Journal of Physics: Conference Series

PAPER • OPEN ACCESS

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To cite this article: Boris V. Balakin and Kirill V. Kutsenko 2018 *J. Phys.: Conf. Ser.* **1133** 012011

IOP Conf. Series: Journal of Physics: Conf. Series **1133** (2018) 012011 doi:10.1088/1742-6596/1133/1/012011

Magnetic enhancement of photothermal heating in ferrofluids

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Abstract. This contribution describes a multiphase CFD model, capable of simulating convective mass and heat transfer in a ferrofluid. The model was used for a parametric analysis of thermomagnetic convection, demonstrating 1.3-fold enhancement of thermal efficiency under the influence of an external magnetic field. The model was validated against two different experimental datasets.

1. Introduction

Ferrofluids, i.e. the nanofluids [1] laden with ferromagnetic particles [2], are presently considered among the list of novel, promising heat transfer fluids. They find applications in electronics, medicine (oncology), petroleum industry and potentially nuclear engineering, where the nanoparticle-enhanced thermal conductivity is of importance. The photothermal properties of the ferrofluids are utilized in areas where the thermal radiation dominates over convection and conduction, e.g. in solar and space engineering. In this case the ferrofluid absorbs heat in bulk of the fluid at greater surface than in convectional case, when a flat-plate wall is utilized. Moreover, the ferrofluids establish thermomagnetic convection being simultaneously heated and radiated with a low-magnitude magnetic field. This additionally improves the heat transfer. The present contribution describes a numerical model which is developed to simulate a photothermal system with thermomagnetic convection.

2. Methodology

The model is based on the two-fluid Euler-Euler CFD approach. Here the ferrofluid is considered as a system of two inter-penetrating phases (the base fluid and the particles), where the flow of each phase is described by a separate set of Navier-Stokes equations [1]:

$$\frac{D\varphi_i\rho_i}{Dt} = 0, \qquad \frac{D\varphi_i\rho_i\vec{v_i}}{Dt} = -\varphi_i\nabla p + \varphi_i\mu_i\nabla^2\vec{v_i} + \vec{M} \quad (1)$$

$$\frac{D\varphi_i\rho_i e_i}{Dt} = \nabla(\varphi_i k_i \nabla T_i) + q_{i,j} + q_{v,i}. \quad (2)$$

The sources of the energy equation represent the inter-phase heat transfer $q_{i,j}$, modelled according to Ranz&Marshall and the volumetric heat generation term $q_{v,i}$ due Beer-Lambert. The momentum source term M represents the superposition of gravity, the Brownian dispersion force (only for i=p) [1], inter-phase drag (Schiller-Naumann) and the magnetic Kelvin force (per unit volume) [2]:

$$\vec{F}_m = \mu_0 M \nabla \mathrm{H} \qquad \mathrm{M} = M_s \cdot \Im\left(V_p M_s \mu_0 H / k_B T\right) \quad \Im(x) = \coth(x) - 1/x \tag{3}$$

The model of photothermal absorption was initially validated against the third-party experimental dataset [3] without thermomagnetic convection, where a cylindrical column (Ø 10 cm, height 7.5 cm) of ionic fluid with dispersed 50 ppm of 500 nm particles was subjected to 2300 W/m^2, coming from the top (scheme in Fig.1). The measurement system included a number of thermocouples, uniformly distributed over the vertical axis of the vessel. The boundary conditions included pressure at the top and mixed convective-radiative, no-slip condition at the walls. Eqs.1-3 were discretized over 27 mm^3 cubical volumes and solved in STAR-CCM+ using SIMPLE and iterating implicitly in time with 1 ms step.

