Experimental and Numerical Study of Forced Circulation Solar Water Heaters (SWHs)

A. Rostamzadeh[1], M. Adim[2], S. Sabzi[2]

Abstract — In this paper, a forced circulation solar water heater (SWH) has been studied both experimentally and numerically. Outdoor condition is based on ambient climate of Tabriz. Flat plate collector was kept facing the equator at a tilt of λ+15° (λ is latitude of the place and λ=38.7 N for Tabriz) from the horizontal for getting maximum radiation. The Investigated system is consisted of a collector with total absorber area of 1.82 (m^2), a storage tank of 60 (liter) capacity, 12 tubes and an overhead tank placed at a higher level respect to the rest of the system. Also, a numerical model was developed to simulation of SWH. To discrete equations, finite volume method is employed. In addition, a numerical model of SWH with elliptical tubes was developed and results show that there is no significant difference in heat transfer rate between circular and elliptical tubes. Two major circumstances were investigated in this study namely parallel and series coupling of collectors. Finally, the simulation outcomes are compared with the experimental data and differences between numerical and experimental results have been reported.

Keywords — Solar water heater (SWH), Flat plate collector, Numerical simulation

1 Introduction

Iran has great potential for solar energy resources (compare with the other countries), over than 280 annual sunny days and mostly clear sky with the average solar radiation of 2000 (w/m^2) (more than world averages) mostly in central part of Iran. Except the nuclear energy and the water hydrodynamic energy behind the dams, the source of the renewable and fossil fuel energy is sun. Water heating is one of cases in which solar energy extensively used. The use of solar water heater raised increasingly because they are relatively inexpensive and easy to manufacture and maintain. They are a good alternative to electrical or gas water heater production. These prevent from emissions of harmful greenhouse gases associated to electrical production. Hot water is used in bathing, drinking and washing in houses, industries and commercial organizations. A number of investigations have been made by several researchers on the thermal performance of large forced circulation solar water heaters. Kettleborough [1] proposed using a system equipped with a temperature-regulating valve and concluded that its efficiency was higher than the traditional system. Mohsen and Akash [2] conducted an experiment on the performance of a compact SWH under local climatic conditions. The tested collector in this experiment was of a box type with single glazing. It was found that a temperature rise of 30 (°C) can be achieved by the system for a particular sunny day during the month of November. A primary study on solar water heaters was done by Whillier and Saluja [3] who tried to determine some factors affecting collector performance to predict the long term performance of solar domestic hot water (SDHW) system from short term test data. Mohsen and Nuseirat [4] evaluated the long term performance of the compact SWH using computer simulation and the results were compared with those obtained experimentally. The location used to perform the analysis is Amman (32° N latitude), the capital of Jordan. Spirkl and Muschaweck [5] used a plug flow model formulation and their focus of attention was on the storage tank of the system. A thermosiphon solar water heating systems with an intake auxiliary electric heater was simulated for different hot water load temperatures using trnsys (an energy system simulation program [6]) by Shariah and Ecevit [7], Shariah and Shalabi [8], Shariah and Löf [9] and Lima et al. [10]. The results of the simulation showed that the annual efficiency and solar fraction were functions of the hot water load temperatures. Sodha et al. [11] have studied and compared the hourly thermal performance of three built in storage solar water heaters with different designs each of 100 (liter) capacity. Design (I)

1. A. Rostamzadeh is Faculty member of Department of Mechanic, Tabriz Branch, Islamic Azad University, Tabriz, Iran, E-mail: arkhosroshahi@gmail.com
2. M. Adim is Mechanical Engineering student of Islamic Azad University-Tabriz Branch
E-mail: adim.mohammad@yahoo.com
2. S. Sabzi is Mechanical Engineering student of Islamic Azad University-Tabriz Branch
E-mail: sabzi.soheil@hotmail.com

