International Journal of Heat and Fluid Flow 73 (2018) 1–15

Contents lists available at ScienceDirect

International Journal of Heat and Fluid Flow

journal homepage: www.elsevier.com/locate/ijhff

Heat transfer and internal fluidity a droplet located in between parallel hydrophobic surfaces with varying spacing

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ARTICLE INFO

Keywords:
Droplet heat transfer
Hydrophobic surfaces
Flow and temperature fields

ABSTRACT

Heat transfer and fluid flow inside the droplet located in between two parallel hydrophobic surfaces are considered. The functionalized silica nano-particles are deposited on the glass plates to create hydrophobic wetting state. The influence of hydrophobic glass plate spacing (plate heights) on the heat transfer characteristics and internal fluidity of droplet is examined. Temperature disturbance is introduced across the droplet via altering temperature settings on the top and the bottom plates. An experiment is carried out to monitor the droplet geometric features via high speed camera during squeezing action of the plates. The flow and temperature fields in the droplet fluid are simulated incorporating the experimental conditions. The direction of heat transfer from the plate surface to the droplet fluid is changed and the effect of heat transfer direction on internal fluidity of the droplet is investigated. The velocity predictions are validated with the Particle image velocimetry (PIV) data. It is found that velocity predictions agree well with the PIV data. The flow and temperature fields are influenced significantly by changing the plates height. In this case, reducing the plates height alters the size and orientation of the circulation cells inside the droplet fluid. Varying the plates temperature changes the Nusselt number; in which case, droplet heating from the bottom plate results in higher values of the Nusselt number than that of the top plate heating. The Bond number remains less than unity while indicating the importance of the Marangoni current on the flow field and heat transfer.

1. Introduction

Thermocapillary effect has a significant impact on the droplet heat transfer enhancement (Won et al., 2017). The flow current created due to the surface tension gradient and the fluid density variation induced by thermal expansion modify the temperature field and alter the heat transfer rates from the hydrophobic surface to the droplet. The surface tension gradient ($\frac{d\gamma_w}{dT}$, where γ_w is the surface tension of the fluid and T is temperature) is related to temperature variation on the free surface (droplet fluid-air interface) of the droplet and it causes the Marangoni current generation inside the droplet fluid. The intensity of the Marangoni current can be formulated through the Marangoni number, which takes the form$Ma = \frac{d\gamma_w}{dT}\frac{a\Delta T}{\mu\alpha_T}$, where α_T is the thermal diffusion coefficient, a represents the characteristics diameter of the droplet, ΔT is temperature difference, and μ is the dynamic viscosity of the droplet fluid. The buoyancy current, which is generated due to fluid density variation under the thermal expansion, is associated with the Rayleigh number, which is $Ra = \frac{\alpha_T g a^3 \Delta T}{\upsilon\alpha}$, where υ is the kinematic viscosity and g is the gravitational acceleration. However, the flow intensity due to the Marangoni and the buoyancy currents can be judged through the velocity ratio due to both currents (Tam et al., 2009). Therefore, the ratio of the flow velocities related to the Marangoni over the buoyancy currents is $\sim \frac{\frac{d\gamma_w}{dT}\Delta T}{\alpha_T \rho g a^2}$. In this case, the large values of the surface tension gradient ($\frac{d\gamma_w}{dT}$) increase the Marangoni current intensity inside the droplet. The Marangoni current becomes significant for $Ma > 100$ (Lu et al., 2011). Alternatively, for large droplet diameters, the buoyancy current intensity increases. In addition, the buoyancy current intensity can be judged via the Grashoff number ($Gr = \frac{\alpha_T g \Delta T L^3}{\upsilon^2}$, where L is the droplet height in the vertical direction); in which case, the buoyancy driven flow current becomes significant for $Gr > 2400$ (Lu et al., 2011). The relative contribution of the buoyancy current over the Marangoni current is also same order of the Bond number ($Bo = \frac{\alpha_T g \rho L^3}{d\gamma_w / dT}$) and $Bo < 1$ gives rise to the Marangoni current influence in the droplet fluid; however, the buoyancy current influence takes place in the droplet fluid for Bo > 1. On the other hand, the Marangoni and buoyancy forces alter for the case of the liquid droplet, which is located in between the confined parallel hydrophobic walls. The three-phase contact

