Eulerian-Eulerian Model for Photothermal Energy Conversion in Nanofluids

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Abstract. In this research photothermal energy conversion in nanofluids was numerically studied using a CFD model. A Direct Absorption Collector (DAC) of cylindrical shape with incident light on one of its surfaces was adopted for the simulations. The Eulerian two-phase transient model included the volumetric absorption of light, losses to the surroundings and the Brownian motion. The simulation results were validated with experimental data, demonstrating modest discrepancies. The model was studied parametrically, altering particle volume fraction, collector height and surface transparency. We found that: the efficiency drops by 43% when the absorber height is reduced from 7.5 to 1.0 cm for 2.5 ppm; the maximum efficiency was 67% at 50 ppm (1 cm absorber); the efficiency of the DAC with nanofluid is 20% greater than the efficiency for the surface absorber; natural convection in the collector improves the efficiency by 7%.

INTRODUCTION

The fact that the Sun is a major source of inexhaustible energy makes solar power technologies one of the key solutions for the increasing demand of energy. However, due to the relatively low efficiency of conventional solar harvesters (collectors, ponds and photovoltaic cells), use of solar energy is challenging. One of the ways to improve their performance is the use of nanofluids. In the last decades several experimental studies have shown the enhancement of the thermal performance by adding nano-size particles to the working fluid. Still a better understanding on thermophysical properties, thermal and flow behaviour of nanofluids is needed for the development of new more efficient technologies.

Jian et al. [1] developed a heat transfer model to predict the temperature and efficiency of a DAC and compared the model with their experimental results. They attributed temperature discrepancies between numerical and experimental results to convection effects not considered in the model. The most common approach among theoretical studies of nanofluids has been the single-phase approach, which assumes thermal equilibrium between the phases and neglects the slip mechanisms between a nano-particle and the host fluid. The results, however, are strongly dependent on the effective parameters models obtained from experimental work. Mahdavi et al. [2] performed a numerical study of the hydrodynamic behaviour of nanofluids. They compared the Eulerian mixture model with the Lagrangian model in a steady-state flow. The first one solves only one momentum and one energy equation, while the last one calculates the slip velocity and temperature difference between particles and liquid. For the mixture model, a strong dependency on the empirical properties of nanofluid was reported. The Lagrangian approach, which only requires thermophysical properties for the base fluid, showed a better agreement with experiments. Nevertheless, a large number of nanoparticles present in the nanofluids, even for a low volume concentration, makes the Lagrangian technique hardly applicable for a numerical simulation of the nanofluid-supported DAC, due to enormous computational costs. Kalteh et al. [3] used an Eulerian-Eulerian two-phase model to study the laminar forced convection heat transfer of a nanofluid inside an isothermally heated microchannel. They included a virtual mass force and a particle-particle interaction force in their model. They observed a negligible relative velocity and temperature between the phases and concluded that the under-estimation of the heat transfer enhancement by single-phase approaches is due to the models for the nanofluid properties assumed.

In the present contribution, a transient Eulerian-Eulerian model was adopted to study the photo-thermal conversion in a DAC under low solar concentration. The volumetric absorption of incident light and the Brownian motion models were included. The effects of particle concentration, height of collector and natural convection on the thermal efficiency were studied.

MODEL

The model presented in the following reproduces the experimental work by Jian et al. [1]: a cylindrical DAC of 10 cm diameter and 7.5 cm height. The Eulerian-Eulerian two-phase model was adopted, which assumes the phases as continuous fluids coexisting in the domain with the volume fraction, φ, specifying the volume occupied by each phase, $i{=}f$ (base fluid) and $i{=}p$ (nanoparticles). The continuity and momentum equations read:

$$\frac{\partial \rho_i}{\partial t} = \nabla(\varphi_i \rho_i \mathbf{v}) = 0 \qquad \text{and} \qquad \frac{\partial(\rho_i \mathbf{v}_i)}{\partial t} + \nabla(\varphi_i \rho_i \mathbf{v}_i \mathbf{v}_i) = -\varphi_i \nabla p + \nabla(\varphi_i \mu_i \mathbf{v}_i) + \varphi_i \rho_i \mathbf{g} + \mathbf{F}_{D,i} + \mathbf{F}_{B,i}, \tag{1}$$

where ρ is the density, $\mathbf{v}$ is the velocity vector, p is the static pressure field, μ is the dynamic viscosity, $\mathbf{g}$ is the gravitational field, and $\mathbf{F}_D$ is drag force calculated using the Schiller-Naumann correlation and corrected by the Cunningham factor, C_c [4].

