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BOOK OF ABSTRACTS

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Comparative analysis of solar-tracking and static solar collector efficiency

Marija Chekerovska
Faculty of Mechanical Engineering,
University "Goce Delchev", Shtip, Republic of Macedonia
e–mail: marija.sumanska@gmail.com

Risto V. Filkoski*
Faculty of Mechanical Engineering,
University „Sts Cyril and Methodius", Skopje, Republic of Macedonia
e–mail: risto.filkoski@mf.edu.mk

ABSTRACT

The objective of the present work is to conduct a comparative analysis of fixed and moving flat-plate solar collectors' operation. A testing programme is performed on an experimental set-up installed on a location in Shtip (R. of Macedonia), latitude 41° 45' and longitude 22° 12', in order to investigate the effect of the sun tracking system implementation on the solar collector efficiency. The set-up consists of two liquid flat-plate solar collectors, one with a fixed surface tilted at 30° towards the South, and the other one equipped with dual-axis solar-tracking system. The research includes development of a 3-D mathematical model of the collectors system and an extensive numerical simulation programme, based on the computational fluid dynamics (CFD). The main aim of 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, compared to the immobile collector unit. The comparative analysis demonstrates a good agreement between the experimental and numerically predicted results for different running conditions. This is a proof that the presented and verified CFD modelling approach can be used for further investigations of different configurations and flow schemes of thermal solar collectors.

KEYWORDS

Renewable energy, solar collector, efficiency, heat transfer, thermal radiation, computational fluid dynamics.

INTRODUCTION

The demand for energy has increased remarkably in recent years, as a result of the growing energy needs in the industry, households, agriculture and other sectors, especially in the developing countries. Some of the negative consequences are the rapid grow in the level of harmful emissions, including greenhouse gas emissions, as well as the increase in fuel prices. These are, also, the main driving forces behind efforts to utilize renewable energy sources more effectively. However, as most renewable energy resources depend on the climate daily

* Corresponding author

and seasonal variations, their effective use usually requires complex design, planning and control optimization methods [1].

A simple and direct application of the solar energy is its conversion into heat, which is one of the ways the residential and other sectors can decrease their share in electricity consumption. Wider use of solar thermal collectors can reduce the annual expenses for domestic water heating by significant share; in some regions, due to the specific climate conditions, reaching as much as 40-50 %. The performances of solar water heater and its geographic variation has been analysed for 147 different sites in all European countries in [2]. Due to the favourable climate conditions in the South-European countries, the possibilities of implementation of solar collectors for conversion of solar energy into heat and/or electricity have been a subject of research efforts in many works, such as [3, 4], demonstrating significant potential for fossil fuels and electricity replacement. A specific approach, using energy and exergy methods, is implemented for analysis of solar assisted heat pump space heating system in [5]. The case study is applied and simulation results are given for Antalya, Turkey.

An experimental study of solar hot water system including two collector types, water-in-glass and heat-pipe, of evacuated tube water heater is presented in [6]. Performance tests were carried out in Hong Kong and under almost identical boundary conditions by placing the two collectors side-by-side. The energy performance has been analysed and the daily efficiency, transient efficiency and night-time heat loss were compared.

The work [7] presents a one-dimensional mathematical model for simulating transient processes that occur in liquid flat-plate solar collectors. The properties of the working fluid, the air gap and absorber, the heat transfer coefficients etc., as well as the boundary conditions are considered as time-dependent. The experimental verification shows a satisfactory agreement of the measured and calculated fluid temperatures at the collector outlet.

The work [8] investigates methods of harvesting solar radiation with 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.

The optical performance of solar panels is theoretically investigated in the work [9], based on a proposed mathematical method and monthly horizontal radiation. A mechanism of the investigated sun-tracking system of solar panels is given. The solar panels attitude angle is adjusted at three fixed positions on a daily basis: eastward, southward, and westward in the morning, noon, and afternoon, respectively.

A mathematical procedure for estimation of the annual collectible radiation on fixed and tracked panels is suggested in [10]. Compared to fixed south-facing solar panels inclined at an optimal tilt-angle, the increase in the annual solar gain due to sun tracking is calculated in the areas with abundant solar resources and in the areas with poor solar resources.

The study of Catarius [11] is carried out in order to investigate the performance of dual-axis solar tracking system and in that way to provide an efficient solar thermal energy system. 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.