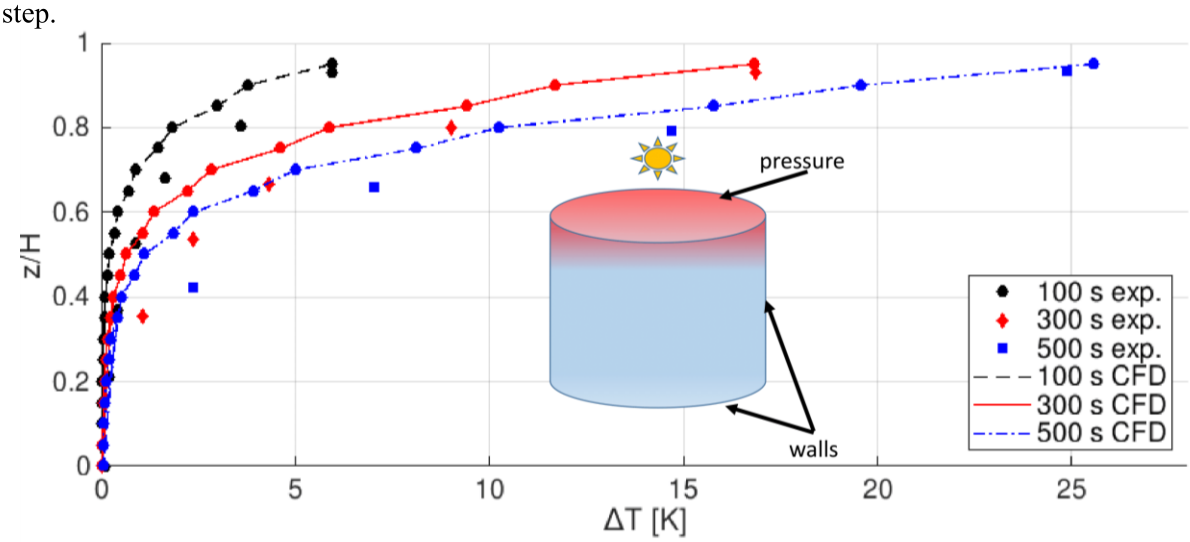

Figure 1. Benchmarking and boundary conditions

The results of model validation are presented in Fig.1 in terms of the vertical profile of excess temperature, relative to ambient conditions. The time-average discrepancies never overcame 20%. The discrepancies originated from an uncertainty in the experimental particle size determination.

Another validation was conducted for an in-house dataset, described previously in Ulset et al. [4]. In this study we conducted experiments on luminate heating of an aqueous nanofluid, synthesized with carbon black nanoparticles. The experimental system, schematically shown in Fig. 2, consisted of a cylindrical glass tube with the diameter of 13.5 mm and nanofluid column height 36.4 mm. The tube was irradiated horizontally with two halogen lamps. Each lamp delivered 5762 W/m^2 heat.

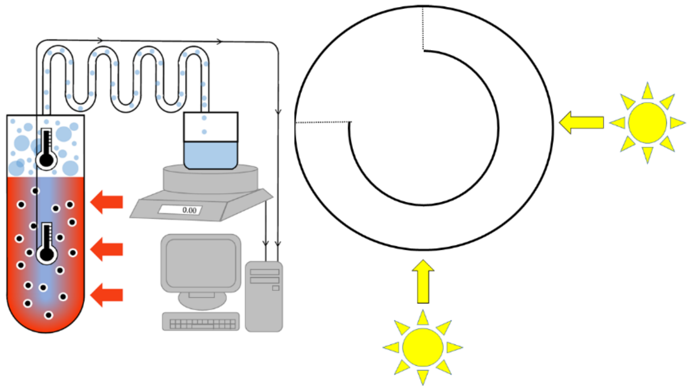

Figure 2. Experimental scheme (Ulset et al.) and heating configuration

The resolution of the second model was higher: 1-mm uniform trimmed mesh and 1 ms time step. The initial conditions included: homogeneous distribution of motionless phases at ambient temperature and φ_p=0.9%. The mean particle size of 1.5 μm was estimated during static-light-scattering analysis of the "luminate" steam, evaporated from the nanofluid.

