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Concentration dynamics of nanoparticles under a periodic light field

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Abstract

Using a system of heat and mass balance equations, we study the dynamics of the concentration of nanoparticles in nanofluids under the influence of a periodic light field. The review will be based on the thermal convection. © 2015 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/). Peer-review under responsibility of the National Research Nuclear University MEPhI (Moscow Engineering Physics Institute)

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1. Introduction

Colloidal suspensions, or, as they are now called, nanofluids, are widely used in various fields of modern technology. For example, a magnetic fluid is used for polishing optical components [Rosensweig (1985)]. A suspension of silica particles in a liquid crystal substantially improves the characteristics of the optical drive [Kreuzer et al. (1993)]. Artificial media with high optical nonlinearity colloids were prepared that contain particles of submicron sizes [Freysz et al. (1985), Vicari (2001)]. Further, as shown by experimental and theoretical studies in recent years [El-Ganainy et al. (2007), Kul’chin et al. (2008), Ivanov and Livashvili (2010), Livashvili et al. (2013), in which a liquid-phase medium acts as a dispersion component, nanoparticles taken from wide bandgap semiconductors or insulators are very effective for a number of nonlinear optical effects. However, the physical mechanisms associated in particular with nonlinear optical processes in such media, in our view, require further study.

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The aim of our work is a theoretical study of the results of thermal diffusion steps, taking into account thermal convection in the fluid dynamics of the nanoparticle concentration and, therefore, the nonlinear optical properties of the medium.

2. Theoretical model

The easiest way to create a regular gradient light field is the interference of two light beams, which leads to harmonic modulation of the radiation intensity with a period $\Lambda$ that varies over a wide range, $\lambda/2 \leq \Lambda \leq \infty$, where $\lambda$ is the wavelength of the laser radiation. In particular, the dynamic hologram recording irradiance distribution in the layer plane of the medium is given by [Ivanov and Livashvili (2010)]:

$$ I(x) = I_0 + \bar{q} \sin kx, \quad -\infty < x < \infty, $$

where $\bar{q} = 2\sqrt{I_0 I_s}$ ($I_0$ and $I_s$ are the intensities of the reference and signal plane waves, respectively; $I_0 >> I_s$), and $k$ is the wave vector of the space grid. Note that the effect of thermal convection in such processes was analyzed only qualitatively in [Kohler and Wiegand (2002)].

We write the system of balance equations describing the processes of heat and mass transfer for the system [De Groot and Mazur (1964)]:

$$ C_p \rho \frac{\partial T}{\partial t} = \chi \frac{\partial^2 T}{\partial x^2} - v \frac{\partial T}{\partial x} + \alpha (I_0 + \bar{q} \sin kx), $$

$$ \frac{\partial c}{\partial t} = D \frac{\partial^2 c}{\partial x^2} + D_l \frac{\partial}{\partial x} (c(1-c) \frac{\partial T}{\partial x}). $$

Here, $D, D_l$ are the diffusion and thermal diffusion, respectively; $C_p, \rho, \chi$ are the thermal constants of the medium, and $\alpha$ is the absorption coefficient of the light wave. Note that all of the above factors are assumed to be constant. Following [Karimzadeh (2012)], we consider the rate of thermal convection to be constant and equal to $V_z = \beta g T_m \eta h^2 / 16 \mu$, where $\beta$ is the coefficient of thermal expansion of the liquid, $\mu$ is its viscosity, $T_m$ is the maximum temperature of the medium, $h$ is the sample thickness, and $g$ is the acceleration of gravity. Equation (3) is considered in the linear approximation for the concentration $c(1-c) \approx c_0$, where $c_0$ is the initial concentration. Equation (2), with the initial condition $T(x,0) = T_0$, can be solved using the corresponding Green function [Polyanin (2001)]. Because thermal processes are established much more rapidly than diffusion, we write its quasi-stationary solution (under the approximation $k^2 at \ll 1$):

$$ T(x,t) = T_0 + bt + \frac{bg}{k(k^2a^2 + v_z^2)^{1/2}} \cos(kx - \varphi), $$

where $a = \lambda / C_p \rho$, $b = \alpha I_0 / C_p \rho$, $q = 2(I_0 / I_s)^{1/2}$, and $\varphi = \arctan(ka / v_z)$.

Using equation (4), we obtain the linearized problem for equation (3):
\[
\frac{\partial c}{\partial t} = D \frac{\partial^2 c}{\partial x^2} - \frac{D \beta k q}{(k^2 a^2 + v_i^2)^{3/2}} \cos(kx - \varphi). \tag{5}
\]

\[
c(x,0) = c_0 \tag{6}
\]

where \( S_r = D_r / D \) is a Soret coefficient.

Note that in the absence of convection \((v_i = 0, \varphi = 0)\), the expression obtained for \( c(x) \) agrees completely with the analogous formula given in [Ivanov and Livashvili (2010)].

3. Results and conclusions

Characteristics of three cameras were used during numerical experiments: From (6), it follows that the term \( v_i^2 \) in the denominator of this expression reduces the amplitude concentration. We denote the estimated quantities as \( ka \) and \( v_i \). Assuming \( \lambda = 4 \cdot 10^{-7} \text{m} \), \( \chi = 0.4 \text{Wt} \cdot \text{m} / \text{K} \), \( C_p = 4.5 \cdot 10^3 \text{J} / \text{kg} \cdot \text{K} \), \( \rho = 0.9 \cdot 10^3 \text{kg} / \text{m}^3 \), \( T_s = 310 \text{K} \), \( \beta = 7.5 \cdot 10^{-4} \text{K}^{-1} \), \( \mu = 1.4 \cdot 10^{-3} \text{m}^2 / \text{s} \), and \( h = 1.5 \cdot 10^{-3} \text{m} \), we obtain the desired estimate: \( ka \approx 1.5 \text{m} / \text{s} \), \( v_i \approx 0.4 \text{m} / \text{s} \).

On the basis of these values, we can say that even a small reduction in the wave vector of the light wave (a shift into the infrared region of the spectrum) leads to \( k^2 a \approx v_i^2 \). That is, the thermal convection speed becomes significant for nanofluids, e.g., in the calculation of the diffraction efficiency, the formula for which is clearly part of the square of the nonlinear refractive index, which in turn is calculated on the basis of an expression for the nanoparticle concentration [Ivanov and Livashvili (2010), Kohler (1993)].

References