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Numerical analysis of laser and nanofluids thermal interaction

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ABSTRACT

In this paper, the thermal lens effect, which is induced by passing a laser beam through nonlinear nanofluids, is investigated using finite element analysis. We used this method for two different laser incidence, i.e., horizontal and vertical direction. The results of this study show that in short time intervals, usually less than 5 s, we can neglect convection effects for both vertical and horizontal modes while for longer periods of time, convection effects can be ignored only for the vertical mode.

1. Introduction

Nanofluids are solid–liquid composites consisting of nanoparticles dispersed in a host medium [1]. The use of solid particles as an additive into the base fluid is a technique for the heat transfer enhancement [2]. Gold and silver nanoparticles strongly absorb and scatter visible light due to the excitation of surface plasmon resonance [3]. For volumetric fractions of the order of 50 ppm, almost no property of the base fluid is changed as much as the absorption coefficient [4,5]. Silver nanoparticles are merely light absorbing impurities which increase the absorption coefficient of the base fluid.

Thermo-optic effect is defined as a change in refractive index as a function of temperature change [6,7]. The simplest expression of temperature dependence is the derivative of refractive index with respect to temperature, i.e., the thermo-optic coefficient (dn/dT) [8]. Thermo-optic effect can be used in fabrication of digital optical switch, Mach–Zender interferometer type optical switch and optical cross-connect [6]. Also, it is important to know (dn/dT) when choosing or designing a window material [9].

The thermal lens effect in thin films has been already studied in different works [7,8,10,11]. In the case of thin films, conduction is the only mechanism of heat transfer. But the situation is more complex for fluids; in addition to conduction, convection also exists. This fact makes the heat transfer equations much more complex, as the heat transfer equation gets coupled to the Navier–Stokes equation through the convection term. Observations show that conduction effects are present from the very first moment the heat source starts working, but the effects of convection do not appear until a few seconds later [12]. Therefore, either the thermal lens experiments should be done during the first few seconds, or an arrangement should be made in which the effects of convection in steady state could be neglected.

In this paper, we have done a number of simulations for different directions of the laser incidence. In the first series of simulations the laser is illuminating vertically from top to bottom on the sample while in the second series the laser is illuminating horizontally. Each series divides into two parts, one with gravitational effects taken into account and one without. Ignoring gravitational effects is equivalent to ignoring convection effects. By comparing the results of the two parts in each series we would like to find an arrangement in which the effects of convection could be ignored.

2. Theory

When a high intensity laser beam is irradiated into the absorbing media, the generated heat in the region of absorption increases the local temperature, thereby modifying the refractive index and inducing an optical lens, which could be diverging or converging depending on the sign of thermo-optical coefficient (dn/dT) [13,14],for most liquids this coefficient behaves like a negative lens indicating that they expand on heating [13].

The change in refractive index Δn can be interpreted as a thermally induced change through the equation [15]

$$\Delta n = \left(\frac{dn}{dT}\right)\Delta T \quad (1)$$

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The temperature increase induced by the irradiated laser can be predicted by the transient state of the heat transfer and Navier–Stokes equations [5].

The heat transfer equation of nanofluids is [5]

$$(\rho c)\left[\frac{\partial T(r,z,t)}{\partial t}+\mathbf{v}(r,z,t)\nabla T(r,z,t)\right]$$
$$=k\nabla^2 T+Q+(\rho_p c_p)\left[D_B\nabla\phi\nabla T+D_T\frac{\nabla T\nabla T}{T}\right] \tag{2}$$

where (ρc) is nano-fluid heat capacity per unit volume, $T(r,z,t)$ is nano-fluid temperature, $\mathbf{v}(r,z,t)$ is velocity of nano-fluid, k is thermal conduction coefficient of nano-fluid, Q is the amount of heat absorbed by nano-fluid as the laser beam passes through and $(\rho_p c_p)D_B\nabla\phi\nabla T$is the Brownian motion term. The terms $(\rho_p c_p)$, D_B, and ϕ represent nanoparticles heat capacity per unit volume, Brownian diffusion coefficient, and nanoparticles volumetric fraction respectively. $(\rho_p c_p)D_T\nabla T\nabla T/T$ is the thermo-phoretic diffusion term; where $(\rho_p c_p)$, and D_T represent nanoparticles heat capacity per unit volume, and thermal diffusion coefficient respectively.

Buongiorno has shown that these two extra terms are of negligible importance in comparison to convection and conduction parts [5]. This fact makes the nanofluid heat transfer heat equation identical to that of pure fluids. Thus nanoparticles affect this equation only via thermophysical properties.

The intensity distribution of a Gaussian laser beam is given by [16]

$$I(r)=\frac{2P_0}{\pi w_0^2}\exp\left(\frac{-2r^2}{w_0^2}\right) \tag{3}$$

where P_0 is the laser power, w_0 is the beam waist and r is the distance from the center of the beam. Here we assume that nanofluid remains homogeneous and consequently obeys Beer–Lambert law, i. e.,

$$Q=\alpha I(r)\exp(-\alpha z) \tag{4}$$

where in above equation both α's are the same and represent the absorption coefficient of nanofluid.

