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Modelling natural convection of fluid in cuvette

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Abstract. Convection is a process of transfer liquid from a hot region to a cool region. This phenomenon is involved in many physical processes. The main characteristic of convection is a temperature field. Modelling of convection allows to get the information about temperature field at any time of process. In this paper the results of modelling natural convection of fluid in cuvette are presented. All results are approved by experimental data. For modelling the process of natural convection Navier-Stokes equations under Boussinesq approximation were used. An experimental setup based on digital holographic interferometry was developed in order to make an experiment. The results for three stages of convection, such as: jet initiation, initial jet formation, jet development with formation of mushroom-shaped convective stream, are presented.

1. Introduction
Nanoparticles are used in many advanced areas. Nanoparticles in membrane are the most effective gas separation filters. Semiconductor with nanometre scale shows interesting optical properties. Also nanoparticles are useful in many other fields: medicine, optoelectronics, photonics, etc. Hydrothermal synthesis is one of the methods of formation of nanotubes. Natural convection is one of the important processes in hydrothermal synthesis. Size of the nanoparticles depends on the initial condition of synthesis and changes of physical parameters during the process. Modelling of convection allows to determine the most effective characteristics for synthesis of nanoparticles with predefined sizes. Mathematical simulation of process allows to get the information about temperature, velocity and concentration fields at any time of process [1-3].

2. Mathematical model
Convective motion occurs due to the difference in the density between the heated and cold areas. To describe the process of natural convection it is easy to use Navier-Stokes equations under Boussinesq approximation. We assume fluid density ρ to depend only on the temperature. Navier-Stokes equations and those of continuity and convective thermal conduction in the above approximation are described as follows:

\[ \frac{\partial V}{\partial t} + (VV)V = -\frac{1}{\rho_0} Vp + \nu \Delta V + \frac{\rho(T)}{\rho_0} g, \]

\[ VV = 0, \]

\[ \frac{\partial T}{\partial t} + VVT = a\Delta T, \]

where \( V \) is the velocity of the fluid, \( p \) is the pressure, \( \nu \) is the kinematic viscosity, \( \Delta V \) is the gradient of the velocity, \( g \) is the gravitational acceleration, \( T \) is the temperature, and \( a \) is the thermal diffusivity.
where $\mathbf{V}$ is the velocity vector, $p$ is the pressure, $\nu$ and $\alpha$ are the kinematic viscosity and thermometric conductivity of the liquid, $g$ is the free fall acceleration.

The first equation of this system in general case may be rewritten as:

$$\frac{\partial \mathbf{V}}{\partial t} = \nu \nabla^2 \mathbf{V} - (\mathbf{V} \cdot \nabla) \mathbf{V} - \frac{1}{\rho_0} \nabla p + \mathbf{f}$$

(2)

where $\mathbf{f}$ is the body force such as gravity or buoyancy.

This equation can be split into two parts (assuming a uniform distribution of pressure):

$$\frac{\partial V_1}{\partial t} = \nu \nabla^2 V + f$$

(3)

$$\frac{\partial V_2}{\partial t} = -(V_1 \cdot \nabla)V_2$$

(4)

The first part is diffusion which is described by the equation (3). This equation can be solved by relaxation method. The second part is advection described by the equation (4). It can be solved by MacCormack method, which consists of two steps: the first one is predictor and the second one is corrector.

Using the Helmholtz decomposition, the velocity of liquid can be split into the following form:

$$\mathbf{V} = \mathbf{V}' + \nabla \phi$$

(5)

where $\phi$ is a scalar field and $\nabla \mathbf{V}' = 0$.

If we apply the operator $\nabla$ to both sides of equation (5) and use the second equation of the system (1), we obtain:

$$\nabla^2 \phi = 0$$

(6)

This is a Poisson equation and it can be solved by multigrid method.

3. Results

Implementation of mathematical model allows to get the temperature field as an output data. Real experiment based on digital holographic interferometry was conducted. As a test-object a cuvette with liquid and heater was used. Mathematical description of an object is presented in Figure 1. Boundary conditions for “Insulator” walls are adiabatic. For the top part of object, the boundary condition is "free surface".

In the experimental setup a lamp was used as a heater. Scheme of a real test-object is presented in Figure 2. This scheme includes heater, liquid level and cuvette.

The results of mathematical modeling and experimental data are presented in Table 1. It describes three stages of convection: jet initiation, initial jet formation, jet development with formation of mushroom-shaped convective stream. The time of stages is 3s, 9s, 25s respectively. I – are the interferograms of the object. They were obtained using Fourier hologram scheme. The time shows which images were subtracted to get interferograms.
The comparison of the experimental and simulation data for the three stages of convection shows a good result. It allow us to continue our investigation in order to implement the experimental scheme at autoclave.

Table 1. Comparison of the experimental and simulation data. I – interferograms, II – simulation data of the temperature field.

| Heating time, s | 3 | 9 | 25 |
|-----------------|---|---|----|
| Stages          |   |   |    |
| I               | 1 | 2 | 3  |
| II              |   |   |    |

4. Future steps
We consider the implementation of the two-scale model as the next step of our investigation. In our opinion, it will allow to manage micro parameters through macro parameters. Also, we intend to implement particles into our model and add the concentration convection.

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