Numerical analysis of heat transfer rate from absorber of a flat-plate type solar collector to the tube

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Abstract. Flat plate type solar collector is known as the simplest solar collector. However, its thermal efficiency is very low in comparison with other type of solar collector such as evacuated tube. The heat transfer mechanism in the flat plate type solar collector should be elaborated to improve thermal efficiency of a flat plate type solar collector. In this work, commercial code computational fluid dynamics is employed to explore heat transfer rate from the collector plate to the collector tube. The objectives are to explore the fluid flow characteristics in the solar collector and to estimate the useful heat transfer rate. The solar collector is modelled as a two-dimensional computational domain. The conservation mass, momentum equations and energy equations are developed and solved iteratively. Temperature and pressure distributions are plotted and velocity vector is presented. The results reveal that the heat transfer rate from the absorber plate is 28.955 Watt. The transfer rate from the air to the pipe is 24.06 Watt. On the other hand, heat loss to the atmosphere is 4.92 Watt.

1. Introduction

The world population and living standard are increasing. In the present time, the population of the world is estimated around 7.5 billion people. The world population has increased more than 1.5 billion in the last twenty years. In parallel, the living standard of the human being is also increasing. In order to support the increases of world population and living standard, the energy demand increases significantly. In the present, the energy demand of the human being is mainly supported by energy from fossil. Since the resources are limited, the new and renewable energy sources are extremely needed. One of the potential renewable energy source is solar energy. This motivates researchers to improve present technology and to search new technology related to solar energy harvesting. As a result, the solar energy industry is building up steadily in all over the world. This is due to high demand for renewable energy need. In the same time, the conventional solar energy sources, the fossil fuel, is limited and becoming less and the price is expensive [1]. The solar energy can be harvested in two different ways, they are solar photovoltaic and solar thermal technologies. The solar energy thermal can be employed to power solar desalination [2 - 6], solar cooling [7 – 10], solar drier [11 – 13], solar water heater [14 - 22] etc. The main component of the solar thermal technology is the solar collector. There are several types of solar collectors have been investigated and reported in literature such as flat-plate type collector, CPC, evacuated tube, etc. The simplest type of solar collector is the flat-plate type collector.
Typically, in the top cover flat-plate type solar collector installed with double glass cover. The objective is to reduce the heat loss from the top. The heat from plat absorber will be transferred as a heat loses to the air above the top cover through the air gap between the glasses. Here, the heat transfer mechanism is natural convection within the enclosure. Investigations on the heat transfer mechanism with in the air gap between the glasses cover have been found in the literature. Varol and Oztop [23] reported a comparative numerical study on natural convection in inclined wavy and flat-plate solar collectors. It was shown that flow and thermal fields are affected by the shape of the enclosure and heat transfer rate increases in the case of wavy enclosure than that of a flat enclosure. The effect of inclination to the wavy and flat-plate solar collectors has also investigated [24]. Kumar [25] reported a study on the natural convective heat transfer in a trapezoidal enclosure of box-type solar cooker. In the study, several indoor simulation experiments in steady state conditions were carried out. The experimental results were used to develop heat transfer correlation. It was shown that the values of convective heat transfer coefficient and top loss coefficient for rectangular enclosure are lower by 31-35% and 7 %, respectively.

Due to increasing of Computational Fluid Dynamic (CFD) method and computational capability, a commercial code has been typically employed to optimize the design of a flat-plate type solar collector. Martinopoulos et al. [26] reported a study on the behavior of a polymer solar collector experimentally and numerically. Solar irradiation, as well as convection and heat transfer in the circulating fluid and between the parts of the collectors, is considered in the model. Selmi et al. [27] reported on the use of CFD commercial code to simulate heat transfer process in a flat-plate type solar collector. Recently, Ambarita [14-22] is focusing research on the development of hybrid solar water heater. Several related studies have been performed such as effect of fins in the plate collector [14], effect of the inclination [15], and effect of the plate absorptivity [16]. It is shown that many parameters affect the performance of the flat-plate type solar collector. The objective of this study is to explore the characteristics of heat transfer mechanism from the plate collector to the tube where the heated working fluid flows. The results are expected to support the necessary information in developing high-performance flat-plate type solar collector.