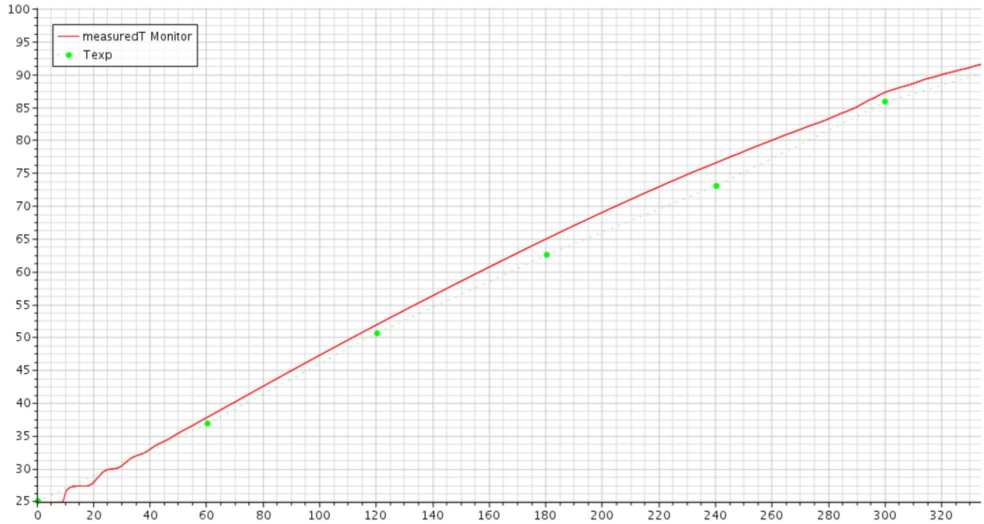

Figure 3. Nanofluid temperature as a function of time

Fig. 3 shows results of the model validation for a typical experimental run. Here we compare temporal change of the nanofluid temperature, recorded experimentally, with the respective prediction of the CFD model. It follows from the picture that the discrepancy is much lower (<10%) for the second case. The CFD-simulations were stopped at the moment of time, when the base fluid (water) in this model was superheated up to the temperature, which corresponded to the onset of nucleate boiling for water.

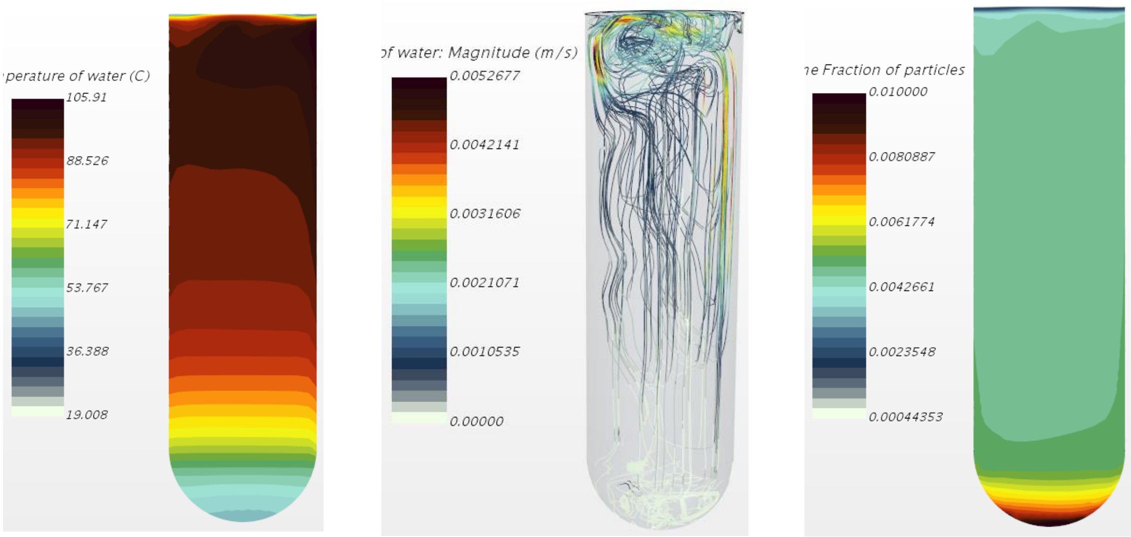

Figure 4. Left->Right: temperature distribution, streamlines and volume fraction of particles

