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Performance and Design Optimization of Solar Collectors

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Abstract: The objective of the present work was to conduct a comparative analysis of solar collectors. The experimental set-up consists of two flat plate solar collectors, the first collector was with a fixed surface tilted at 30o towards the South, and the second one was equipped with dual-axis rotation system. A programmable chronological tracker was used to control the motion of the moving collector. An experimental programme was performed to investigate the effect of the sun tracking system usage on the collector efficiency. The study includes development of a 3-D mathematical model of the system and extensive numerical simulation, based on the computational fluid dynamics (CFD) approach. The main aim of the modelling is to provide information on heat transfer, and to numerically simulate the heat transfer performances and the energy capture capabilities of the fixed and moving collectors in various operating modes. The comparative analysis shows that there is a good agreement between the experimental and numerically predicted results for different running conditions, and the presented modelling approach can be used for further investigations, including more complex problems.

Keywords: Solar collector, Solar energy, Heat transfer

Introduction

One of the simplest and most direct applications of the solar energy, which is cost effective, is its conversion into heat. It is also one of the ways the residential and other sectors can lessen their share in electricity consumption and impact on the environment. The cost effectiveness of solar thermal collectors depends on the cost of collector components, the efficiency and the thermal losses associated with the collector at the local operating conditions. Flat plate solar water heaters are traditionally in use in domestic hot water systems because of the low temperature requirement and low equipment cost (Sumathy, 1999). Conventional solar water heater systems and solar assisted heat pump systems for hot water production in specific local conditions are presented in (Li & Yang, 2009).

A 3-D numerical model for flat-plate solar collector that considers the multidimensional and transient character of the problem, the effect of the non-uniform flow on the collector efficiency was quantified and the degree of deterioration of collector efficiency was defined by Molero - Villar et al.(2009). 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 with a steady-state conditions.

- Selection and peer-review under responsibility of the Organizing Committee of the Conference

The model in time-dependent conditions, 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 experimental verification showed a satisfactory convergence of the measured and calculated fluid temperatures at the collector outlet. This study relay heavily on the model developed by (Zima & Dziewa (2011). Yanjuan et al. (2015) presented numerical simulation method to solve the complex problem coupled with fluid flow, heat transfer and thermal stress in their system. The effects of the key operating parameters on the performances of the receiver are numerically investigated. Ramaswamy et al. (2020) worked on thermal and CFD analysis with different fluid air, water and different solar collector's i.e flat plate and parabolic trough was modeled by using CATIA design software. Thermal analysis were done with solar collectors with aluminum & copper).

Methodology of the Research

Experimental Research

The experimental set-up considered in this study was located in the town of Shtip, latitude 41^{o} 45' and longitude 22^{o} 12', (Figure 1). The system, consists of: moving collector equipped with a two-axis tracking device (a programmable chronological tracker is used to control the motion of the moving collector), static collector, horizontal water tank, circulating pumps, non-return valves, flow-meters, three-way valves, expansion vessel, manometers, air-vent devices, pressure-relief valves, drain valves, cold water entrance, automatics, temperature sensors, solar irradiation (heat flux) sensor etc.

Figure 1. Experimental set-up and a segment of the tracking system: electric drive (a), gear spindle (b), auxiliary mechanism (c)

a) b)

Figure 2. Installation of the a) movable collector and b) static collector

The main components of the experimental set-up enabling one of the collectors to move arround two axes of rotation can be seen in Figure 1. The main technical parameters of the flat solar collector is shown in Table 1. The collector consists of a transparent cover, absorber (absorber plate which absorbs heat), insulation (to protect against loss of heat), 10 copper pipes placed in pipe register with U-body construction and the collector body. The system is filled with working fluid which is a mixture of water and propylene glycol (in 50: 50% ratio), whose flow in the system is controlled by a differential thermostat. The differential thermostat has a direct communication with the pump, providing information and whether to switch-on or switch-off.

In this system there are two flow circles, one for the static and one for the movable collector, each one equipped with its own pump. Two circles are equipped with adequate equipment, shown in Figures 2, which includes a pipe line with appropriate fittings, valves - irreversible, spherical, valve for air relief, valves for filling and drenage, as well as flow-meters for hot water. The system has been equipped with an expansive vessel, safety valve and pressure gauge.

