Numerical Study of the Convection in the Air Gap of a Solar Collector

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Abstract

World energy coming from the fossil resources is limited in its supply and it is responsible of the emission of many gases with greenhouse effect. Thus it is urgent to find new clean sources which are unlimited in their supply. Solar energy can have a good position to be a candidate of clean, inexhaustible and free source. Incidental solar energy can be transformed into thermal energy for various applications such as heating and production of hot water by using solar collectors. The thermal solar collectors present interesting problems which require more detailed studies. Among these studies, we can quote the problem of the transfer by convection between the absorber and the glass. Knowledge of this transfer by convection would allow an optimization of the solar collector. The objective of this work is to study numerically the influence of the thickness of the air gap between the absorber and the glass on the losses by convection at the glass.

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1. Introduction

Solar energy is a free and clean energy. It was used for a long time in several fields. With the pollution problem which is currently known with fossil energies which are limited in their supply, solar energy got a considerable technical development.

This energy is used in several applications such as heating, production of electricity, drying,… etc.

At low temperature, the plane solar collector plays a big role in the conversion of solar energy. Generally, a solar collector consists of an absorber surmounted by one or more glasses and isolated in bottoms and on the sides by a material with a low thermal conductivity (rockwool, glasswool, etc,…). The heat rate on the level of the absorber which is transferred to the heating fluid, is transported for use in several applications.

The efficiency of a thermal installation using solar energy depends on the efficiency of the solar collector. To increase the efficiency of a solar collector, it is necessary to increase the quantity of heat received by the absorber and to decrease the losses of heat towards the outside.

The most important thermal losses are located at the glass of the collector [1].

The solar heat collectors are installed with a slope to receive the maximum of the solar radiation. Convection heat occurs in the air gap of the solar collector as result of the difference in densities due to a difference in temperatures between the absorber and the glass.

The study of heat transfer in the space located between the absorber and the glass of a solar collector can give an idea on the structure of the flow and on the dominating heat transfer mode. While summarizing, this study is equivalent to a study of natural convection in tilted cavity having dimensions of the solar collector.

Several numerical studies of natural convection in a cavity were realized by several authors and we can quote the work of Shiralkar and Tien [2], Paolucci and Chenoweth [3], Durmmond and Korpela [4].

These authors analyzed the laminar natural convection in cavities heated with variable Prandtl numbers. Elsherbiny [5], studied the natural convection in tilted cavity by using an experimental method. For this study, various correlations were obtained for various slopes.

To have a good performance of a solar collector, it is necessary to limit the thermal losses towards the outside where the majority is localised on the level of the glass.

Several parameters such as the solar radiation, the slope of the collector, the choice of the fluid to heat, the thickness of the air gap etc…., have a direct effect on the efficiency of a solar collector.

The goal of this study is to see the influence of the air gap on the effectiveness of the collector. For that, we studied numerically the three-dimensional natural convection in various thicknesses of the air gap in order to have an optimal thickness allowing to giving minimal thermal losses at the glass of the solar collector.

2. Theory

For a steady flow of an incompressible and Newtonian fluid, the equations of continuity, movement quantity and energy can be written:
\[
\frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} = 0
\]  
(1)

\[
u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} = -\frac{1}{\rho} \frac{\partial P}{\partial x} + v \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right) - g \beta (T - T_0) \cos \alpha
\]  
(2)

\[
u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} = -\frac{1}{\rho} \frac{\partial P}{\partial y} - g + v \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} \right) - g \beta (T - T_0) \sin \alpha
\]  
(3)

\[
u \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z} = -\frac{1}{\rho} \frac{\partial P}{\partial z} + v \left( \frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} \right)
\]  
(4)

\[
u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} + w \frac{\partial T}{\partial z} = a \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right)
\]  
(5)

To write the equations above, viscous dissipation was taken negligible, gravity has a vertical effect and the properties of the fluid are supposed to be constant. The approximation of Boussinesq is applied [6]. The Rayleigh number can be given by the following formula:

\[
Ra = \frac{g \beta q e^4 \Pr}{\lambda S v^2}
\]  
(6)

\(g, \beta, \lambda, v\) are the gravity, the dilation coefficient of the fluid, the thickness of the air gap, thermal conductivity and the kinematic viscosity of the fluid (air).

