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Address of the editorial office
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CONTENT

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NUMERICAL MODELING OF FLAT PLATE SOLAR COLLECTORS WITH A CFD APPROACH

MARIJA CHEKEROVSKA[1], RISTO FILKOSKI[2], TODOR CHEKEROVSKI[3], SARA SREBRENKOSKA[1]

[1]University “Goce Delcev”, Faculty of Mechanical Engineering, Stip, R. Macedonia
marija.cekerovska@ugd.edu.mk
sara.srebrenkoska@ugd.edu.mk
[2] University "Ss Cyril and Methodius, Faculty of Mechanical Engineering, Skopje, R. Macedonia;
risto.filkoski@mf.edu.mk
[3]University “Goce Delcev”, Faculty of Electrical Engineering, Stip, R. Macedonia
todor.cekerovski@ugd.edu.mk

Abstract. The objective of the present paper is to conduct an analysis of the solar collectors’ operation. The study includes the development of a 3-D mathematical model of the collectors' system and extensive numerical simulation, based on the computational fluid dynamics (CFD) approach. The main aim is to form a mathematical model that reflects the operation of the flat solar collector under changing conditions to determine the speed of flow of the working fluid, temperature distribution and the parameters that characterize the intensity of heat transfer, within any cross section at any given time. The analysis shows that the presented modelling approach can be used for further investigations,

Keywords: numerical modelling, computational fluid dynamics (CFD), solar collector, heat transfer.

1. **Introduction**

The focus of the research are the devices for transformation of solar energy into heat. The two main components of the solar energy collector system, which are required in order to have a functional solar energy heat generator, are a collector and a storage unit, the latter needed due to the solar energy non-constant nature. A typical flat-plate solar collector consists of an absorber in an insulated box, including a pipeline system filled with working fluid, transparent cover sheets (glazing) and other components. The absorber is usually made of a metal sheet of high thermal conductivity, such as copper or aluminum, with integrated or attached tubes. Its surface is coated with a special selective material to maximize radiant energy absorption, while minimizing emission. The insulated box reduces heat losses from the back and sides of the collector. The cover sheets allow sunlight to pass through to the absorber, but insulate the space above the absorber to prevent cool air from flowing into this space.

A comprehensive literature review on different modelling approaches of solar collector systems is given in [1]. In addition, a one-dimensional mathematical model for simulating the transient processes that occur in liquid flat-plate solar collectors is proposed in the same work [1]. The model considers time-dependent thermo-physical properties and heat transfer coefficients and it is based on solving energy conservation equations for the glass cover, air gap between the cover and the absorber, absorber, working fluid, insulation, and storage tank.

Wang and Wu [2] proposed a discrete numerical model to calculate the flow and temperature distribution to analyze the performance of a flat-plate solar collector with Z-arranged collector arrays, in which the flows are parallel in the dividing and combining manifolds.

A 3-D numerical model for a flat-plate solar collector that considers the multidimensional and transient character of the problem is presented in [3]. The effect of the non-uniform flow on the collector efficiency was quantified and the degree of deterioration of the collector efficiency was defined. Their analysis showed that this deterioration increases with the increase of the flow non-uniformity, although this effect is very limited. The model was verified under steady-state conditions. Their results show that the collector efficiency does not change appreciably even when the flow at the outer risers is 1.5 times the flow of the central one but the outlet temperatures for each tube are very dissimilar.

The model developed in [4], which is an extension of the Duffie and Beckman's model [5], is verified by an experiment data conducted on single and double glazed collectors under steady-state conditions.

A one-dimensional mathematical model for simulating the transient processes that occur in liquid flat-plate solar collectors is presented in [6, 7]. The model considers time-dependent conditions, meaning that the properties of the working fluid, air gap and absorber are computed in real time, the heat transfer coefficients are also computed in the on-line mode and time-dependent boundary conditions are considered.

The problem of a flat-plate solar energy collector with water flow is simulated and analyzed using CFD technique in [8]. The considered case includes CFD modelling of solar irradiation, modes of mixed convection and radiation heat transfer between the tubes' surfaces, glass cover, sidewalls and insulating base of the collector. It also covers the mixed convection in the circulating water inside the tube and conduction between the base and the tube material.

