Eulerian CFD Model of Direct Absorption Solar Collector with Nanofluid

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Solar energy is the most promising source of renewable energy. However, the solar energy harvesting process has relatively low efficiency, while the practical use of solar energy is challenging. Direct Absorption Solar Collectors (DASC) have been proved to be effective for a variety of applications. In this article, a numerical study of a nanofluid direct absorption solar collector was performed using CFD. A rectangular DASC with incident light on the top surface was simulated using an Eulerian-Eulerian two-phase model. The model was validated against experiments. A number of parameters such as collector height, particle concentration, and bottom surface properties were optimized. Considering particle concentration we observed that the optimum volume fraction of particles for enhancing efficiency was obtained for 0.3 wt%, and a decrease in efficiency was observed for ≥ 0.5 wt%. Design recommendations based on the numerical analysis were provided. The optimum configuration of the considered collector reaches the best efficiency of 68% for 300 μm thickness of the receiver and the highest total efficiency is 87% at a velocity of 3 cm/s. The thermal destabilization of the nanofluid was studied. It was found that over 10% of the nanoparticles are captured in the collector.

I. INTRODUCTION

Solar energy has the greatest potential among other sources of renewable energy when traditional energy sources are depleted. However, the electricity generation from solar energy is not efficient enough to replace fossil fuels and coal in northern countries, where solar resources are insufficient. In this case, the solar thermal power becomes more interesting, as over 65% of a household's electrical energy consumption is used to heat the premises. Enhancing the heat transfer process in solar energy systems is essential to achieving a better performance of these systems and reducing their dimensions. In a direct absorption solar collector (DASC), a semi-transparent heat transfer fluid absorbs the incident solar radiation volumetrically. This limits thermal leaks inherent for the traditional blackbody-based solar collectors.

Nanofluids are considered to be the most efficient heat transfer fluids for this type of collector. Otanicar et al. demonstrated four advantages of using DASCs over conventional collectors by studying how to improve the efficiency of nanofluid technology. These advantages include limiting heat losses from peak temperature, maximizing the spectral absorption of solar energy, enhancement of thermal conductivity, and enhancement of surface areas due to tiny particle sizes. They also studied a microsized DASC and observed a very promising enhancement of the collector's thermal efficiency relative to the flat-plate collector. Mirzaei et al. compared conventional flat-plate collectors and direct absorption solar collectors and observed an efficiency increase of 23.6% for nanoparticle (NP) volume fractions of 0.1%. The nanofluid used in their experiment was produced of 20-nm Al2O3 particles dispersed in water.

Recently, Neumann et al. have presented a detailed experimental description of photothermal heating of nanofluid exposed to thermal radiation. They studied several types of NPs dispersed in water and demonstrated efficient steam generation using solar illumination. The experiments were performed to study boiling by illumination and the resulting steam temperatures were over the boiling point of the base fluid. The thermodynamic analysis of the process showed that 80% of the absorbed sunlight was converted into water vapor, and only 20% of the absorbed light energy was converted into heating of the surrounding liquid. Ni et al. studied the effect of different nanofluids on the receiver efficiency by performing solar vapor generation experiments on a custom-built scale receiver. In their study, for low concentration sunlight (10 suns), the efficiency was 69%. Running a numerical analysis of the problem, better performance was found in transient situations for graphitized CB and graphene nanofluids than for CB nanofluid. Finally, the study by Ghaseemi et al. shows a solar thermal efficiency of up to 85% at low concentration sunlight.

Although there have not been many computational studies of the flow of nanofluids in DASC, a number of papers consider flow and heat transfer of nanofluids in thermal systems of other types. Yin et al. investigated the motion of aerosol NPs demonstrating that the main forces acting on the particle are the drag, Brownian and thermophoretic forces. The simulation results included the efficiency and deposition patterns at different temperature gradients. Haddad et al. observed that thermophoresis and Brownian motion enhanced heat transfer in the nanofluid. The enhancement was higher at lower volume fractions. Another study, by Burelbach et al., depicted the behavior of colloids under the impact of a thermophoretic force. They discovered that the thermophoretic force varies linearly with the temperature gradient.

