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Simulation of a solar domestic water heating system

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Abstract

This paper shows the modelling of a domestic solar water heating installation. The results of simulations performed on daily basis for a solar system (collector with surface of 2 m² and a storage tank of 200 litres), operated in Constantine (Algeria), which provides hot water for heating. The installation consists in a solar flat collector, a water storage tank, a source of auxiliary energy and radiators.
We analyse more accurately the influence of the thermosiphon-flow rate and consequently the stratification degree of the tank on the water heating system performances. The interest of this study resides in the approach used to model the tank and in the analysis of the number of the nodes used on the gained energy.

Keywords: Solar collector; Stratified tank; Flow rate; Modeling; thermosiphon

1. Introduction

Solar water heating systems have reached technical maturity and are used in many countries. After the first oil crisis in 1973, the strategies used by industrialised and developing countries to reduce their oil dependence have been numerous. A diversification of energy import, a structural change of the large domestic product (industrial development of activities using a low energy expenditure) or an increase of the national supply have been the essential measures taken by the countries with various degree of importance[1].
One of the most classical ways to use the solar energy is making domestic hot water. Solar systems for DHW production should be optimally designed and operated. This way, the energy effectiveness of these systems are often investigated, by using experiments or through modelling and simulations. This paper

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shows the results of the computer simulations carried out in order to investigate the effectiveness of a particular type of the solar system.
Such a system should consist of two main elements as solar collector and a storage tank. The mathematical model takes into account daily variations of ambient temperature and solar radiation. This mathematical model is used to develop specific simulation software, give the storage temperature and collector temperature we analyse the influence of the thermosiphon flow and consequently the stratification of the tank.

Nomenclature

Ac	area of solar collector (m²)
C_p	specific heat of water (J/kg K)
d	diameter of pipe (m)
f_2, f_1	outlet and inlet of the collector, respectively
L_{ct}	length connecting tubes (m)
K	thermal conductivity of material (W/m K)
g	acceleration of gravity (m/s²)
It	solar irradiation upon horizontal surface, (W/m^2)
m_h	water mass flow rate of the tank inlet (kg/s)
m_l	mass flow rate of hot water load from the tank (kg/s)
N	number of stratified layer
t	time (s)
T	temperature (K)
N_c	number of tubes in the collector
Q_u	heat transfer coefficient between air and collector surface(W/m² K)
Greek symbols	
ρ	density of the fluid, (kg/ m^3)
ν	kinematic viscosity (m²/s)
η_c	collector efficiency
θ	inclination angle of collector (°)
Subscripts	
i	i th segment of water in tank ,solar collector
c	circulating water
s	tank

a	ambient

2. Description of the System

A schematic diagram of the solar system modeled is shown in Fig. 1. It consists of a flat plate solar collector, a water-storage tank, a source of auxiliary energy [2]. The circulating water from the collector it gives its heat to the storage tank water and then returns to the solar collector where it is heated again by solar energy. An electric resistance heater is used for auxiliary heating when the temperature of the water in the storage tank is lower than 55ºC, before distributing it in the building (space to be heated) using a radiators heating.

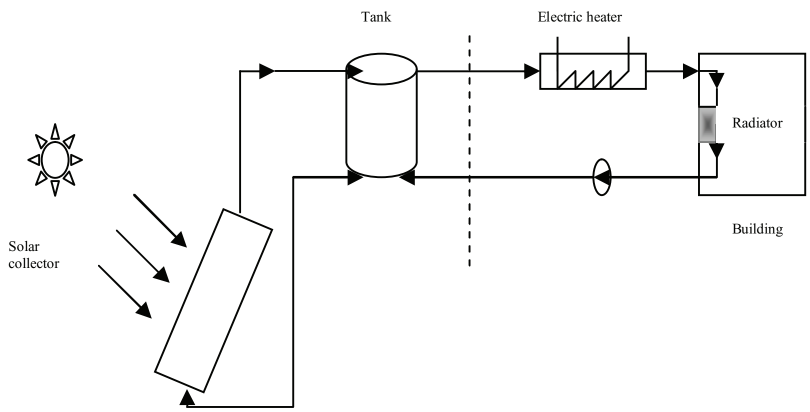

Fig. 1. Schematic diagram of solar heating system- type thermosiphon

3. Theoretical analysis: Equations and resolution

The mathematical simulation of a solar heating system operation is complex and not easy to exploit directly. Indeed, the analytical equations that characterize the heat and mass transfers in the collector that we use and that one finds in the works of referenced authors [1,2], are difficult to solve without significant simplified assumptions.

