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Flat Plate Type Solar Collector Performance Using Double Thermal Insulation

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Abstract. Indonesia is a country that has a huge potential of solar radiation energy since it is located in the equator. This causes Indonesia to have a tropical climate and receives almost the same emission of solar radiation throughout the year. National average solar energy potential is 16 MJ/day. This energy potential can be used as a source of thermal energy. To improve the energy potential, a research performance is done by using double thermal insulation solar collectors so that the energy can be received optimally. One alternative that is used is adding Styrofoam and Polyurethane which are installed on all sides of the collector except the upper side. Styrofoam and Polyurethane have 3 cm thickness and low thermal conductivity value therefore it is able to isolate the energy inside the solar collector. This experiment was done in a day with energy coming at the test reached 8,798,634 j/m2 with 69% efficiency level.

1. Introduction

One of the abundant renewable energy availability is solar radiation energy. With current technology, solar radiation energy can be converted into electrical energy using solar batteries, using thermal energy using solar collectors, and becoming mechanical energy using solar power plants [1][2]

The amount of solar radiation energy is very abundant. About half the sun's energy enters the earth's surface. Earth receives 174 peta watts (PW) of incoming solar radiation in the upper atmosphere. About 30% is reflected back to space while the rest is absorbed by clouds, oceans and land. The total solar energy absorbed by clouds, oceans, and soil is around 3,850,000 exa joules (EJ) per year. The amount of solar energy reaching the earth's surface is vast. Solar energy is twice as much as all non-renewable sources such as coal, oil, natural gas, etc.

Indonesia is one of the countries that have a huge potential for solar radiation energy, as Indonesia is located in the equator which make it to have a tropical climate and receives almost the same amount of solar radiation throughout the year. National average solar energy potential is 16 MJ/day. This energy potential can be used as a source of thermal energy as well as a source of electrical energy using photovoltaic cells.

The use of solar energy to heat water is done using a device called a solar thermal collector. Solar thermal collector or commonly called solar collector is equipment used to absorb energy contained in solar radiation, which then converts that energy into thermal energy. The energy will be transferred directly to the heated fluid and to other fluids used to heat. One of the most commonly used types of collectors is flat plate solar collectors.

Researches on the use of flat plate solar collectors have been carried out. Chen, Z, et al. conducted a study on two flat plate solar collectors by varying the flow rate to improve the efficiency. The result is if the flow rate is increased, the efficiency of solar collector increases[3][4][5][6]. Research on flat plates using double glazing and between glazing filled with argon has been carried out and the results have been proven to increase the thermal efficiency of collectors[7][8]. Research by adding a thermo chromic layer to the absorber plate has been carried out to reduce temperature stagnation on the absorber plate[9][10][11].

Research on flat plate solar collectors in Indonesia has also been increasingly active[12][13][14]. In this study, collectors designed are flat plate system collectors by utilizing solar energy into thermal energy equipped with thermal insulation. It is necessary to do research on collectors designed using double thermal insulation.The collector is isolated using steofofoam acted as an insulator installed on all collector sides except the upper side and polyurethane used as a second insulator installed on all collector sides except the upper side, because the top is paired with transparent glass with a black plate inside to absorb the incoming solar energy.[15][16]

2.   Method

In order to test this solar collector, the process of the collector includes the collector body, absorber plate, transparent cover (glass) and insulation on the collector. Considerations in designing the collectors are: economical, strong, high productivity, easy to manufacture and easy to operate. The length of the solar collector is 1.6 m with a width of 1.1 m.

a. the design of a solar collector that has been built

b. a fabricated solar collector design

Figure 1. Solar Collector

The frame used is aluminum ekstruction profile C with added thermal insulation which

serves to minimize the heat lost from the collector to the environment on the back and sides of the collector. In the isolation process, heat conduction occurs therefore heat loss is affected by the properties [16] of the material used.

In this experiment, collectors designed using double thermal insulation.The collector was isolated using 3 cm thick styrofoam which was used as an insulator installed on all collector sides except the upper side while polyurethane was used as a second insulator installed on all collector sides except the upper side 2 cm thick. The absorber plate was also added to absorb solar radiation and convert it to heat. Then the absorbed solar energy will be flowed using a circulation pipe installed in the collector for 16 passes. Pipes are installed in series using elbow with a distance of 8 cm each pipe. The total length of the pipe is 1405 cm. Common materials used for collecting plates are: aluminum, copper, brass and steel. In accordance with the above considerations, in this design aluminum plates are used and the surface is coated with dull black paint (dof), so that corrosion will not occur and will provide maximum absorption. The black paint absorber plate is installed inside the collector. The upper part is closed using a transparent glass which serves to forward the solar radiation and prevent the heat leaking out from the collector to the environment at the top. Based on this function, the transparent cover must have high transmissivity (τ), low absorptivity (α), low reflexivity (ρ) and heat resistance. In this test, thermo couples installed at the temperature measured using thermo couple dataloger are used therefore heat movements in the solar collector can be discovered every minute while also use a data logger pyranometer to measure the solar radiation.