A comprehensive literature review on different modelling approaches of solar collector systems is given in [12]. Also, a one-dimensional mathematical model for simulating the transient processes that occur in liquid flat-plate solar collectors is proposed in the same work [12]. The model considers time-dependent thermo-physical properties and heat transfer coefficients and is based on solving energy conservation equations for the glass cover, air gap between the cover and absorber, absorber, working fluid, insulation, and the storage tank.

Simulation of the heat transfer phenomena in flat-plate solar collectors using commercial CFD (computational fluid dynamic) codes is presented in [13], by considering the mixed heat transfer modes of conduction, convection and radiation between tube surface, glass cover, side walls and insulating base of the collector, and their results achieved good agreement with test data.

The work [14] deals with the numerical simulation of air flow around the arrays of flat plate collectors and determination of the flow field, which should provide a basis for estimating a convective heat losses. The results obtained with the numerical simulation of flow around collectors were used as boundary conditions in modelling of thermal-hydraulic processes inside the solar collector.

Wang and Wu [15] proposed a discrete numerical model to calculate the flow and temperature distribution 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.

A prototype of flat plate collector with plastic transparent insulation and low-cost overheating protection has been constructed and experimental and numerical modelling research related to this installation is presented in [16]. The numerical model is based on the resolution of the different components of the solar collector by means of a modular object-oriented platform. Indoor and outdoor tests have been performed in order to check the effectiveness of the designed overheating protection system and to validate the model. The comparison of the numerical results with experiments has shown a good agreement.

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 [17]. The flow and heat transfer in the collector panel are studied numerically, by means of CFD technique, as well as experimentally. The comparison shows a good agreement between the CFD results and the experimental data at high flow rates. Large differences appear between the computed and measured temperatures for small flow rates, which is most likely due to the oversimplification of the solar collector model.

One-dimensional model for flat plate collector has been developed and experimentally validated in the work [18]. It consists of calculation of the thermal resistances and thermal heat capacitances in order to determine the collector heat loss and the thermal inertia. The heat loss has been found depending on collector aging, wind velocity and direction, collector components heat capacitances, and external and internal radiation losses.

A 2-D CFD simulation in [19] estimates the hourly yield of a single-slope solar collector. The results are in a good agreement with the results of well-known models, they show that there is an optimum length in which the productivity is maximized. On the other hand, in a fixed length of a solar collector, the specific height has an inverse effect on productivity.

A 3-D numerical analysis of unglazed solar water heater is presented in [20]. The research gives a concept of enhancing the heat transfer from the absorber plate of the forced circulation flat plate solar collector to working fluid, by using finned circular tube and rectangular tubes with and without fins.

A detailed numerical model of a flat-plate solar collector is presented in [21]. It is noticed by the author that the flow and the heat transfer through the collector are essentially one-dimensional. The developed model is an extension of the Duffie and Beckman’s model [22] and it is verified by an experiment data conducted on single and double glazed collectors under steady-state conditions.

The present work deals with experimental and mathematical analysis of two flat plate solar collectors, one static and one moving equipped with a sun tracking system, which could be easily applied to other devices without changing or redesigning the collector's shape. 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, 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 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.

THEORETICAL BACKGROUND

Two main components of the solar energy collector system, which are required in order to have a functional solar energy heat generator, because of the non-constant nature of solar energy are a collector and a storage unit. 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. However, the glass also reflects a small part of the sunlight, which does not reach the absorber.

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 that simple. For a detailed analysis, it is necessary to set-up a 3-D model, which considers time-dependent change of variables and includes conservation equations for mass, momentum and energy, solar ray tracing and thermal radiation modelling. Because of the nature of the solar energy, the working conditions of the solar collector regarding the heat transfer and fluid flow are unavoidably transient and non-uniform.

A comprehensive modelling of a flat plate solar collector should consider an incompressible, predominantly laminar fluid flow problem, which includes heat transfer in fluid and solid regions, as well as solar radiation to semi-transparent and other surfaces. The flow is mostly steady and possesses laminar flow characteristics, as the fluid flow velocity through the manifolds and vertical pipes is low. Under steady-state conditions, the overall energy balance is defined as:

Heat energy delivered by the collector = Heat energy absorbed by the plate and the pipes - Heat losses to the surroundings

In the case of a solar collector, the heat transfer includes conduction, convection and radiation within fluid and solid regions and the process should necessarily be analyzed as transient phenomenon. An overall energy balance of a flat-plate solar collector is illustrated in Figure 1 [23, 24], indicating the distribution of the incident solar energy into useful energy gain, thermal losses and optical losses.