We present a model of finite differences which includes the essential thermal transfers. This model is composed of a serial assembling of many elementary models. Each model is based on a nodal discretisation of a collector section and of the storage circuit.

3.1. Solar collector

The simulation is done by dividing the transversal section collector into six isothermal regions: the glass cover, the air layer, the top half of the absorber, the water layer, the bottom half of the absorber and the insulation, therefore, we propose to dividing the length collector into ten sections in order to take into account the temperature distribution of the working fluid inside the collector.

Global equations [3]

$$m_i cp_i (dT_i / dt) = \sum_j U_{i,j} \left(T_j - T_i\right) + \phi \qquad (1)$$

The thermal performance of the solar collector was investigated, and the efficiency of the collector. Note that the efficiency of the η_c is defined as [4]:

$$\eta_c = Q_U / I_t A_c \qquad (2)$$

3.2. Storage tank

The heat storage water tank could be considered as a stratified water tank and could be modeled by dividing the tank into N nodes (sections), with energy balances written for each section of the tank. The energy equation took into account the energy gain from the solar collectors, energy lost to surroundings and energy consumed by the heating system. The result was a set of N differential equations that could be solved for the temperatures of the N nodes as a function of time. The simulation model of the heat storage water tank is shown in fig 2[5].

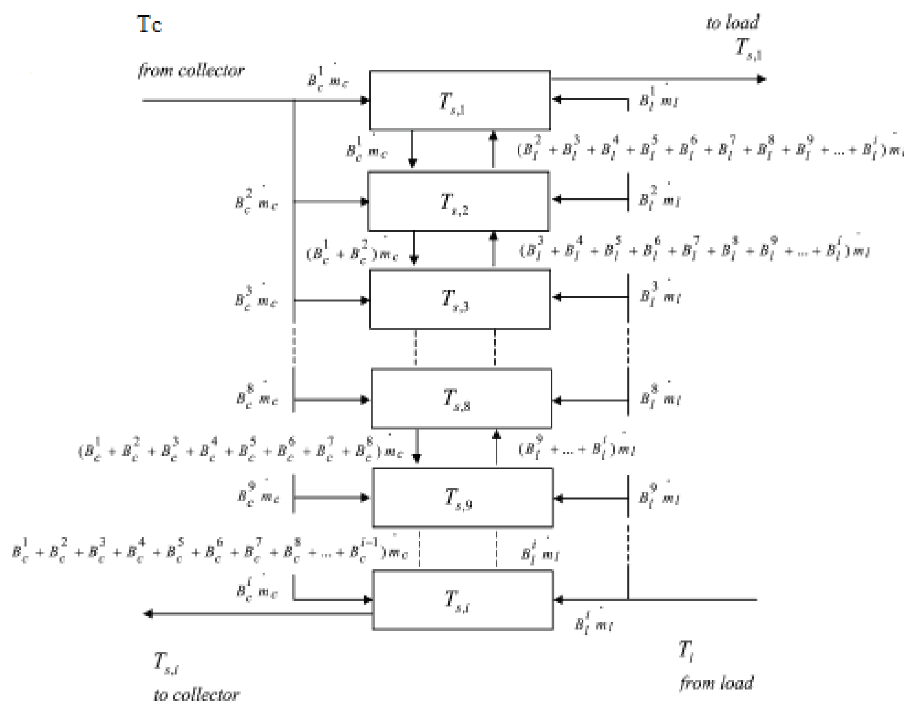

Fig. 2. *i* nodes stratified liquid storage tank

B^i_c is a collector control function, which can be defined to identify which node receives water from the collectors. [5, 6]:

$$B_c^i = \begin{cases} 1 & if \quad T_{s,i-1} \rangle T_c \rangle T_{s,i} \\ 0 & other \end{cases} \qquad (3)$$