consists of three tanks connected in series; in Design (II), a parallelepiped tank is divided into five zones with baffles and Design (III) is a simple parallelepiped tank. The first two designs help in inducing thermal stratification in the tank. They concluded that the performance of Design (II) is the best of the three. Hasan [12] performed experiments on solar water heaters with vertical as well as horizontal storage tank and concluded that horizontal tank systems work as good as systems with vertical tank. Pederson [13] gave a system design optimization for large building integrated solar heating systems in Denmark. Thermosiphon solar water heating systems have been studied extensively both experimentally and theoretically. Norton et al. [14] investigated adoption of three different approaches to performance modelling of solar water heaters and concluded that while simplified models could be used for family-size systems; the rigorous simulation models were better suited to larger scale and commercial applications. A numerical model to study horizontal and vertical storages in thermosiphon solar water heaters was proposed by Morrison and Braun [15]. In this work, changes in the collector efficiency factor, the overall loss coefficient, flow rate and the dependence of overall loss coefficient on the temperature have been neglected. The temperature of the collector and the storage and the resulting thermosiphonic flow rate were calculated and compared with the experimental data. Vertical storage tanks have lost popularity due to aesthetic issues and to lesser extent due to higher aerodynamic resistance to blowing winds. Tarhan et al. [16] investigated the effect of different phase change materials (PCM) on temperature distributions in trapezoidal built-in-storage solar water heaters and concluded that PCM storage units can be used to stabilize the water temperature during the day time and as a thermal barrier against heat loss during the night time. Several researchers worked on TSWH with direct connection to a horizontal storage tank. Kalogirou and Papamarcou [17] performed experimental validation of their numerical model of the system and found out that the annual solar fraction obtained was 79% for Nicosia, Cyprus and the system could cover all the hot water needs of a house of four people during the three summer months.

2 Experimental Procedure

The Investigated system in the present work is a flat plate collector which consists of tube to sheet collector modules (see Fig. 1). The experimental apparatus consists of a collector with total absorber area of 1.82 (m^2), a storage tank of 60 (liter) capacity, 12 tubes and an overhead tank placed at a higher level respect to the rest of the system. Tubes have a diameter of 1.5 (cm) with 194 (cm) length. Mass flow rate in all experiments is 0.005 (kg/s) and Inlet and outlet temperatures were 298 (K) and 358.3 (K), respectively. The fins of the absorbers are made of aluminium and are anodized black coating to increase the collectors overall absorption coefficient. The collector glazing is 3 (mm) sheet glass. The collector box is made of extruded aluminium with anodized coating. Since the local ambient temperature did not go below zero in the testing period, water has been used as the working fluid in the collector. The mantle storage tank is made of galvanized iron which is insulated by 8 (cm) of injected polyurethane foam. Temperature measurements were done by digital thermocouples with the range of -50 (°C) to 200 (°C) with accuracy of 0.1 (°C). In the present study, outdoor condition is based on the average climate of Tabriz. Flat plate collector was kept facing the equator at a tilt of λ+15° (λ is latitude of the place and λ = 38.7 N for Tabriz) from the horizontal for getting maximum radiation in winter. The test has done on 23 of July at noon (altitude = 66° and azimuth = 217° [18]) in a clear sky where the ambient temperature is 31 (°C) and relative humidity is 57%. Wind speeds achieve 3 (km/h) according to meteorological records.

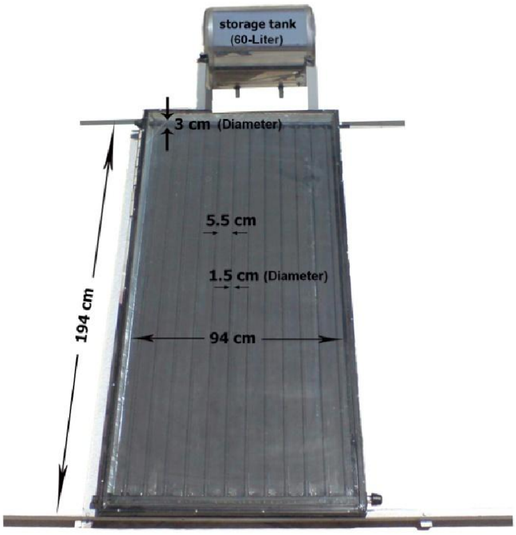


Fig. 1. Geometry of experimental apparatus

3 Governing Equations

Governing equations in the tubes are as follows:

$$div(\rho V) = 0 \tag{1}$$

$$div(\rho V u_i) = div[\mu .grad u_i] - \frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}[\mu \frac{\partial u_j}{\partial x_j}] + \rho g_i \tag{2}$$

$$div(\rho VT) = div[(\mu .grad .T] + S \tag{3}$$

Where ρ is water density, V is velocity vector, μ is viscosity, T is temperature, u_i is Velocity components and S denotes source term due to solar radiation.