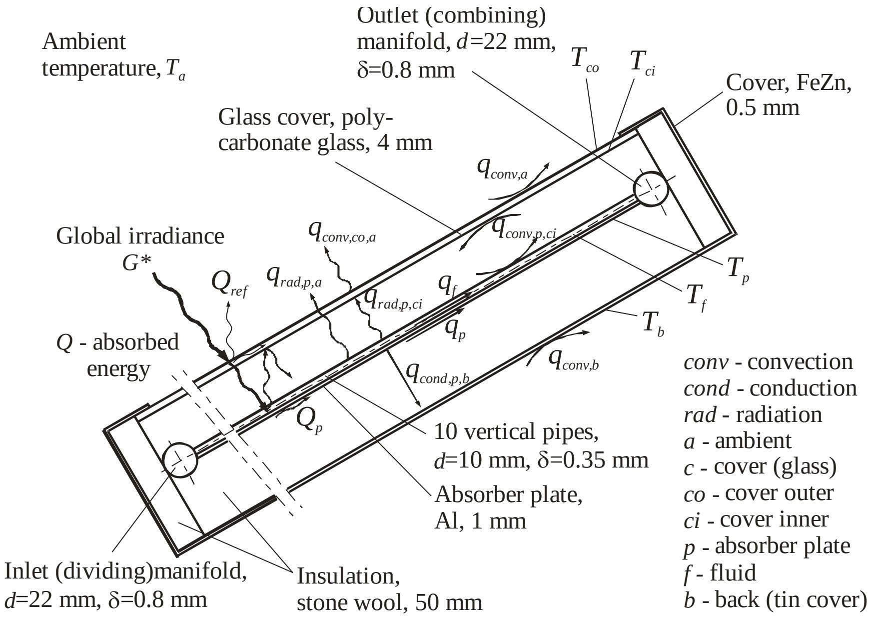


Figure 1. A schematic representation of an energy balance of a typical flat-plate solar collector [23,24]

The input parameters of the model are detailed geometrical and physical properties of the collector, climatic and operation parameters. Basic outputs of the model are usable heat gain *Qu* [W] and collector efficiency. The useful gain from the collector *Qu* is defined with:

$$Q_u = A_c \left[S - U_L (T_{pm} - T_a) \right] \tag{1}$$

where: A_c is the gross area of the collector, m^2; S is the solar radiation absorbed by the collector per unit area of absorber, W/m^2; UL is the collector overall heat loss coefficient, W/m^{2}K; T_{pm} is the mean absorber plate temperature, K and T_a is the ambient temperature, K. The collector thermal efficiency is defined as the ratio of the useful gain over a specified time period to the incident solar energy over the same period, which is a proportion of the total incident radiation G that is converted into usable heat Q_{col}, is given by the following equation:

$$\eta_c = \frac{Q_{col}}{G} \tag{2}$$

RESEARCH METHODOLOGY

Experimental work

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 2 [25]. The system, schematically presented in Figure 3, consists of a 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 2. Experimental set-up and a segment of the tracking system including:+ electric drive (a), gear spindle (b), auxiliary mechanism (c)