A comprehensive numerical analysis of a microsized DASC with nanofluid was performed by Sharaf et al., who modelled the collector using an Eulerian-Lagrangian approach.
They discovered that the Reynolds number has a strong effect on the local NP distribution in the flow of nanofluid. Thus, theoretical results obtained are important when designing the type of solar collector because they demonstrate how the performance of the collector depends on the spatial distribution of NPs. The simulation results were in excellent agreement with the experiment. However, the collector was modeled using two dimensions using the Lagrangian approach, demanding excessive computer power for a 3D-geometry due to a large number of particles. This method, therefore, becomes hardly scaled to a DASC with dimensions of industrial relevance.

Another work by Sharaf et al. investigated the geometry of microfluid collectors. Their study indicated that lower collector tor heights give the best collector performance. Additionally, various surface materials were tested. Gorji and Ranjbar studied how to optimize the dimensions of a nanofluid-based DASC. They focused on the DASC geometry and its effect on thermal efficiency and entropy. Oppositely to Sharaf et al., one of the conclusions was that increased length and larger heights were beneficial for the desired parameters. Therefore, it may be concluded that there is no clear understanding of how the geometry of DASC influences the overall thermal performance of the collector.

A parametric analysis of a standalone nanofluid-based photothermal receiver was conducted in our previous work. The analysis was conducted using a two-fluid Eulerian-Eulerian multiphase CFD-model, which demands less computational power than the Lagrangian technique. The simulations were carried out for a three-dimensional geometry of the receiver considering how the composition of the nanofluid (consisting of water and NPs) constitutes two different interpenetrating fluids, with the molecules of the considered process, and the stabilization time, the CFD-model of a full-scale 3D DASC-NF demands large computational costs. To address this challenge, a conventional downscaling technique used previously in DASCs and other multiphase systems was applied. A quasi-3D model of the collector was built. To reproduce the optical performance of DASC-NF, we used an equivalent depth of 150 µm. In addition, the equivalent residence time and incident thermal radiation were set with the length of the numerical model equal to 5 cm. This corresponded to the respective dimension along the main flow direction in the experiments. The thickness of the collector was equal to the size of four computational cells (60 µm), and symmetry boundaries were set at the sides of the collector. The scaled model assumed minor variation of flow parameters in the direction orthogonal to the light path and the main flow, which is a reasonable assumption for a fully developed flow with adiabatic thermal boundaries at the sides. The geometry was discretized with 20-µm uniform cubical mesh.

The nanofluid was modelled using the Eulerian-Eulerian two-fluid model, which assumes that both phases (base fluid and NPs) constitute two different interpenetrating fluids, with equal pressure. In this work, we used a standard Eulerian model of the commercial CFD-software STAR-CCM+. Conservation equations were assigned separately for each of the phases. The continuity equation is:

\[
\frac{D(\alpha_i \rho_i)}{Dt} = 0, \tag{1}
\]

where \(D/\partial t\) is the substantial derivative, and \(\alpha_i, \rho_i\) and \(\mathbf{v}_i\) are the volume fraction, the density and the velocity vector of the respective phase. Each phase is denoted by \(i = p\) for the NPs and \(i = f\) for the base fluid, \(\mathbf{v}_p = 0\). The thermophysical properties of water were defined by IAWPS formulation. The molecular properties of graphite were not available in the experimental article. Therefore, for this model we used the properties of graphite available from STAR-CCM+ database. The density of the particle material \(\rho_p\) was 2210 kg/m³.

