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Solar evaporation of a hanging plasmonic droplet

Guohua Liu[a], Hui Cao[a], Jinliang Xu[b,*]

[a] Key Laboratory of Condition Monitoring and Control for Power Plant Equipment of Ministry of Education, North China Electric Power University, Beijing 102206, China
[b] Beijing Key Laboratory of Multiphase Flow and Heat Transfer for Low Grade Energy Utilization, North China Electric Power University, Beijing 102206, PR China

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ABSTRACT

Plasmonic nanoparticles attract great attention owing to their strong light-to-heat conversion properties. Fundamental understanding of their photothermal performance is critical to develop solar-to-heat systems. Here, we use gold nanoparticles as the photothermal agent. Solar water evaporation are explored through a hanging droplet containing the nanoparticles. These nanoparticles induce multiple scattering events, increasing photon absorption and concentrating the light within the mesoscale domain, leading to an intense collective heating that trigger the evaporation. The droplets with different initial-particle-concentrations lead to evaporation at various rates (e.g. K constant in D^2-law), and an optimal initial-particle-concentration can be expected. With steam releasing from the surface, shrinking of the droplet increases the particle concentration in the domain that accelerates the surface evaporation. The surface evaporation rate increases with the increasing concentration of nanoparticle, reaching an optimized value at a threshold concentration and then stable. K values demonstrate a nonlinear dependence over the time, reflecting complex heat-transfer physics behind the phenomenon. We assume that the collective heating is controlled by two parameters: one that relates the morphology properties of the droplet and the other that characterizes the gap between nanoparticles. This work provides an important insight on the evaporation dynamics of plasmonic droplets, and stands for a basis to design the plasmonic solar heating systems.

1. Introduction

Solar water evaporation is an important process in many industries, such as power generation, absorption chillers, medical and waste sterilization, water purification and desalination systems, etc. (Gao et al., 2016; John A. Duffie; Kalogirou, 2004; Lewis, 2016; Liu et al., 2017; Neumann et al., 2013a; Shang and Deng, 2016; Thirugnanasambandam et al., 2010). The current technologies rely on absorbing solar energy through macroscopic cavity or vessel surface and transferring the heat into the surrounding media and thus suffer from energy loss from the absorbing surface to bulk fluid. High optical concentration are normally used to overcome the inefficiencies (Weinstein et al., 2015). However, this adds complexity and cost to the solar thermal system. Alternative strategies are proposed to use solar energy under a moderate intensity, for example, directional selectivity of the radiation by spectrally selective vessel inner walls achieving a efficiency of 75% without high heat fluxes (Weinstein et al., 2014). Other examples introduce carbon nanofluids (Deng et al., 2017; Loeb et al., 2018; Wang et al., 2016) or porous graphene materials to assist water evaporation, demonstrating solar thermal efficiencies above 45 or 80% respectively, due to their broadband absorption in the solar spectrum (Chen et al., 2017; Ghasemi et al., 2014; Li et al., 2016).

Despite of the above approaches, a highly active surface of metal nanoparticles in a volumetric dispersion can be engineered to locally enhance the evaporation. The volumetric absorbers ranging from plasmonic porous membranes, biomaterial aerogels to gas-particle suspensions and nanofluids have been reported to reduce surface temperatures (Bertocchi et al., 2004; Lenert and Wang, 2012; Neumann et al., 2013b; Otanicar et al., 2010; Tian et al., 2016; Zhou et al., 2016; Zhu et al., 2017). Among which, the plasmonic nanofluid is an attractive route for steam generation since it can implement easily and enhance critical heat flux in certain boiling condition (Deng et al., 2017; Jin et al., 2016b; Kim et al., 2007; Liu et al., 2006; Loeb et al., 2018; Lombard et al., 2014; Neumann et al., 2013a). Different mechanisms have been proposed for understanding the underlying physics. Earlier studies focus on vapor nucleation around the nanoparticles (Fang et al., 2013; Lombard et al., 2014; Neumann et al., 2013b; Zielinski et al., 2016). They hold that the initial vapor expand and coalesce to produce micro-bubbles that can be further released at air-water interface. However, the nanobubble is unlikely to occur under normal radiation because that only can be observed under intensive laser heating (Baffou et al., 2014; Lombard et al., 2017; Metwally et al., 2015; Wang, Y. et al.,

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[*] Corresponding author.
E-mail address: xjl@ncepu.edu.cn (J. Xu).