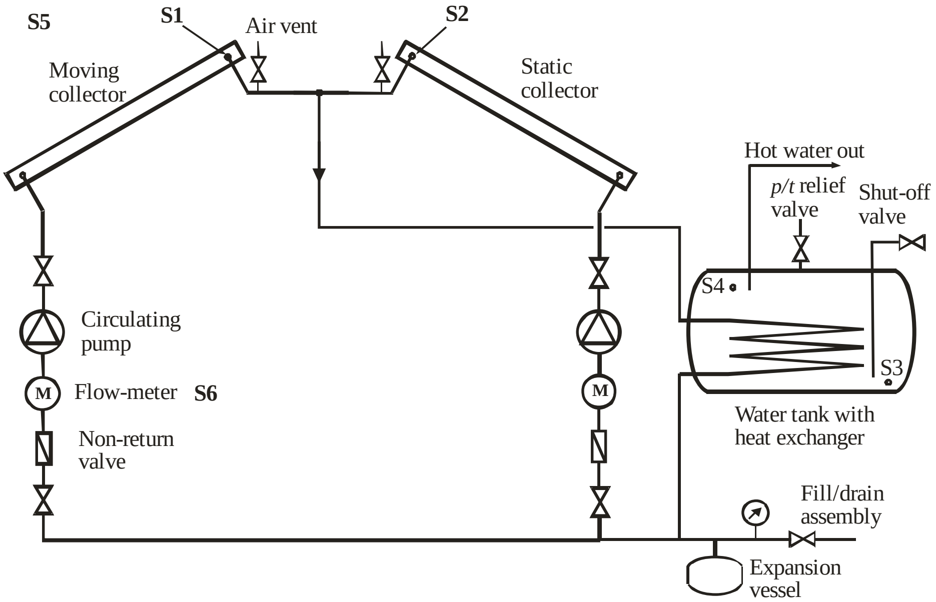


Figure 3. A schematic diagram of an experimental set-up
S1 – temperature sensor of the moving collector; S2 – temperature sensor of the static collector; S3 – temperature sensor of the cold water in the tank; S4 - temperature sensor of the hot water in the tank; S5 – solar irradiation sensor; S6 – flow meter for the moving collector

The experimental set-up has two hydraulic circles, the first one composed of a collector (static or moving one), heat exchanger in a horizontal water tank and an associated equipment and the other one composed of a horizontal tank of 150 liters and heated water consumers. Working fluid in the primary circle is a 50:50 % water and propylene glycol mixture by weight. Each collector is a flat plate, consisting of two manifolds, dividing and combining one, and 10 Cu tubes in a Z-arrangement. The main technical parameters of the collectors are given in Table 1 [25].

Table 1. Main technical parameters of the solar collector [25]

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 °C
Weight	18 kg

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

$$\eta_c = \frac{m_f c_{p,f} \left(T_{f,out} - T_{f,in}\right)}{G A_{col}} \tag{3}$$

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.

CFD model set-up and numerical 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 [26]. 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 Figure 4 [24]. 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 [24]. 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 [26]. 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, icluding standard wall functions for the near-wall treatment. In the framework of the considered case are the 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.

