Numerical study on the effects of absorptivity on performance of flat plate solar collector of a water heater

D R S. Tambunan¹, Y P Sibagariang², H Ambarita¹,²,*, F H Napitupulu¹ and H Kawai³

¹Mechanical Engineering Department, Faculty of Engineering, Universitas Sumatera Utara, Jl. AlmamaterKampus USU, Medan 20155, Indonesia
²Sustainable Energy and Biomaterial Centre of Excellent, Universitas Sumatera Utara, Jl. AlmamaterKampus USU, Medan 20155, Indonesia
³Mechanical Engineering Department, Muroran Institute of Technology, 27-1 Mizumoto-cho, Muroran 8585, Hokkaido, Japan

Corresponding author: himsar@usu.ac.id

Abstract. The characteristics of absorber plate of a flat plate solar collector play an important role in the improvement of the performance. In this work, a numerical analysis is carried out to explore the effect of absorptivity and emissivity of absorber plate to the performance of the solar collector of a solar water heater. For a results comparison, a simple solar box cooker with absorber area of 0.835 m × 0.835 m is designed and fabricated. It is employed to heat water in a container by exposing to the solar radiation in Medan city of Indonesia. The transient governing equations are developed. The governing equations are discretized and solved using the forward time step marching technique. The results reveal that the experimental and numerical results show good agreement. The absorptivity of the plate absorber and emissivity of the glass cover strongly affect the performance of the solar collector.

1. Introduction
In order to avoid the catastrophe of the globe due to global warming, emission of Greenhouse gas gases to the atmosphere must be reduced. One of the potential solutions is to enhance the use of renewable energy resources. Solar energy is known as a potential renewable energy resource. It is convinced, it will play an important role in the future energy demand. In a year, the globe is exposed by 3,400,000 Exa-Joule of solar energy. This is a vast amount of energy. It can fill the present world energy consumption by only 1 hour 15 minutes of irradiation [1]. However, at the present time, only a very little portion of the human energy consumption is filled with the solar energy. According to REN21, since 2030 solar energy application will increase significantly. Thus, studies on solar energy have increased significantly [2]. Industry related to solar energy application is developing constantly in all over the world. This is because of twofold, increasing energy demand and limitation on major energy source the fossil fuel. Indonesian islands have a big potency of solar energy. It is also constant in every year [3]. The solar energy can be harvested by solar photovoltaic and solar thermal methods. In the solar thermal method, the solar energy can be collected and used as a heat energy for several applications such as solar drying process [4], solar adsorption refrigeration [5], solar desalination [6,7,8], solar water heater [9], solar cooker [10], etc.
There are many types of solar collectors have been studied and reported in literature. The most popular one is flat-plate type of solar collector due to simplicity and easy to use [11]. However, the thermal performance of the flat-plate type of solar collector is still low. Many researchers have been reported their study on the heat transfer characteristics and heat loss from a flat-plate type solar collector. Varol and Oztop [12] reported a comparative numerical study on natural convection in inclined wavy and flat-plate of solar collectors. It was shown that flow and thermal fields were affected by the shape of the air space (cavity). The heat transfer rate increases in the case of the wavy cavity in comparison with the flat surface cavity. The influence of inclination to the flat-plate and wavy solar collectors has also investigated [13]. It was shown that heat transfer is increased with increasing Rayleigh number and aspect ratio, and it is decreased with increasing wavelength. Kumar [14] studied natural convective heat transfer in the trapezoidal profile of an enclosure of a box-type solar cooker. It was revealed that in comparison with the rectangular profile, the values of convective heat transfer and top loss coefficient for rectangular enclosure are lower by 31-35% and 7%, respectively.

Those reviewed studies showed that investigation on the heat transfer characteristics of flat-plate type solar collector has come under scrutiny. The focuses are mainly on the profile and operating parameters such as Rayleigh number. To the best knowledge of the authors, the only limited study focused on thermal characteristics of the flat-plate solar collector materials. In this study, a flat-plate type solar collector that is used in a simple solar box cooker is studied numerically. The objective is to explore the effect of the absorptivity and transmissivity of the solar collector material to the performance. The results are expected to supply the necessary information in developing an effective and efficient solar box cooker.