The Eulerian momentum equation is given by:

\[
\frac{D(\alpha_i \rho_i \mathbf{v}_i)}{Dt} = -\alpha_i \nabla p + \nabla \cdot (\alpha_i \mu_i \nabla \mathbf{v}_i) + \alpha_i \rho_i \mathbf{g} + \mathbf{F}_D + \delta_p \mathbf{F}_\alpha, \tag{2}
\]

where \(p\) is the static pressure, \(\mu_i\) is the dynamic viscosity, \(\mathbf{g}\) is the acceleration due to gravity and \(\delta_p\) is Kronecker delta. The volume fraction of the particles in DASC is below 1%, so that the contribution of nanoparticles to the apparent viscosity of the nanofluid is assumed negligible. This is confirmed by the rheological study by Duan et al. Thus, we assumed

II. MODEL DESCRIPTION

A. Flow geometry

The rectangular geometry modelled in this study was adapted from Otnicar et al., who constructed a micro-scale thermal-collector pumping nanofluid between two parallel plates with dimensions of 3 × 5 cm². The thickness of the gap was 150 µm. The experimental geometry is shown schematically in Fig. 1. The thermal stabilization of this systems occurs after three minutes. Considering the fine meshing that is required for a system of a micrometric depth, the multiphase nature of the considered process, and the stabilization time, the CFD-model of a full-scale 3D DASC-NF demands large computational costs. To address this challenge, a conventional downscaling technique used previously in DASCs and other multiphase systems was applied. A quasi-3D model of the collector was built. To reproduce the optical performance of DASC-NF, we used an equivalent depth of 150 µm. In addition, the equivalent residence time and incident thermal radiation were set with the length of the numerical model equal to 5 cm. This corresponded to the respective dimension along the main flow direction in the experiments. The thickness of the collector was equal to the size of four computational cells (60 µm), and symmetry boundaries were set at the sides of the collector. The scaled model assumed minor variation of flow parameters in the direction orthogonal to the light path and the main flow, which is a reasonable assumption for a fully developed flow with adiabatic thermal boundaries at the sides. The geometry was discretized with 20-µm uniform cubical mesh.
where the extinction cross-section of an individual spherical
particle was derived following Bohren and Huffman22
and further corrected with Cun-
ningham’s expression for rarefraction22:

\[
C_e = 1 + Kn(l(2.49 + 0.85e^{-1.74/Kn})),
\]

(3) where Knudsen’s number Kn=\( \lambda _n/d_p \), \( d_p=30 \text{ nm} \) is the size of the
particles and \( \lambda _n \) is the molecular mean free path in the base
fluid.

Thermophoresis in dilute suspensions is driven by hydrody-
namic stresses resulting from micro-scale interaction between
the particle and fluid10. The thermophoretic force \( F_{th} \) is computed fol-
lowing Brock’s approximation23:

\[
F_{th} = -6\pi \eta \nu \nabla C_m \cdot k_f/k_p + 2\pi \eta \nu \nabla T,
\]

(4) where \( k_i \) is the thermal conductivity of phases, \( n_i \) is the num-
ber density of the particles, \( \nu \) is the kinematic viscosity, \( C_i \) is the
thermal slip coefficient, \( C_m \) is the thermal exchange coeffi-
cient, and \( C_m \) is the momentum exchange coefficient. The
best values based on kinetic theory are \( C_i = 1.17 \), \( C_i = 2.18 \),
and \( C_m = 1.14 \)24. The thermal conductivity of the particles was
24 W/mK.

The energy equation is given by24:

\[
\frac{D}{D\tau} \left[ \sigma _p \rho _e \theta \right] = \nabla (\rho _p \nu \nabla \theta) - q_f + \alpha _p q_i,
\]

(5) where \( \epsilon _i = C_p,T_i \) is the phase-specific enthalpy, \( C_p,T = 708 \text{ kJ/kg K} \),
\( q_i \) is the volumetric heat generation due to absorption of
distant heat by the phases, and \( q_f \) is the inter-phase heat trans-
fer term. With the assumption that the convective heat transfer is esti-
ated by the phases, the inter-phase heat transfer term is computed according to Ran
d-Marshall25:

\[
\sigma _p = \sigma _f + (1 - \alpha _p) \sigma _f,
\]

(10) where \( \sigma _f \) is the extinction coefficient of the continuous phase,
which can be calculated according to Bohren and Huffman25
\( \sigma _f = 4\pi k(\lambda )/\lambda \) and \( k(\lambda ) \) is the imaginary part of the
complex refractive index of the base fluid. The optical proper-
ties of the base fluid \( k(\lambda ) \) and the particles \( m \) are found
elsewhere26,27.