Table 1. Main technical parameters of the solar collector

Description	**Specification**
Collector annotation	Еко Mag 2
Collector body	Aluminum
Dimensions, in mm	1500 x 970 x 81
Fluid content (water and propylene glycol)	1.76 liters
Vertical pipes: number, material, dimensions	10, Cu, 10.0/0.35 mm/mm
Manifolds (headers): number, material, dimensions	2, Cu, 22.0/0.8 mm/mm
Absorber plate	Aluminum, selective colour
Thermal insulation	Mineral wool, 50 mm
Transparent (glass) cover	Polycarbonate glass, 4 mm
Maximum temperature	165 ^{o}C
Weight	18 kg

For getting information from the collectors automatics UVR 61-3 was used, whose role is control of the system operation, as well as data storage. The installation contains temperature sensors at the movable and static collectors, at the cold water inlet in the tank, at the hot water tank, radiation sensor and water flow-meters. Appropriate information about the measured values of the sensors and pump work during the day are displayed on computer using the device D-LOGusb using the appropriate programs Winsol and Memory Manager. With the use of these programmes the data are continuously stored and can be displayed in tabular and graphical Excel.

Numerical Model Set-Up and Simulations

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 3) and (Figure 4). 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 %, which was previously decided as criteria, 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.

The numerical simulations were carried out using steady state implicit pressure based solver. 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. The turbulence is covered with the RNG k-ε model and standard wall functions for the near-wall treatment. 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 side walls 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.

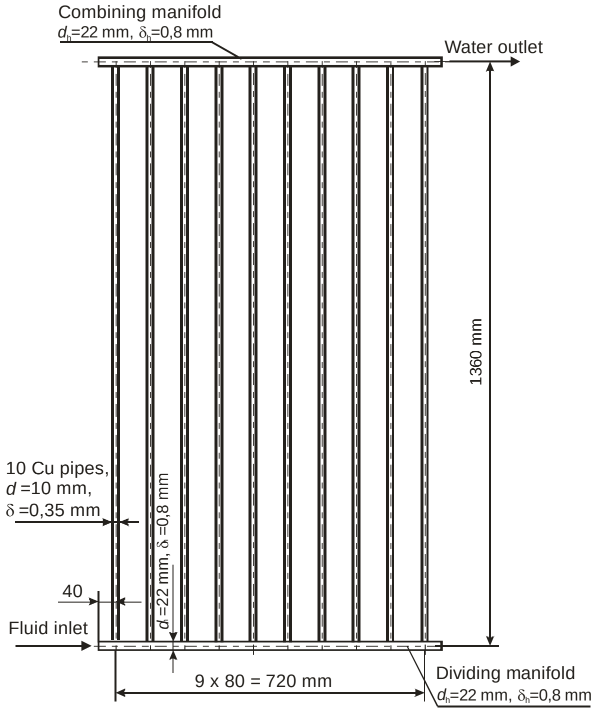

Figure 3. The collector pipeline system geometry

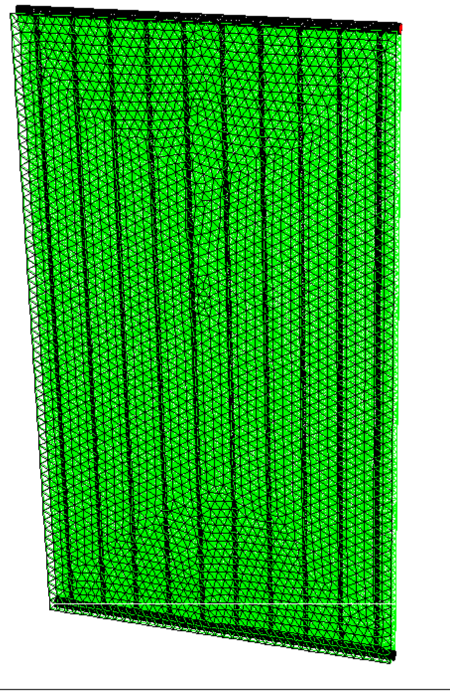

Figure 4. Numerical mesh

The selection of the most appropriate thermal radiation model in certain conditions depends on various factors, and in the case of solar collector modelling it becomes even more complex due to the necessity to include solar load model. The Discrete Transfer Radiation Model (DTRM) has been already proved as an efficient radiant transfer method in solar energy collector applications. 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 (Saha & Mahanta, 2001). The DO radiation method considers the radiate transfer equation (RTE) in the direction **s** as a field equation:

