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RESEARCH OF FIXED AND SOLAR TRACKING LIQUID FLAT-PLATE SOLAR COLLECTOR WITH EXPERIMENTAL AND MATHEMATICAL APPROACH

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Abstract

Experimental set-up with two flat plate solar collectors is installed on a location in Shtip (Republic of Macedonia), latitude 41° 45’ and longitude 22° 12’, one with a fixed surface tilted at 30° towards the South, and the other one equipped with dual-axis rotation system. The study includes development of a 3-D mathematical model of the collectors system based on the computational fluid dynamics (CFD) approach.

The main aim is to investigate the effect of the sun tracking system implementation on the collector efficiency. The mathematical modelling is to provide information on conduction, convection and radiation heat transfer, so as to numerically simulate the heat transfer performances and the energy capture capabilities of the fixed and moving collectors in various operating modes. The feasibility of the proposed method was confirmed by experimental verification, showing significant increase of the moving collector efficiency, compared to the immobile collector unit. The comparative analysis demonstrates a good agreement between the experimental and numerically predicted results for different running conditions.

Keywords

Solar energy, solar collector, heat transfer, thermal radiation model, computational fluid dynamics (CFD).

1 Introduction

Interest in solar energy has been growing in recent years and is considered one of the main promising alternative sources of energy to replace the fossil energy resources. One of the simplest, most direct and cost-effective applications of the solar energy 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 [1].

Very comprehensive literature review on different modelling approaches of solar collector systems is given in [2]. A one-dimensional mathematical model for simulating the transient processes that occur in liquid flat-plate solar collectors is proposed in the study.

Wang and Wu [3] proposed a discrete numerical model for calculation of the flow and temperature distribution in order to analyze the performance of flat-plate solar collector with Z-arranged collector arrays, in which the flows are parallel in the dividing and combining manifolds.

Experimental and theoretical investigation of the flow and temperature distribution in a solar collector panel with an absorber consisting of horizontally inclined fins is presented in [4]. Numerically, the flow and heat transfer in the collector panel were studied by means of CFD calculations. Experimentally, the flow distribution through the absorber was evaluated by temperature measurements on the backside of the absorber tubes. A 3-D numerical model for flat-plate solar collector that considers the multidimensional and transient character of the problem is presented in [5]. The effect of the non-uniform flow on the collector efficiency was quantified and the degree of deterioration of collector efficiency was defined. The model was verified for steady-state operating conditions.

A detailed numerical model of flat-plate solar collector is presented in [6]. It is noticed by the author that the flow and heat transfer through the collector are essentially one-dimensional. The model, which is an extension of the model of Duffie and Beckman [7], is verified by experiment data of single and double glazed collectors under steady-state conditions.

A one dimensional mathematical model for simulating the transient processes, which occur in liquid flat-plate solar collectors is presented in [8]. The model considers time-dependent conditions, which means 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 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 in [9].

A simulation problem of a flat-plate solar energy collector with water flow using CFD is described in [10]. The considered case includes CFD modelling of solar irradiation, modes of mixed convection and radiation heat transfer between the tubes surfaces, glass cover, side walls 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 tube material. Martinopoulos et al. [11] developed a polymer solar collector in which the solar energy is directly absorbed by the black-colored working fluid. The model was investigated both experimentally and with CFD technique under steady-state conditions.

The work of Haytham [12] investigates methods of harvesting solar radiation for a flat-plate collector in cloudy-sky conditions, in order to optimize the energy capture of the system. It proposes an improved method for irradiance optimization by using a controlled tracking system. Investigation of the performance of dual-axis solar tracking system and in that way to provide an efficient solar thermal energy generation system is presented in [13]. According to the report, the use of the dual-axis tracking system increases the annual energy gain by around 48 % compared to an immobile solar panel and by around 36 % compared to a collector with single-axis tracking system.

Experimental and numerical studies of heat transfer in an integrated collector storage solar water heater were performed by Gertzos in [14]. In their investigation a 3-D CFD model was defined and validated with experimental results.