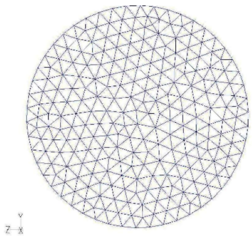
4 THE NUMERICAL METHOD

In the present paper, simulation of collector was done by using pressure-based finite volume method. In order to achieve thermal characteristics of SWH, both momentum and energy equations were solved. 3D, Steady state Navier-Stokes and energy equations with constant property of materials were discredited using finite volume method. Due to large difference in dimension of tube length and tube diameter, a very fine grid distribution is needed in the cross section of the tubes. The flow distribution through the tubes is investigated with heat transfer. The collector assumed to operate at a constant ambient temperature of 31 (°C) and to be heated with a solar irradiance of 1168 (W/m^2). The flow in tubes is laminar without phase change.

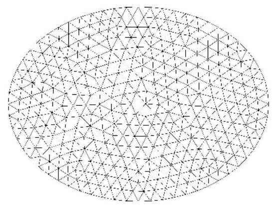
Table 1. Used parameters for simulations

Total absorber area	1.82 (m^2)
Collector tubes:	
Number of tubes	12
Tube diameter	1.5 (cm)
Length of tubes	194 (cm)
Space between tubes	5.5 (cm)
Header and lower tube diameter	3 (cm)
Storage tank capacity	60 (liter)
Storage tank insulation	Polyurethane foam
Thickness of Storage tank insulation	8 (cm)
Thickness of glazing sheet glass	3 (mm)
Experiment Conditions:	
Mass flow rate in tubes (Q)	0.005 (kg/s)
Inlet temperature	298 (K)
Outlet temperature	358.3 (K)
Ambient Conditions:	
Ambient temperature	304.2 (K)
Ambient relative humidity	57%
Wind speed	3 (Km/h)
Altitude of place	66°
Azimuth of place	217°
Digital thermocouples range	-50 (°C) to 200 (°C)
Solar irradiance	1168 (W/m^2)

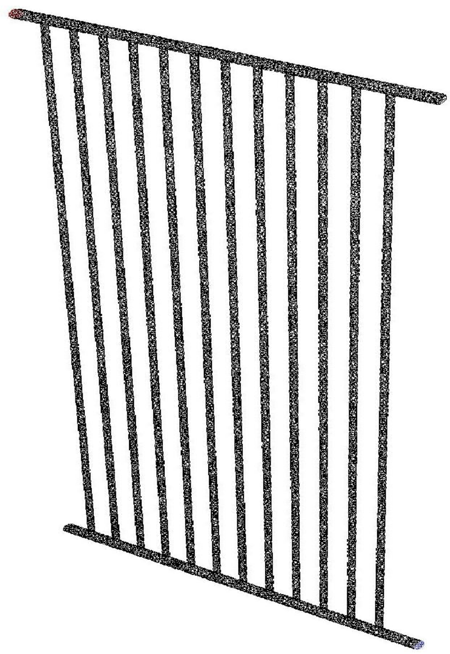
Simulation parameters is listed in Table 1. In order to achieve mesh-independent solution, meshes were refined gradually and the best mesh structure is shown in Fig. 2. Calculations were done so much until precious results were obtained, so preventive criteria for momentum, energy and continuity is 10^{-6}.



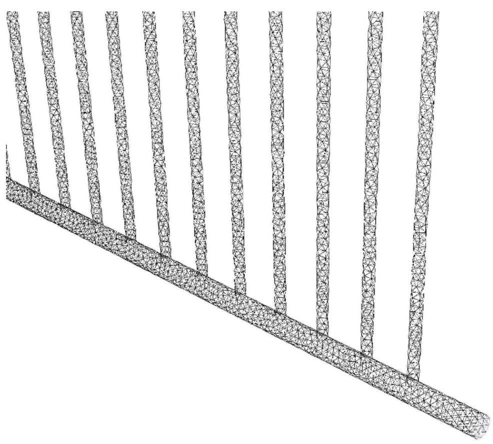
(a)



(b)



(c)



(d)

Fig. 2. Meshes used for domain of study: (a) Circular tube, (b) Elliptical tube, (c) and (d) Overal 3D mesh

Boundary conditions are as follows:
Mass flow for inlet and atmospheric pressure for flow outlet. Also, solar irradiance of 1168 (W/m^2) is applied to collector surface.