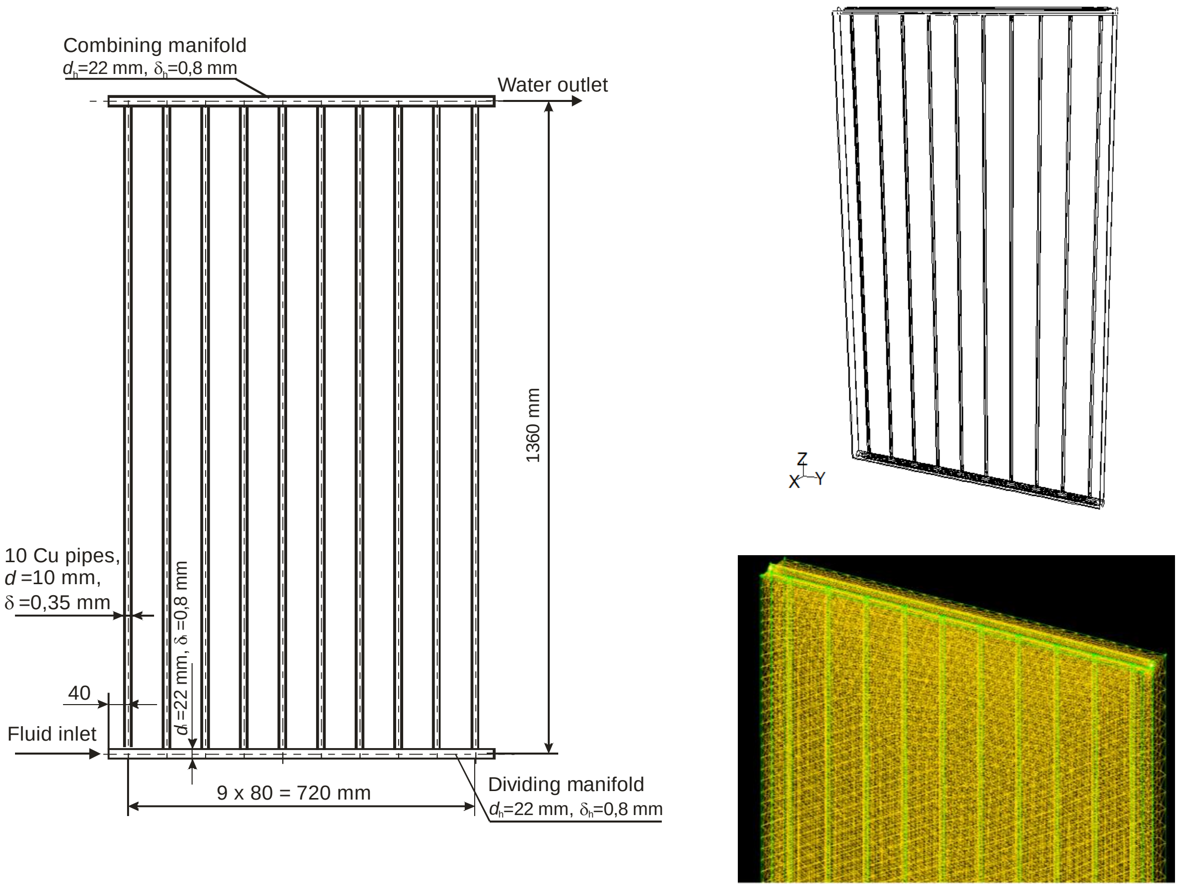


Figure 4. The collector pipeline system geometry, the outline of the numerical domain and the numerical mesh [24]

Heat transfer, thermal radiation and solar load modelling

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 [27]. 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 [24]. The DO radiation method considers the radiate transfer equation (RTE) in the direction **s** as a field equation. In this case, the so-called S6 approximation was applied in the framework of the DO model, 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. Appropriate boundary conditions were imposed on the numerical domain, for the inlet of the working fluid a ‘velocity inlet’ boundary condition is specified and for the outlet, an ‘outflow’ condition is specified.
The properties of the collector materials for the CFD analysis purposes are represented with the values given in Table 2 [25]. Polynomial interpolation formulae given in Tables 3 and 4 are used in the calculations for the thermo-physical properties of the water/propylene glycol mixture and for the air [24].

Table 2. Properties of the materials used in the experimental research [25]

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 3. Properties of the water/propylene glycol mixture (*T* in K) [24]

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 4. Properties of the air (*T* in K) [24]

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	$\lambda = 0.0228 + 8 \cdot 10^{-5} T$

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.

Compared to fixed south-facing solar collector inclined at an optimal tilt-angle, the increase in the solar gain due to using sun tracking system is shown in Figure 5 with the thermal energy produced by solar collectors in a given day.

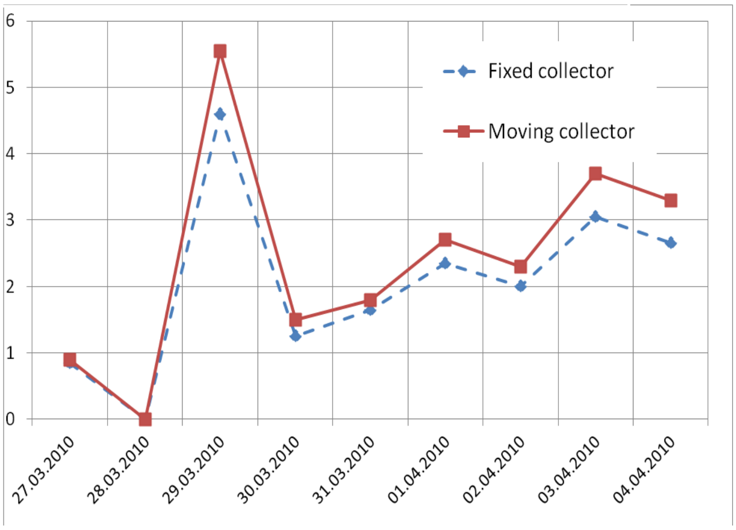
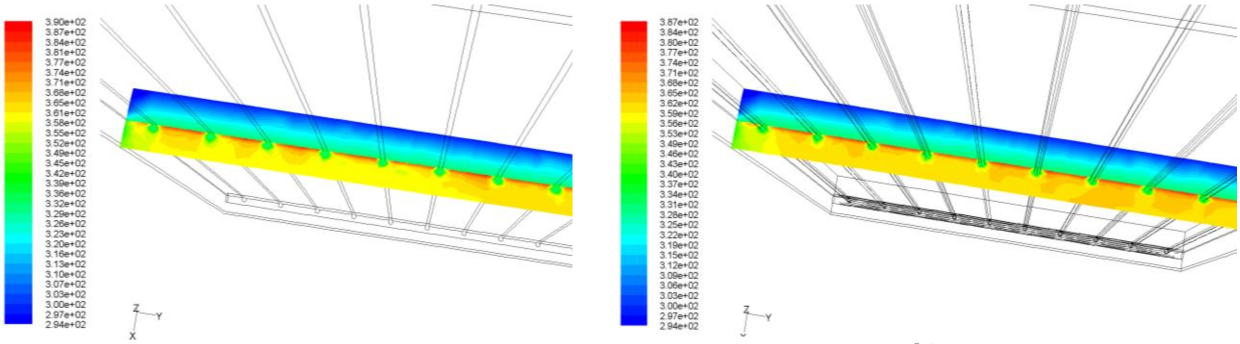