The Brownian motion term in the momentum equation, $\mathbf{F}_B$, reads [5]:

$$\mathbf{F}_{B,i} = \zeta \sqrt{\frac{216\,\nu k_B T_f}{\pi \rho_f d_p^5 (\frac{\rho_p}{\rho_f})^2 C_c \Delta t}}, \tag{2}$$

where ζ is a vector of zero-mean, unit-variance-independent Gaussian random numbers, ν is the kinematic viscosity of the fluid, k_B is the Boltzmann constant, T_f is the absolute temperature of the base fluid, d_p is the diameter of the particles and Δt is the integration time step.

The energy equation is written as:

$$\frac{\partial(\varphi_i \rho_i e_i)}{\partial t} + \nabla(\varphi_i \rho_i e_i \mathbf{v_i}) = \nabla(\varphi_i k_f \nabla T_i) - \frac{6 k_f Nu \varphi_p}{d_p^2}(T_i - T_j) + q_{v,i}. \tag{3}$$

Here e is the specific energy, k_f is the thermal conductivity of the fluid, Nu is calculated using the Ranz-Marshall correlation and q_v is the volumetric heat generation calculated as: $q_{v,i} = I_0 K_i \exp\left(-\left(K_f + K_p\right) y\right)$, where $I_0 = 2300$ W m^{-2} is the light intensity, y refers to the optical path, K_f is the extinction coefficient of the base fluid and $K_p = 6\varphi_p/d_p$ is the extinction coefficient of the particles [6].

Figure 1a presents the geometry and the boundary conditions. The exposed boundary refers to the surface, which receives the light. A mixed convective and radiative boundary condition was used to model the exposed surface prescribed following Jian et al. [1]. The opposite surface was assumed to be adiabatic and at the side surface a convective boundary was considered. The no-slip boundary condition was assumed for both phases at all the surfaces. In addition, two symmetry planes were applied to reduce the computational domain to a quarter of cylinder. The initial conditions included: uniform temperature field 290.15 K, zero velocity and atmospheric pressure.

The thermal efficiency of the solar receiver is defined as a ratio between the collected thermal energy to the total incident energy [1]: $\eta = \left(m c_p (\bar{T}_f - T_{amb})\right) / \left(\int_0^t I_0 A dt\right)$.

The numerical model was built in the commercial software Star-CCM+. The discretization of the governing equations in space was done by a finite volume technique with 3840 hexahedral cells and an implicit advancement in time with a step of 5 ms. The equations were solved using the SIMPLE numerical technique.

RESULTS AND DISCUSSIONS

Figure 1b shows the comparison of simulations with experiments [1]. The temperature at the bottom of the collector when the top is exposed to the Sun radiation remained constant even after 1000 s of exposure, leading to a more pronounced temperature gradient with time. This behaviour was expectable since the light beam attenuates as it travels

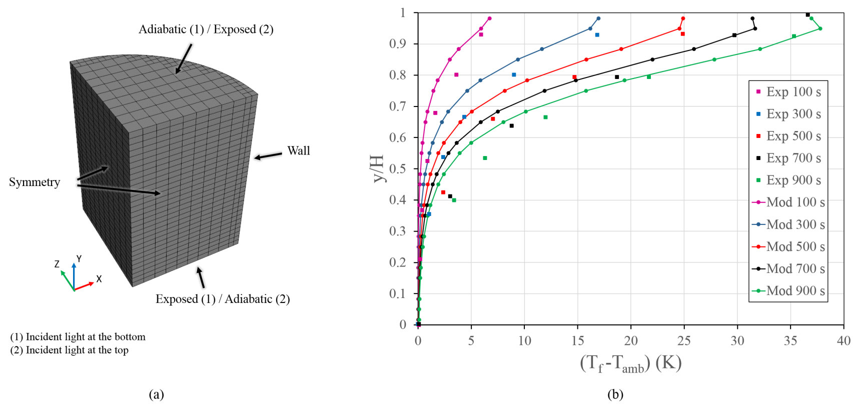

FIGURE 1. Mesh and boundary conditions (a). Nanofluid temperature profile in axial direction. Simulation results (Mod) are compared with experiments (Exp) at 100, 300, 500, 700 and 900 s of the heating process (b). H=7.5 cm, ' $_p$=2.5 ppm, d_p= 500 nm.

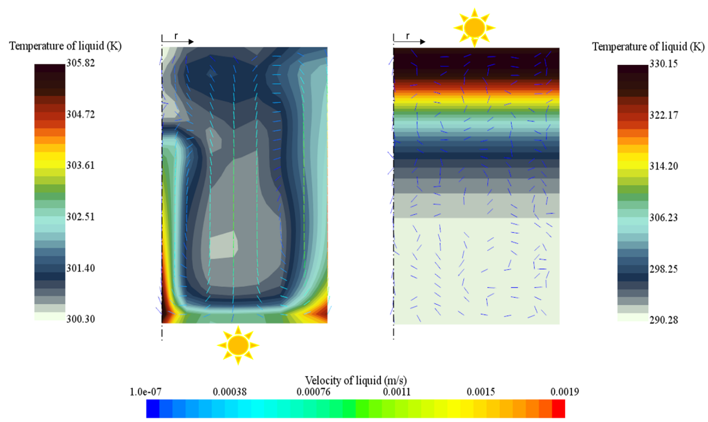

FIGURE 2. Temperature distribution and velocity vectors when incident light is at the bottom (left) and at the top of the receiver (right) after 1000 s of exposure.

through the nanofluid column according to the Beer-Lambert law. The discrepancies with the model were lower than 8% and can be attributed to the assumption of the constant extinction coefficient over the full wavelength spectrum.

