NUMERICAL STUDY OF AN INTEGRATED COLLECTOR STORAGE SOLAR WATER HEATER

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Abstract

In this paper, we propose a numerical study of an integrated collector storage solar water heater. The numerical resolution of the governing equations was carried out using a commercial CFD code FLUENT 6.2 which is based on a finite volume method. The discussion is related firstly to the validation of the CFD model. Then, the effect of storage tank position was investigated with keeping the collecting area and the storage volume constant. The mean water temperature profile over time is studied for a day of May, from 6 am to 18 pm, to highlight this change’s effect on water heating process. Streamlines and temperature contours were also investigated for a cross section of the solar water heater.

Results show that this change improves the system’s operating by increasing conductive exchange.

Keywords

Integrated collector storage solar water heater
Energy generation and transmission
Heat and mass transfer

1. Introduction

The integrated collector storage (ICS) is the type of solar water heater that has retained its existence for well over a century. Compared to the flat plate thermosiphonic units (FPTU), ICS systems are less applied solar water heaters, although they are cheaper and more aesthetically attractive. The main causes are their higher thermal losses of storage tank during the night. Also, thermal protection of water storage tanks of ICS systems is not efficient enough, as the total, or a significant part, of its external surface, is used for the solar radiation absorption.

Since the sixties, ICS systems were the object of many studies, in order to understand and to improve the functioning of this type of solar water heater. An experimental investigation of integrated collector storage solar water heater has been performed, during a whole year, by Souliotis and al. [1], in order to correlate the observed temperature rise and the stratification of the stored water with the non-uniform distribution of the absorbed solar radiation. This study indicates that the upper part of the tank surface collects the larger fraction of the total absorbed solar radiation for all incident angles throughout the year. The research of Smyth and al. [2] are devoted to the study of an integrated collector storage solar water heater (ICSSWH) that can significantly reduce heat loss to ambient during non-collection periods. Results showed that over 60% of the thermal energy stored within the total vessel, and up to 67% of that in the upper immediate draw-off region can be retained over 16h non-collection period. A numerical study of an novel solar water heating system, modified cuboid solar integrated-collector-storage system with transparent insulation material(TIM), was carried out by Sridhar and al. [3] using FLUENT software. The specific conclusion mentioned here is that there is a marginal effect of the system’s depth and inclination angles on the convection in the enclosure. An experimental study of an ICSSWH has been performed by Chaouachi and al. [4]. This study indicates that such solar system presents acceptable thermal performances in spite of the collector simplicity.

Taking into consideration the great interest of understanding the operation of this solar system and the necessity of its performance improvement, an attempt is made to study this configuration of integrated collector storage solar water heater.
2. Numerical modeling

2.1. Governing equations
The equations governing the turbulent non stationary flow are the mass, momentum and energy conservation equations:

\[ \frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j} (\rho \bar{u}_i) = 0 \]  

\[ \frac{\partial}{\partial t} (\rho \bar{u}_i) + \frac{\partial}{\partial x_j} (\rho \bar{u}_i \bar{u}_j) = - \frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j} \left[ \mu \left( \frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} - \frac{2}{3} \delta_{ij} \frac{\partial \bar{u}_l}{\partial x_l} \right) \right] + F_i \]  

\[ \frac{\partial (\rho \overline{T})}{\partial t} + \frac{\partial (\rho \overline{u}_i \overline{T})}{\partial x_j} = \frac{\partial}{\partial x_j} \left( \frac{\lambda}{c_p} \frac{\partial \overline{T}}{\partial x_j} - \rho \overline{u}_j \overline{T} \right) + S_h \]  

2.2. k-\varepsilon Model
The turbulence model used for closing this problem is a first order model (k-\varepsilon). This model is governed by turbulent kinetic energy and dissipative kinetic energy equations:

\[ \frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho k u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k + G_b - \rho \varepsilon - Y_M + S_k \]  

\[ \frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho \varepsilon u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + C_{1\varepsilon} \frac{\varepsilon}{k} (G_k + C_{3\varepsilon} G_b) - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} + S_\varepsilon \]  

With:

\[ \mu_t = \rho C_{\mu} \frac{k^2}{\varepsilon} \]

This model requires the use of different empirical constants:

\[ C_{1\varepsilon} = 1.44, \quad C_{2\varepsilon} = 1.92, \quad C_{\mu} = 0.09, \quad \sigma_k = 1 \text{ and } \sigma_\varepsilon = 1.3. \]

2.3. S2S radiation model
The radiative transfer equation is given as follows:

\[ \frac{dI(\vec{r}, \vec{s})}{dS} + (\alpha + \sigma_s) I(\vec{r}, \vec{s}) = a n^2 \frac{\sigma T^4}{\pi} + \frac{\sigma_s}{4\pi} \int_0^{4\pi} I(\vec{r}, \vec{s}') \varphi(\vec{s}, \vec{s}') d\Omega' \]  

