Numerical simulation of spreading characteristics for nanofluids droplet impinging on the solid surface

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Abstract: The nanofluid is a class of fluids with high thermal conductivity and non-Newtonian flow behaviors. In this work, we present numerical simulations of spreading characteristics for nanofluids droplet impinging on the solid surface which is of great importance in a number of applications such as multiphase flows, corrosion of solid surface, thermal management, spray coating, ink-jet printing and others. In order to better understand spreading phenomena during the impinging process, the finite-element based scheme is implemented and evaluated and the level-set method is used for capturing the interface movement. All the simulations have been carried out with the interface 'Laminar Two-Phase Flow, Level Set' in the CFD Module of COMSOL Multiphysics® software.

The case 'Rising Bubble' in the 'Application Libraries' has been referred to build the model to simulate the impinging process. The viscosity is measured at different shear rates and the shear-thinning behaviors of the nanofluids are incorporated to this study by employing the Carreau-Yasuda model. We investigate the evolution of droplet morphology during the spreading process under various Weber number (We) of nanofluids with different viscosity. The results show that the degrees of shearing thinning in nanofluids are dissimilar and thus influence the spreading behaviors of nanofluids droplet. Specify the shear thinning behaviors suppress the spreading and rebounding stage of droplets during impinging and this suppression in nanofluids with large infinite shear viscosity is more prominent.

Keywords: Droplet impingement, level set method, nanofluids, spreading dynamic behavior

1. Introduction

The phenomenon of droplets impinging on the solid wall have been an important research topic for numerous applications, such as multiphase flows, corrosion of solid surface, thermal management, spray coating, ink-jet printing and others. [1]. The process of droplet impinging on the solid wall is a complex multiphase flow problem [2]. The study of the transient deformation process of the droplet impinging on the solid surface is an important basis, which for understanding the dynamic characteristics of droplet spread and the nature of the free surface multiphase flow.

The process of droplet impinging on the solid surface was first explored by Worthington [3]. Since then, a lot of research on Newtonian fluid droplets such water and anhydrous ethanol impinging on solid surface have been done [4]. However, there was a few of experimental studies on non-Newtonian droplets impinging on solid surface. The pioneering work of non-Newtonian droplets impact on the wall has been done by Bergeron et al [5]. They found that addition of small amounts of flexible polymer that inhibited the droplets' receding motion and suppressed the rebound without changing the shear viscosity. Moon et al [6]. An et al [7] examined the impact dynamics of a shear-thinning droplet on various solid surface with different hydrophobicity and suggested a new model for estimating the maximum spreading diameter. Significant research has been dedicated to study the droplet impingement under various conditions, experimentally, numerically, and analytically [8]. Tanaka et al. [9] numerically investigated the droplet impact using a 2D lattice Boltzmann method (LBM). Gupta and Kumar [10] developed a 3D LBM model to simulate the spreading behavior of a droplet colliding with a solid dry surface at low impact velocity. Hu et al studied the glycerin and water droplet impingement on a solid surface by the Level Set Method with COMSOL. However, there is still a few of research on the dynamic characteristics of nanofluids droplets with nanoparticles or fibers that impinging on the solid surface. We investigate the influence of important factors such as impact velocity, different microstructure of nanometer dispersed phase (granular nano-graphite powder, cylindrical multi-walled carbon nanotubes (MWNTs), flaky graphene) on the dynamic behavior of nanofluids droplets.

To better understand the dynamic process of droplet impingement which is complex and the mechanism of droplet and surface interaction. Our study is aimed to study the dynamic behavior of different nanofluids droplet impinging onto a dry solid surface with particular velocity and surface wettability using COMSOL Level Set method. The established droplet impingement model will be further coupled with heat transfer and electric field.

2. Numerical Modeling

2.1 Governing Equations for Fluid Flow

Consider that the fluid flow is incompressible and in laminar condition. Constant density and viscosity are used for both air and liquid phase. The governing equations for the fluid flow describing the impingement process are time-dependent incompressible Navier-Stokes equations for conservation of mass and momentum formulated as follows:

$$\nabla \cdot \boldsymbol{u} = 0$$

$$\rho(\frac{\partial \boldsymbol{u}}{\partial t} + \boldsymbol{u} \cdot \nabla)\boldsymbol{u} = \nabla \cdot [-P\boldsymbol{I} + \mu(\nabla \boldsymbol{u} + (\nabla \boldsymbol{u})^T)] + \rho g + \boldsymbol{F}_{st}$$

Where ρ is the fluid density, $\boldsymbol{u}$ is the velocity vector, μ is the fluid dynamic viscosity, t is time, p is fluid pressure, g is the gravitational acceleration, $\boldsymbol{F}_{st}$ is the surface tension force and $\boldsymbol{I}$ is the identity matrix.