Figure 2. The Experimental Set up

As shown in Figure 2, the Surface is an important part of the solar collector. It serves to absorb black energy by transferring energy absorbed by fluid that is transparent to solar radiation on the sun's absorbent surface which can reduce convection and radiation losses to the atmosphere, and heat insulation to reduce conduction losses. Figure 2. describes a water heater, and most of the analysis of this research relates to this geometry. Basically the air heater is the same except the fluid tube is replaced with duct. Flat plate collectors are almost always installed in positions 00-450 (for example, on the walls of houses or roofs of houses) with orientations that are optimized for the particular location at issue throughout the time at which solar devices are designed to operate.
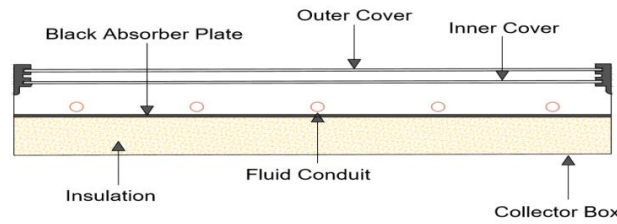
Figure 3. Basic Flat-Plate Solar Collector

2.1 Flat Plate Collector Energy Balance

In a steady state, the performance of a solar collector is illustrated by an energy balance which indicates the distribution of solar energy which occurs as a useful energy benefit, thermal losses, and optical losses.

$$Q_u = A_c[S - U_L(T_{pm} - T_a)] \qquad (1)$$

S [W / m2] is the absorption of radiation based on the size of the collector formulated by the following equation:

$$S = I_b R_b (\tau\alpha)_b + I_d(\tau\alpha)_d \left(\frac{1 + \cos\beta}{2}\right) + \rho_g I(\tau\alpha)_g \left(\frac{1 - \cos\beta}{2}\right)$$

$$(2)$$

The thermal energy lost from the collector by conduction, convection, and radiation is treated as UL heat transfer coefficient [W / m2.K] which differs between the average temperature of T_{pm} absorber plate and the T_a outside air temperature, while A_c is the area of the solar collector itself.

2.2 Collector's Total Heat Loss Coefficient

This whole heat loss coefficient is a value which results from heat loss in the collector due to the effect of solar radiation that occurs on the collector's top, collector's bottom, and collector's side. This heat loss coefficient can be converted into a thermal network in which the energy lost along the collector to the top will produce convection and radiation on the collector plate, Figure 3. is a thermal network for double-glazed collectors.

This study will only discuss a double-glass collector in order to obtain U_t [W / m2.0C] overall heat loss coefficient in the glass of the two collectors, which then formulated with the following equation:

$$S = I_b R_b(\tau\alpha)_b + I_d(\tau\alpha)_d \left(\tfrac{1+\cos\beta}{2}\right) + \rho_g I(\tau\alpha)_g \left(\tfrac{1-\cos\beta}{2}\right) \qquad (3)$$

The radiation coefficient that occurs from plate to glass 1 h_ (r, p-c1) [W / m2.0C] is:

$$h_{r,p-c1} = \frac{\sigma(T_p^2 + T_{c1}^2)(T_p - T_c)}{\frac{1}{\varepsilon_p} + \frac{1}{\varepsilon_c} - 1} \qquad (4)$$

While the radiation coefficients that occur from glass 1 to glass 2 h_ (r, c1-c2) [W/m2.0C] are:

$$h_{r,c1-c2} = \frac{\sigma(T_{c1}^2 + T_{c2}^2)(T_{c1} - T_{c2})}{\frac{1}{\varepsilon_c} + \frac{1}{\varepsilon_c} - 1} \qquad (5)$$

The radiation coefficient that occurs from glass 2 to the outside air $h_{r,c2-a}$ [W/m^2.^{0}C] is:

$$h_{r,c2-a} = \frac{\varepsilon_c\sigma(T_{c2} + T_s)(T_{c2}^2 + T_s^2)(T_{c2} - T_s)}{(T_{c2} - T_a)} \qquad (6)$$

Where:
 Tp = Absorber plate temperature (°C)
 T_{c1} = First cover temperature (°C)
 T_{c2} = Second cover temperature (°C)
 Ts = Environmental Temperature (°C)
 σ   = Stefan constant - Boltzmann (5.67 x 10-8 W/m² K⁴)

At the heat transfer coefficient by convection$h_{c,p-c1}, h_{c,c1-c2}$, and h_w [W/m².⁰C] are obtained by calculating the *Rayleigh* number and for other data can be seen in the table of air properties. After being obtained, the Nusselt number can be calculated to obtain the convection heat transfer coefficient which is formulated as follows:

$$\text{Nu} = 0.68 + \frac{0.67 Ra^{1/4}}{[1+(0.492/Pr)^{9/16}]^{4/9}} \qquad (7)$$