Figure 5. Thermal energy (in kWh) produced by solar collectors in a given day

Temperature contours of the air gap and the working fluid on a level 0.68 m above the central axis of the collector's inlet (dividing) manifold are given in Figure 6. The contours (a) are obtained using laminar flow assumption and the figure (b) represents temperature contours obtained with the RNG k-ε turbulence model, with standard values of the model constants.



a) b)

Figure 6. Temperature profiles in a horizontal intersection

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.

Some examples of comparative results concerning the change in the working fluid temperature at the outlet of the collectors combining manifolds, during five days characterised with variable meteorological conditions, are shown in Figures 7 to 11. They present the measured and simulated outlet temperatures of the working fluid, propylene glycol/water mixture, versus time. The designation 1 refers to the collector equipped with solar tracking system and 2 refers to the static collector. The measured total solar radiation in the experimental facility spot is also given in Figures 7 to 11.

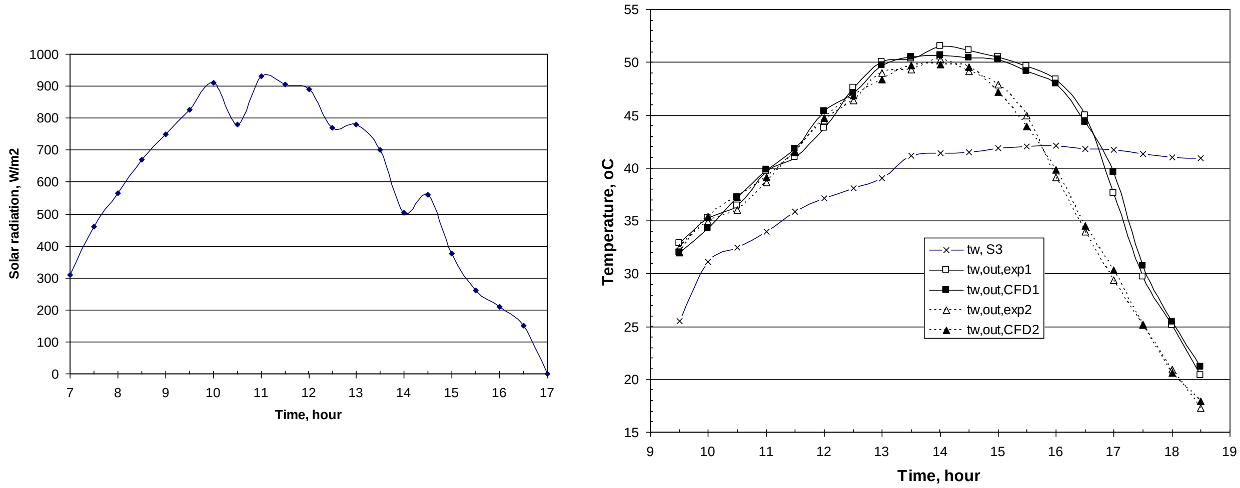


Figure 7. Solar radiation and working fluid temperature change, a comparison between the experimental and CFD results: 16.03.2010

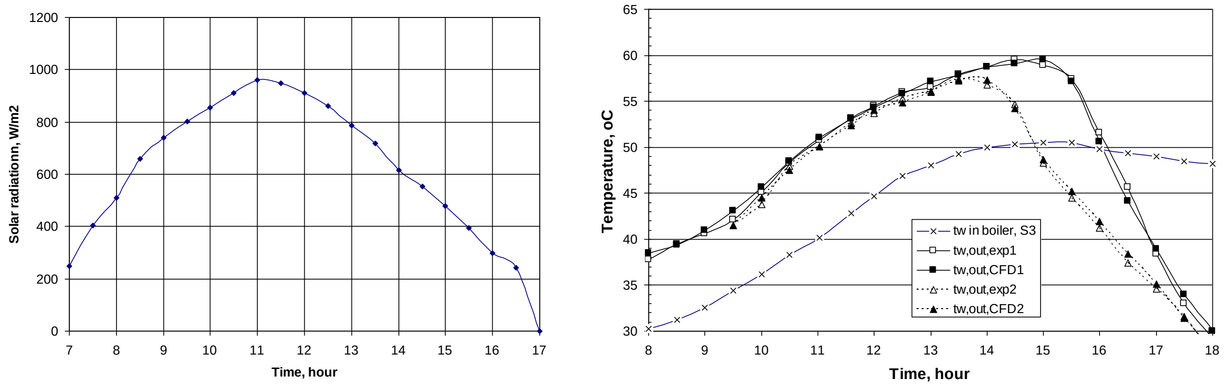


Figure 8. Solar radiation and working fluid temperature change, a comparison between the experimental and CFD results: 20.03.2010