2. Method
In this study, two approaches have been carried out, they are numerical and experimental methods. The experimental work is used to validate the numerical results. The validated numerical method will be used to investigate the effect of absorptivity and transmissivity of the solar collector. Here, an experimental apparatus has been designed and fabricated. The experimental apparatus is depicted in figure 1.
Figure 1. (a) Photograph of the solar collector and (b) computational domain

As shown in figure 1, the solar collector is categorized as a flat-plate type solar collector with double glasses cover in the top with absorber area of 0.835 m × 0.835 m. In order to decrease the heat loss, the bottom and wall of the solar collector are made of a series of insulation materials. They are rock wool, styrofoam, and wood, respectively. The dimension and configuration of the material are shown in the figure. The load to the solar collector is water which is placed in a cylindrical cooking container and placed in the middle of the collector. The container is made of aluminum with diameter and height of 30 cm and 12 cm, respectively.

2.1 Numerical Method

In the numerical method, the solar collector is divided into 12 components. The lumped capacity assumption is employed for all divided components. Thus, the temperature of all materials is uniform. The properties of each component are assumed to be uniform. Figure 2(b) shows the dimensions and temperature notation of every component. The governing equation is developed by employing energy conservation to each material. The energy conservation for absorber plate yield:

\[ m_p c_p \frac{dT}{dt} = \tau^2 \alpha I A_p - FC_{15} (T_1 - T_{s1}) - FR_{13} (T_1 - T_3) - FR_{12} (T_1 - T_2) - \frac{1}{R_{t1}} (T_1 - T_{t1}) \]  

where \( m_p \) [kg] and \( c_p \) [J/kg K] are the mass and specific heat of the absorber plate. The parameters of \( I \) [W/m\(^2\)], \( \alpha \), and \( \tau \) are solar irradiance, absorptivity of the absorber plate and transmissivity coefficients of the glass cover, respectively. The air inside the solar collector is assumed to be one substance with uniform temperature of \( T_{t1} \). Thus, energy conservation to the air gives:

\[ (\rho V_{a} c_p) \frac{dT_a}{dt} = FC_{15} (T_1 - T_{s1}) - FC_{52} (T_5 - T_{2}) - FC_{53} (T_5 - T_{3}) - FC_{56} (T_5 - T_{6}) - FC_{56a} (T_5 - T_{6a}) \]  

Where \( FC \) [W/K] is a factor to represent convective heat transfer coefficient from any surface. The subscript 1, 5, 2, 3, 6 refer to surfaces shown in figure 1. In addition, 6t and 6w refer to the top surface and the wall surface of the container, respectively. The double glasses cover is made of two glasses with similar emissivity (\( \varepsilon \)) and thickness. The energy conservation to the glass gives:

\[ m_c c_s \frac{dT_s}{dt} = (1 - \tau) I A_s + FR_{15} (T_1 - T_{s1}) + FC_{34} (T_3 - T_{4}) - FR_{43} (T_4 - T_{amb}) - h_s A_s (T_4 - T_{amb}) \]  

\[ m_c c_s \frac{dT_s}{dt} = (1 - \tau) I A_s + FC_{35} (T_3 - T_{s2}) + FR_{34} (T_3 - T_{4}) + FR_{32} (T_2 - T_{s2}) - FC_{34} (T_3 - T_{4}) - FR_{43} (T_3 - T_{4}) \]  

Where \( h_s \) [W/m\(^2\) K], \( A_s \) and \( T_{amb} \) [°C] are convective heat transfer coefficient from the top glass to the ambient air and temperature of the ambient air, respectively.

As mentioned above that the load for solar collector is water placed in a cooing vessel. In the process, the cooking vessel and water receive the heat from the air inside the solar collector through side wall and top wall of the vessel. In addition, the top surface of the cooking vessel also acting as a solar collector and it receives solar irradiance. Heat transfer from the absorber plate to the bottom and radiative heat transfer from the wall of the vessel are neglected. The temperatures of the vessel and the water are assumed to be homogenous. Thus, energy conservation in the container yields to:

\[ (m_f c_f + m_v c_v) \frac{dT_v}{dt} = FC_{56a} (T_5 - T_{s5}) + FC_{56b} (T_5 - T_{s5}) + \tau^2 \alpha I A_i \]  

Where the subscript \( f \) and \( c \) represent the water and the vessel, respectively.