It is particularly interesting to elucidate this moment in terms of the main flow parameters. This has been done in Fig.4, where we present contours of the nanofluid temperature, velocity streamlines and volume fraction of the nanoparticles in the midline cross-section of the nanofluid column. As it follows from the figure, maximum of the nanofluid temperature is lifted to the top of the column due to the natural convection, which is clearly seen from the streamlines. It is important to note the asymmetry of the convective currents, which are shifted towards the corner of the cylinder, located opposite to the zone, which is subjected to thermal radiation. The particles, which are agglomerates of smaller 51-nm carbon nanoparticles, tend to settle and form a packed zone at the bottom of the tube. This zone is just very slightly affected by the natural convection and so expands in time.

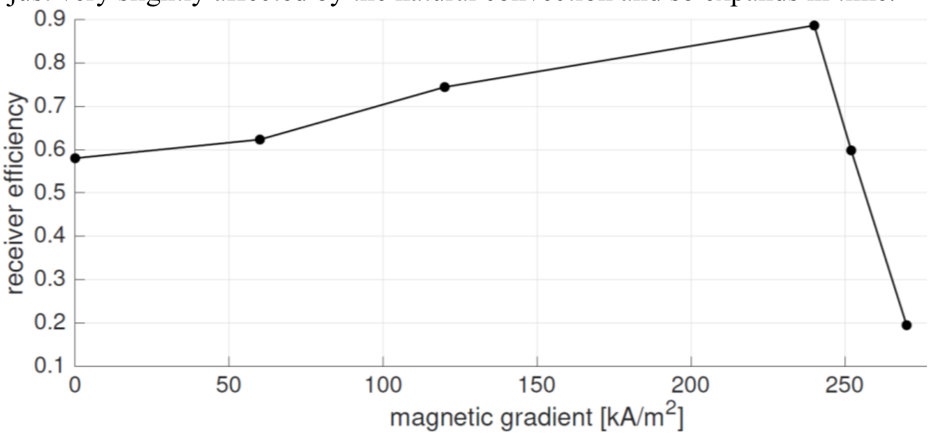

Figure 5. Collector efficiency as a function of magnetic field gradient

Simulating effect of the magnetic field in the first model with the geometry, taken from Liu et al. [3], we changed the nanoparticle magnetic properties to those reported in Aursand et al. [2]. The simulation results reveal 6-fold enhancement of the convective flow patterns in the vicinity of the boundary, where the magnetic field originates. Considering the efficiency of the photothermal light absorption, defined as a ratio of the harvested heat to the incident radiant heating, we note about 30% increase relative to the benchmark without magnetic effects at the magnetic gradient 240 kA/m^2. As it follows from Fig.5, further increase of the magnetic field gradient dramatically drops the photothermal performance of the system, which is related to magnetic attraction of the particles. The therefore form a “black surface” just at the boundary of computational domain and absorb major part of the radiant heat.

3. Conclusions

The multiphase CFD-model to simulate flow of ferromagnetic nanofluid was developed using the modified Eulerian-Eulerian technique. The model accounts for multiple details of the process, including the Brownian dispersion of nanoparticles and, being applied to a direct solar collector case, photo-absorption of radiant heat. The model was validated against two independent datasets, exhibiting modest discrepancies in the interval 10-20%. Modelling thermomagnetic convection, we noted superior performance of the ferrofluids relative to other nanofluid types in case the magnetic field is involved when during the heat transfer management. The efficiency rise is about 30% due to magnetic effects.

Acknowledgments

This study was supported by Russian Science Foundation (project No. 17-79-10481).

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