7th International Conference on Sustainable Energy & Environmental Protection

DUBAI - UAE
November 23-25, 2014

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FIRST ANNOUNCEMENT
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CALL FOR PAPERS

Introduction

The Sustainable Energy and Environmental Protection conference provides a forum for both researchers and practitioners around the world to present papers on recent developments in the fields of Sustainable Energy and Environmental Protection. The organising committee of the conference invites papers from researchers and practitioners from academic as well as industry within the scope of the conference subjects.

Scope

The conference particularly welcome papers related to industrial based projects. Papers dealing with one or more of the following topics will be considered for the conference:

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- Materials and Fuel Developments, Including: Nano-technologies, Light weight structures, Bio-composite materials, Fuel Cell Materials, Membranes, Sensor Technologies, Combustion

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All Correspondence:

SEEP-2014 Team
Prof. Bassam AbuHijleh
Email: seep14@buid.ac.ae
Tel: +971-4-367-1966
or Prof. Abdul Ghani Olabi
Tel: +44-141-8483450/8483101
Skype name: olabia1
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Interested contributors are requested to submit abstract(s) of up to 200 words, along with the completed preliminary registration form.

EXPERIMENTAL AND NUMERICAL STUDY OF A FLAT-PLATE SOLAR ENERGY COLLECTOR PERFORMANCE

R.V.Filkoski[1] and M.Chekerovska[2]

1. Faculty of Mechanical Engineering, University „Sts Cyril and Methodius", Skopje, R. Macedonia; e–mail: risto.filkoski@mf.edu.mk
2. Faculty of Mechanical Engineering, University "Goce Delchev", Shtip, R. Macedonia; email: marija.sumanska@gmail.com

Abstract

The objective of the present work is to conduct a comparative analysis of fixed and moving flat-plate solar collectors' performance. An experimental set-up installed on a location in Shtip (Republic of Macedonia), latitude 41° 45' and longitude 22° 12', consists of two flat plate solar collectors, the first one with a fixed surface tilted at 30° towards the South, and the other one equipped with dual-axis rotation system. An experimental programme is performed to investigate the effect of the sun tracking system implementation on the collector efficiency. The study also includes development of a 3-D mathematical model of the collectors system and extensive numerical simulation, based on the computational fluid dynamics (CFD) approach. The efficiency of the implemented system was confirmed by experimental verification, showing significant energy efficiency increase, compared to the immobile collector unit. 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: Renewable energy, solar collector, heat transfer, thermal radiation, computational fluid dynamics

1 INTRODUCTION

Increasing attention in the last few decades is being given to renewable energy sources, due to the environmental issues, limited fossil fuel resources and rising energy prices. One of the simplest, and most direct applications of the solar energy, which is becoming more and more 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 evaluation results of conventional solar water heater systems and solar assisted heat pump systems for hot water production in specific local conditions are presented in [1, 2]. Flat plate solar water heaters, traditionally in use in domestic systems due to the low temperature requirements and low equipment cost, have been analysed with regards to the efficiency and the thermal losses associated with the collector at the local operating conditions in [3, 4].

A comprehensive literature review on different modelling approaches of solar collector systems is given in [5]. 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 [5]. The model considers time-dependent thermophysical 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.

Wang and Wu proposed a discrete numerical model to calculate the flow and temperature distribution to analyse the performance of flat-plate solar collector with Z-arranged collector arrays, in which the flows are parallel in the dividing and combining manifolds [6].

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 [7]. The flow and heat transfer in the collector panel are studied numerically, by means of CFD technique, as well as experimentally. The flow distribution through the absorber is evaluated by means of temperature measurements on the backside of the absorber tubes. The results show a good agreement between the CFD results and the experimental data at high flow rates, but large differences appear for small flow rates.

A 3-D numerical model for flat-plate solar collector that considers the multidimensional and transient character of the problem is presented in [8]. The effect of the non-uniform flow on the collector efficiency was quantified and the degree of deterioration of 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.

A detailed numerical model for flat-plate solar collector is presented in [9]. It is noticed (emphasized) by the author that the flow and the heat transfer through the collector are essentially one-dimensional. The model developed in [9], which is an extension of the Duffie and Beckman’s model [10], 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 [11,12]. The experimental verification show a satisfactory agreement of the measured and calculated fluid temperatures at the collector outlet. This study relay heavily on the model developed in [12].