2.2 The Level-Set Function

There are several numerical approaches in handling the interface of the two phase fluid system: the interface-tracking method, the volume-of-fluid method, the diffuse–interface method, the level-set method, etc. In the present work, the level-set method is employed to capture the interface movement The following equation describes the convection of the reinitialized level set function:

$$\frac{\partial \phi}{\partial t} + \boldsymbol{u} \cdot \nabla \phi = \lambda \nabla \cdot (\varepsilon \nabla \phi - \phi(1-\phi)\frac{\nabla \phi}{|\nabla \phi|})$$

The interface is not explicitly tracked but is defined to be the zero level set of a smooth function ϕ. where ϕ equals 0 in air and 1 in liquid and the interface is defined by the 0.5 isocontour of ϕ. The interface moves with the fluid velocity, $\boldsymbol{u}$ at the interface. The ε is the parameter to determine the thickness of the transition layer and is to be taken as half size of the typical mesh size in the region passed by the droplet. The parameter γ determines the amount of reinitialization of stabilization and usually the suitable value for γ is the maximum magnitude occurring in the velocity field. The level set function is used to smooth the density and viscosity jumps across the interface through the definitions.

$$\rho = \rho_1 + (\rho_2 - \rho_1)\phi$$
$$\mu = \mu_1 + (\mu_2 - \mu_1)\phi$$

Where ρ_1, ρ_2, and μ_1, μ_2 are the densities and dynamic viscosities of the air and liquid, respectively. The surface tension force is computed as

$$F_{st} = \nabla \cdot ((\sigma(\boldsymbol{I} - \boldsymbol{n}\boldsymbol{n}^T))\delta)$$

Where $\boldsymbol{I}$ is the identity matrix, $\boldsymbol{n}$ is the interface normal, and σ is the surface tension, and δ is the Dirac delta function that is nonzero only at the fluid interface.

2.3 Carreau-Yasuda Model

The Carreau-Yasuda model for the shear thinning behavior of non-Newtonian fluid is also commonly used in hemodynamical simulations. In this model, the apparent viscocity is given by

$$\mu = \mu_\infty + (\mu_0 - \mu_\infty)[1 + (\lambda \dot{\gamma})^a]^{(n-1)/a}$$

where μ is the dimensionless shear-dependent apparent viscosity, μ_∞ is the infinite shear rate viscosity, μ_0 is the zero shear rate viscosity. where a, n, and λ are Carreau-Yasuda model parameters. Those parameters control how the fluid behaves in the non-Newtonian regime between these two asymptotic viscosities. The continuity of this model at low shear rates allows for an easier implementation in numerical modeling schemes.

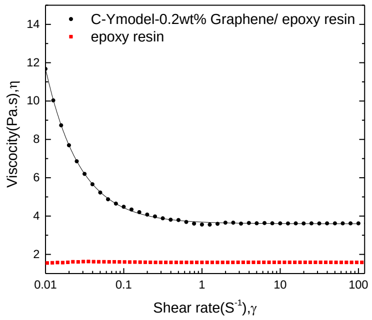

Figure 1. Viscosity of test nanofluid

2.4 Numerical Model

The numerical model is implemented in COMSOL 5.3 using the Laminar Two-Phase Flow, Level Set interface. The computational domain of the two-dimensional axis-symmetric problem is shown in Figure 2, where the droplet is placed at a location above the solid surface with an initial velocity. The location and initial velocity will ensure a particular impact velocity of U and We number.

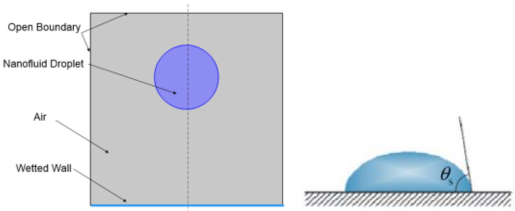

Figure 2. Schematic of computational domain and droplet attached to a surface

Open boundary conditions are used at the top and side to simulate an infinite domain. A wetted wall boundary condition is used for the substrate at the bottom. The boundary condition also allows specifying the contact angle θ_s between the wetted wall and the fluid interface.

3. Results

The paper presented simulation results of various nanofluids droplet impingements onto a dry solid surface. The simulation condition followed the experimental conditions. The impact velocity of nanofluids droplet is 1.71 m/s and in this paper we only present the results of pure epoxy resin and 0.2wt%MWNTs nanofluid droplet.