B_l^i is a load return control function, which can be denoted to identify which node receives water returning from the floor heating system. [7]

$$B_l^i = \begin{cases} 1 & if \quad T_{s,i} \rangle T_L \rangle T_{s,i+1} \\ 0 & other \end{cases} \qquad (4)$$

The net flow between nodes can be either up or down depending upon the magnitudes of the collector and load. Flow rates and the values of the two control functions at any particular instant. It is convenient to define a mixed flow rate that represents the net flow into node i from node $i-1$, excluding the effects of flow, if any, directly into the node from load.

$$\gamma_i = m_h \sum_{j=1}^{i-1} B_c^j - m_l \sum_{j=i+1}^{N} B_l^i \qquad (5)$$

an energy balance on node i can be expressed as [7,8]:

$$m\, c_{p,i}(dT_{s,i}/dt) = U_i\, A_i (T_a - T_{s,i}) + B_c^i\, m_h\, cp_i (T_c - T_{s,i}) + B_l^i\, m_l\, cp_i (T_L - T_{s,i}) \qquad (6)$$

$$+ \begin{cases} \gamma_i\, cp_i (T_{s,i} - T_{s,i+1}) & if\ \gamma_i \langle 0 \\ \gamma_i\, cp_i (T_{s,i-1} - T_{s,i}) & if\ \gamma_i \rangle 0 \end{cases}$$

3.3. The thermosiphon loop

The governing equation for the momentum balance equation of the natural circulation loop is [9, 10]:

$$(8k\, m_c^2 / \rho\, \pi^2 d^4) + (1+\varphi).(128\, \nu\, L_{ct} m_c / \pi\, N_c d^4) - g\, \rho\, \beta \sin(\theta).(L_{ct}/2).(T_{f2} - T_{f1)} = 0 \qquad (7)$$

This quadratic equation in m_c allows calculation of the instantaneous theoretical fluid mass flow rate in the thermosiphon loop.

4. Results and discussion

A detailed simulation of the whole system was carried out in order to study the operation and the behaviour of water heating System and to simulate the diurnal temperature variations of the storage fluid and energy fluxes exchanged of each part in the solar heating system: collecting, storage and distribution. In the present study the simulation is carried out for the calculation, the month of February was chosen, which is considered as the coldest month according to the weather data of Constantine**.**

The performance of the systems was modeled by a simulation program written in Fortran programming language developed at the University of Constantine.

The program calculates the solar gain for the specified system, based on the radiation, the ambient temperature, the latitude, the parameters specifying the solar collector system, the volume of storage tank, the total energy demand of heat water and their daily load profiles. The time step for the calculation is set to two seconds

Table1: Input parameters of the simulation model

Design parameters	Data
Collectors surface	2m²
Glass	
1. Thickness	0.003 m
2. Mass density	2700 Kg m^{-3}
3. Specific heat	840 $J.k^{-1}m^{-1}$
Plates	
1. Thickness	0.002 m
2. Mass density	8900 Kg m^{-3}
3. Thermal conductivity	300 $W.k^{-1}m^{-1}$
Insulation	
1. Thickness	0.02 m
2.Mass density	24 Kg m^{-3}
3.Specific heat	919 $J.k^{-1}m^{-1}$
Storage tank Material—galvanized iron	
1. Height	1m
2. Diameter	0.5m
3. Capacity	200l
Load	
1. mass flow rate m_l	0.025 kg/s
2. inlet temperature T_{au}	55°C
3. outlet temperature T_L	45°C

Fig. 3 show the influence of the number of nodes on tank temperature calculated on one day of data. We modeled the tank using respectively 5, 10 15, 18, 20 and 22 nodes corresponding to the orifices number of the manifold diffuser. According to the number of nodes, the calculated performances are different, in order to take into account this stratification, We note that the modeling with 20 and 22 nodes conduces to the same results: so it seems to be not necessary to use more than 20 nodes and so, no more than 20 orifices, to study the behaviour of this solar domestic hot water. In the following of this article all the presented results will be computed with a twenty nodes model for the tank and so with a manifold diffuser with 20 orifices.