A flat-plate solar energy collector is simulated and analyzed by use of the CFD technique in [13]. 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, also covering mixed convection in the circulating water inside the tube and conduction between the base and tube material. Martinopoulos et al. [14] have developed a polymer solar collector in which the solar energy is directly absorbed by the black-colored working fluid in a research that includes experimental part and CFD modelling. The obtained values for the temperature and velocity distribution over the collector area using the CFD modelling were found to be in good agreement with the experimental results. The performance of the collector was modelled by CFD under steady-state conditions.

H. Ayoub investigates methods of harvesting solar radiation for a flat-plate collector in cloudy-sky conditions, in order to optimise the energy capture of the system. It proposes an improved method for irradiance optimisation by using a controlled tracking system [15].

The study of Catarius, [16] is carried out in order to investigate the performance of dual-axis solar tracking system, reporting that the use of the 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.

The research in the present work consists of experimental and mathematical analysis of the flat plate solar collectors efficiency, a static and a moving one, equipped with a two-axis tracking system, which could be easily applied 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 analyse its performance and to experimentally verify the proposed mathematical model.

2 THEORETICAL BACKGROUND

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. 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. Due to 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. Therefore, for a detailed analysis, it is necessary to set-up a 3-D 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. 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 analysed as transient phenomenon. An overall energy balance of a flat-plate solar collector is illustrated in Figure 1 (modified from [17]), indicating the distribution of the incident solar energy into useful energy gain, thermal losses and optical losses.

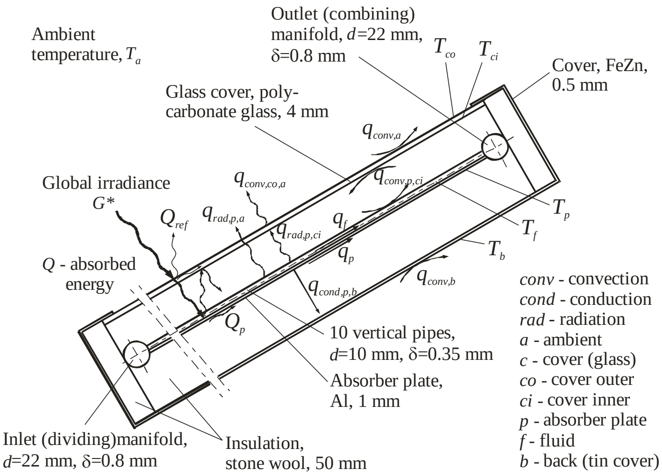

Figure 1. A schematic representation of an energy balance of a typical liquid flat-plate solar collector (modified from [17])

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 Q_u [W] and collector efficiency. The useful gain from the collector Q_u is defined with:

$$Q_u = A_c \left\lfloor S - U_L (T_{pm} - T_a) \right\rfloor \quad (1)$$

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; U_L 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:

$$\eta_c = \frac{Q_{col}}{G} \quad (2)$$

3 METHODOLOGY OF THE RESEARCH

3.1 Experimental work

A typical flat-plate collector consists of an absorber in an insulated box, together with transparent cover glazing. The absorber is usually made of a metal sheet of high thermal conductivity, such as Cu or Al, with integrated or attached tubes. 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. The glass also reflects a small part of the sunlight, which does not reach the absorber. The experimental set-up considered in this study was located in the town of Shtip, latitude 41º 45’ and longitude 22º 12’ [18]. Continuous measurements were carried out on a system presented schematically in Figure 2, consisting 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. Each collector consists of two manifolds, dividing and combining one, and 10 Cu tubes in a Z-arrangement.

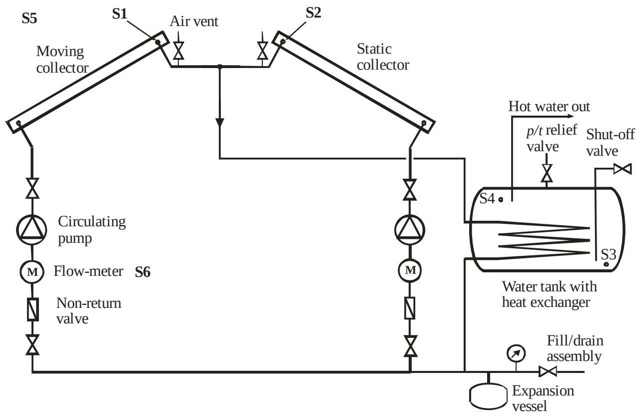

Figure 2. A schematic diagram of an experimental set-up
S1 – temperature sensor of the moving collector; S2 – temperature sensor of the static collector; S3 – temperature sensor of the cold water in the tank; S4 - temperature sensor of the hot water in the tank; S5 – solar irradiation sensor; S6 – flow meter for the moving collector

As shown in Figure 2, 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 % water and propylene glycol mixture by weight. The other hydraulic circle is composed of the horizontal tank and the heated water consumers. The main technical parameters of the collectors are given in Table 1 and the properties of the materials used in the tests are presented in Table 2 [18].

