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Plasma resonance effects on bubble nucleation in flow boiling of a nanofluid irradiated by a pulsed laser beam☆

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ABSTRACT

An experimental investigation has been carried out on bubble generation in flow boiling of a nanofluid (suspending gold nanorods in deionized water), heated by a pulsed laser beam with a wavelength of 792 nm. The laser beam can excite the longitudinal mode of localized surface plasma resonance in gold nanorods, having 10 ± 1 nm in diameters and 43 ± 3 nm in lengths. At a concentration of 1.824 μg/ml of gold nanorods, effects of inlet temperature of the nanofluid, laser pulse frequency (at a fixed pulse duty ratio of 50%) and pulse period of the laser (at a fixed pulse duration of 10 ms), on the minimum laser intensity for bubble generation are investigated. It is found that (i) higher inlet temperature of the nanofluid can lower the laser intensity needed for the vapor generation, and (ii) increasing the pulse frequency of the laser with a given pulse duration can decrease the minimum laser intensity with the same observation time. It is also found that the minimum laser intensity required for bubble generation in the nanofluid has a maximum value at a laser pulse frequency of 100 Hz, when the velocity is in the range of 0.01 m/s to 0.1 m/s.

1. Introduction

Localized surface plasma resonance (LSPR) phenomena can occur on the surface of metal nanoparticles when free electrons are excited to oscillate collectively (i.e., in resonance condition) by a certain wavelength of the light [1,2]. For plasmonic nanoparticles irradiated by incident light at their plasma resonance wavelength, a large number of conduction electrons on the metal surface will participate in resonance, leading to higher photothermal conversion efficiency [3]. It has been found that LSPR can be affected by chemical composition [4], morphology [5], and size [6] of nanoparticles, surrounding environment [7], and the wavelength of the incident light [8]. Extending Mie's theory, Gans [9] obtained optical properties of spheroidal particles, and showed their localized surface plasma resonance consisting of two modes [6]: a longitudinal mode along the long axis of the rod and a transverse mode along the short axis of the rod.

Because of the low internal quantum efficiency of metal particles, it can be assumed that nearly all the absorbed optical energy is converted into heat [3]. Taylor et al. [10] showed that light energy absorbed in nanoparticles could be used for bubble generation locally without heating the bulk liquid to the nucleation temperature. Recently, a number of researchers [11–20] have studied vapor bubble generation in nanofluids heated by a laser beam or focused solar light. It appears that there are two different modes of bubble generation in nanofluids: Baral [12] pointed out that bubble nucleation occurs in the bulk liquid (i.e., a homogeneous nucleation phenomenon). On the other hand, Neumann et al. [13] showed that nanoparticles could be heated well above the nucleation temperature under focused solar illumination, and produced a thin layer of steam at the particle-liquid interface (i.e., a heterogeneous phenomenon).

Using a continuous laser, it was found experimentally that the minimum laser intensity for bubble generation can be affected not only by the material of nanoparticles [14] but also by concentration of nanoparticles [15] as well. Also, the nucleation time can be shortened by higher laser intensities [15]. Instead of using continuous lasers, a pulsed laser has also been widely used in nanofluid experiments [16–20] in order to confine a large amount of energy into a short time and space, causing intense heating for vapor bubbles generation. In particular, Siem et al. [17] used a two temperature model to predict temperature of nanoparticles and the predicted results were in good agreement with their experimental data. Kotaidis et al. [18] found that (i) radius of the nanoparticle influenced the water temperature and the nucleation heat flux, and (ii) the bubble radius increased with the increase of laser's intensity, and (iii) no heat transfer took place from nanoparticles to their surrounding fluid after the appearance of the nanobubbles. For medical applications,

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the accumulation of nanoparticles on the cell surface led to a significant reduction of bubble nucleation heat flux when compared with those of nanoparticles suspended in the liquid [19]. Lapotko [20] found that no heat transfer occurred between gold nanoparticles and the surrounding liquid during the existence of nanobubbles, but heat transfer took place between nanoparticles and the surrounding liquid before bubble nucleation and after collapse of the bubbles. It should be pointed out that all of the above pulsed laser experiments were carried out for one pulse only. Kalyon and Yilbas [21] carried out an analysis on pulse laser with repetitive laser pulses to study the heating process on the surface of a metal. They found that the heat flux on the surface of the metal decreased drastically during the initial time of the cooling period (i.e., during the initial time in pulse waiting period) and decreased only slightly at later times.

It is relevant to point out that vapor bubbles generated on nanoparticles by LSPR effects has the advantage that there is no need to heat bulk liquid to the nucleation temperature. The absorption of the laser beam by nanoparticles and heat transfer from nanoparticles to its adjacent water in forming a superheated thermal boundary layer are two important processes during bubble generation process. Previous experimental investigations on bubble generation in nanofluds irradiated by a pulsed laser [14-20] focused mostly on stationery liquids (i.e., pool boiling phenomena). Very few have studied bubble nucleation by a pulsed laser beam to excite plasma resonance of metallic nanoparticles in flow boiling conditions.

In this paper, we will focus our attention on parameters that may affect the minimum intensity of a laser for bubble generation in flow boiling of a nanofluid containing gold nanorods in DI water. Experiments were carried out in a nanofluid with a concentration of gold nanorods of 1.824 μg/ml in water. Effects of inlet temperature of the nanofluid, pulse frequency of the laser and pulse period of the laser beam on minimum power of the laser for bubble generation have been investigated. Results of this study will be helpful to optimize bubble generation in flow boiling of nanofluids irradiated by a pulsed laser beam.