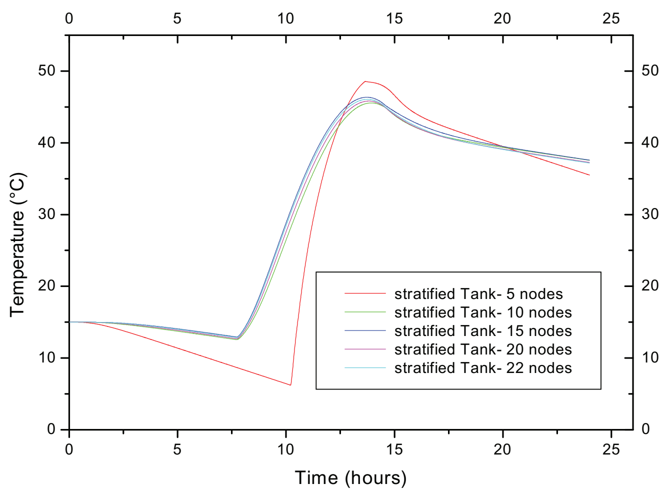

Fig. 3. Temperature in tank nodes 5.10.15.20

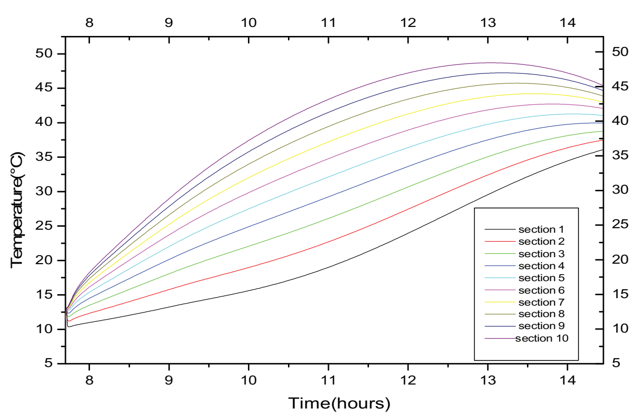

Fig. 4. Temperature profile in the collector

In what follows, all the results presented will be calculated with a model of twenty nodes for the tank.
We see in Fig. 4 the temperature profile in the collector computed from simulations.
We note in Fig. 5 the temperature profiles in the tank for a winter day, the final average temperatures in the storage tank 45°C ,degree of stratification max ($T_{s,1} - T_{s,20}$) = 25°C, the water temperatures of the sections distributed in a way increasing of bottom to the top of the tank.

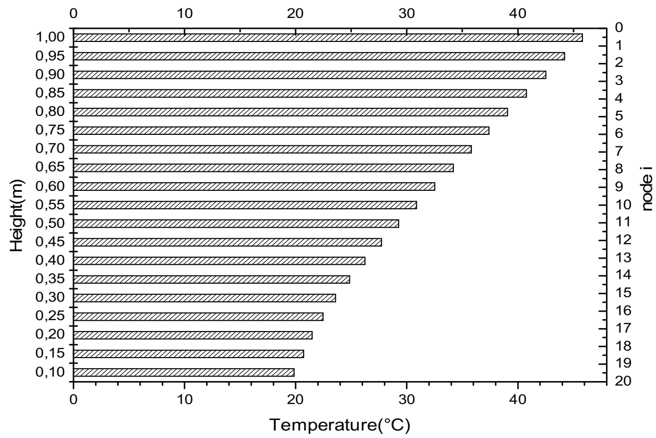

Fig. 5. Temperature profile in the tank

The storage fluid temperature and solar radiation for two days is shown in Fig 6, it is observed that the maximum temperature of the average tank is 48°C, starting from an initial temperature of 17°C for fresh water in the tank at 7.00 a.m. Three phases of heating-up periods can be observed. From 7.00 to 9.00 a.m., the water in the tank hardly warms up, as redistribution of temperature within the tank is taking