2. Method
In the Sustainable Energy and Biomaterial Centre of Excellent, Faculty of Engineering University of Sumatera Utara, we are developing a high-performance flat-plate solar collector. The developed solar collector is designed for several applications such as drying, adsorption cycle, solar desalination, and solar water heater. Figure 1(a) shows a solar water heater system developed in our laboratory. The system consists of a flat-plate solar collector, transfer fluid system and hot water tank. In the present work, the authors focus on the flat-plate solar collector. The schematic diagram of the solar collector is shown in Figure 1(b). It consists of double glasses cover, insulation material and serpentine tube. The heated water is flowed inside the tube by using a pump. The pump which is used to flow the transfer fluid is powered by photovoltaic.

2.1 Numerical Method
As mentioned in the previous section, the objective of the study is to explore the heat transfer rate from the absorber plate to the tube. It is assumed that all each tube experiences the similar flow characteristics. By adopting this assumption, only a symmetrical computational domain is taken into account. Figure 1(c) shows the computational domain that is used in this study. For the computational domain several assumptions have been made as follows. The analysis is assumed to be the two-dimensional problem. The fluid is air which is treated as an incompressible fluid and it is a laminar flow and no variation during time (steady state flow). In addition, viscous dissipation is neglected, the gravity generates buoyancy force in the vertical direction. It is assumed that fluid properties are constant but density is not constant but varied with variation of temperature of the fluid. In order to model the buoyancy force, the Boussinesq approximation is employed. The radiative heat transfer is neglected. By using the above assumptions, the governing equations are developed.
The generated governing equations are mass conservation, $x$-momentum and $y$-momentum equations, and energy equation. They are written in the following equations, respectively.

\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0
\]  

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

\[
u \left[ \frac{\partial u}{\partial x} + v \frac{\partial v}{\partial y} \right] = -\frac{1}{\rho} \frac{\partial P}{\partial y} + \mu \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right) + g \beta (T - T_i)
\]  

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

Where $u$ and $v$ are the velocity vector in $x$- and $y$-directions, respectively. In the analysis, non-dimensional parameters are stated in the followings.

\[
Ra = \frac{g \beta \Delta T H^3}{\nu^2}
\]  

\[
Pr = \frac{\nu}{\alpha}
\]  

The rate of energy leaving the absorber is calculated by the following equation:

\[
\dot{Q}_{abs} = \int_{x=0}^{x=L} -k \frac{\partial T}{\partial y} |_{y=0} \, dx
\]  

Since the temperature distribution above the absorber plate is not calculated, the heat transfer rate to the ambient air is given by the below equation.

\[
\dot{Q}_{abs} = \int_{x=0}^{x=L} h(T - T_w) \, dx
\]
where \( h \) is the convective heat transfer coefficient. In this is study it is given. As mentioned in the previous section, the objective of this study includes the heat transfer rate from the plate collector to the tube, here the heat transfer rate to the tube is calculated by the below equation.

\[
\dot{Q}_{\text{tube}} = \int_{r} -k \frac{\partial T}{\partial r} \, ds
\]

The well known finite volume method is used to convert the governing equations into a set of linear equations. The SIMPLE algorithm is employed to couple the velocity field, pressure field, and temperature field. The simulations are carried out using FLUENT code.