The main objectives of the research are to derive a mathematical model that portrays the operation of a flat plate solar collector under transient conditions and to calculate the flow and temperature distribution for any cross-section at any certain time. Furthermore, one of the aims of this paper is to demonstrate the potential of the use of CFD simulations, in order to obtain a more detailed insight into the flow and transport processes in facilities for solar energy utilization.

2. Numerical research

2.1 Object geometry and numerical mesh

The flat-plate solar collector geometry considers the transient properties of its different zones. The numerical domain for the mathematical model comprises all functionally important parts of the collector, presented with their real geometry: manifolds (distributing and combining), vertical pipes, working fluid, transparent (glass) cover, absorber plate, air region and thermal insulation. The back and sides metal cover is also included in the model.

The geometry was created using Gambit pre-processor. The basic geometry of the collector pipe system used in the research, with the main dimensions, the outline of the computational domain and the mesh generated for calculations, are presented in Figures 1 and 2. The numerical grid consists of 791033 volume cells and 171743 computational nodes. The grid independence was tested and verified using three different grids in order to ensure that the grid resolution would not have a notable impact on the results: (1) 632800 volume cells, (2) 791033 volume cells, (with 171743 nodes) and (3) 949300 volume cells. Since the grid refinement changed the results by less than 0.5 %, it was concluded that the influence of eventual further refinement would be negligible and, therefore, the mesh No. 2 was taken as appropriate for computation.

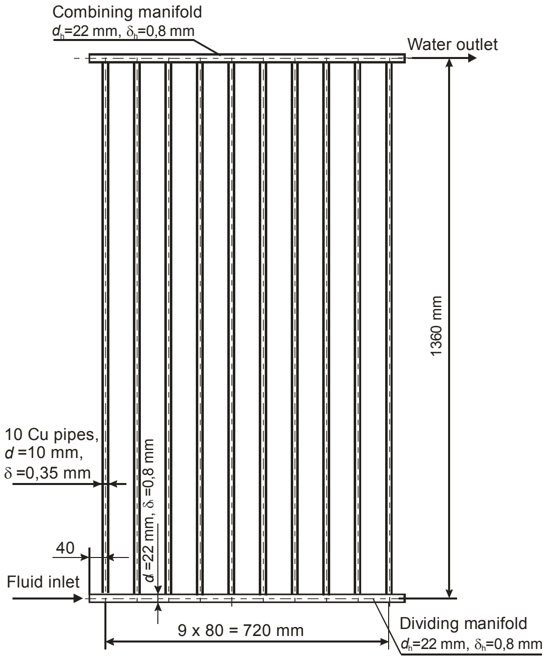

Figure 1. *The collector pipeline system geometry*

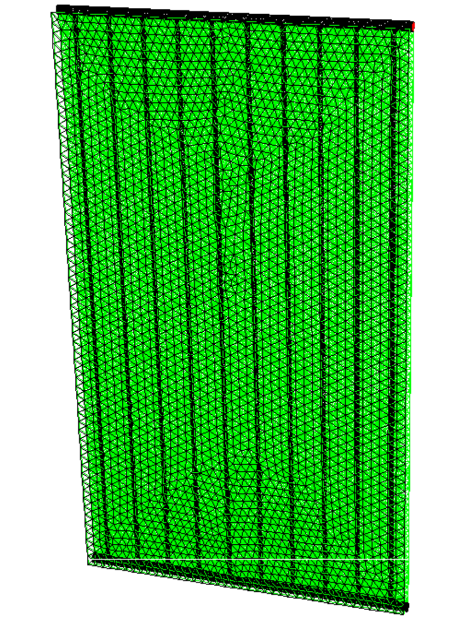

Figure 2. *Numerical mesh*

2.2 Numerical model set-up and simulations

The working fluid in the collector, which is in the present study water / propylene glycol 50:50 % mixture, can be considered as a continuous incompressible medium. The flow in the collector is steady and it possesses laminar flow characteristics, as the fluid flow velocity through the manifolds and vertical pipes is low.