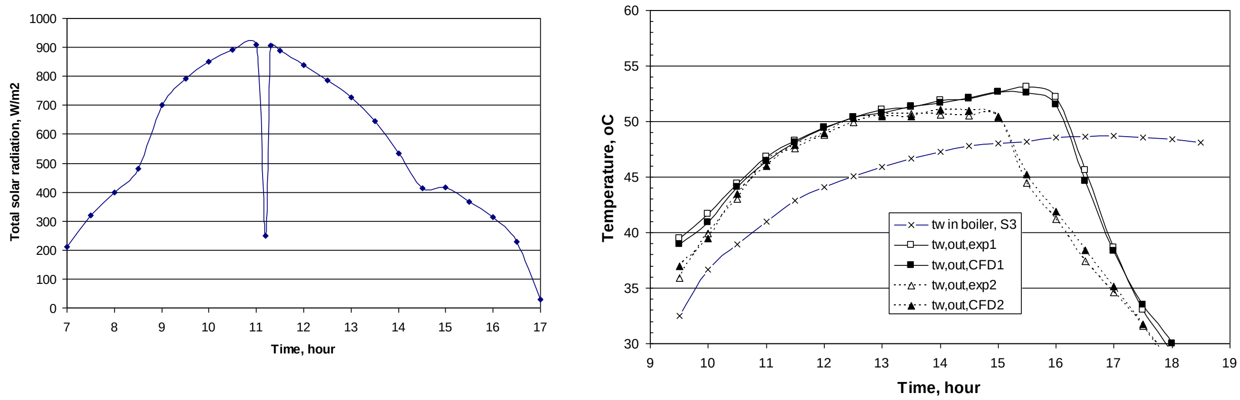


Figure 9. Solar radiation and working fluid temperature change, a comparison between the experimental and CFD results: 25.03.2010

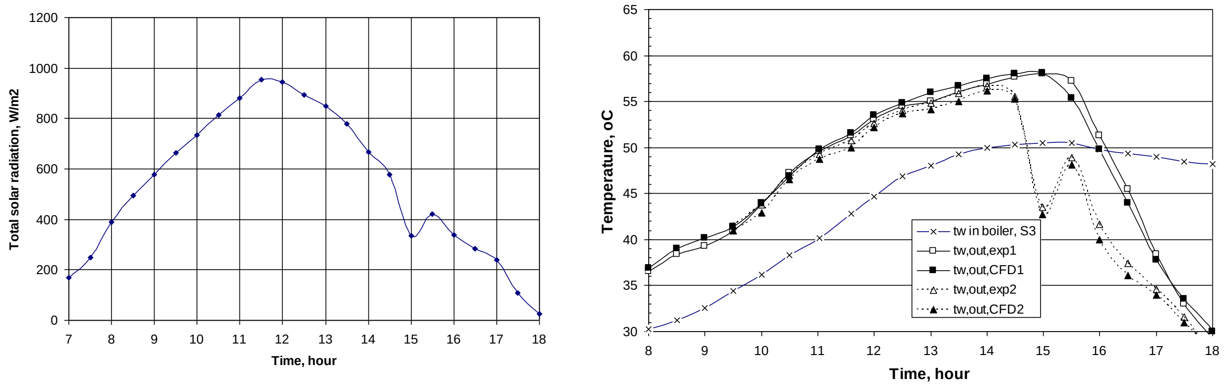


Figure 10. Solar radiation and working fluid temperature change, a comparison between the experimental and CFD results: 01.04.2010