The other equation which might be solved is the Navier–Stokes equation

$$\rho\left(\frac{\partial \mathbf{v}}{\partial t}+\mathbf{v}\nabla\mathbf{v}\right)=-\nabla p+\mu\nabla^2\mathbf{v}+\rho\mathbf{g} \tag{5}$$

where ρ is nanofluid density, $\mathbf{v}$ is velocity of nanofluid, p is pressure, μ is viscosity and $\mathbf{g}$ is gravitational acceleration.

Eq. 2 is coupled to this equation through the term $\mathbf{v}(r,z,t)\nabla T(r,z,t)$, which requires them to be solved simultaneously. Since it is often impossible to solve these two equations analytically, it seems necessary to use finite element analysis for solving this problem numerically. This part has been done by the finite element analysis using COMSOL software.

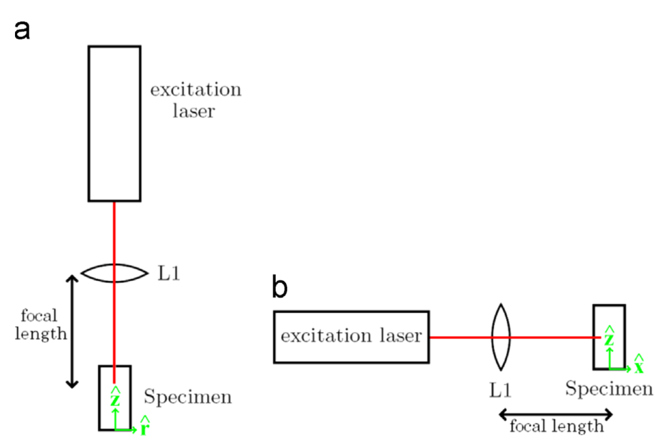

Fig. 1. Schematic diagram of a thermal lensing setup: (a) vertical mode; and (b) horizontal mode, L1 is the focusing lens.

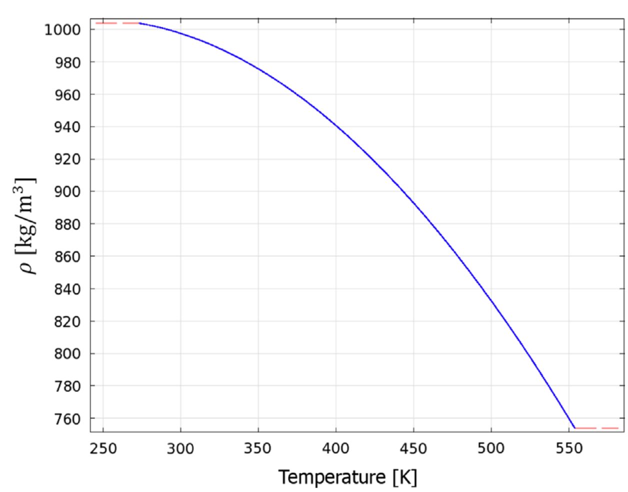

Fig. 3. Graph of water density as a function of temperature.

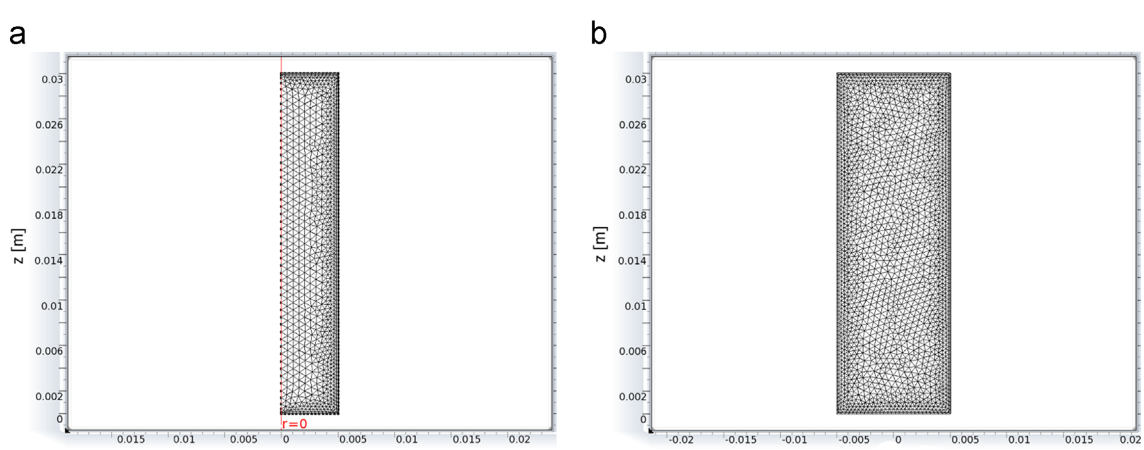

Fig. 2. The whole region is chopped into small pieces for finite element method: (a) meshing of half of the cell for vertical study; and (b) meshing of the whole cell for horizontal study.