The wettability of the surfaces is represented by static contact angle. The numerical and experimental consequence of shape evolution at various time during the dynamic impingement process of pure epoxy resin and 0.2wt% MWNTs droplet onto a solid surface are shown in Figure 3. and Figure 4.

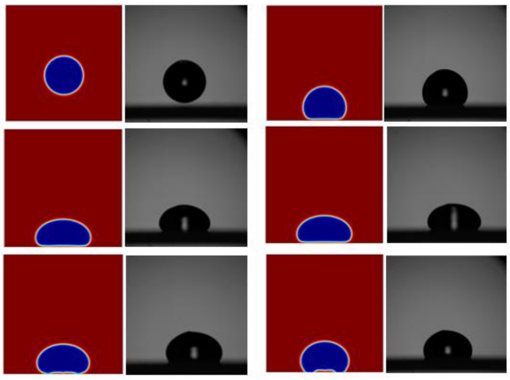

Figure 3. Impingement process of pure epoxy resin: t=1,2,3,4,10,30ms

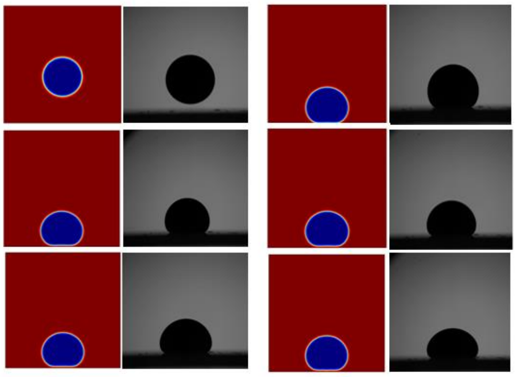

Figure 4. Impingement process of 0.2wt% MWNTs epoxy resin: t=1,2,3,4,10,30ms

4. Conclusion

This work simulated the dynamic process of nanofluids droplet impinging onto solid surface with a particular velocity using the Level Set method. The dynamic process was validated against experimental results. It was found that the Level Set method can predict the overall dynamic process accurately, especially the spreading process.

Both the simulations and experiments show that the addition of nanoparticles makes the epoxy resin solution show shear thinning phenomenon, and in our previous experiments, we found that the addition of different microstructure of nano-dispersed phase because epoxy showed varying degrees of shear thinning phenomenon. What’s more, under the same mass fraction the shear thinning degree of nano-graphite powder / epoxy resin solution was the strongest, followed by graphene / epoxy resin solution, the shear thinning degree of MWNTs/ epoxy resin solution was the least obvious. We will investigate the conditions of different nano-dispersed phase in our future numerical research.

Reference

1. Lee J B, Lee S H, "Dynamic Wetting and Spreading Characteristics of a Liquid Droplet Impinging on Hydrophobic Textured Surfaces". Langmuir the Acs Journal of Surfaces & Colloids, 2011, 27(11): 6565-73.
2. MOITA A S, HERRMANN D, MOREIRA A L N., "Fluid dynamic and heat transfer processes between solid surfaces and non-Newtonian liquid droplets". Applied Thermal Engineering, 2015, 88(33-46).
3. WORTHINGTON A M, "On the forms assumed by drops of liquids falling vertically in a horizontal plate". Proceedings of the Royal Society of London,1876,25;261-272.
4. MAO T, KUHN D C S, TRAN H., "Spread and rebound of liquid droplets upon impact on flat surfaces". AICHE Journal, 1997, 43(9): 2169-79.
5. BERGERON V V, BONN D, MARTIN J Y, et al., "Controlling droplet deposition with polymer additive". Nature, 2000, 405(6788): 772.
6. AN S M, SANG Y L., "Observation of the spreading and receding behavior of a shear-thinning liquid drop impacting on dry solid surface". Experimental Thermal & Fluid Science, 2012, 37(1): 37-45.
7. AN S M, SANG Y L., "Maximum spreading of a shear-thinning liquid drop impacting on dry solid surfaces". Experimental Thermal & Fluid Science, 2012, 38(1): 140-8.
8. S. SIKALO and E.N. GANIC, "Phenomena of droplet-surface interactions", Experimental Thermal and Fluid Science, 31, 97-110 (2006).
9. Y. TANAKA, Y. WAASHIO, M. Yoshino, and T. Hirata, " Numerical simulation of dynamic behavior of droplet on solid surface by the

two phase lattice Boltzmann method", Computers and Fluids, 40, 68-78 (2011).

10. AMIT GUPTA and RANGANATHAN KUMAR, "Droplet impingement and breakup on a dry surface", Computers and Fluids, 39,1696-1703 (2010).