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2017). Other research claim that the global temperature rising in nanofluids by collective heating is the key mechanism (Baral et al., 2014; Govorov and Richardson, 2007; Ni et al., 2015; Richardson et al., 2009). While non-linearly decay of optical depth in nanofluid undoubtly results in temperature difference (Khullar et al., 2014; Lee et al., 2012). Recent studies assume that an intense localized heating under focal area induces the evaporation, albeit considerable non-uniform temperature exist within the liquid (Amjad et al., 2017; Hogan et al., 2014; Jin et al., 2016a; Jin et al., 2016b; Wang, X. et al., 2017). For such cases, it is difficult to control the heat diffusion under subcooled condition as that represents a mixture of material properties and fluid transport (Baffou et al., 2010; Berry et al., 2015; Roxworthy et al., 2014). Obviously, a better understanding on solar evaporation of plasmonic nanofluids is highly demanded.

In this paper, we propose a nano/mesoscale engineering concept that combines the plasmonic properties of nanoparticles and the extended active surface provided by mesoscale droplet to boost solar vapor generation. A set of experiments are performed on photoheating of a water droplet containing gold nanoparticles. Key elements such as temperature and morphology evolution of the droplet are traced to understand the evaporation dynamics. A four-stage heating scenario has been identified based on the results. The highlights of this work are (i) localizing the light energy into the mesoscale domain by both scattering and absorption that leads to a collective photoheating, (ii) providing the small fluid volume to minimize the temperature difference and the large surface area for steam generation and escape, (iii) demonstrating a detailed picture on the evaporation process of plasmonic droplet. These studies will be useful for application of this unique phenomenon.

2. Materials and methods

2.1. Gold nanofluids

Gold chloride hydrate ($HAuCl_4$, Au ≥ 49%) solution and aqueous tri-sodium citrate ($Na_3C_6H_5O_7$, 99.8%) were purchased from Sigma-Aldrich and used as received. Deionized water was used throughout the experiments. Gold nanoparticles generally can be synthesized by the citrate reduction method, the Brust-Schiffrin and the modified Brust-Schiffrin method (Zhao et al., 2013). In our experiment, the synthesis of gold nanoparticles followed by the citrate reduction method (Ji et al., 2007; Jin et al., 2016b). Specifically, gold chloride hydrate solution was mixed with trisodium citrate solution. The mixture was then heated to boiling temperature until its color shift to wine red. After sonication and aged, the resultant was last purified by a membrane dialysis method. The obtained nanofluids present good stability and can be further used for our experiments by diluting it into the required concentration.

2.2. Experimental setup

Fig. 1a shows a setup image of the experiment. The main apparatus consist of (1) data acquisition model (Yokogawa DL750), (2) synchronization hub, (3) computer, (4) Xenon lamp (CEL-S500), (5) thermocouple tip (Omega TT-T-36), (6) high speed camera with a micro-focal lens (IDT Motion Pro Y4 model, MP-E65mm lens), (7) glass cloak, (8) thermocouple wire, and (9) four-axis positioning guide. The thermocouple positioned on an iron beam (Fig. 1b is the circled part in Fig. 1a) that is linked with the positioning guide to precise control of the distance between the couple tip and the light source. The thermocouple has wire diameter of 0.12 mm and a tip diameter of 0.40 mm with a response time of 50 ms, pinned into the droplet center (Fig. 1c). The thermocouple with data acquisition model was used to measure the droplet temperature at a frequency of 5 Hz. The high-speed camera captured the images through hole 1 at speed of 10 Hz. The synchronization hub connected to computer was introduced to synchronize the both systems, and their acquisition duration was set to 20 min for each experiment. The light spectrum offered by Xenon lamp with an AM1.5 filter was resembled to the solar spectrum in visible range of 300–800 nm (Fig. 2), which therefore can be used as the simulated solar source.