A comprehensive modelling of a flat plate solar collector should consider heat transfer in fluid and solid regions, as well as in solar radiation to semi-transparent and other surfaces. Although the heat transfer mechanism related with a flat-plate solar collector system seems quite common at first sight, in a real situation it is not always that simple. Due to the nature of the solar energy, the working conditions of the solar collector regarding heat transfer and fluid flow are unavoidably transient and non-uniform. Therefore, for a detailed analysis, it is necessary to set-up a three-dimensional model, which considers these aspects (time-dependent change of variables) and includes conservation equations for mass, momentum and energy, solar ray tracing and thermal radiation modelling.

The considered case includes CFD modelling of solar irradiation, modes of mixed convection and radiation heat transfer between the tubes' surfaces, glass cover, absorber and sidewalls of the collector. It also covers mixed convection in the circulating water/propylene glycol mixture inside the tubes and conduction between the absorber plate, the tubes material, the insulation region and the collector cover.

The energy equation is used in the following Cartesian tensor notation form

$$\frac{\partial}{\partial x_j}\left(\rho u_i T\right)=\frac{\partial}{\partial x_j}\left(\frac{\mu}{\Pr}\frac{\partial T}{\partial x_j}-\rho\overline{u_i T}\right)+S_h \qquad (2.1)$$

where x is linear coordinate, ρ denotes fluid density, u is fluid velocity, T is absolute temperature, μ is fluid dynamic viscosity, thermal conductivity, Pr is Prandtl number, and the term S_h includes any volumetric heat sources.

The numerical simulations were carried out using steady state implicit pressure based solver [9]. The governing partial differential equations for mass and momentum are solved for the steady incompressible flow. The velocity-pressure coupling has been effected through the SIMPLEC algorithm. Second order upwind scheme was chosen for the solution scheme. Laminar flow conditions are used as most appropriate in the numerical model.

2.3 Energy transfer modelling

In the present study, it was decided to correlate the experimental results with a mathematical model that incorporates the Discrete Ordinates (DO) radiation method, due to the opportunity of applying a solar load directly to the DO model [10]. The DO radiation method considers the radiate transfer equation (RTE) in the direction **s** as a field equation:

$$\frac{dI(\mathbf{r},\mathbf{s})}{ds}+(a+s_s)I(\mathbf{r},\mathbf{s})=an^2\frac{\sigma_0 T^4}{\pi}+\frac{\sigma_s}{4\pi}\int_0^{4\pi} I(\mathbf{r},\mathbf{s}')\Phi(\mathbf{s}\cdot\mathbf{s}')d\omega' \tag{2.2}$$

where: $I_l(\mathbf{r},\mathbf{s})$ [W/m^{2}srad] is the spectral intensity, λ is the wavelength, a [m^{-1}] is the spectral absorption coefficient, **r** [-] is the location vector, **s** [-] is the direction vector (defined as **s**= $\mu\vec{i}+\eta\vec{j}+\xi\vec{k}$), **s**' [-] is the vector of scattering direction, σ_s [m^{-1}] is the scattering coefficient at wavelength λ, σ_0 [W/m^{2}K^4] is the Stefan-Boltzmann constant, σ_0=5,672·10^{-8} W/m^{2}K^4, ω' [-] is the solid angle, Φ is the phase function, which represents the probability that a ray with frequency v' from the direction **s** in a finite discrete solid angle $d\omega$' will veer in the direction **s**' inside the angle $d\omega$, with frequency v.

The DO radiation model solves the RTE for a finite number of discrete solid angles, each associated with a vector direction **s**, fixed in the Cartesian system. The fineness of the angular discretization can be changed accordingly and the DO model solves as many transport equations as there are directions **s**. In this case, the so-called S6 approximation was applied, corresponding to 48 flux approximations. This approach gives sufficiently reasonable results for the amount of the numerical work. The higher-order approximations, such as the S8, with 80 flux approximations, require considerably more numerical effort.