After that the Nusselt number can be entered into the following equation:

$$h = NU \frac{k}{l} \qquad (8)$$

Glass 1 and glass 2 used the same equation as above, except for the temperature assumed at the beginning if there is no known average plate temperature.
To calculate the temperature on each glass the following equation was used:

$$T_j = T_j - \frac{U_t(T_p - T_a)}{h_{c,i-j} + h_{r,i-j}} \qquad (9)$$

Where symbols *i* and *j* can be distinguished depending on where the temperature is to be sought. If all the temperatures of the collector are known, the following equations can be used to facilitate the calculation of previous trial and error.

$$U_t = \left(\frac{N}{\frac{C}{T_{pm}} \left[\frac{(T_{pm}-T_a)}{(N+f)} \right]^e} + \frac{1}{h_w} \right)^{-1} + \frac{\sigma(T_{pm}^2 + T_a^2)(T_{pm}-T_a)}{\frac{1}{\varepsilon_p + +0,00591 N h_w} + \frac{2N+f-1+0,133\varepsilon_p}{\varepsilon_g} - N} \qquad (10)$$

Where:
N   = Number of glass from the collector
T_{pm} = the average temperature of the collector plate
εc   = Cover sensitivity
εp   = Plate emissivity
h_w = Air convection coefficient
f   = correction factor
        $= (1 + 0,089h_w - 0,1166h_w\varepsilon_p)(1 + 0,07866N \qquad (11)$
C   = Number to print degrees on a collector
        $= 520(1 - 0,000051\beta^2) \qquad (12)$
B   = Collector's tilt angle, for $70^0 < \beta < 90^0$ the fixed value is used 70^0
e $= 0,430(1 - 100/T_{pm}) \qquad (13)$

For the loss coefficient on the U_b collector side [W/m².⁰C] formulated with:

$$U_b = \frac{k}{L} \qquad (14)$$

Where:
k = Conductivity of insulation used in the collector (W/m.^{0}C)
L = Thickness of insulation under the collector (m)

The heat loss coefficient on the collector side is formulated with:

$$U_e = \frac{(UA)_{edge}}{A_c} \qquad (15)$$

For the overall heat loss coefficient formulated by the following equation:

$$U_L = U_t + U_b + U_e \qquad (16)$$

Where:
  U_t = Upper side heat loss coefficient
  U_b = Koefiisen loses heat on the lower side
  U_e = Side side heat loss coefficient

2.3 Energy that reaches the Collector
To calculate the energy reaching the collector, it is necessary to know how the solar energy is distributed by the collector. Illustration of heat absorbed by Soteric solar collector absorber can be seen in Figure 4.
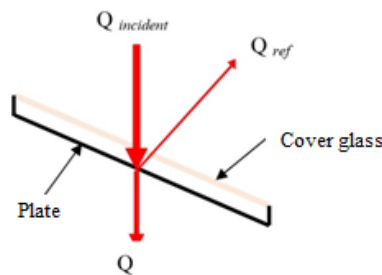

Figure 4. Illustration of Absorber's Heat Absorbed

According to Mehmet Esent, the amount of Qincident can be calculated using the formula below:

$$Q_{incident} = A \int_1^2 I dt \qquad (17)$$

Where:
 A = cross-sectional area of the absorber plate (m^2)
 I = sunlight intensity (W/m^2)

While heat absorbed by absorber can be calculated using the formula:

$$Q_{abs} = aQ_{incident} \qquad (18)$$

The heat reflected back to the atmosphere is:

$$Q_{ref} = (1\text{-}a)Q_{incident} \qquad (19)$$

where a is material diffusion.

The heat energy that has been received by the collector will be given to water. The amount of energy according to Mehmet Esent can be determined using the formula:

$$Qu = m_w.Cp_w.(Tw_2 - Tw_1) \qquad (20)$$

Where:

m_w = Water mass (kg)

Cp_w = Hot type of water (kJ/kg. °C)

Tw_1 = Initial water temperature before collector heating (°C)

Tw_2 = Actual temperature after heated by the collector (°C)