\(q\) is the heating rate of the fluid. This parameter corresponds to the flow imposed on the absorber.

To calculate the average Nusselt in the air gap, the correlation of Hollands et al. (1976) is used:

\[
\bar{Nu} = 1 + 1.44 \left[ 1 - \frac{1708}{Ra \cos \phi} \right]^{1/6} \left[ 1 - \frac{1708}{Ra \cos \phi} \right]^{-1} - \left[ \frac{Ra \cos \phi}{5830} \right]^{1/3} - 1
\]  
(7)

Where the sign (+) implies that the term between brackets is taken equal to zero when it is null.

2.1. Boundary conditions

The studied geometry is a tilted rectangular cavity, composed of an absorber (lower face), of an insulating sides and a glass (higher face). This geometry is represented in figure 1. The studied geometry is 1.05 m width and 2.002 m length. The thickness of the cover is fixed at 0.004m. The thickness of the air gap varies according to the studied case and it takes values of 1 cm, 1.5 cm and 2 cm.
By reason of symmetry and in order to decrease the computing time, half of the geometry in z direction was taken and the slope of the collector is selected equal to $50^0$. The above equations depend on the boundary conditions.

On the walls, the speed satisfies the nonslip condition except for the wall located on half of the collector length (symmetry) where a null gradient speed is applied.

Null variations in temperature on the side walls are also applied because the walls are insulated. A condition of symmetry was applied to the half of the collector length.

On the absorber and on the glass, a condition of constant flow and a mixed condition of flow (convective and radiative) are applied respectively.

3. Results and discussion

The convection in the air gap of the solar collector is studied numerically by using Fluent software. The thermal losses are in relation with the climatic conditions surrounding the collector, such as the outside and the sky temperatures. This is confirmed by the boundary condition imposed on the outside of the glass.

Simulations are carried out in stationary mode with the Boussinesq approximation and the SIMPLE algorithm is used to couple the speed and the pressure. The results convergence is strongly related to the grid, a choice of the finest grid is necessary, however the computing time depends on the number of selected nodes. A solution is to take a grid tightened near the walls and slightly evolutionary to the centre of the cavity.

The choice of the relaxation factor has also an effect on the various results obtained and its value must be around of 0,9.

Fig. 1. Studied solar collector
To see the effect of the grid on the results, two grids were selected for each configuration (each thickness of the air gap). After superposition, we see clearly that the grid does not influence the results obtained.

In this study, the profiles of speeds and temperature are presented for various thicknesses of the air gap at $x=L/2$ according to the height of the collector (Table 1).

The air movement is characterized by a recirculation with a high speed in the center of the cells, and a low speed along the walls. The average air velocity varies between two values of which one has a zero value near to the walls and the other is maximum in the center of each rotation cell.

For a temperature difference between the hot wall and the cold one which exceeds a certain threshold, movements in the fluid occur in the form of convectives cells what allows the fluid to overheat more. Under special conditions, the configurations are stable (the resultant of all the forces which intervene is equal to zero), however a numerical disturber can always exist, the convectif movement can start and for a particle which is near the absorber, it warms up, its density decreases and it goes up under the action of Archimedes push. For a cold particle located in top having a high density it goes down.

For a tilted solar collector, the convection is weak compared to the horizontal case where it becomes maximum and this maximum value depends on the thickness of the air gap and on the imposed temperature variations.

When the inclination angle of the confined space (air gap) varies, the heat transfer by convection decreases from the horizontal case (lower wall heated) to a zero value (pure conduction) for the case of the confined space heated by the top.

The number of Nusselt evaluates the ratio of the convectif transfer to that by conduction. It is equal to the unit in the case of conduction.

In the case of a tilted solar collector (figure 2) with a flow of 105 W imposed on the absorber, we note that the cells of convection do not appear contrary to the horizontal case, this is due to the fact that the heat transfer by convection is weak.