2. Description of experimental setup

Top and side views of the experimental setup are sketched in Figs. 1(a) and (b) respectively. The nanofluid (consisting of gold nanorods in deionized water) in the container was driven by a micro-pump, and flowed through a vertical square silica glass tube with a cross section of 950 × 950 μm. The test section of the vertical glass tube was irradiated by a pulsed laser at the wavelength of 792 nm. A CCD camera was placed at the same elevation as the laser to observe bubble generation in the nanofluid in the test section. A thermostatic heater was placed under the container to control the inlet temperature of the nanofluid. Gold nanorods (see Fig. 2(a)) used in this experiment were 10 ± 1 nm in diameter and 43 ± 3 nm in length. The nanofluid was formed by adding 91.2 μg nanorods in 50 ml DI water, resulting in the weight concentration of nanorods in 1.824 μg/ml with a particle concentration of 3.08×10^{10} NPs/ml. A pulse laser, at a wavelength $\lambda_s = 792$ nm with a pulse period $\boldsymbol{\tau}$, was used to excite local surface plasma phenomenon. As shown in Fig. 1(c), the pulse period $\boldsymbol{\tau}$ consists of a pulse duration period t, and a pulse waiting period $(\boldsymbol{\tau}\textbf{-}\boldsymbol{t})$ during which no incident of light would occur (a cooling period). The micro-pump could control the flow velocity precisely. We chose the criterion for which a bubble is generated in the nanofluid in the test section when a bubble appeared within 1 s of observation time and another bubble appeared in the next second.

3. Absorption property of the nanofluid

As mentioned in Section 2, nanorods used in this experiment had 10 ± 1 nm in diameter and 43 ± 3 nm in length. Sizes of these nanorods were chosen so that the wavelength at which maximum absorption of light in the nanofluid would match the wavelength of the laser, which was 792 nm in the present experiment. The absorbance of light $\gamma(\lambda)$ in the nanofluid chosen for this experiment can be computed according to the following expression given in Ref. [6]:

$$\gamma(\lambda) = \frac{2\pi \mathrm{NV}\varepsilon_{\mathrm{m}}^{3/2}}{3\lambda} \sum\nolimits_j \frac{\left(1/P_j^2\right)\varepsilon_2}{\left(\varepsilon_1 + \frac{1-P_j}{P_j}\varepsilon_m\right) + \varepsilon_2^2} \tag{1a}$$

where N is the particle concentration; V is the volume of each particle; ε_m is the dielectric constant of the surrounding media, ε_1 and ε_2 are real and imaginary parts of the material dielectric function of the metal (which depends on the wavelength of the incident light λ) given by Olmon et al. [22]; P_j (with $j =$ A, B and C) are depolarization factors for respective axes with A > B = C (as shown in Fig. 2(a), A, B are dimensions of the nanoparticle, and C is the length perpendicular to A and B), given by the following equations,

$$P_A = \frac{1-e^2}{e^2}\left[\frac{1}{2e}\,1\mathrm{n}\left(\frac{1+e}{1-e}\right) - 1\right] \tag{1b}$$

$$P_B = P_C = \frac{1\text{-}P_A}{2} \tag{1c}$$

with

$$e^2 = 1\text{-}(B/A)^2 \tag{1d}$$

Computations of the absorbance of light in the nanofluid $\gamma(\lambda)$ were carried out according to Eq. (1). Computed results are expressed in terms of the normalized absorbance given by $\gamma(\lambda) = \gamma(\lambda)/\gamma_{\max}$, where $\gamma_{max} = \gamma_{792nm}$. The computed normalized absorbance $\gamma(\lambda)$ at different wavelengths is presented as dashed lines in Fig. 2(b), confirming that the maximum absorption occurred at a wavelength of 792 nm. For comparison purpose, the absorbance of the nanofluid was also measured by a spectrophotometer (manufactured by the Ocean Optic Company). The measured absorbance was normalized with respect to $\gamma_{\max} = \log(I_{inc}/I_{tra})$ where I_{inc} is the intensity of incident light and I_{tra} is the intensity of the transmission light, this measured normalized absorbance at different wavelengths is presented as a solid line in Fig. 2(b), where the maximum absorbance also occurs at a wavelength of 792 nm. As seen from this figure, nanorods have two different modes of plasma resonance with two absorption maxima at 502 nm and 792 nm corresponding to the transverse and longitudinal modes of plasma resonance [6]. It can be seen that the curve for computed normalized absorbance (indicated by dashed lines) is sharper and thinner in shape than experimental results (indicated by the solid line). This is because the geometric parameters A and B of nanorods used in the experiment were not exactly the same, which can be seen from Fig. 2(a). As shown from Eq. (1d), different ratios of B/A will give different plasma resonances. In general, a mixture of different sizes of nanorods (such as those used in this experiment) will broaden the absorption spectrum compared with nanorods of the same size used for computation. The longitudinal plasma resonance of the nanorods can greatly enhance the absorption of the laser beam as shown from Fig. 2(b) so that bubble can be generated at low laser intensities as will be shown in Section 4.

4. Results and discussion

The minimum laser intensity of the laser required for bubble generation P depends on the velocity of the nanofluid v, the inlet temperature of the nanofluid T_i, wavelength λ and pulse frequency f of the laser, the pulse duration t and the pulse period τ of the laser beam, and so on, i.e.,

$$P = F(v, T_i, \lambda, f, t, etc\ldots) \tag{2}$$

In this experiment, the wavelength of the laser was fixed at 792 nm ($\lambda = 792$ nm), and the nanofluid velocity was fixed at 0.1 m/s