5 Results and Discussion

5.1. Circular Tubes

In the present research, simulation of SWH was done by using finite volume. Temperature distribution through the absorber tubes is shown in Fig. 3.

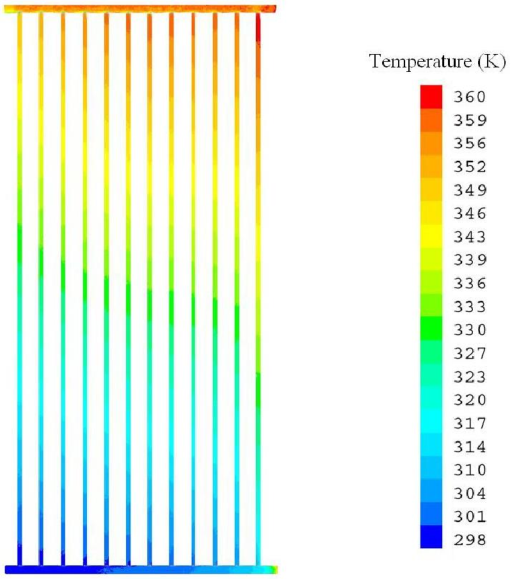


Fig. 3. Temperature contour for circular tubes

As shown in Fig. 3, temperature at the outlet is 360 K, while our experimental result was 358.3 K and there is 0.5% difference between numerical and experimental results. Axial temperature distributions along all tubes are approximately the same and linear distribution, as the results in Fig. 4.

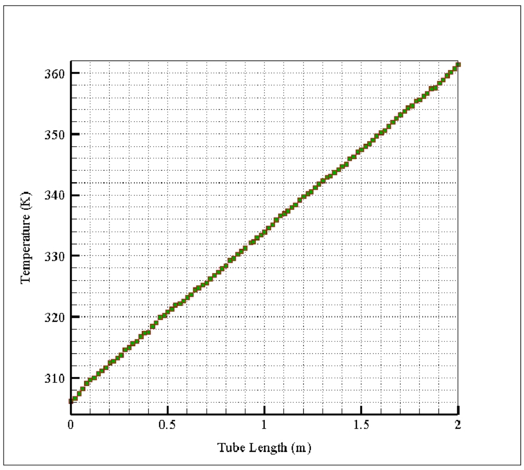


Fig. 4. Temperature distribution along tubes

An important parameter in thermal study is Nusselt Number and Fig. 5 illustrates Nusselt number along tubes. Theoretical correlation as Equation (4) can be expressed for Nusslet variation along tubes.

$$Nu = 78.3 - 89.3x + 56.8x^2 - 13.6x^3 \quad (4)$$

In above equation, x demenestrates tube length.

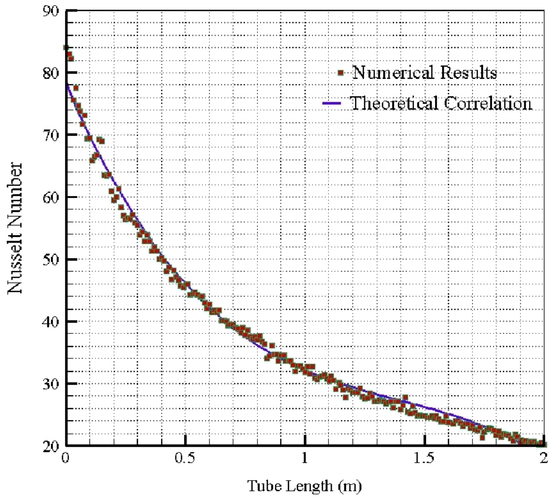


Fig. 5. Nusselt number along tubes

5.2. Elliptical Tubes

Numerical study was also done for SWH with elliptical tubes and outcome results compared with circular tubes. Temperature contour for this study is given in Fig. 6. As results show, outlet temperature with elliptical configuration is 362 (K) and there is no significant difference between circular and elliptical tubes. According to our results, because of difficulty in production of elliptical tubes, using elliptical tubes instead of circular tubes is not economically appropriate.