2.4 Boundary conditions and working parameters

In the model developed with the software package Fluent CFD, taking into account the physicality of the problem, appropriate boundary conditions are applied on the borders of the numerical domain. The glass plate of the solar collector, which has a direct and substantial influence on the energy transfer by radiation, is simulated as a transparent wall.

Permeability, regarding the radiation, is defined by the coefficients of absorption and transmission of the material - glass. The boundary of the metal casing of the collector is set as wall, with defined conditions for heat transfer that includes convection and radiation transfer to the environment. At the inlet pipe connection in the collector "velocity inlet" condition is set, and at the outlet "outflow" condition is set.

The values of the properties of the collector materials for the CFD analysis purposes are presented in Tab. 1. Polynomial interpolation formulae are used in the calculations for the thermo-physical properties of the water/propylene glycol mixture and for the air, given in Tables 2 and 3.

Table 1. *Properties of the materials used in the experimental research*

Property, unit	Absorber plate, Al	Water pipes, Cu	Insulation (mineral wool)	Transparent cover (glass)
Density, kg/m^3	2720	8800	60-200	2230
Specific heat capacity, J/kgK	875	4200	1000	750
Thermal conductivity, W/mK	210	380	0.04 (at 20°C)	1.05
Transmissivity	0	0	0	0.84
Emissivity (IR emittance)	0.95	0.95	-	0.1
Solar absorbtance	0.9	0.9	-	

Table 2. *Properties of the water/propylene glycol mixture (T in K)*

Density, kg/m^3	$\rho = 978.2 + 0.973T - 0.003T^2 + 1.0{\cdot}10^{-6}T^3$
Dynamic viscosity, kg/ms	$\mu = 1.4274 - 0.016{\cdot}T + 7{\cdot}10^{-5}T^2 - 1{\cdot}10^{-7}T^3 + 9{\cdot}10^{-11}T^4$
Specific heat capacity, J/kgK	$c_p = 3901 - 2.674T + 0.0058T^2 + 5{\cdot}10^{-8}T^3$
Thermal conductivity, W/mK	$\lambda = 0.2674 - 0.0002T$

Table 3. *Properties of the air (T in K)*

Density, kg/m^3	$\rho = 2.829 - 0.0084T + 0{,}00001T^2 - 5{\cdot}10^{-9}T^3$
Dynamic viscosity, kg/ms	$\mu = 5{\cdot}10^{-8} + 4{\cdot}10^{-10}T$
Specific heat capacity, J/kgK	$c_p = 1014.7 - 0.0005T + 0.0001T^2$
Thermal conductivity, W/mK	$\lambda = 0.0228 + 8{\cdot}10^{-5}T$

3. **Results and discussion**

According to the CFD model and the conducted numerical simulation, the change of the temperature coefficient of the working fluid at a flow rate of 0,01 m/s is presented in Figure 3, where the dimensionless tube length of the collector is defined as the ratio between the distance from the beginning of the tube to the specific (measured and / or modeling) point and the length of the tube. The temperature difference between the absorber and the working fluid decreases along the relative length of the pipe system.