The research in this work is concerned with experimental and mathematical analysis of the efficiency of the flat plate solar collector by using a sun tracking system. The main objectives of the study are: to derive a mathematical model that portrays the operation of a flat plate solar collector under transient conditions, to calculate the flow and temperature distribution for any cross-section at any certain time, to analyze the overall performance of flat-plate solar collector and to experimentally verify the proposed mathematical model. Also, one of the aims of the work is to demonstrate the potential of the use of computational fluid dynamics CFD simulations, together with experiments, in order to obtain a more detailed insight into the flow and transport processes in facilities for solar energy utilization.

In that sense, an experimental test rig (experimental setup) of two flat-plate solar collectors, one immobile and one moving, is fabricated and tested. This is examined by the design of collectors' system model, utilizing CFD technique and conducting numerical simulations in various operational modes of the experimental facility.

2 Methodology of the research

2.1 Experimental work

Due to the non-constant nature of solar energy, two main components are required in order to have a functional solar energy heat generator: a collector and a storage unit. A typical flat-plate collector consists of an absorber in an insulated box together with transparent cover sheets (glazing). 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. However, the glass also reflects a small part of the sunlight, which does not reach the absorber. The collector can reach temperatures up to 200°C when no liquid flows through it and therefore all the materials used must be able to resist such temperature level.

Continuous measurements are carried out using a collector system with two identical flat-plate solar collectors, presented schematically in Fig. 1. The experimental set-up considered in this study was located in the town of Shtip, latitude 41^{o} 45' and longitude 22^{o} 12' [15]. Each collector consists of two manifolds, dividing and combining one, and 10 Cu tubes in a Z-arrangement. The system consists of two hydraulic circles. The first one is composed of the collector (static or moving one), heat exchanger in the horizontal water tank and the associated equipment. Working fluid in this circle is a 50:50 % mixture by weight of water and propylene glycol. The other hydraulic circle is composed of the horizontal tank and the heated water consumers. Both circles are equipped with proper equipment: pumps, non-return valves, etc. and automatics. The used water/propylene glycol mixture widens the collector operational temperature range between the boiling and freezing points.

For the proper functioning of this parallel system with two solar collectors, six sensors are placed in the installation: S1 is temperature sensor of the moving collector; S2 is temperature sensor of the static collector; S3 is temperature sensor of the cold water in the tank; S4 is temperature sensor of the hot water in the tank; S5 is solar irradiation sensor and S6 is flow meter for the moving collector. Corresponding information on the values of the sensors, pump operation during the day with the device D-LOG usb are displayed on the computer using the appropriate programs Winsol and Memory Manager. These programs provide an opportunity for continuous preservation of the results of the recorded material in the D-LOG usb, and therefore the results are displayed tabular in Excel as well as graphically.