The surface to surface radiation model allows writing this equation as follows:
With:
K: N*N matrix
J: radiosity vector
E: emissive flux vector

2.4. Boussinesq approximation
This approximation considers that the fluid density is a function of temperature:

\[(\rho - \rho_0)g \approx -\rho_0 \beta (T - T_0)g\] (8)

With \(\beta\): Thermal expansion coefficient

For \(\beta (T-T_0) \ll 1\), this approximation gives the relation:

\[\rho = \rho_0 (1 - \beta \Delta T)\] (9)

2.5. Boundary conditions
Boundary conditions adapted for solving the equations governing the problem are:

<table>
<thead>
<tr>
<th>Surfaces</th>
<th>Boundary conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tank inlet and outlet</td>
<td>Adiabatic wall</td>
</tr>
<tr>
<td>Tank surface</td>
<td>Wall with heat exchange</td>
</tr>
<tr>
<td>Glass cover</td>
<td>Wall with imposed flow</td>
</tr>
<tr>
<td>Reflector surface</td>
<td>Adiabatic wall</td>
</tr>
</tbody>
</table>

Table 1: Imposed conditions on the solar water heater’s surfaces

3. Results and discussion

We consider the case of an integrated collector storage solar water heater, 36° inclined to the horizontal, tested between 6h and 18h under a Tunisian climate, to compare the numerical results with the experimental data of Chaouachi and al. [4], in order to validate our numerical code. Then we study the effect of the absorber’s position on the mean water temperature.

3.1. Comparison: Computed values – experimental data

3.1.1 Model validation
To validate our numerical computations, results obtained by the CFD simulation of the integrated collector storage solar water heater are compared with experimental data of Chaouachi and al. [4].

A three-dimensional modelling of the solar water heater was performed using Gamgit2. On figure 1, we present the most important components of the solar water heater which are the CPC reflector, the cylindrical tank and the glass, with their dimensions.
Figure 1: Description of the solar water heater

On figure 2, we plot a cross section of the solar system, which shows the generated hexahedral cells. The use of these cells is preferable as long as they fit perfectly to the geometry.

Figure 2: Mesh generated for a cross section of the solar water heater

On the figure below, we present the evolution of the incident solar flux on the 17th May, between 6am and 18pm. This solar flux incident on the glass surface is determined by the solar calculator of the S2S radiation model.
Figure 3: Temporal evolution of the incident solar flux on the glass surface

We present on the figure 4, for the same day and the same period, a comparison between the mean water temperature determined by numerical simulation, and that measured experimentally by Chaouachi and al. [4].

![Figure 4: Temporal evolution of the temperature](image)

The examination of this figure shows a good agreement between these two results.

### 3.1.2. Streamlines and temperature contours for the initial configuration

On figure 5, we present the temperature contours and streamlines each two hours, from 8am, for the plane (XOY).
We note that the recirculation zones are present since the beginning of the heating process. As the solar water heater is south-east oriented, these areas are duplicated and concentrated in the upper air volume, which has the highest temperature up to 14 pm. From 14 pm, when the solar radiation decreases, the water in the storage tank presents the highest temperature and these vortex structures decrease gradually.

### 3.2. Influence of the absorber position on the solar water heater's operating

#### 3.2.1. Geometry description and temperature profile

In this section, the absorber is placed at the bottom, in contact with the reflector. The studied configuration is shown below.
The mesh generated for the integrated collector storage solar water heater, after moving its tank is shown on figure 7:

![Mesh generated for the integrated collector storage solar water heater](image)

Figure 7. Mesh generated for a cross section of the modified solar water heater

The mean water temperature is shown in the graph below:

![Graph showing mean water temperature](image)

Figure 8: Effect of the tank position on the mean water temperature

This change allows an increase in temperature, especially in the afternoon. This can be explained by the fact that the solar water heater is south-east oriented, and direct sunlight is less important in the afternoon, which promotes heat transfer by conduction to that by radiation.

In addition, we obtain a 4°C higher water temperature at 18pm, which is an advantage considering the important night losses of this systems.

3.2.2. Streamlines and temperature contours for the modified configuration
We note that the recirculation zones are intense between 8am and 14pm. For the rest of the day, these areas become symmetrical, then disappear at 18pm. The contribution of conductive transfer in water heating process is marked by the temperature of 330k which is higher than that on the previous case.

4. Conclusion

In this present work, a numerical study of an integrated collector storage solar water heater has been conducted. The k-ε turbulence model is used to simulate the flow, and the S2S radiation model is considered to introduce the radiative term in the energy equation. It is shown that the prediction of this models agree reasonably with experimental results in the case of unsteady simulation of the solar water heater. Also, an attempt to improve the system’s operating was made; by changing its tank position. This change proved its efficiency, by raising the water temperature in the storage tank.

References