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https://doi.org/10.1016/j.ijheatfluidflow.2018.07.001
Received 17 April 2018; Received in revised form 26 June 2018; Accepted 7 July 2018
0142-727X/

line on the top and bottom hydrophobic surfaces varies with plates spacing, which in turn complicates the force balance between the Marangoni and buoyancy flows. This, in turn, modifies and alters the heat transfer rates and internal fluidity of the droplet. Consequently, investigation of internal fluidity and heat transfer of a sessile droplet located in between parallel hydrophobic surfaces becomes essential.

Considerable research studies were carried out to examine droplet heat transfer and internal fluidity of the droplet located on the hydrophobic surfaces. Heat transfer and droplet evaporation on hydrophobic surfaces were studied earlier (Gao et al., 2018; Gibbons et al., 2018). The findings revealed that evaporation rate depended mainly on the water droplet contact angle, the ambient conditions, and the droplet size. The influence of the Marangoni force on the flow field and evaporation rate remained significantly important (Phadnis and Rykaczewski, 2017). The buoyancy flow had considerable influence on the droplet heat transfer for the hydrophilic surfaces (Al-Sharafi et al., 2017a); however, when switching from the hydrophilic to the hydrophobic, the Marangoni current influence on the Nusselt number became significant (Al-Sharafi et al., 2018b). Heat transfer characteristics and internal fluidity of a sessile droplet on the hydrophilic and the hydrophobic surfaces altered the temperature field in the droplet fluid because of formation of the circulation cell structures inside the droplet (Al-Sharafi et al., 2016c, 2017c). Hence, the combine effect of the Marangoni and the buoyancy forces on the flow field altered the flow structures inside the while enhancing the Nusselt number. The droplet contact angle and surface texture remained critical for the droplet condensation and the evaporation (Rajkumar et al., 2018; Misyura, 2017); in which case, the heat transfer rates reduced for the smooth surfaces despite the presence of the large contact area between the droplet fluid and the wall. The droplet dynamics and the droplet adhesion changed with the surface wetting state (Li et al., 2018; Al-Sharafi et al., 2017b, 2018a). As the surface energy was lowered and the surface roughness parameter increased, the droplet contact angle hysteresis reduced. This, in turn, reduced the droplet pinning on the surface while influencing the heat transfer rates and internal fluidity of the droplet. In addition, increasing the droplet volume enhanced the Nusselt and Bond numbers in the droplet (Al-Sharafi et al., 2018a). The dropwise condensation and the surface wetting state were closely associated (Qi et al., 2018; Yang et al., 2017). The grooves like surface textures resulted in the hydrophobic surfaces and liquid condensate flowed along the channels while enhancing the rate of condensation. The heat transfer coefficient for the hydrophobic surface was greater than that of the hydrophilic surface irrespective of the operational velocity and relative humidity. The dropwise condensation was also improved when the surface was covered with hydrophobic meshes with increased wire spacing (Venkateshan and Vahedi Tafreshi, 2018). The growing and coalescing of droplets on the water repellent surfaces with superhydrophobic wetting state gave rise to relatively high heat transfer rates than that of the hydrophobic surfaces provided that the liquid droplets on the superhydrophobic surface could be shed away efficiently (Seo et al., 2017; Lu et al., 2017). The thermalcapillary influence and buoyant forces resulted in circulation cells inside the droplet; in which case, two counter rotating circulation cells were formed in the upper part of the droplet when the contact angle was in the range of $110^{\circ} \le \theta \le 150^{\circ}$ (Al-Sharafi et al., 2016a). The average Nusselt number increased with increasing droplet contact angle.