In order to calculate the solar heat flux in nanofluid as a
function of distance from the exposed surface, it is necessary to
specify the spectral distribution of incident radiation \( I(\lambda ) \),
which is given in28,29.

According to Beer-Lambert’s law, the solar heat flux in
nanofluid decays as follows:

\[
q = \int \frac{I(\lambda ) \exp [-\alpha \sigma _f]}{x} dx.
\]

(11) Eq. (11) is not applicable for use in CFD simulation due to
the high computational costs associated with the integra-
tion of the function. To realize the calculation of solar heat
flux in the model, the equivalent depth of optical penetration
\( \ell _eq \) was computed for 30 nm carbon nanoparticles at differ-
ent particle concentrations. The equivalent depth of opti-
cal penetration is defined as a distance from the light entrance
to the nanofluid, towards the place at which the total heat flux
becomes \( e \) times smaller. Thus, the equivalent depth of opti-
cal penetration is computed when the numerically-solved Eq.
(11) becomes equivalent to \( q_{\text{eff}}^{-1} \). The reciprocal of the equivalent extinction coefficient, \( \tau = \frac{1}{q_{\text{eff}}^{-1}} \), is considered as the solar heat flux penetrating the nanofluid down to the bottom of the collector and further absorbed by the bottom.

Eqs. (1-5) were solved using the commercial CFD package STAR-CCM+ 13.06.012, running in parallel on eight cores of 2.5 GHz. The numerical solution was obtained using an implicit SIMPLE technique, and the following relaxation coefficients were applied: 0.3 for pressure, 0.7 for velocity, 0.5 for phase volume fraction, 0.9 for the enthalpy, and 0.8 for the turbulence model (see section III.D). The governing equations were discretized temporally with the second-order Euler technique matching by 1.0 ms. The upwind scheme was applied for spatial discretization. Each simulation point was run for two-three periods of the system’s thermal relaxation time until the residuals reduced below \( 10^{-6} \) and the system pressure drop converged at a steady-state value.

III. RESULTS AND DISCUSSION

A. Model validation

The model was validated against the experimental results from Otanicar et al.\(^3\). The model-predicted thermal efficiency of the collector was compared to the respective parameter determined experimentally. Following ASHRAE standard\(^3\), this parameter is defined as a ratio of the collector-harvested heat to the incident heat. In this study, the harvested heat is defined according to Sharaf et al.\(^11\) as the spatially-averaged rate of the enthalpy difference between the open ends of the collector:

\[
\eta_f = \frac{\int_{0}^{H} \left( \frac{\sum_{i} C_{nf,i} \rho_{nf,i} \frac{\partial T}{\partial y} - \frac{\sum_{i} C_{nf,i} \rho_{nf,i} T_{nf,i}}{\rho_{nf,i}} \right) dy}{q_{0} \cdot H},
\]

where \( H \) is the thickness of the collector in the direction normal to flow and solar radiation: \( C_{nf} = \alpha_{nf} C_{nf}^{\rho_{nf}} + \alpha_{nf}^{\rho_{nf}} \) and \( \rho_{nf} = \alpha_{nf} \rho_{n} + \alpha_{pf} \rho_{f} \) are the equivalent specific heat and the density of the nanofluid, and indices \( n \) and \( i \) denote inlet and outlet boundaries. The proposed method accounts for the spatial variation of the main flow parameters.

It is important to note that another expression for the harvested heat was used in the original work by Otanicar et al.\(^3\): \( m C_{nf} (T_{nf} - T_{nf,i}) \), where \( m \) is the mass flow rate. In the case of the constant volumetric flow rate at the inlet, the latter parameter was dependent on the reference temperature of DASC, which might differ between the model and the experiment.