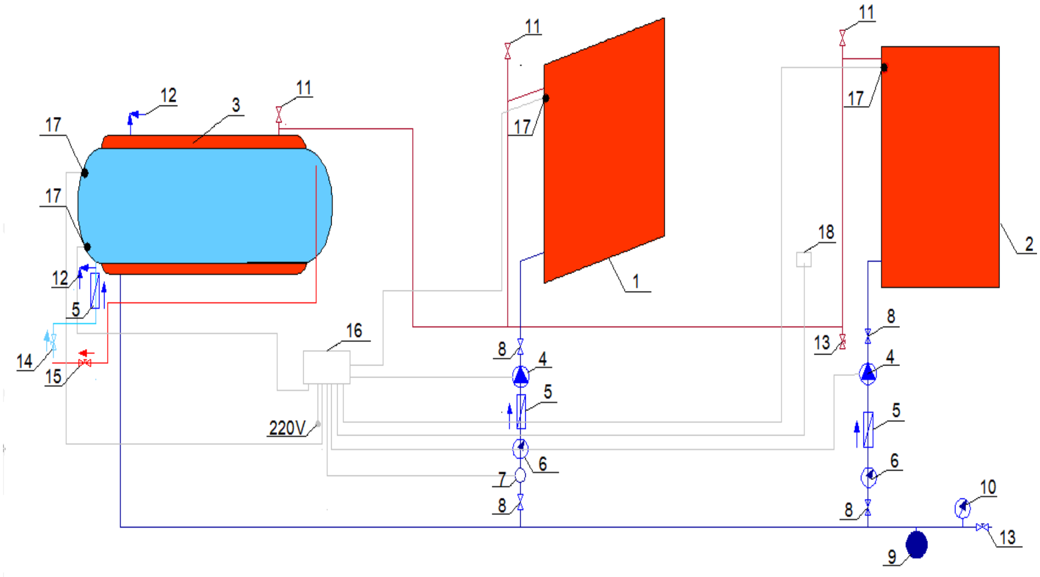

Figure 1: A schematic diagram of an experimental set-up

1. Moving collector, 2. Static collector, 3. Water tank, 4. Circulating pumps, 5. Non-return valves, 6. Flow-meters, 7. Impulse flow meter, 8. Three-way valves, 9. Expansion vessel, 10. Manometers, 11. Air release valve, 12. Pressure-relief valves, 13. Drain valves, 14. Cold water entrance, 15. Hot water exit, 16. Automatics, 17. Temperature sensors, 18. Solar irradiation (heat flux) sensor.

A photography of the experimental set-up used in this research is given in Figure 2.

Figure 2: Experimental set up

Using the measured parameters, the collector thermal efficiency is calculated as:

$$\eta_c = \frac{m_f c_{p,f} \left(T_{f,out} - T_{f,in}\right)}{G A_{col}} \qquad (1)$$

where: m_f is working fluid mass flow rate, kg/s; $c_{p,f}$ is average specific heat capacity of the working fluid, J/kgK; $T_{f,out}$ is working fluid outlet temperature, K; $T_{f,in}$ is working fluid inlet temperature, K; G is total normal incident radiation, W/m^2 and A_{col} is the area of the collector transparent cover, m^2.

2.2 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 [16]. The basic geometry of the collector pipe system used in the research, with the main dimensions and the mesh generated for calculations, are presented in Figure 3. 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.

