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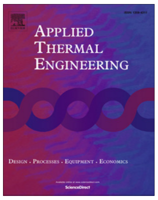

Research Paper

Water droplet mobility on a hydrophobic surface under a thermal radiative heating

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HIGHLIGHTS

- Bond number remains less than unity for all volumes of droplet considered on hydrophobic surface.
- Combination of Marangoni and buoyancy currents generates fluid acceleration causing droplet roll off.
- Fluid inertia force remains higher than adhesion and shear forces at droplet solid surface interface.
- Nusselt and the Bond numbers increases with increasing droplet volume.

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ABSTRACT

Side heating of a water droplet on the hydrophobic surface is considered and the droplet internal fluidity is examined. An experiment is carried out to assess the droplet mobility on the hydrophobic surface when subjected to the heating load. Temperature and flow fields are simulated in line with the experimental conditions and fluid acceleration inside the droplet is predicted for various droplet sizes. Predictions of the flow field are validated via particle image velocimetry (PIV) measurements. The adhesion, inertia, and shear forces are determined for possible rolling off the droplet on the hydrophobic surface. The Bond and the Nusselt numbers are predicted and the influence of the droplet size on the Bond and Nusselt numbers are presented. It is found that the velocity predictions agree well with the PIV data. Two counter rotating circulation cells are formed inside the droplet due to the combination of the Marangoni and buoyancy currents. The Bond number remains less than unity (in the range 0.03–0.2) for all the droplet sizes incorporated in the study (15–100 μL). This indicates that the Marangoni current dominates over the buoyancy current inside the droplet. The droplet fluid inertia force becomes greater than the adhesion and the fluid shear forces during the heating period; consequently, the droplet rolls off on the hydrophobic surface, which is also observed from the experiments. The Nusselt and the Bond Numbers increase with increasing droplet volume and reach maximum of 151 and 0.2 for the droplet size of 100 μL.

1. Introduction

Recent climate change triggers regular dust storms, particularly in the Middle East [1]. The efforts required towards removing the dust particles from the surfaces are significant because of the coverage of the large surface area. Cleaning the soiled surfaces with a water film is one of the solutions of the dust particles removal from the surface; however, scarcity of the clean water, particularly in the Middle East, makes the cleaning process costly. On the other hand, surface cleaning by a water droplet is one of the interesting options for the particles removal from the surface. Droplet mobility at the surface is important for the surface cleaning applications in order to cover large area of cleaning. Since the environmental temperature remains high almost all times during the day, utilization of high temperature ambient towards improving droplet mobility becomes fruitful. Droplet mobility on surfaces is governed by the contact line dynamics of the droplet, which is mainly influenced by the hydrophobic characteristics of the surface and the surface free energies of liquid-air, liquid-solid, and solid-air interfaces. The thermal state of the droplet can alter the droplet internal fluidity through generating Marangoni and buoyancy currents inside the droplet, which play an important role for the removal

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Nomenclature

a	characteristic diameter, m
C_p	specific heat capacity, J/kg K
f	solid surface fraction
F_a	inertial force, N
F_{ad}	adhesion force, N
F_τ	shear force, N
Gr	Grasshoff number
k	thermal conductivity, W/m K
Ma	Marangoni number
MN	Merve number
p	pressure, Pa
R	wetting radius, m
T	temperature, K
U	liquid velocity, m/s
V_d	volume of the droplet, m^3
Greek letters	
α	thermal diffusivity, m^2/s
β	thermal expansion coefficient, K^{-1}
θ	contact angle, degree
μ	dynamic viscosity, Pa s
ν	kinematic viscosity, m^2/s
ρ	water density, kg/m^3
σ	surface tension, N/m

of particles from the surfaces [2]. In this case, heat transfer and hydrophobic characteristics of the surface play critical role on the internal fluidity of the droplet. The convection current generated, due to the combination of Marangoni and buoyancy flows, is significantly influenced by both the rate of heat transfer from/towards the droplet and the contact angle of the droplet [3]. The internal fluidity of the droplet influences the droplet mobility on the hydrophobic surfaces because of the local, convective and radial accelerations of the flow under Marangoni and buoyant forces. The non-uniform and localized non-mechanical contact heating of droplet surfaces can further alter the flow filed inside the droplet while influencing the droplet mobility at the surface. One of the methods to create a non-mechanical contact heating is the radiative heating of the droplet surface by a localized point heat source. In this case, the variation of density and the surface tension of the droplet fluid with temperature causes localized flow acceleration in the droplet, which in turn alters the momentum and force balance across the droplet. Consequently, investigation of the internal fluidity of the droplet on the hydrophobic surface subjected to a localized radiative heating becomes essential.