Employing the energy conservation to the rock wool, styrofoam, and wood result in the following equation.

\[ m_w c_w \frac{dT_w}{dt} = \frac{1}{R_{t1}} (T_1 - T_{t1}) - \frac{1}{R_{t3}} (T_3 - T_{t3}) \]  

\[ m_r c_r \frac{dT_r}{dt} = \frac{1}{R_{t1}} (T_1 - T_{t1}) - \frac{1}{R_{t3}} (T_3 - T_{t3}) \]
Employing the energy conservation in every material of the wall of the solar box solar cooker (inner plate, rock wool, Styrofoam, and wood) will give the following equations:

\[
m_c c_w \frac{\partial T_w}{\partial t} = \frac{1}{R_{w}} (T_w - T_i) - \frac{1}{R_{w}} (T_w - T_o)
\]  

(7)

\[
m_w c_w \frac{\partial T_o}{\partial t} = \frac{1}{R_{o}} (T_o - T_i) - FC_{wo} (T_o - T_w)
\]  

(8)

Where the subscripts \(rw\), \(st\), \(wd\), and \(a\) refer to the rock wool, styrofoam, wood, and ambient, respectively. Employing the energy conservation in every material of the wall of the solar box solar cooker (inner plate, rock wool, Styrofoam, and wood) will give the following equations:

\[
m_c c_p \frac{\partial T_{pp}}{\partial t} = F_{R_{12}} (T_p - T_{1}) + FC_{52} (T_5 - T_{2}) - F_{R_{23}} (T_{2} - T_{3}) - \frac{1}{R_{210}} (T_{2} - T_{0})
\]  

(9)

\[
m_c c_o \frac{\partial T_{o}}{\partial t} = \frac{1}{R_{210}} (T_{2} - T_{o}) - \frac{1}{R_{o11}} (T_{10} - T_{1})
\]  

(10)

\[
m_c c_{st} \frac{\partial T_{st}}{\partial t} = \frac{1}{R_{o11}} (T_{10} - T_{st}) - \frac{1}{R_{112}} (T_{11} - T_{12})
\]  

(11)

\[
m_w c_{wd} \frac{\partial T_{wd}}{\partial t} = \frac{1}{R_{112}} (T_{11} - T_{wd}) - \frac{1}{R_{210}} (T_{12} - T_{0})
\]  

(12)

All of those governing equations, equation (1) to equation (12), are converted into linear equation system by using discretization technique. In this method, the used technique is forward time step marching. After several numerical experiments, the value of \(\Delta t = 1\text{sec}\) is used due to stability consideration.

3. Results and Discussions

3.1. Solar Irradiance and Numerical validation

![Figure 2. Measured, theoretical and modelled solar irradiance](image.png)

As a note, the source of energy for the solar collector is solar irradiance. The solar irradiance during the experiment is measured and recorded. The measured data will be used to model energy input in the numerical simulation. The theoretical clear sky irradiance measured solar irradiance, and the modelled one is depicted in figure 2. In the modelled solar irradiance, the maximum solar irradiance is 722 W/m²,
and it occurred at 12.19 of local time. The total solar energy resulted from the solar radiation and by the proposed model is the same. This model will be used in the numerical simulation as heat flux to the absorber plate of the collector.

A numerical validation test has been performed to the method before it is employed to analyze the problem. Two experiments have been carried out. Temperature history of water vessel at loads of 3 kg and 6 kg water are selected for comparison. Numerical simulations using the developed method are also carried out at the same load as experiments. Temperature history resulted from numerical simulation, and experimental one is shown in Figure 3. The figure reveals that for all loads the temperature history from the experimental and numerical results agree very well. It can be said that the numerical simulation accurately predicts the value of the temperature of the water. Based on this numerical validation, the developed numerical method can be employed to analyze the problem.

