Effects of the inclination angle on the performance of flat plate solar collector

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Abstract. Double glasses cover is typically used in a flat plate solar collector to decrease heat losses to ambient. The working principal of the cover is to allow the solar irradiation hit the plate absorber and blocks it using natural convection mechanism in the enclosure between the glasses. The performance of the enclosure to block the heat loss to the surrounding affected by the inclination angle of the collector. The objective of this study is to explore the effect of the inclination angle to the performance of the solar collector. Numerical simulation using commercial code Computational Fluid Dynamic (CFD) has been carried out to explore the fluid flow and heat transfer characteristics in the enclosure. In the result, streamline, vector velocity, and contour temperature are plotted. It was shown that the inclination angle strongly affects the performance of the collector. The average heat transfer coefficient decreases with increasing inclination angle. This fact suggests that too high inclination angle is not recommended for solar collector.

1. Introduction
As a fact, the world population has increased significantly. It is estimated that the present world population is 7.5 billion people and it will be increased more than 1.5 billion, in the last two decades. To support the people activities and life needs, the world’s energy demand also increasing significantly. Preventing an energy crisis is one of the most common issues of the 21st century. Solar energy, among other renewable sources of energy, is a promising and freely available energy source for managing long term (sustainable) issues in energy crisis. Solar energy industry is developing steadily all over the world because of high demand for energy while major energy source, fossil fuel, is limited and other sources are expensive [1]. In particular, Indonesia has a big potency of solar energy [2] that can be harvested in solar thermal and photovoltaic. Solar energy thermal can be used as an energy source to power solar desalination [3,4,5], solar refrigeration [6,7], solar water heater [8,9], solar cooker [10,11], solar drying process [12], etc. One of the key component of solar thermal development is the solar collector. Many types of solar collector can be found in the literatures and the flat-plate type solar collector is the simplest solar collector and it is very popular [13].

In the flat-plate type solar collector, to decrease the heat loss from the top, a double glass cover is typically used. Studies on the free convective heat transfer mechanism in the enclosure between cover
of flat-plate solar collector have been reported in literature. Varol and Oztop [14] reported their work on a comparative numerical study on natural convection in inclined wavy and flat-plate solar collectors. It was shown that flow field and thermal characteristic are affected by the shape of the enclosure and heat transfer rate increases in the case of wavy enclosure than that of flat enclosure. The effect of inclination to the wavy and flat-plate solar collectors has also explored [15]. Kumar [16] reported the study on natural convective heat transfer in trapezoidal enclosure of box-type solar cooker. 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.

Recently, Computational Fluid Dynamic (CFD) commercial code has been used to optimize the design of a flat-plate type solar collector. Martinopoulos et al. [17] studied 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 their model. Selmi et al. [18] employed CFD commercial code to analyze heat transfer process in a flat-plate type solar collector. The above studies show that heat transfer analysis and flow characteristics within the enclosure of double glass cover play an important role in designing and developing a high performance flat-plate type solar collector. In the field, the flat-plate type solar collector usually installed with inclined position. Thus, the fluid flow and heat transfer coefficient within an inclined double glasses cover need to be explored. The objective of this paper is to explore the heat transfer and flow characteristics in the inclined enclosure of a double glass cover. The numerical results will be compared with empirical correlations found in the literature. The results are expected to support the necessary information in developing high performance flat-plate type solar collector.

2. Method

As a note, our research group known as Sustainable Energy and Biomaterial Centre of Excellent, Faculty of Engineering University of Sumatera Utara is developing high performance flat-plate solar collector. The collector is designed for several applications such as drying, adsorption cycle, solar desalination, and solar water heater. Typical of the flat-plate type solar collector is shown in Figure 1. The focus on the present study is the enclosure in the top cover of the solar collector, and the inclination angle of the flat-plate solar collector is from 30°, 45°, 60°, 70° respectively.

2.1. Numerical Method

The problem of the present works is solved using numerical approach. For simplicity, only the enclosure between the upper and bottom glasses is taken account into consideration. The computational domain is shown in Figure 1. In the analysis, the domain is assumed to be two-dimensional case. The flow in the computational domain is incompressible laminar flow and steady state. In addition, there is no viscous dissipation, the gravity acts in vertical direction, and fluid properties are constant except in density of the fluid. The Boussinesq approximation is employed to model the buoyancy force. By using the above assumptions, the governing equations are shown in the following.