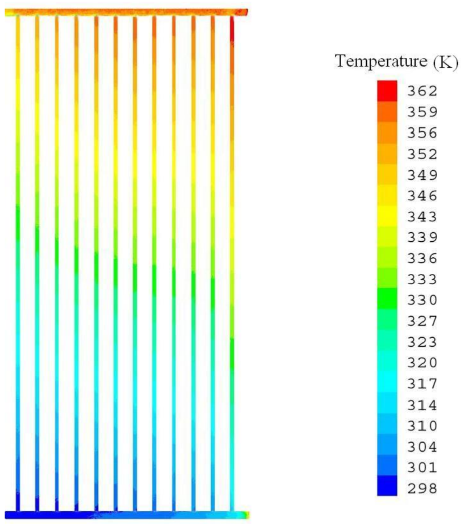
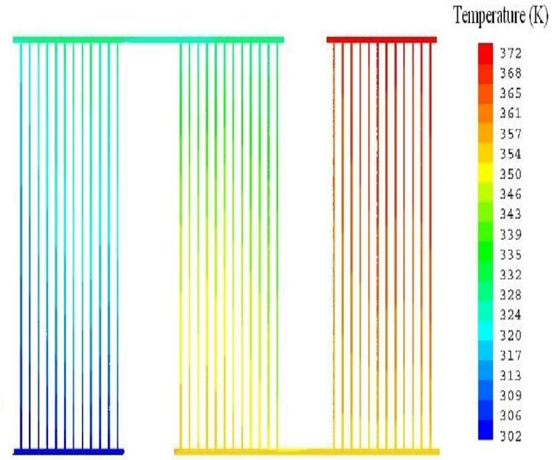


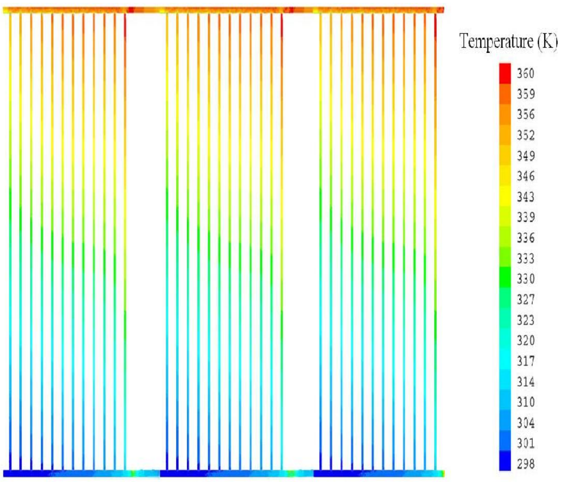
Fig. 6. Temperature contour for elliptical tubes

5.3. SERIES AND PARALLEL COUPLING OF SWHS

Another case that study in the present paper is series and parallel coupling of SWHs. By using series coupling of collectors, as illustrated in Fig. 7 (a), it is possible to reach high temperature differences with constant solar irradiance.



(a)



(b)

Fig. 7. Coupling of SWHs: (a) Series, (b) Parallel

Parallel coupling of SWHs causes to reach high mass flow rates in constant temperature. By using solenoid valves in construction of Fig. 7 (b), it is possible to change between series and parallel coupling when high temperature or high mass flow rate is needed, respectively.

6 CONCLUSIONS

A numerical and experimental investigation of the flow and temperature distribution in a forced circulation solar water heater is performed. Experimental tests were performed in Tabriz in clear sky where the ambient temperature is 31 (°C) with a solar irradiance of 1168 (W/m^2). In order to achieve constant mass flow rate, a forced circulation solar water heater (SWH) has been studied. Also, a numerical model was developed to simulation of SWH and finite volume method was applied to discrete governing equations. Temperature contour, Nusselt number and tempature distribution in tubes is presented. Mass flow rate in all experiments is 0.005 (kg/s) and Inlet and outlet temperatures were 298 (K) and 358.3 (K), respectively. According to numerical simulations, the maximum water temperature at the outlet is 360 (K). Both circular and elliptical tubes was sudied and results show that thermal characteristics of both systems are almost identical. In other case, parallel and series connection of SWHs is discussed. Parallel coupling of SWHs is suitable for high mass flow rates and series ones for high temperature at SWHs outlet.

NOMENCLATURE

λ	Latitude of the place
Nu	Nusselt Number $(Nu = hD/k)$
h	Heat transfer coefficient
D	Tube diameter
k	Thermal conductivity
Q	Mass flow rate
V	Velocity Vector
ρ	Water Density
T	Temperature
u_i	Velocity Components
S	Source Term
x	Tube Length

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