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

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

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.

Table 1. Main technical parameters of the solar collector [18]

Description	Specification
Collector annotation	Eко Mag 2
Collector body	Aluminum
Dimensions, in mm	1500 x 970 x 81
Fluid content (water and propylene glycol)	1.76 litres
Vertical pipes: number, material, dimensions	10, Cu, 10.0/0.35 mm/mm
Manifolds (headers)	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 ^oC
Weight	18 kg

3.2 Numerical model set-up and simulations

The numerical domain comprises all functionally important parts of the collector: manifolds, vertical pipes, working fluid, transparent cover, absorber plate, air region, thermal insulation and the metal cover. The basic geometry of the collector pipe system, with the main dimensions and the numerical mesh are presented in Figure 3. The geometry was created using Gambit pre-processor [19]. The numerical mesh 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 and (3) 949300 volume cells. Since the grid refinement changed the results by less than 0.5 %, previously decided as criteria, it was concluded that the influence of eventual further refinement would be negligible.

The numerical simulations were carried out using steady state implicit pressure based solver [19]. 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 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.

3.3 Heat transfer, thermal radiation, solar load modelling and boundary conditions

The selection of the most appropriate thermal radiation model in certain conditions depends on various factors [20]. Additional factor in the case of solar collector modelling is 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 [21]. 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 [19]. The DO radiation method considers the radiative transfer equation in certain direction 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.

Taking into consideration the physics of the problem, 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 taken with the values presented in Table 2. Polynomial interpolation formulae are used in the calculations for the thermo-physical properties of the water/propylene glycol mixture and for the air.

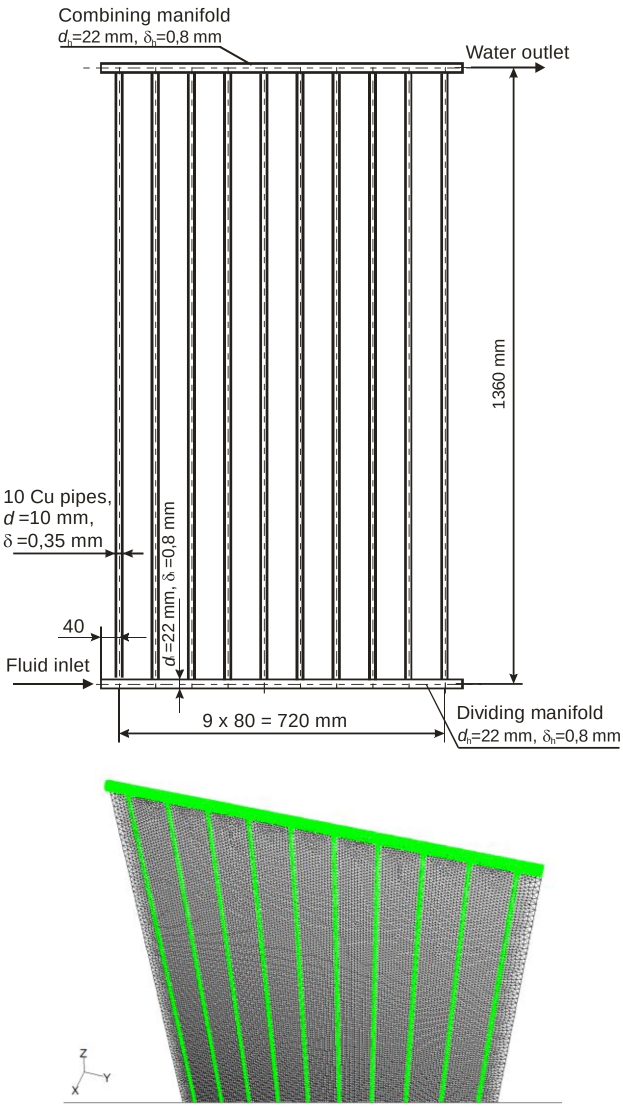

Figure 3. Basic geometry of the collector pipe system used in the research and a segment of the numerical mesh

4 RESULTS

There is a complex matrix of measurement results from the experimental research campaign conducted in the spring 2010 [18]. A comparative analysis between the experimental data and the CFD simulation results is a basis for optimisation 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 collector parameters fixed, which means that the solar radiation flux for the simulation module is varied. Examples of comparison charts are shown in Figures 4 and 5, indicating the measured total solar radiation at the experimental facility spot and the change of the measured and simulated outlet temperatures of the working fluid versus time.

