented. Grid with a resolution of $R_0/\Delta x$=90 is used in all simulations. drop has a radius of 2.5 mm. In this case, no phase change occurs. Under an electric field, electric stresses have a tendency to deform the drop. On the other hand, interfacial forces resist against deformation. To characterize the drop deformation, the deformation parameter is defined as:

$$D = \frac{A-B}{A+B} \quad (1)$$

where A and B are diameters of drop, parallel and perpendicular to the electric field direction, respectively.

Fig. 2 shows the deformation of drop as a function of the electric capillary number ($Ca_E=\varepsilon e E_0^2 R_0/\gamma$) in comparison with the numerical work of Feng and Scott [5] and experimental work of Ha and Yang [6]. ε_e is the electric permitivity outside the drop and γ is surface tension. As it is observed, simulation results are in good agreement with numerical and experimental results.

Now, the effect of an electric field on the heat transfer of a drop is considered. The corresponding Jakob and Prandtl numbers for gas phase are 2 and 1, respectively. Liquid phase is at saturation temperature. Gas phase has an initial temperature of 283.15 K. Also, Dirichlet boundary condition (T=283.15 K) is imposed on all boundaries.

Fig. 3 represents Nusselt number as a function of Fourier number for various Capillary numbers. In the absence of an electric field, at the first moment, Nusselt number has a maximum value as a result of high temperature difference. By advancing in time, temprature gradient and consequently Nusselt number decreases. Finally, a steady manner is attained and Nusselt number becomes almost constant. When an electric field is applied, the pattern becomes somewhat different. After the initial reduction, Nusselt number increases and finally attains a constant value. In the presence of an electric field the drop deforms. So, the heat transfer surface and as a result Nusselt number increases. On the other hand, drop deformation increases evaporation rate by creating high temperature gradients around drop surface. This increase leads to the reduction of heat transfer surface. In fact, the latter effect acts in contrary to the former. These two effects are balanced after a period of time. Therefore, after a temporary increase, Nusselt number reaches a steady value. For electric capillary number equal or greater than 0.72, this pattern changes. In fact, the former effect becomes dominant and after initial reduction, Nusselt number increases with a high rate. In fact, there is a critical value for electric capillary number which is different from common critical capillary number and can be called evaporation critical electric Capillary number ($Ca_{E,ev}^{Cr}$). In this case $Ca_{E,ev}^{Cr}$=0.72.

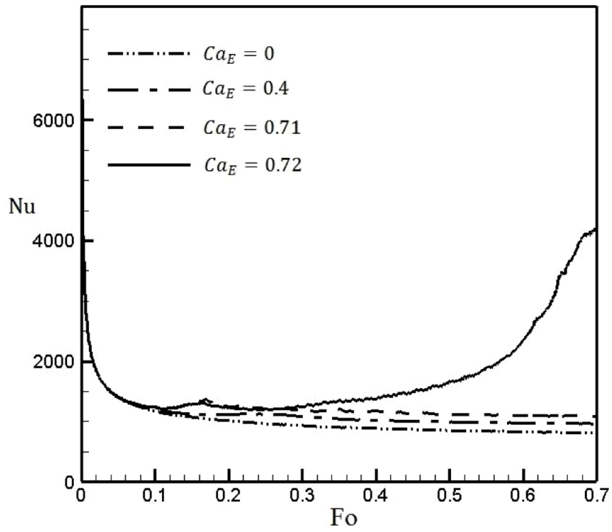

Fig. 3. Variations of Nusselt number versus Fourier number for different electric capillary number

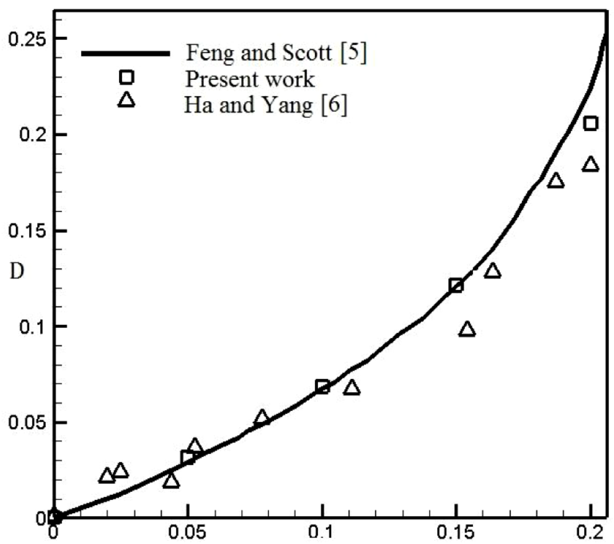

Fig. 2. Variations of drop deformation versus electric capillary number

4- Conclusion

In this study, the effect of an electric field on the deformation and phase change of a perfect conductive drop suspended into a perfect dielectric fluid is investigated. First, drop deformation without evaporation is considered. The results are in good agreement with available results. Next, the effect of an electric field on the evaporation of a drop is studied. The results show that the Nusselt number increases by an increase in electric capillary number. For electric Capillary number smaller than a critical value, after a period of time the Nusselt number reaches a steady value, whereas for electric capillary number greater than the critical value no steady value exists for Nusselt number. In this case, after initial reduction, Nusselt number increases considerably.

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