Figure 2 shows the temperature distribution and vectors of the nanoparticle velocity in the midline cross-section of the DAC. For the case with incident light at the top surface, the velocity is negligible and the temperature variation along the y-axis is significant. With incident light at the bottom surface, convective currents were found during the simulation, which lead to a more uniform temperature profile. The temperature difference between the top and bottom surfaces was reduced from 39.3 to 3.4 K, so that the losses to the surroundings were limited.

To elucidate the benefits of the volumetric absorption in DACs when using nanofluids, the results are compared to a surface absorption collector in Figure 3a. In the latter case, the volumetric heat generation was set to zero and a heat flux of I_0 W m ^{2} was delivered at the exposed boundary. As a result, the thermal receiver efficiency is enhanced over 20% for the volumetric absorption receiver for both cases considered: incident light on top or bottom surface. Even though the emissivity of solar selective surfaces is much lower than for nanofluids [7], the localization of high temperatures to the interior of the receiver resulted in lower radiative losses in the case of the volumetric absorption.

For a larger collector height, the nanofluid absorbs more of the incident light as shown in Figure 3b, while the temperature at the surfaces was found to be lower. Due to the insulation at the sides of the receiver, the higher losses are found from the non-insulated surface because of radiation and convection. Therefore, the thermal efficiency of the receiver was enhanced for the larger collector height. For 1 cm height solar collector the efficiency increased with volume fraction up to 0.005%. As volume fraction increases, the transmitted light intensity into the nanofluid is greater,

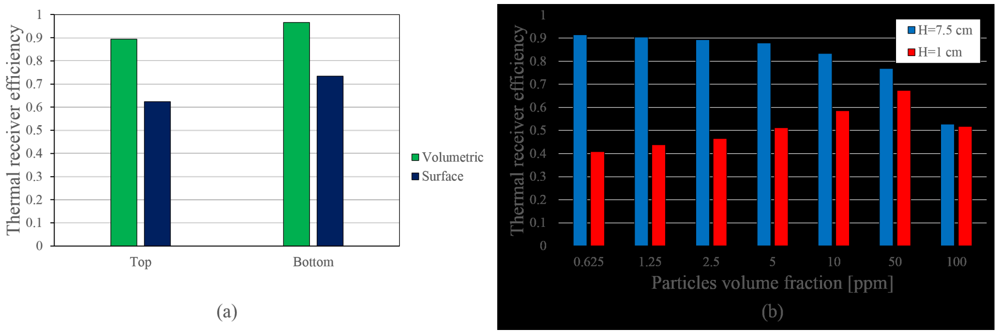

FIGURE 3. Thermal receiver efficiency comparison at 1000 s for: (a) volumetric and surface absorption, considering a selective surface with absorption 0.8 and emissivity 0.12 [9]; (b) 7.5 and 1 cm height solar receiver for different particle volume fraction.

but it also attenuates faster. Consequently, the absorption capability is limited. For a high volume fraction all the light will be absorbed by a top thin layer where the thermal energy is easily transferred to the surroundings [8]. Accordingly, for a 7.5 cm nanofluid column, the temperature gradient and losses from the top surface will increase with the volume fraction, while temperature at the bottom remains constant. Thus, a reduction of the average temperature of the bulk fluid with the volume fraction was found for all the range studied and, as a consequence, efficiency decreases with volume fraction.

CONCLUSIONS

An Eulerian two-phase model was developed to study nanofluids in a DAC. The enhancement in efficiency due to the use of nanofluids was demonstrated by comparison against a selective surface absorption collector, 20% enhancement was found. A strong dependency on the size of the nanofluid column and convection currents was shown. The efficiency decreased by 43% when the collector height was reduced from 7.5 to 1.0 cm. The radiative and convective losses from the DAC surfaces were increased with the nanoparticle volume fraction. For 1 cm absorber, the maximum efficiency (67%) was found at 50 ppm. The accuracy of the model was satisfactory. The most important discrepancies appeared due to the fact that the nanofluid extinction coefficient was assumed independent of the radiation wavelength. Further research should focus on the performance of the model when taking into account other effects such as agglomeration, particle size distribution or use of non-spherical particles.

ACKNOWLEDGEMENTS

This study was supported by Russian Science Foundation (project 17-79-10481).

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