$$\frac{dI(\mathbf{r},\mathbf{s})}{ds}+(a+s_s)I(\mathbf{r},\mathbf{s})=an^2\frac{\sigma_0 T^4}{\pi}+\frac{\sigma_s}{4\pi}\int_0^{4\pi} I(\mathbf{r},\mathbf{s}')\Phi(\mathbf{s}\cdot\mathbf{s}')d\omega' \tag{1}$$

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.

Results and Discussion

According to the CFD model and conducted numerical simulation, the fluid temperature change in the dividing and collecting manifolds, is presented in Figure 5. The change of the temperature of the working fluid versus the fluid velocity (wf,i) in proper working condition, according to the conducted CFD simulations are shown in (Figure 6). The values of the fluid velocity at this diagram are: wf,1 = 0.0001 m/s, wf,2 = 0.0005 m/s, wf,3 = 0,001 m/s, wf,4 = 0,005 m/s, wf,5 = 0,01 m/s. Temperature profiles of the air gap in three horizontal intersections along the collector height are shown in (Figure 7). The working fluid velocity vectors in the lower left part of the collector’s pipe system is shown in (Figure 8).

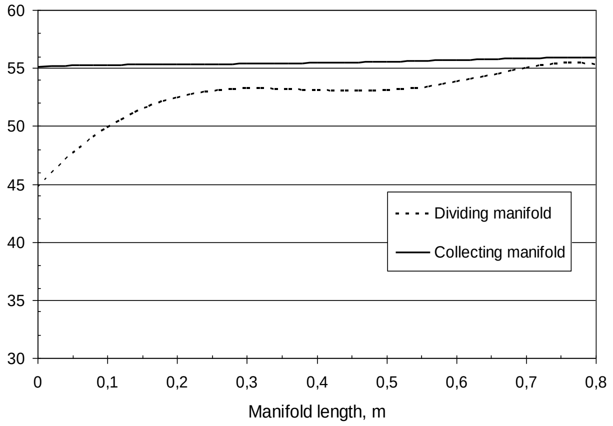

Figure 5. The change of the fluid temperature in the dividing and collecting manifolds

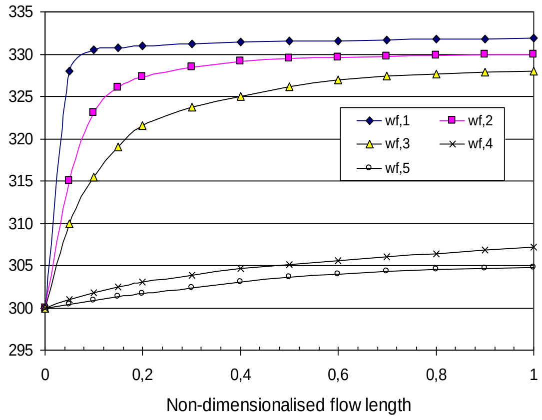

Figure 6. Change of the fluid temperature at different fluid velocities

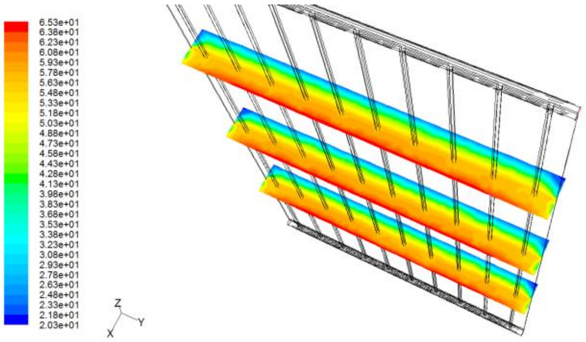

Figure 7. Temperature profiles in three intersections

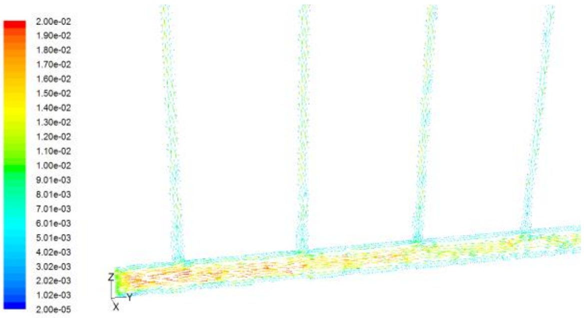

Figure 8. Velocity vectors at the bottom of the collector pipe system (dividing manifold)