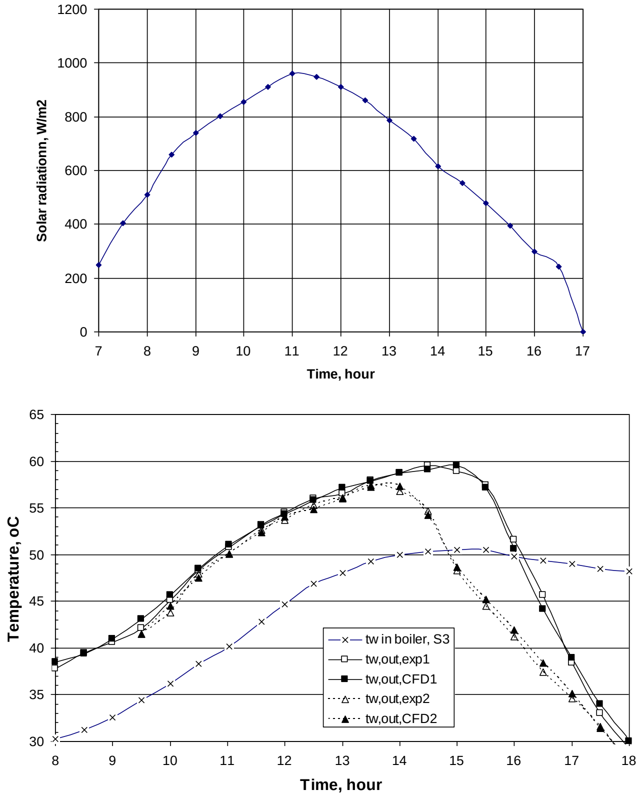

Figure 4. Solar radiation and working fluid temperature change, experimental and CFD results, 20.03.2010: 1 - moving collector, 2 - static collector

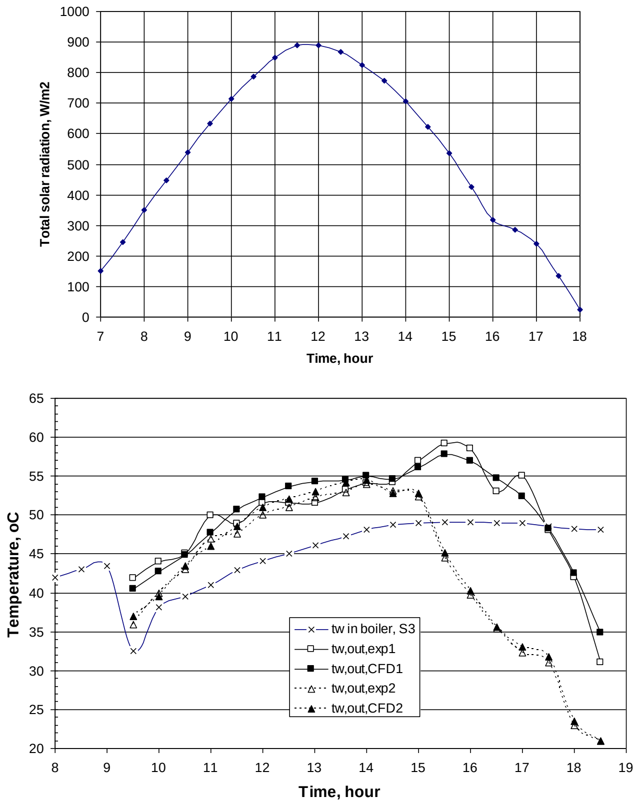

Figure 5. Solar radiation and working fluid temperature change, experimental and CFD results, 04.04.2010: 1 - moving collector, 2 - static collector

5 RESULTS

An experimental and CFD research has been conducted with the aim to assess the operation and to enhance the efficiency of a flat plate solar collector, by use of a controlled tracking system. The analysis shows that there is a satisfactory agreement between the experimental and numerically predicted values for different running conditions and flow rates. The CFD model results are closer to the experimental data in the case of the static collector.

The efficiency of the tracking system was confirmed by experimental verification, showing significant energy efficiency increase, compared to the immobile collector unit, which is particularly obvious in the afternoon hours.

Although there are some discrepancies, a general conclusion can be drawn that the CFD modelling and simulation gives good results and can be used for more complex problems.

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