3. Results and Discussions

3.1. Method Validation

Before used to simulate the problem, the developed method has been tested. In the first test, grid independent test is carried out. In the second test, numerical validation test is performed. In the numerical validation test, natural convection in a cavity was analysed. The results are compared with previous results. At Rayleigh number \( 10^5 \), the averaged Nusselt resulted by Vahl Davis [28], Fusegi et al. [29] and Tiwari R K and Das [30] are 4.519, 4.646 and 4.45, respectively. At the same conditions, the result of the present method is 4.518. The maximum difference is only 2.8\%. In addition, At Rayleigh number \( 10^6 \), the averaged Nusselt resulted by Vahl Davis [28], Fusegi et al. [29] and Tiwari R K and Das [30] are 8.779, 9.012 and 8.806, respectively. The maximum difference with the present method is only 1.49\%. Based on this method validation, it can be said that the present method shows a good agreement in comparison with method found in literature. Thus, the present method can be used to analyse the problem.

3.2. Fluid flow characteristics

Fluid flow characteristics will be analysed in term of pressure distribution and vector velocity. Figure 2 shows the pressure distribution in the computational domain. It can be seen that the domain can be divided into two different pressure distributions. The first is in the upper part which is the fluid between the double glass cover. The second is in the lower part which is the fluid between the lower glass cover and the absorber plate. The high pressure and the low pressure shown by red and blue colour.

![Figure 2. Pressure distribution in the computational domain](image-url)
Figure 3 shows the vector velocity distribution in the computational domain. It can be seen that the method can clearly predict the flow within the cavity. The fluid flow can be divided into two different domains. In the first domain, the fluid inside the enclosure between the double glass cover, some Rayleigh-Bénard cells captured. These cells make the natural heat transfer mode from the bottom glass to the top glass. In the second computational domain, the enclosure between the bottom glass cover and plate absorber, two circulations are captured. Starts from the middle of the computational domain, the fluid will flow up to the top. Before reaching the top, it will separate into two different streams to the right and to the left. Each stream will flow down and hit the the pipe. As a note, the working fluid flows inside the tube. This tube is heated by the fluid that circulates in the enclosure. The heat transfer on the surface of the tube affected by the velocity distribution around the tube.

![Figure 3. Vector velocity within the computational domain](image)

3.3. Heat transfer rate
The heat transfer rate will be analysed by using temperature distribution and the value of heat transfer rate from the absorber to the surrounding and to the tube. Figure 4 shows the temperature distribution within the computational domain. In the top enclosure, between the top and bottom glasses, the temperature distribution is stratified by the flow pattern. It can be seen the temperature of the top glass close to the ambient temperature and temperature of the bottom glass closer to the upper part of the bottom enclosure. Temperature distribution in the enclosure between the bottom glass and plat absorber strongly affected by the flow pattern in the enclosure. Since the flow starts from the middle of the plate, temperature of the fluid around this area is relatively higher. It means heat transfer rate from the plate absorber to the air is relatively low on this area. The circulation of the fluid within the enclosure transfer the heat from the absorber plate to the tube.

In this simulation, temperature of the absorber plate, tube surface and ambient temperature are kept constant at 100°C, 40°C and 35°C, respectively. By using these data, heat transfer analysis is carried out.
The results reveal that the heat transfer rate from the absorber plate is 28.955 Watt. The transfer rate from the air to the pipe is 24.06 Watt. On the other hand, heat loss to the atmosphere is 4.92 Watt.

![Temperature distributions](image)

**Figure 4.** Temperature distributions in the computational domain

4. **Conclusions**
Numerical analysis of heat transfer rate from absorber of a flat-plate type solar collector to the tube has been carried out. The objective is to explore the characteristics of heat transfer mechanism from the plate collector to the tube where the heated working fluid flows. The solar collector that is analyzed is the collector from a hybrid solar water heater. Two dimensional governing equations are developed and those equation are solved using CFD commercial code. The pressure distribution, vector velocity and temperature distributions were plotted. The results reveal that the heat transfer rate from the absorber plate is 28.955 Watt. The transfer rate from the air to the pipe is 24.06 Watt. On the other hand, heat loss to the atmosphere is 4.92 Watt.

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