The temperature variation, has the form of layers in the air gap and these layers are dense close to the hot wall what is in agreement with the theory.

Fig. 2. Temperature variation with a flow of 105W
To see the effect of the flow imposed on the absorber, on the structure of the flow, we have applied other larger values (500 W and 800 W) what corresponds to sunnier days, for that, convection cells appear. There is a structure which corresponds to that of Rayleigh Bénard which appears (figure 3 (a)).

For low Rayleigh numbers, the structure of the flow is ordered, which is represented in figure 3 (a). When the Rayleigh number increases, these structures become deformed, irregular and chaotic. This implies the passage to the transitory turbulent mode explained by the appearance of the plumes. This is shown in figure 3 (b).

The Rayleigh number was calculated from the flow imposed on the absorber by replacing the difference temperatures by its expression calculated from the heating flow. In this case, the Rayleigh value is over-estimated owing to the fact that the thermal losses front face of the collector are not taken into account.

\[ Ra = \frac{g \beta qe^4 Pr}{\lambda V^2} \]  

(8)

Fig. 3. (a) Temperature variation with a flow of 500W; (b) Temperature variation with a flow of 800 W

Fig. 4. (a) Rayleigh variation; (b) Nusselt variation
In figure 4 (a), we see that the Rayleigh number increases with the increase of the thickness of the air gap and with the increase of the flow imposed on the absorber.

In Figure 4 (b), we note that the average Nusselt in the air gap has the same variation as the Rayleigh number.

In addition, we note that the slope of the solar collector has an effect on the convection coefficient. This coefficient decreases with the slope of the collector.

Figure 5 (b) shows that with the increase of the thickness of the air gap, the flow lost through the glass decreases and it is also proportional to the flow imposed on the absorber. The temperature of the absorber decreases with the increase of the confined space thickness (figure 5 (a)).

We can conclude that the heat taken from the absorber was not lost completely through the glass, a part will be used in the heating of the air gap.

With the increase of the thickness of the air gap, we reduce the flow released towards outside but we increase the heating flow of the confined air.

Thus it is necessary to find an optimum between the two flows allowing to have a good collector thermal efficiency.

With regard to the influence of the flow imposed on the absorber, we note that the temperature of the absorber and the flow lost by the glass increase with the increase of the flow imposed on the absorber.

Table 1. Speed and temperature profiles for various thicknesses of the air gap for two types of grids

<table>
<thead>
<tr>
<th>Air gap thickness : 1 cm</th>
<th>Air gap thickness : 2 cm</th>
<th>Air gap thickness : 1.5 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>First Grid (B): 35x156x35</td>
<td>First Grid (B) : 35x216x35</td>
<td>First Grid (B): 35x196x35</td>
</tr>
<tr>
<td>Second Grid (C): 40x166x40</td>
<td>Second Grid (C) : 40x226x40</td>
<td>Second Grid (C): 40x206x40</td>
</tr>
</tbody>
</table>

Fig. 5. (a) Absorber temperature variation; (b) Lost flow variation
4. Conclusion

A three-dimensional thermal convection study in various thicknesses of the air gap of a thermal solar collector was carried out by using the Fluent software. Various simulations carried out showed us the importance of certain parameters to arrive at a good results convergence, in particular the form and the size of the grid as well as the iteration number. For a weak heat flow imposed on the absorber, conduction dominates, for high heat flows, the convection dominates and the structures of the flow develop: it is the Rayleigh Bénard convection. In this study, we concluded that the convection in the air gap is unsteady and turbulent. The absorber temperature varies with the thickness of the air gap, consequently the temperature of the heated fluid varies in the same way. This study will enable us to determine the thermal losses of the glass of a solar collector and consequently, we will determine the optimal thickness allowing to arrive at a better efficiency. In this first study, we note that for a thickness of about 1 cm the glass losses are weak. We intend to introduce in this study a model of the radiation but before adding it, we want to make sure of the independence of the numerical tool on the physical phenomenon.

References