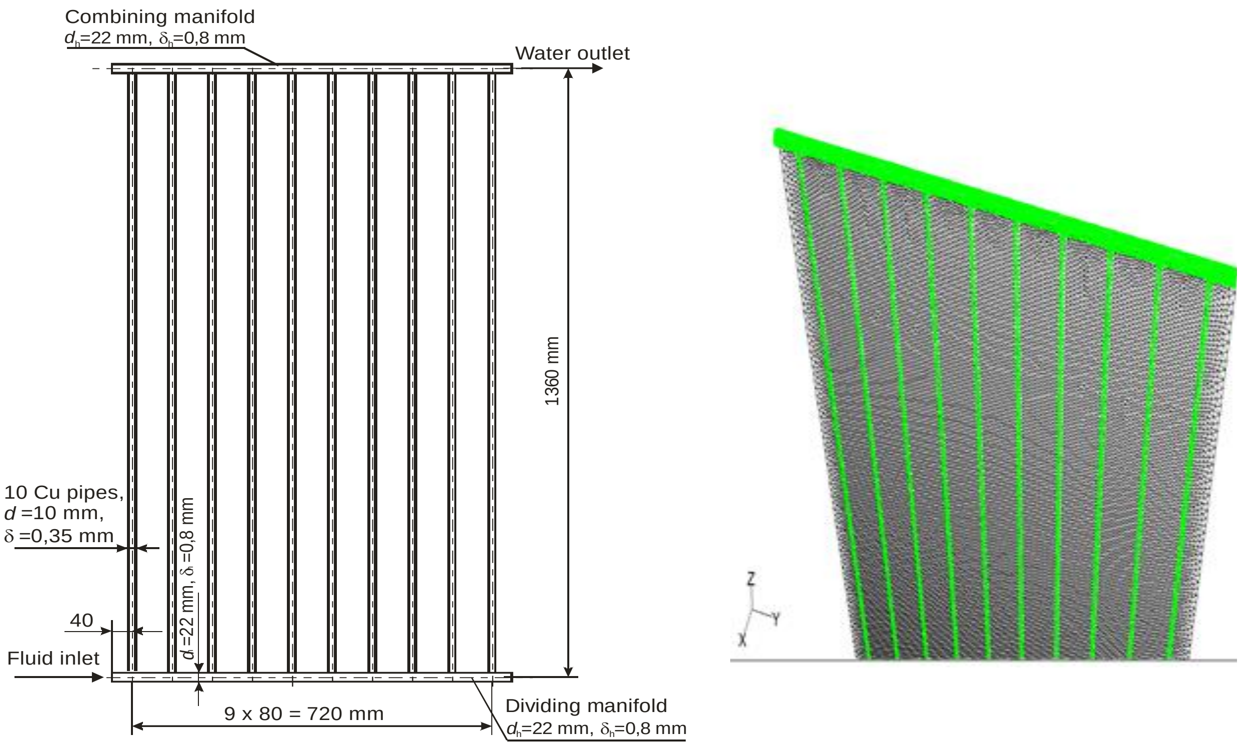

Figure 3: Basic geometry of the collector pipe system used in the research and the mesh

The numerical simulations were carried out using steady state implicit pressure based solver [16]. 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 the most appropriate in the numerical model.

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.

The selection of the most appropriate thermal radiation model in certain conditions depends on various factors [17]. Additional issue in the solar collector modelling is the necessity to include solar load model. In the present study, it was decided to correlate the experimental results with a mathematical model that incorporates the Discrete Ordinates (DO) radiation model, due to the opportunity of direct application of a solar load [16, 18]. Within the DO model the radiation transfer equation is solved for a finite number of discrete solid angles, each associated with a certain vector direction, 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. In this case, the so-called S6 approximation was applied, corresponding to 48 flux approximations [16, 18]. 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.

More details regarding the CFD modelling approach, including the boundary conditions that were imposed on the numerical domain, the values of the thermo-physical properties of the collector materials for the CFD analysis purposes, as well as the interpolation formulae that were used in the calculations for the thermo-physical properties of the water/propylene glycol mixture and for the air are given in [19, 20].

3 Experimental and Modelling Results

There is a complex matrix of measurement results from the experimental research conducted in the spring 2010. Also, there is already a plentiful of results arising from the CFD simulations, which should be compared to the available experimental results. In this section, just a small share of the available experimental and/or CFD modelling results are presented, as an overview of the provided study. The increase in the thermal energy gain in a given day due to the implemented sun tracking system, compared to the fixed south-facing solar collector inclined at an optimal tilt-angle, is shown in Figure 4.

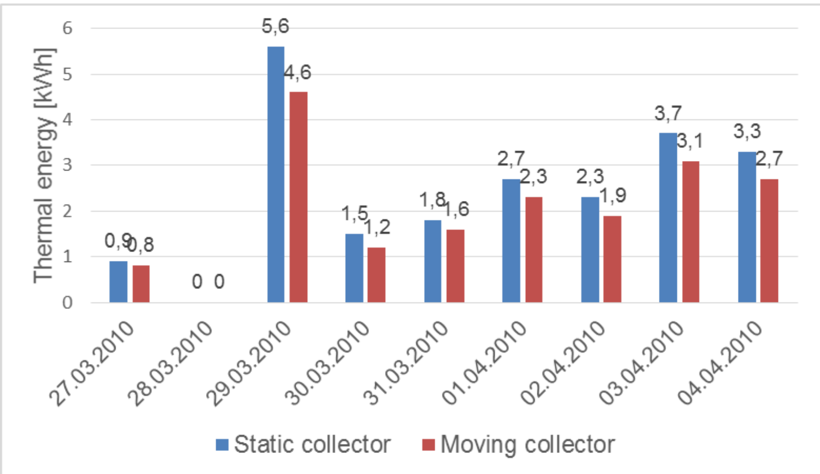

Figure 4: Thermal energy produced by solar collectors in a given day

Calculated values of the efficiency of the moving and the static solar collector in a given day is presented in Figure 5.