Validating our model in Fig. 3, we note a qualitatively similar evolution of the thermal efficiency at different particle concentrations. The DASC does not entirely absorb the radiant heat at a dilute particle concentration so that the efficiency is low there. Furthermore, when increasing the number of nanoparticles the efficiency goes up to 62% at 0.3 wt%. For even higher NP concentration, most of the radiant heat absorbed at the top surface of the collector, increasing the temperature of the top boundary. This enhances the thermal leak to the surroundings and the thermal efficiency of the collector
Sample title in the determination of thermal leaks. Analyzing the infrared images of the experimental system (Fig. 1 of the original article), we detect a very non-uniform temperature field in the most remote corners of the collector. Most probably, this is associated with the not entirely developed flow field, particles deposition, and the resulting local thermal leaks. These details are not reproduced in the model using the symmetry assumption, so that the experimental efficiency is expected to be lower than the theoretical. In addition, we note that the model does not account for particle-wall collisions and thus the near-wall absorption is higher. This increases the thermal leaks. The unknown reference temperature, the approximated extinction coefficient (Eq. 12), and a potential agglomeration of nanoparticles in liquid contribute to the discrepancy.

B. Flow asymmetry

To highlight the development of flow patterns in the collector, Fig. 4a demonstrates profiles of the nanoparticle concentration at different axial positions of the collector. According to the figure nanoparticles are not uniformly distributed over the cross-section; the profiles are asymmetrical. This is explained by the mutual action of gravity and thermophoresis, drifting the particles towards the bottom boundary. The asymmetry increases closer to the outlet from the collector. The deposition of particles influences the optical properties of the nanofluid. Our model results are shown in Fig. 4b confirm that simulations by [11], who first demonstrated a reduction of the extinction coefficient at the surfaces of the collector.

To highlight the development of flow patterns in the collector, Fig. 5 shows the particulate phase velocity and the temperature distribution in transverse cross-sections at 1 cm, 2 cm, 3 cm, 4 cm from the inlet. In the figure, it is possible to note the development of convective flow patterns from the top of the collector at 2 cm and further from the bottom at 3 cm. The maximum magnitude of the secondary flow is below 7% of the main flow velocity. This means the secondary flow plays a minor role in transport of particles. The upper vortex is formed under the influence of the thermophoresis of particles, and the Rayleigh-Taylor structure at the bottom is caused by the sedimentation of particles and the respective up-rise of the base fluid. The distribution of temperature is very uniform in these cross-sections, even though it is possible to observe a gradual reduction of the temperature gradient due to the hanced mixing of the flow. The insert at the bottom of the figure presents the axial distribution of the temperature profile. We notice that the temperature gradually increases in the axial direction until the profile stabilizes at 1.3 cm from the inlet.

In order to investigate how the nanoparticles deposit in the solar collector, we considered another parameter, termed the deposition efficiency, which is given as:

$$\eta_{dep} = \frac{\alpha_{p, in} - \alpha_{p, out}}{\alpha_{p, in}} \times 100\%,$$

where $\alpha_{p, in}$ and $\alpha_{p, out}$ are the volume fraction of particles at inlet and outlet, respectively.

Fig. 6a shows the results from these simulations for different collector sizes and types of boundary conditions. As the figure shows, the greatest deposition efficiency was 11% for the lowest size of the gap. Furthermore, increasing the size reduces the deposition efficiency. This is explained by the destabilizing action of the thermophoretic force, which deposits more particles in a narrow gap, while the disperse action of drag becomes stronger for a wider collector. Moreover, the temperature decreases with the height of the collector, weakening the thermophoresis. For the model with a black absorptive bottom surface, the deposition efficiency is higher. Fig. 6b shows that the deposition efficiency reduces asymptotically to 0.8% with the mean flow velocity, due to better agitation of the dispersed phase.