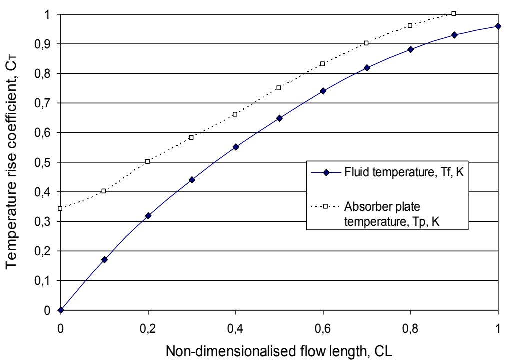

Figure 3. *Change of the temperature coefficient of the absorber and the fluid*

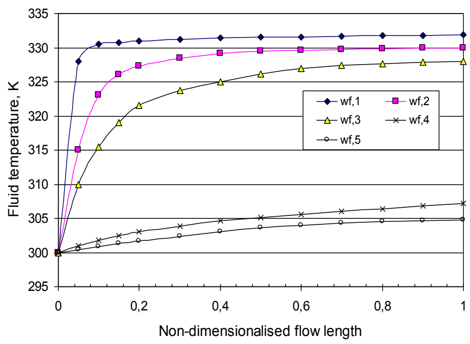

Figure 4. *Change of the fluid temperature at different fluid velocities*

The change in temperature of the working fluid with the change of fluid velocity in proper working condition, according to the conducted CFD simulations, are shown in Figure 4. The values of the fluid velocity on this diagram are: $w_{f,1} = 0.0001$ m/s, $w_{f,2} = 0.0005$ m/s, $w_{f,3} = 0{,}001$ m/s, $w_{f,4} = 0{,}005$ m/s, $w_{f,5} = 0{,}01$ m/s, and from this it can be concluded that the heating of the working fluid in the pipes is followed by a large increase in temperature at low flow rates of the fluid (consequently, lower speed). The rise in temperature is lower at a higher value of the flow of the working fluid. The system is characterized by almost constant heat transfer when the temperatures of the absorber and the working fluid are approaching.

The fluid temperature change in the dividing and collecting manifolds is presented in Figure 5.

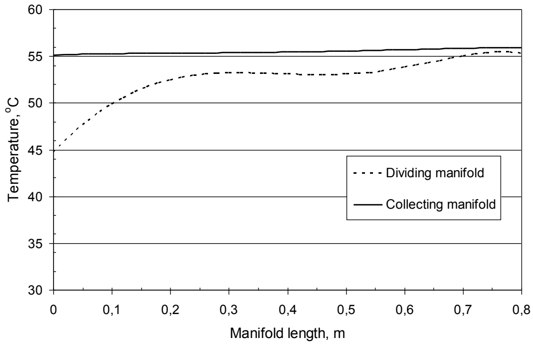

Figure 5. *The change of the fluid temperature in the dividing and collecting manifolds*

Fig. 6 presents the temperature profile in three intersections along the collector height, and Fig. 7 shows velocity vectors at the bottom of the collector pipe system.

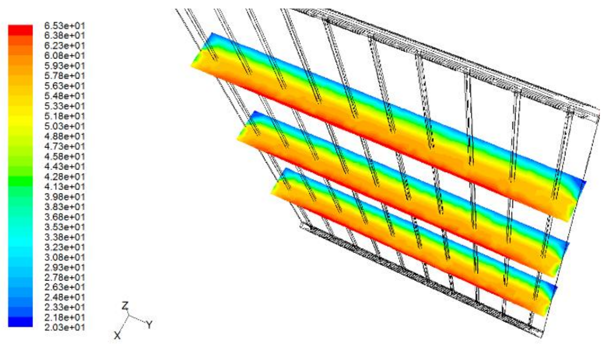

Figure 6. *Temperature profiles in three intersections*

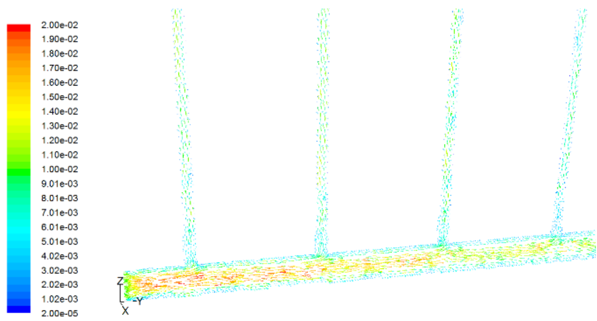

Figure 7. *Velocity vectors at the bottom of the collector pipe system (dividing manifold)*

In this work the potential of the use of modelling and numerical simulation using the CFD technique was demonstrated, in order to gain a detailed insight into the processes in solar collectors. Given that the work establishes a model of a solar collector using CFD technology, the verified mathematical model can be applied for further research in order to gain a detailed insight into the thermal and fluid flow processes in thermal devices and plants, including other solar collectors' types and designs. The model will be a useful tool for improving the technical characteristics of the flat solar collectors and for comparative analysis of different collectors configurations and technical solutions. The proposed CFD strategy can be used as a partial replacement for the installation and performance of expensive experiments for estimating the performance and energy losses of other thermal appliances.

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