Figure 5: Calculated values of the efficiency of solar collectors in a given day

A comparative analysis between the experimental data and the numerical simulation results is a basis for optimization of the design and the operation mode of the collector. In order to accomplish this, measurements are conducted in different meteorological conditions, while keeping the main collector parameters fixed, which means that the solar radiation flux for the simulation module is varied. Examples of comparison charts are shown in Figures 6 to 9, indicating the measured and simulated outlet temperatures of the working fluid (propylene glycol/water mixture) versus time in four days with variable solar radiation.

It is obvious from the presented diagrams that the frequent or quick but sharp lows in solar irradiation have consequent impact on the change of the working fluid temperature. In general, the temperature change of the working fluid is quite well predicted by the numerical simulations.

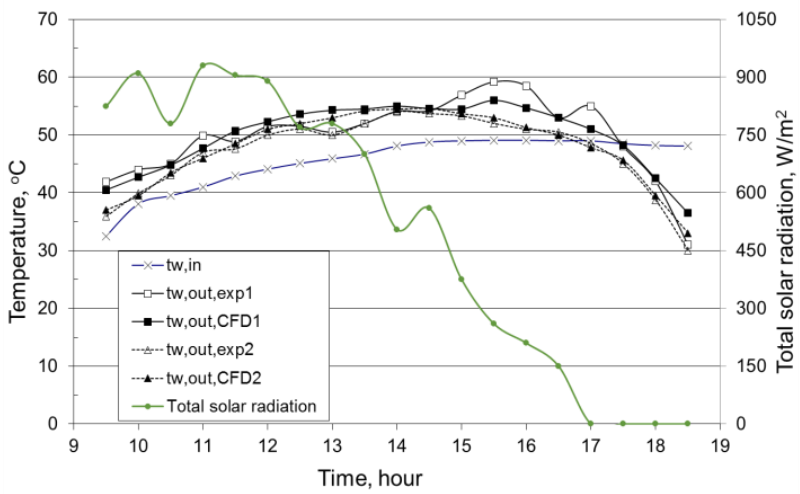

Figure 6: Comparison between the experimental and CFD results of working fluid temperature change, 16.03.2010

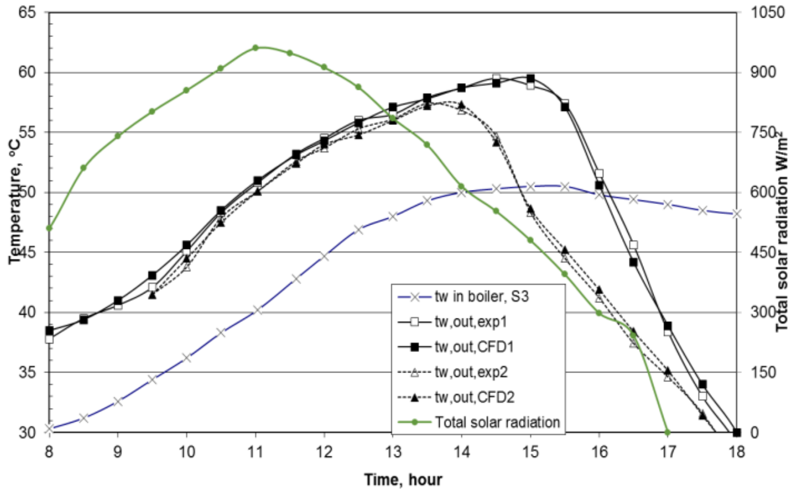

Figure 7: Experimental and CFD results of working fluid temperature change, 20.03.2010