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

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

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

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

Where \(u\) and \(v\) are the velocity vector in \(x\)- and \(y\)-directions, respectively. In the analysis, the non-dimensional parameters are explained below.
\[ Ra = \frac{\gamma \beta \Delta T H^3}{\nu^2} \text{Pr} \]  

(5)

Where Pr is Prandtl number and calculated by

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

(6)

\[ \text{Figure 1. Computational domain for several analysis} \]

The convective heat transfer coefficient \( (h) \) is calculated using non-dimensional Nusselt number. It is calculated using the below equation.

\[ h = \frac{Nu \times k}{H} \]  

(7)

Where \( k \) [W/mK] is the conductive heat transfer coefficient of the air in the enclosure and \( H \) [m] is the distance between the double glasses. The Nusselt number in equation (7) is presented using local and average Nusselt number. The local Nusselt number in the bottom and top surfaces are formulated by

\[ Nu_x = \frac{H}{(T_i - T_e)} \left. \frac{\partial T}{\partial y} \right|_{y=0} \]  

(8)

and

\[ Nu_x = \frac{H}{(T_i - T_e)} \left. \frac{\partial T}{\partial y} \right|_{y=H} \]  

(9)

, respectively. The average Nusselt number is calculated by the below equation.
\[
\bar{Nu} = \frac{1}{L} \int_{-L}^{L} Nu, dx
\]  
(10)

All of those governing equations are converted into linear equations by employing finite volume discretization method. The system of linear equations for all fields are solved using SIMPLE algorithm. The commercial code of ANSYS FLUENT is employed to carry out the simulation.

2.2. Empirical correlation

The results of numerical simulation will be compared with the analytical results. In the analytical solution, the below empirical correlations are found in the literature. The first correlation is given by Jacob [19].

\[
\bar{Nu} = 0.195 Ra_H^{0.25} \quad \text{for} \quad 10^4 < Ra_H < 4 \times 10^5
\]

(11a)

\[
\bar{Nu} = 0.068 Ra_H^{1/3} \quad \text{for} \quad 4 \times 10^5 \leq Ra_H < 10^7
\]

(11b)

In the more recent experimental study using air inside the enclosure, Holland et al. [20] proposed an empirical correlation for inclined enclosure between average Nusselt number and Rayleigh number. The equation is given in the below equation.

\[
Nu = 1 + 1.44 \left[ 1 - \frac{1708 (\sin 1.8 \phi)^{1.6}}{Ra \times \cos \phi} \right] + \left[ \left( \frac{Ra \times \cos \phi}{5830} \right)^{1/3} - 1 \right]^2
\]

(12)

The above equation is claimed to be valid for tilt angle from 0° to 75°. In that equation the meaning of the “+” exponent is that only positive values of the terms in the square bracket are to be used and if the value is negative, the value will be converted into zero.

3. Results and Discussions

3.1. Numerical Validation

The present numerical method has been validated with previous work and reported in the previous work [21]. The selected numerical validation case is a laminar natural convection heat transfer from a square cavity heated left wall and cooled from right wall. While, the top and bottom walls are insulated. The results are compared for Rayleigh number $10^5$ and $10^6$. The results of the present method show a very good agreement with the previous results. Thus, the present method can be used to explore the problem.

3.2. Flow and heat transfer characteristics

Numerical simulation has been performed for a case with Rayleigh number $Ra_H = 1.90 \times 10^6$. The dimension of the enclosure are $L = 1 \text{m}$ and $H = 10.0 \text{cm}$. Thus, the aspect ratio of the enclosure is $AR = 10$. The inclination angle is varied. Figure 2 shows streamlines, temperature distributions, and vector velocity for the case with inclination angle of 30°. The streamlines show that the Bernard cells are generated in the enclosure. However, the dimension is not similar as shown in the horizontal enclosure [21]. The temperature distribution shows that on the hot surface of the glass, several hot spots (dead zones) are captured. On these areas the heat transfer coefficient will be decreased due to low temperature gradient. The plotted vector velocity shows that the pattern of Bernard cell follows the inclination surface. In other words, the form of Bernard cell is not horizontal rectangular but a rhombus form. These facts will affect the heat transfer characteristics.