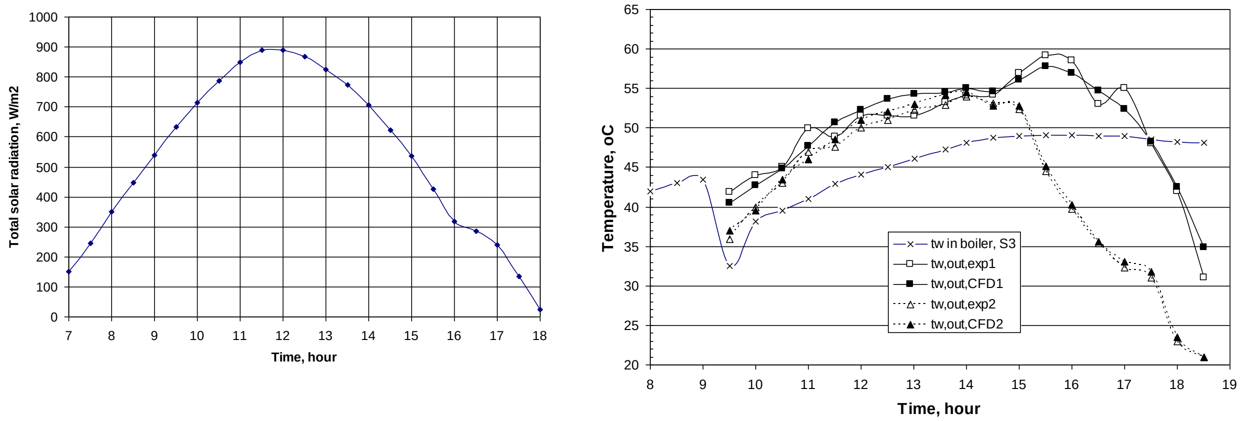


Figure 11. Solar radiation and working fluid temperature change, a comparison between the experimental and CFD results: 04.04.2010

The temperature rise coefficient, C_T, is defined by the following equation:

$$C_T = \frac{T_f - T_{f,in}}{T_{f,out} - T_{f,in}} \qquad (4)$$

where T_f is the actual working fluid temperature, $T_{f,in}$ is the fluid inlet temperature, and $T_{f,out}$ is fluid outlet temperature. According to the provided numerical simulations for the conditions on 4 April 2010, 13.00 CET, the temperature rise coefficient is presented in Figure 12.

The change of the working fluid temperature versus velocity ($w_{f,i}$) in certain operating conditions, according to the CFD simulations, as for the conditions on 4 April 2010, 13:00 CET, is given in Figure 13. In this diagram, the annotation means as follows: $w_{f,1}$ = 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.

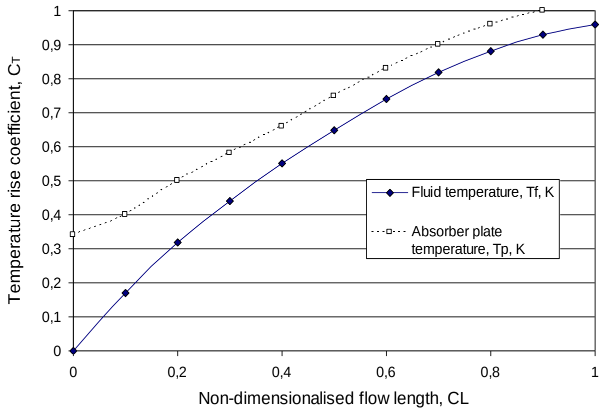


Figure 12. Temperature rise coefficient of absorber plate and fluid, corresponding to w_f=0.01 m/s (4 April 2010, 13:00)

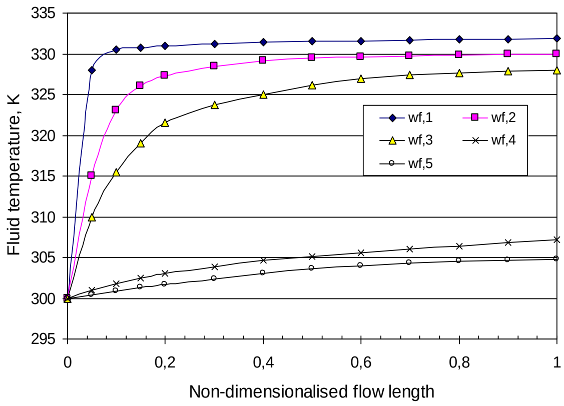


Figure 13. Fluid temperature vs. velocity, corresponding to 4 April, 13:00

The presented results demonstrate that there is a good agreement between the measured and mathematically predicted results, indicating that the model can be applied for investigation of other configurations of solar receivers, such as the one described in [28].

CONCLUDING REMARKS

An experimental facility consisting of two flat plate solar collectors, the one fixed and the other with controlled solar tracking system, was constructed for the purpose of this work.
The efficiency of the proposed solar tracking 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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