Although droplet heat transfer on hydrophobic surfaces was studied previously (A. Al-Sharafi et al., 2017a, 2016c, 2017b, 2018a, 2016a), the main focus was the influence of the droplet contact angle on the heat transfer rates, surface texture effects on heat transfer rates, and radiative heating and heat transfer characteristics. However, the influence of Laplace pressure in terms of droplet height on the droplet internal fluidity and heat transfer was left for future study. In addition, droplet can suffer from the three-phase contact with the multi-wall hydrophobic surfaces such as those observed in channels or confined enclosures. This, in turn, alters the heat transfer rates and modifies the flow behavior inside the droplet. Consequently, in the present study, heat transfer and internal fluidity of the droplet on the multi-wall horizontal hydrophobic surfaces are investigated when the droplet is squeezed between two parallel flat hydrophobic plates at different temperatures. The motion of the top hydrophobic plate modifies the droplet shape and changes the Laplace pressure inside the droplet via droplet squeezing and this influence is also incorporated in the analysis. The study is extended to include the effect of heat transfer direction and squeezing height on the internal fluidity of the droplet. An experiment is carried out to monitor and record the droplet geometry under the squeezing action of the hydrophobic plates. The flow velocity and heat transfer are predicted incorporating the experimental conditions. The flow velocity predictions are validated with the data obtained from the particle imaging velocimetry (PIV).

2. Flow and heat transfer analysis

Heat transfer and internal fluidity of the water droplet in between two parallel superhydrophobic surfaces are investigated. The conservation equations including continuity, momentum, and energy equations are incorporated and solved numerically in accordance with the conditions of experiment. The time required towards achieving the quasi-steady flow field inside the droplet is estimated as of 30 s (Tam et al., 2009); therefore, the droplet heat transfer and flow field are simulated for the heating duration of 30 s. Since the heating duration is 30 s, which is short, the evaporation from the droplet surface is omitted in the analysis. To verify this consideration, an experiment is realized towards assessing the liquid mass loss from the droplet during 100 s of the heating period incorporating the parallelly located hydrophobic plates in the experiments. The high-speed camera (Dantec Dynamics SpeedSense 9040) is utilized to monitor and record the droplet images in between the plates. The droplet volume change is monitored through measurement of the droplet geometric feature recorded by the high-speed camera for every 0.1 s. The findings revealed that the droplet volume remains almost constant for the period of 100 s. In addition, the evaporation of the droplet is calculated and the amount of water evaporated from the droplet surface is estimated as 0.00015244 g after 30 s for the droplet volume of 80 μL under the ambient conditions of 300 K and 85% of the air relative humidity. Consequently, the water droplet mass loss due to evaporation of the droplet surface is in the order of 0.23% of the total mass of 80 μL water droplet. Hence, neglecting the evaporation from the droplet surface in the analysis can be justifiable for the short heating duration considered, such as 30 s.

The flow and temperature fields are simultaneously coupled in the simulations through the energy equation. The continuity equation for the incompressible flow can be expressed as:

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

where ρ is the fluid density and V is the fluid velocity.

The momentum equation can be written as:

$$\rho\left(\frac{\partial V}{\partial t} + V\cdot\nabla V\right) = -\rho_o\beta(T - T_O)\vec{g} - \nabla(p - p_o) + \nabla[\mu(\nabla V + (\nabla V)^T)] \tag{2}$$

where p is the pressure, μ is the dynamic viscosity of the liquid, g is the gravity and p_o is the hydrostatic pressure corresponding to density ρ_o and temperature T_o. It should be noted that the density variation can be formulated via Boussinesq approximation, which is:

$$\rho = \rho_o[1 - \beta(T - T_o)] \tag{3}$$

where β is the thermal expansion of the water.

The flow field should satisfy the energy balance according to:

$$\rho\, C_p \frac{\partial T}{\partial t} + \rho\, C_p\, V\cdot\nabla T = \nabla\cdot(k\nabla T) \tag{4}$$