In order to explore the effect of the inclination to the flow field characteristics, streamline, temperature distribution, and vector velocity for inclination angle of 45°, 60°, 70° respectively are shown in figure 3, figure 4, and figure 5, respectively. The comparison of the figure shows when the inclination angle increased over than 30° the flow pattern become unpredictable. At inclination angle of 45°, only several Bernard cells presence in the enclosure. For inclination angle of 60° and 70°, only small cells are captured and at the upper part a bigger circulation flow is captured.
Figure 2. Flow characteristics with angle $30^\circ$

Figure 3. Flow characteristics with angle $45^\circ$

Figure 4. Flow characteristics with angle $60^\circ$
Figure 5. Flow characteristics with angle 70°

(a) Streamlines

(b) Temperature Distribution

(c) Vector velocity

Figure 6. Locally heat transfer Coefficient

(a) 30°

(b) 45°

(c) 60°

(d) 70°
Figure 6 shows local heat transfer coefficient on the hotter surface of the glass cover. The figure shows that at 30°, the pattern of local heat transfer coefficient is similar. This is because the Bernard cell in the enclosure presence with similar size. This results in similar pattern, maximum on the areas with high temperature gradient and minimum at low temperature gradient. When the inclination angle increased to 45°, only several maximum heat transfer coefficients presence in the enclosure. For the inclination angle of 60° and 70°, the heat transfer rate on the surface is mainly low. However, only on the upper part the heat transfer coefficient is high. It is even higher than the maximum value at low inclination angle.

The average heat transfer coefficient and average Nusselt number at different inclination angles are shown in Table 1. The table shows that heat transfer coefficient decreases with increasing inclination angle. This is because at high inclination angle the hot surface is dominated by dead zones which has low temperature gradient. This fact suggests that too high inclination angle is not recommended for solar collector. However, further research need to be carried out to combine the effect of solar radiation to the absorber plate.

| Collector Angle | $\bar{N}_u$ Number | $\bar{h}$ [W/m²K] |
|-----------------|----------------------|-------------------|
| 30°             | 4.35                 | 2.38              |
| 45°             | 4.15                 | 2.27              |
| 60°             | 3.84                 | 2.09              |
| 70°             | 3.53                 | 1.93              |

4. Conclusion

A numerical simulation using commercial code CFD has been carried out in order to explore the heat transfer and fluid flow characteristics in enclosure between double glasses cover of a flat-plate type solar collector. The method has been validated for a natural convection in a square enclosure heated and cooled from side walls, respectively. The validated method than used to explore the problem. The conclusions of this study are as follows. The inclination angle strongly affects the fluid flow and heat transfer characteristics of in the enclosure. The average heat transfer coefficient decreases with increasing inclination angle. This fact suggests that too high inclination angle is not recommended for solar collector. However, further research need to be carried out to combine the effect of solar radiation to the absorber plate.

References
[1] Kannan N and Vakeesan D 2016 Renewable and Sustainable Energy Reviews 62, 1092-1105
[2] Ambarita H 2017 Journal of Physic: Conference Series 801(1), 012093
[3] Ambarita H 2016 Case Studies in Thermal Engineering 8, 346-358
[4] Ambarita H 2016 IOP Conference Series: Materials Science and Engineering 180(1), 012024
[5] Setyawan E Y, Napitupulu R A M, Siagian P and Ambarita H 2017 IOP Conference Series: Materials Science and Engineering 237 012012
[6] Ambarita H and Kawai H 2016 Case Studies in Thermal Engineering 7 36-46
[7] Sitorus T B, Napitupulu F H and Ambarita H 2016 International Journal of Technology 7(5), 910-922
[8] Ambarita H and Sitepu T 2017 IOP Conference Series: Materials Science and Engineering 237 012014
[9] Ambarita H, Abdullah I, Siregar C A, Siregar R E T and Ronowikarto A D 2017 IOP Conference Series: Material Science and Engineering 180(1), 012030
[10] Ambarita H 2017 ARPN Journal of Engineering and Applied Sciences 12(19), 5357-5365
[11] Sitepu T, Gunawan S, Nasution D M, Ambarita H, Siregar R E T and Ronowikarto A D 2016 IOP Conference Series: Materials Science and Engineering 180(1) 012032
[12] Dina S F, Ambarita H, Napitupulu F H and Kawai H 2015 Case Studies in Thermal Engineering 5 32-40
[13] Pandey K M and Chaurasiya R 2017 Renewable and Sustainable Energy Reviews 67 641-650
[14] Varol Y and Oztop H F 2008 Building and Environment 43 1535-1544
[15] Varol Y and Oztop H F 2007 Building and Environment 42 2062-2071
[16] Kumar S 2004 Renewable Energy 29 211-222
[17] Martinopoulos G, Missirlis D, Tsilingiridis G, Yakinthos K and Kyriakis N 2010 Renewable Energy 35 1499-1508
[18] Selmi M, Al-Khawaja M J and Marafia A 2008 Renewable Energy 33 383-387
[19] Jacob M 1949 Heat Transfer, New York, Wiley
[20] Hollands K G T, Unny T E, Raithby G D and Konicek L 1976 Journal of Heat Transfer 98, 189-193
[21] Ambarita H 2017 IOP Conference Seris: Material Science and Engineering (Accepted for publication)