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Optical thermogeneration induced enhanced evaporation kinetics in pendant nanofluid droplets

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ABSTRACT

Optofluidic manipulation using lasers and colloidal systems have immense applications in microscale thermofluidic devices. The present study analyses the effect of laser as an external optical source in modulating the evaporation characteristics of pendent nanofluid microdroplets (which are free from substrate effects) so as to capture the physics behind the interfacial mass transport. The study analyses the effect of the power of laser, nature and concentration of the particle on evaporation rate of the complex fluids. Evidence of internal circulation was observed with Particle Image Velocimetry (PIV) technique in colloidal systems which together with the volumetric heat generation due to laser irradiation can be attributed to be the cause behind the enhanced evaporation rate. The nanoparticles are observed to efficiently convert the energy of radiant photons to heat while water is observed to show poor evaporative performance under laser irradiation. Theoretical analysis of the evaporation rate with the classical diffusion driven evaporation model is found to fall short in predicting the evaporation rate in colloidal systems, even in the absence of laser irradiation. Thermal Marangoni and Rayleigh numbers are calculated from the theoretical examination and are found not potent enough to induce the circulation in such systems which could improve evaporation. Hence the observed weak internal circulation can be attributed to the solutal Marangoni arising out of the local concentration gradients of nanoparticles in the droplet and the enhanced Thermophoretic drift and Brownian dynamics of the nanoparticles. Also the enhancement in the diffusion coefficient and its strong dependence with the particle concentration is also contributing to the enhancement in enhanced evaporation rate in nanocolloidal systems. The augmentation in the evaporative process under laser radiation is found to be governed majorly by the optical heat generation with weak solutal Marangoni and a scaling model is able to accurately predict the experimental observations. The present findings could have implications in modulation of thermofluidic and species transport phenomena in microscale devices.

1. Introduction

Evaporation kinetics of microscale droplets and the physics behind the phenomenon find crucial application in various domains, for instance in internal combustion engines, gas turbines and aviation, heat transfer equipment involving phase change [1,2], spray cooling, HVAC systems, etc. Recent developments in domains such as desalination, painting, and smart cooling technologies and even in biological domains such as DNA synthesis and cell culture via substrate patterning have triggered new interest in the field of droplet evaporation and towards understanding the more fundamentals behind the process [3,4]. Microscale droplet evaporation poses a very classical multiphysics problem where fluid dynamics, heat transfer, mass transfer and interfacial physics play combined roles at diminished length and/or time scales, making the process in general difficult to understand and model. Due to their unique thermophysical properties, intensive research has been dedicated in recent times towards exploring the fundamentals behind the suspensions of nano sized colloidal dispersions often dubbed as nanofluids [5,6]. The recent trend shows an enhancement in the amount of literature dedicated towards understanding the fundamental interfacial, electromagnetic and thermophysical properties of these smart fluids [7–9] for micro-nanoscale thermofluidic manipulation and transport processes. A thorough understanding of the fundamentals of evaporation kinetics of such colloids and the physics behind is essential

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Nomenclature

D	diameter of droplet (m)
t	time (s)
D_o	initial diameter of droplet (m)
k	evaporation rate constant (m^2/s)
$\dot{m}$	evaporation rate (kg/s)
D_v	vapour diffusivity (m^2/s)
R	radius of droplet (m)
Sh	Sherwood number
C_{pf}	specific heat of the vapour film
Nu	Nusselt number
B_M	mass transfer number
B_T	heat transfer number
Y_s	mass fraction of the vapour at the droplet surface
Y_∞	mass fraction of the vapour far away from droplet
C_{pg}	specific heat of the surrounding gas (kJ/kg)
Le	Lewis number
V_d	volume of droplet (m^3)
Q_v'''	volumetric hat generation (W/m^3)
r_b	beam broadening radius term (m)
$U_{c,m}$	Marangoni circulation velocity (m/s)
I_o	volume of droplet (m^3)
ΔT_m	temperature difference due to Marangoni (K)
ΔT_r	temperature difference due to Rayleigh convection (K)
$U_{c,r}$	Rayleigh circulation velocity (m/s)
L^*	characteristic length (m)
h_{fg}	specific enthalpy of vaporisation (kJ/kg K)
g	acceleration due to gravity (m/s^2)
D_{nf}	diffusivity of nanofluids (m^2/s)
D_w	diffusivity of water (m^2/s)
$HRSEM$	High Resolution Scanning Electron Microscopy
$MWCNT$	multiwalled carbon nanotubes
Ma	Marangoni number
Ra	Rayleigh number
PIV	particle image velocimetry