![Figure 3](image)

**Figure 3.** Numerical validation of the proposed model

### 3.2. Effect of glass transmissivity

The simulation is made for water load of 5 kg. Figure 4 shows the effect of glass transmission coefficient to the characteristics of the solar collector. Here the characteristics are examined by using temperature of the absorber plate, temperature of the glass cover 1 and temperature of the glass cover 2. In this study, the coefficient of glass transmission is varied from 0.70 to 0.95. The figure shows that temperature of the absorber plate increases with increasing glass transmission coefficient. This is because the higher transmission coefficient transfers more solar irradiance to the plate absorber. The increasing temperature of absorber plate is proportional to the increasing glass transmission. It can be seen that at transmission coefficient of 0.7, the maximum temperature of the absorber plate was only 102°C. If the transmission coefficient increased to 0.95 the maximum increased up to 122°C. However, the increasing maximum temperature is not followed by glass cover temperature. The figure shows that temperature of both glasses cover decreases with increasing transmission coefficient. This is because the higher transmission coefficient of the glass means less solar irradiance absorbed by the glass. As a result, there is no sufficient energy to increase its temperature. It can be seen that transmissivity of the glass shows the stronger effect to the top glass in comparison with the lower glass. This is because of the lower glass closer to the plate absorber. This makes it receives more energy from the absorber plate.
3.3. Effect of absorptivity

Figure 5 shows the effect of the absorptivity to the characteristic of the solar collector. In the figure, the simulation is made for water load of 5 kg, and transmissivity is fixed at 0.95. The absorptivity is varied from 0.7 to 0.95. The figure shows that temperature maximum of the plate absorber increases linearly with increasing absorptivity. This is because at higher absorptivity more solar energy converted into heat and made the temperature of the absorber plate increases. Furthermore, the temperature of the glass cover also increases with increasing absorptivity. However, the rate of increasing glass temperature is lower than the rate of absorber plate. This is because the absorptivity has no direct impact on the glass cover. The increasing temperature of the glass cover is caused by convective heat transfer from the plate absorber to the glass cover.

![Figure 5. Effect of absorber absorptivity](image-url)
3.4. Performance

The effect of the transmissivity and absorptivity to the performance is shown in figure 6. In the figure, the simulation is made for the load of 5 kg. For the case of variation absorptivity, the transmissivity is fixed at 0.95. On the other hand, for the case with the variation of emissivity the absorptivity is fixed at 0.95. The figure shows that absorptivity and emissivity show the strong effect to the thermal efficiency of the solar collector. Increasing absorptivity will increase the thermal efficiency of the collector. Furthermore, thermal efficiency increases with increasing transmissivity. The comparison of both coefficients shows that the effect of transmissivity is stronger than the effect of absorptivity.

![Figure 6. Effects of Absorptivity and Transmissivity to the performance](image)

4. Conclusions

A numerical study has been conducted to study the effect of glass cover transmission coefficient and absorption coefficient. The governing equations are developed and solved numerically. The conclusion of this study is as follows. The increase of glass transmission coefficient will increase the temperature of the absorber plate. Increasing absorptivity coefficient will also increase the thermal efficiency of the solar cooker. The comparison of both coefficients shows that the effect of transmissivity is stronger than the effect of absorptivity. This fact shows that in the design of solar cooker it is recommended to use appropriate paint with high absorption coefficient and high coefficient of glass transmission.

References

[1] Thirugnanasambandam M, Iniyan S and Goic R 2010 Renewable and Sustainable Energy Reviews 14 312-322.
[2] Kannan N and Vakeesan D 2016 Renewable and Sustainable Energy Reviews 62 1092-1105
[3] Ambarita H 2017 Journal of Physics: Conference Series 801(1), 012093
[4] Dina S F, Ambarita H, Napitupulu F H and Kawai H 2015 Case Studies in Thermal Engineering 5 32-40
[5] Ambarita H and Kawai H 2016 Case Studies in Thermal Engineering 7 36-46
[6] Ambarita H 2016 Case Studies in Thermal Engineering 8 346-358
[7] Ambarita H 2016 *IOP Conference Series: Materials Science and Engineering* **180**(1) 012024
[8] Setyawan E Y, Napitupulu R A M, Siagian P and Ambarita H 2017 *IOP Conference Series: Materials Science and Engineering* **237** 012012
[9] Ambarita H and Sitepu T 2017 *IOP Conference Series: Materials Science and Engineering* **237** 012014
[10] 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
[11] Pandey K M and Chaurasiya R 2017 *Renewable and Sustainable Energy Reviews* **67** 641-650
[12] Varol Y and Oztop H F 2008 *Building and Environment* **43** 1535-1544
[13] Varol Y and Oztop H F 2007 *Building and Environment* **42** 2062-2071
[14] Kumar S 2004 *Renewable Energy* **29** 211-222