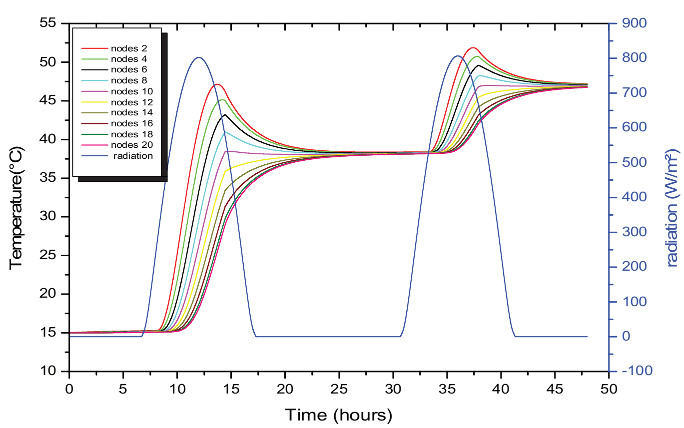

FIg.6. Evolution of the storage fluid temperature and solar radiation

place. After this period, there is a very rapid increase in the rate of heat collection, the water in the storage tank heats up very fast and increases in temperatures until, about 4 p.m. After this time there is a redistribution of temperature, whereas the maximum value of solar flux during the day is about 800 W/m².

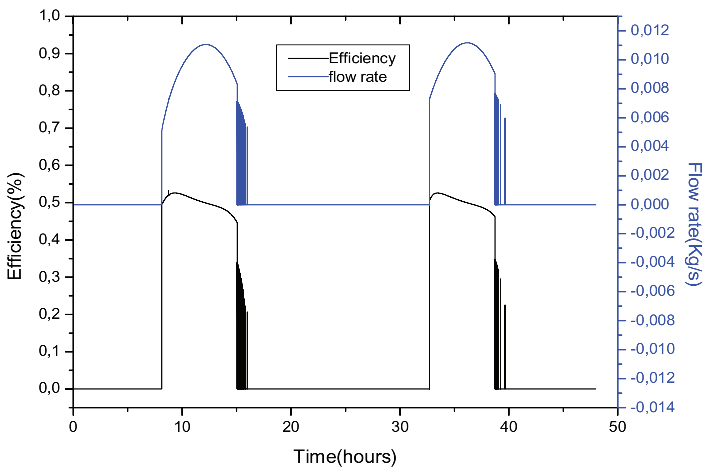

Fig.7. Evolution of the efficiency and flow rate

The variation of the flow thermosiphon and efficiency of the collector for two days is illustrated by fig 7, at about 8:30 a.m., $T_c \rangle T_s$ there is no flow in the collector, T_c increases rapidly until the difference ($T_c - T_s$) reaches the preset activation level the controller.

The collector loop flow is controlled by a controller, Flow is turned on when collector temperature is higher than the temperature of the tank the system is moving (natural circulation), in the contrary case, the system stops and the flow and efficiency is equal to 0.

Conclusion

The present model can be viewed as a new simulation model, which can be used for parametric analysis of domestic water heating systems. The theoretical model presented can be an efficient tool to predict and design solar systems operating under thermosiphon principle flow conditions.

The stratified storage tank has an advantage of obtaining higher heat energy output when compared to a conventional fully mixed hot water storage tank. In this study, a ulti-node model with variable inlets was chosen to analyse the temperature distribution in storage tanks. Consequently there is better stratification in the tank which improves the efficiency of both the auxiliary heater and the solar collectors.

Nevertheless, the presented results are theoretical and explanatory, we must in future work develop this system and verify all these simulation results.

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