Greek symbols

ψ	Ratio of square of normalized diameter
λ	Thermal conductivity of the surrounding gas
ρ_g	Gas density (kg/m^3)
σ_I	Gaussian beam profile coefficient
α	Absorption coefficient (m^{-1})
β	Scattering coefficient (m^{-1})
α^*	Thermal Diffusivity (m^2/s)
σ_T	Rate of change of surface tension with temperature
β^*	Volume coefficient of expansion
ν	Kinematic viscosity (m^2/s)
μ	Dynamic viscosity (Pa·s)

in implementing colloidal systems to such applications so as to effectively tune the performance of several engineering devices.

Classical examples of research on sessile droplet evaporation characteristics in order to understand the physics of heat and mass transfer across the interface on water [10–12] exist in literature. In general, most of the studies on evaporation are limited to sessile droplet evaporation characteristics [12–14]. The most important aspect in case of sessile mode of evaporation is that the surface effect comes into picture and the whole process is dominated by the preferential affinity of the fluid molecules to the surface molecules and the gas phase. There are few studies which report probing the evaporation characteristics in case of complex fluids like nanofluids when in rest on a substrate. When it comes to the case of such complex multicomponent fluids, the real physics of the evaporation mechanism can be elucidated only with the pendant mode of evaporation where the surface effects do not come into the picture. Especially in nanofluids, where the nanoparticles experience interfacial adsorption desorption mechanisms [7,15,16] and Brownian fluctuations, the surface can drastically alter the evaporation kinetics due to the fact that the presence of nanoparticles makes the contact line a four phase contact line. When a colloidal droplet comes in contact with a surface, it is subjected to complex liquid-air interface and complex liquid-solid interface. Then there exists a preferential adsorption tendency of these complex fluids [8] which may further lead to phenomenon such as layering of the nanoparticles at the three phase contact line [8,9], thereby changing evaporation dynamics.

Accordingly, the proper methodology to probe into evaporation dynamics of colloidal droplets is the pendent drop method as it is free from surface effects. Suspended droplet or the pendent drop method of evaporation characterization has been in practice among researchers since a long time [17]. The method is technically sound for formulating correlations for estimating the life time of droplets and in developing physics based evaporation models for CFD [18]. Scarce attempts to understand the effect of suspended particles in modulating the evaporation kinetics exist [19] which reports that the nanoparticles in nanofluid solutions are capable of altering the evaporation characteristics. It has been experimentally shown that the presence of aluminum nanoparticles in ethanol droplets reduces the evaporation rate with particle concentration. D^2 law based model was developed to analyze the problem. Nanoparticle agglomerate packing within the evaporating droplet surface and reduction of the liquid fraction available for evaporation are found to be responsible for deterioration in the evaporation rate. The effects of dynamic concentration of the nanocolloids have also been discussed [20] and a transition in the evaporation rate constant from one value to another during the evaporation process was noticed, making colloidal evaporation quasi-linear by nature. It was also reported that the change in evaporation rate constant of different fluids is linked to the change in latent heat of vaporisation due to addition of nanoparticles [20]. Recently, attempts have been made to make a predictive model for evaporation behavior of liquid droplets containing nano-sized insoluble particles taking into account of the shell formation phenomenon at the surface of droplet [21]. Also the same group has explored the effect of internal circulation in a colloidal droplet analytically [22]. A recent literature reports an enhancement in evaporation rate with the addition of nanoparticles (Al and Al_2O_3) in ethanol especially at different levels of radiation [23].

There are some studies on the effect of laser irradiation in modulating the thermophysical properties of the nanofluids [24]. In the present era of microfluidics, optical manipulation of fluid within microscale domains is an active tool to achieve enhanced mixing, biological reactions, cell mobility, fluid pumping by opto-capillarity, etc. In all such domains, focused lasers are employed as coherence and narrow beam width is essential in microfluidic manipulation. Even though there are some literatures on the effects of suspended particles on the evaporation kinetics of fluids, there are no studies that probe the effect of laser irradiation on the nanofluid droplet evaporation kinetics. This finds application in many industrial and engineering applications; with prime importance especially in areas like printing technology, such as pulsed