C. Parametric analysis

The height of the solar collector has a vital influence on the amount of heat absorbed and transferred by the nanofluid. There is an optimum height/length ratio associated with the best thermal performance of the collector [13]. The results of the model-based optimization are presented in Fig. 7, where the thermal efficiency and the outlet temperature are shown for different heights of the collector and types of the bottom boundary. As the figure shows, by increasing the thickness of the collector less heat is taken by the nanofluid flow and the outlet temperature decreases. The outlet temperature decreases almost linearly with the collector height. This limits the thermal losses and the collector efficiency increases. The observed dependence of the thermal efficiency on the height of the volumetric receiver is consistent with the results obtained by [15]. However, at a thickness of 300 µm, the efficiency begins to reduce as the volumetric absorption is no longer active across the entire volume of nanofluid. The consumed heat, therefore, is transferred to internal fluid layers with the incipient volumetric absorption, which reduces the thermal efficiency.

Fig. 7 shows that for collector heights lower than 200 µm, the efficiency is higher for the model with the black absorbing bottom plate. In this case, a warmer bottom surface returns absorbed heat back into the process, boosts the thermal efficiency, and increases the outlet temperature. At the point of maximum difference, the efficiency is 12% higher for the black bottom plate, than for the transmissive adiabatic plate. This occurs at the lowest collector height tested, 50 µm. For collector heights above 200 µm, the thermal efficiency decays towards the values for the case with the adiabatic bottom. This can be explained by the fact that on increasing the gap, the nanofluid consumes most of the thermal radiation in the bulk and the bottom does not receive sufficient heat.
turbulence that occurs when the flow boosted the thermal efficiency. We reproduced this experiment numerically for the case where only the continuous phase (water) was present in the collector. In addition, we performed another simulation, where the perfect absorption was assumed at the top boundary so that the heat flux equivalent to \( q_0 \) was prescribed there. The volumetric absorption results were obtained from the model with a volume fraction of particles at 0.3 wt\% and a collector height of 300 \( \mu \)m. The results of the CFD-analysis demonstrate asymmetry in the particulate phase concentration profile and the respective non-uniformity of the optical properties of the nanofluid. The deposition of the particles takes place in the collector so that a maximum 10\% of the particles are captured in the DASC.

The model-based optimization resulted in 0.3 wt\% optimum concentration of 30-nm nanoparticles and 300 \( \mu \)m thickness of the collector. The nanofluid velocity through the collector also has a significant impact on thermal efficiency. The maximum total efficiency of 87\% is obtained when the flow velocity is 3 cm/s and decreases with higher velocities. The deposition efficiency and outlet temperature decrease for higher velocities.

The effect of the absorbing bottom surface of the collector was tested. The collector with a black bottom containing only water proved to be less effective than the collector with the volumetric absorption of the nanofluid. A top surface black absorber was also tested and was not shown to be efficient. However, the light-absorbing bottom boundary, when used together with the nanofluid, improves the thermal performance of the collector by a maximum of 12\% for the cases when the channel size is under the optimum.

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The model was validated against the experimental data and furthermore used for the parametric optimization of the collector. The parameters considered were the concentration of the nanoparticles, the geometry of the collector, the flow rate and the absorptive properties of the boundaries.

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FIG. 1. Schematic description of the model and the experiment.

FIG. 2. Equivalent extinction coefficient as a function of particle concentration.
FIG. 3. Thermal efficiency as a function of particle concentration.

FIG. 4. a) Transverse distribution of particle concentration, scaled by the inlet value and b) the nanofluid extinction coefficient at different axial coordinates of the collector.
FIG. 5. Contours of the fluid phase temperature together with the particle velocity vectors in the orthogonal cross sections at 1 cm, 2 cm, 3 cm, 4 cm from the inlet. The insert at the bottom presents the axial distribution of temperature in DASC. The particle concentration is 0.5%.

FIG. 6. Deposition efficiency as a function of a) collector height and b) inlet velocity.
FIG. 7. Thermal efficiency and outlet temperature as a function of collector height for different types of boundary conditions at 0.3 wt% NPs and 0.26 cm/s fluid velocity.

FIG. 8. Thermal efficiency for different types of boundary conditions.
FIG. 9. Total efficiency and pressure loss as a function of nanofluid velocity.