Considerable research studies were carried out to examine thermal effects on the droplet internal fluidity. Conjugate heat transfer of evaporating thin film in a sessile droplet was studied by Zheng et al. [4]. They showed that the percentage contribution of the thin film region to the overall heat transfer increased significantly with decreasing droplet size and improved surface wettability. Heat transfer characteristics and internal fluidity of a sessile droplet on the hydrophilic and the hydrophobic surfaces were examined by Al-Sharafi et al. [5]. The findings revealed that the Nusselt and the Bond numbers demonstrated increasing trend with increasing droplet contact angle, which was more pronounced for the high droplet contact angles. The Bond number and the droplet contact angle were correlated into a new number, Ayse number, which demonstrated a linear variation with the Nusselt number. Evaporation of a thin and the water droplet due to environmental heating was studied by Mehrizi and Wang [6]. They demonstrated that the microscopic contact angle at nanoscale was approximately equal to the optically detected macroscopic contact angle under the weak environmental heating. A study on the dynamic wetting and heat transfer characteristics of a liquid droplet impinging on the heated textured surfaces was carried out by Moon et al. [7]. They showed that for the textured surfaces, the maximum contact diameter of the impinged droplet decreased owing to decrease in the surface energy. For increased surface temperatures, the maximum contact diameters slightly increased and the maximum recoil diameters decreased because of change in liquid viscosity. For the textured surfaces, the cooling effectiveness increased with the Weber number and its change substantially depended on the wetting state of the surface. In case of the total-wetting state, the cooling effectiveness increased with the texture area fraction, because of the change in liquid-solid interface area. A simplified analysis of heat and mass transfer model in droplet evaporation process was presented by Wu et al. [8]. In the analysis, they introduced a mathematical model incorporating the molecular diffusion on the droplet surface. They assumed the constant temperature boundary conditions for the droplet outer surface together with the constant thermal properties. Coalescence-induced droplet behavior on superhydrophobic surfaces due to dropwise condensation was studied by Cheng et al. [9]. They demonstrated that the contact angle hysteresis had significant effect on the droplet jumping; in which case, the large advancing contact angle could improve the droplet jumping velocity while the low receding contact angle could reduce the droplet jumping velocity. Investigation of a single-droplet/wall collision heat transfer characteristics was carried out by Jung et al. [10]. They analyzed the various physical characteristics associated with the heat transfer during the collision of a single droplet with a heated plate. These characteristics included the local heat flux distribution, effective heat transfer area, instantaneous heat transfer rate, total heat transfer, and vapor film thickness. They observed that the dynamic Leidenfrost point at which the total heat transfer from a single-droplet collision was significantly degraded. The impact of droplets and resulting heat transfer during spray cooling under the vibration environment was studied by Wang et al. [11]. The findings revealed that heat was mainly removed by strong convection due to the droplet impact. The heat transfer process could be categorized into four stages including before the impact, impacting droplet, which formed thin film on the surface, film extension outwards on the surface, and film breakage. In addition, the vibration had invigorating effect on the heat transfer rates. The effects of droplet ratio and void fraction on the attenuation of radiative heat flux in water curtain were examined by You and Ryou [12]. They introduced the general form of the attenuation efficiency of radiative heat flux as a function of droplet ratio and void fraction. A study on the heat and mass transfer of saline water droplets was carried out by Sadafi et al. [13]. They demonstrated that using saline water in spray-cooling resulted in reduced energy extraction from the air per unit droplet volume, which could be compensated by increasing the liquid flow rate. Moreover, the period for the wet surface was shorter as compared to the time taken for the evaporation of pure water droplet. Thermal analysis of droplets on heated superhydrophobic surfaces was carried out by Hays et al. [14]. They showed that the droplet evaporation times increased with substrate cavity fraction while overall heat transfer rates decreased. At subcritical substrate temperatures, the Nusselt number was larger for lower cavity fraction substrates. For supercritical substrate temperatures, as the cavity fraction increased nucleate boiling was delayed to higher substrate temperatures and the Lei-