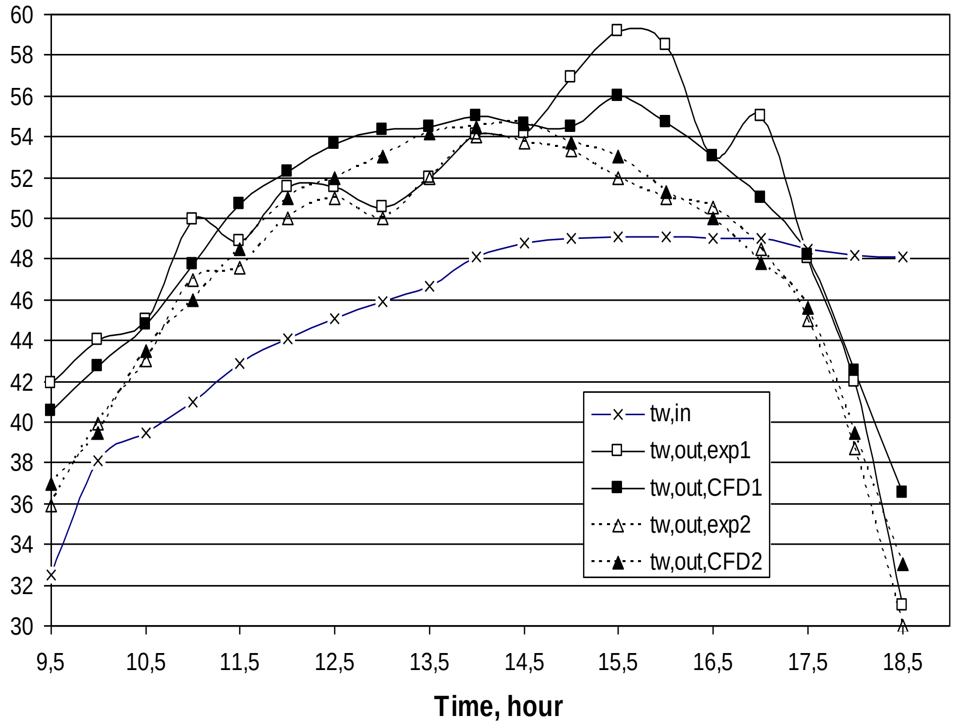

Figure 9. Working fluid temperature change, a comparison between the experimental and CFD results: 1 – experimental and CFD results, moving collector; 2 - experimental and CFD results, static collector

In order to draw up conclusions a comparison between the experimental and numerical simulation results has to be done. To accomplish this, while keeping other collector parameters fixed, the solar radiation flux for the simulation module is varied. An example of a comparison chart is shown in (Figure 9), indicating the measured and simulated outlet temperatures of the working fluid (propylene glycol/water mixture) versus time.

Conclusion

An experimental and CFD research has been conducted with the aim to assess the operation and to enhance the efficiency of a passive flat plate solar collector, by use of a controlled tracking system that could be easily applied in a typical (conventional) collector, without changing its shape. The efficiency of the proposed method was confirmed by experimental verification, showing significant increase, compared to the immobile collector unit. In order to provide a complete analysis in different operating conditions, a comprehensive CFD modelling and simulation is undertaken.

The analysis shows that there is a good agreement between the experimental and numerically predicted values for different running conditions and flow rates. In the present case, the outlet fluid temperature is the main parameter for comparison. It can be noticed that the CFD model results are much closer to the experimental data in the case of the static collector. Although there are some discrepancies, which may be explained by some experimental imperfectness matters, a conclusion can be drawn that the CFD modelling and simulation gives good results and can be used for more complex problems.

Recommendations

Given that the work establishes a model of a solar collector using CFD technology, together with the experimental analysis, 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.

Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Acknowledgements or Notes

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