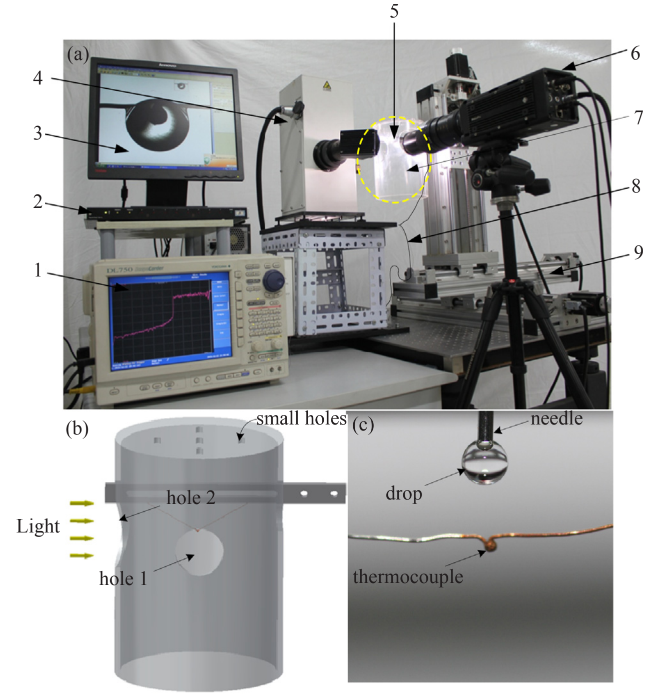

Fig. 1. The experimental setup (a) (1) data acquisition model, (2) synchronization hub, (3) computer, (4) Xenon lamp, (5) thermocouple tip, (6) high speed camera with a micro-focal lens, (7) glass cloak, (8) thermocouple wire, and (9) four-axis positioning guide. (b) A schematic diagram of the circled part in Fig. 1a. (c) A close-up image of the couple tip and the droplet.

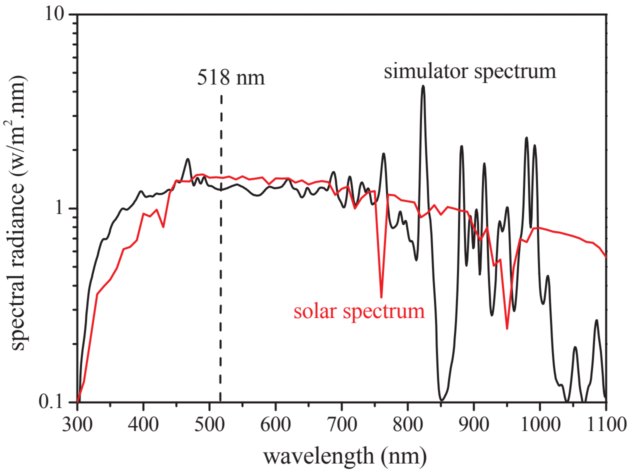

Fig. 2. Simulated spectrum offered by Xenon lamp with an AM1.5 filter versus solar spectrum.

2.3. Experiment procedure

Evaporation experiments were conducted in batch under irradiation on calm sunny days. The xenon lamp run for 15 min before the experiment to achieve a stable intensity. Then the intensity was quantified by an optical power meter (NP2000). A knob of xenon lamp was used to adjust the intensity at 1200 W/m^2, and then the light output was shut with an opaque shade. The diluted nanofluids were sonicated for 5 min