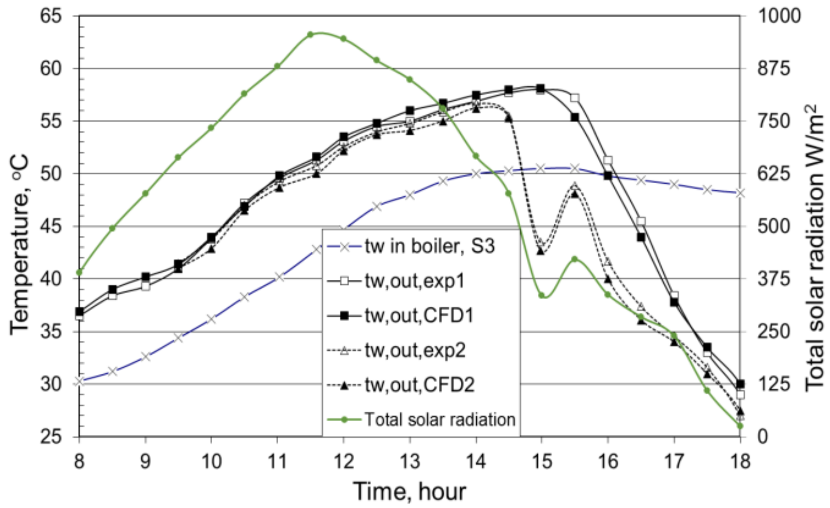

Figure 8: Experimental and CFD results of working fluid temperature change, 01.04.2010

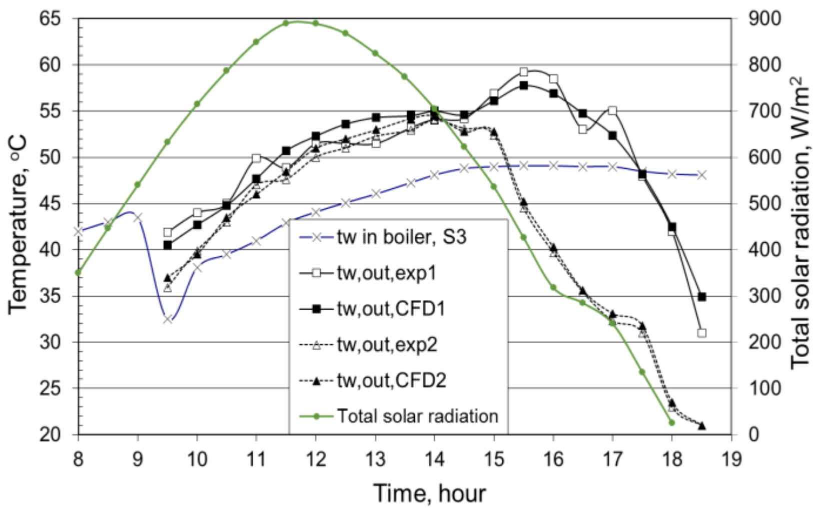

Figure 9: Experimental and CFD results of working fluid temperature change, 04.04.2010

4 Conclusion

An experimental set up of two flat plate solar collector was constructed for the purpose of this work. One collector is fixed and the other has controlled tracking system that could be easily applied in a typical (conventional) collector, without changing or redesigning its shape.

The efficiency of the proposed method was confirmed by experimental verification, showing significant increase, compared to the immobile collector unit, which is particularly obvious in the afternoon hours. In order to provide a complete analysis in different operating conditions, due to the limitations of the experimental research, a comprehensive CFD modelling and simulation is undertaken. The numerical domain of the collector, includes dividing and combining manifolds, water pipes, absorber plate, glass top, air gap, insulation region and the collector metal cover. 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. The analysis shows that there is a good agreement between the experimental and numerically predicted values for different running conditions and flow rates.

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