2.4 Thermal Collector Efficiency

Thermal efficiency is a dimensionless size that shows the performance of thermal equipment. Thermal efficiency can be formulated as in flat plate solar collectors and can be calculated by the equation:

$$\eta = \frac{Q_{used}}{Q_{in}}. \tag{21}$$

Based on the definition above, the thermal efficiency of flat plate solar collectors is a comparison between the energy that can be absorbed by circulating water and the intensity of solar radiation that come, which can be calculated by the following equation:

$$\eta = \frac{Q_u}{Q_{incident}} \tag{22}$$

3. Results and Discussions

The experimental results show that the measurement radiation curve with HOBO is below the theoretical radiation curve. This number shows that solar radiation measured is lower than the theory. This occurs as the sun radiation is blocked by clouds above the sky. Visible measurements show that solar irradiation increases in line with the increasing time because the more the sun sets (starts from 2:00 p.m.) the solar radiation falls gradually. The total energy achieved for 1 day during the experiment reached 8,798,634 j/m^2.
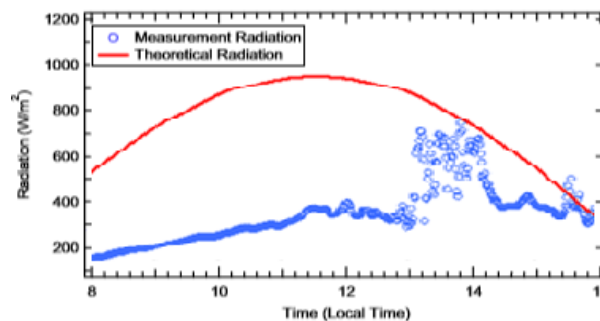

Figure 5. Theoretical radiation and measurement radiation

3.1 Solar Collector

To obtain the total heat received on the collector, the following equation is used:

$$Q_{in} = A \int_1^2 q_{radiation}\ dt \tag{23}$$

The value of $\int_1^2 q_{radiation}\ dt$ can be calculated from the area under the curve using trapezoidal method. Where every 1 minute (60 seconds) we calculate the area under the curve as follows:

$$L_1 = \frac{y_0 + y_1}{2} + \Delta X \tag{24}$$

where:

L_1 = Area under the intensity curve in 1 minute (60 seconds)

y_0 = Intensity at the beginning of the study (08.00 WIB)
y_1 = Intensity 1 minute later
ΔX = 1 minute time (60 seconds)

The use of solar collectors is to absorb sunlight from the heat generated by solar collectors, and then transfer heat energy into the evaporator with the help of water fluids, which will be used to heat the seawater contained in the evaporator. The principle of collector work is to absorb the radiation energy that touches the surface of the absorber plate. The absorbed radiation energy is then trapped inside the collector. This is done by isolating the outer surface of the collector, and installing double glazing on the top side of the collector. In the collector, absorber plate temperature and air temperature around the collector measurement were carried out to determine how much energy is being wasted from the collector into the environment. The temperature of the plate absorber and the environment during the experiment is shown in Figure 17. It is known that the overall plate temperature is increasing, at the beginning of the experiment at 08.00 the plate temperature has left the temperature of the environment of the collector system working effectively, to increase the temperature generated by the intensity of the solar radiation until the end of the experiment gradually decreases until 16:00 as seen in Figure 6 below.
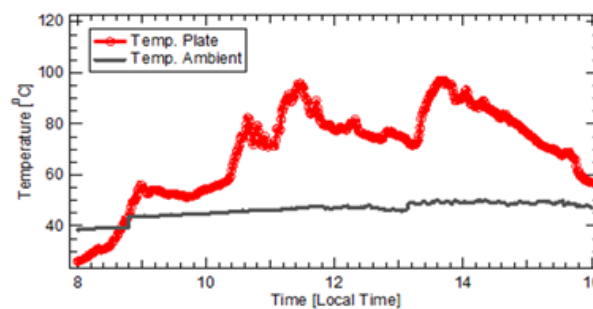

Figure 6. Heat Loss on Collectors

3.2 Wasted heat from the collector

The analysis of heat loss at the collector includes wasted heat which on the heat wall is wasted from the collector wall, below the collector and above the collector as shown in Figure 7. The scheme explained the heat transfer from plate temperature T_p (^{0}C) to T_u environment temperature (^{0}C) while t_p is plate thickness (m) and used some material for heat transfer in the $_{pu}$ collector is polyurethane, steorofoam, $_{pc}$ is aluminum profile and $_{acp}$ is an aluminum composite panel. Therefore the equation below is used to find out the heat wasted on the collector's wall and side.

$$q_{out,} = U.\ A.\ (T_p - T_u) \tag{25}$$

$$q_{out,} = \frac{Tp - Tu}{\frac{t_{plat}}{k_{plat}.A_{plat}} + \frac{t_{pu}}{k_{pu}.A_{pu}} + \frac{t_{st}}{k_{st}.A_{st}} + \frac{t_{pc}}{k_{pc}.A_{pc}} + \frac{1}{h_u}} \tag{26}$$

k_p is the thermal conductivity of the plate (W/mK), k_{pu} is the thermal conductivity of polyurethane (W/mK), k_{st} is steorofoam conductivity (W/mK), k_{pc} aluminum profile conductivity (W/mK) and h_u is the air convection coefficient (W/mK).
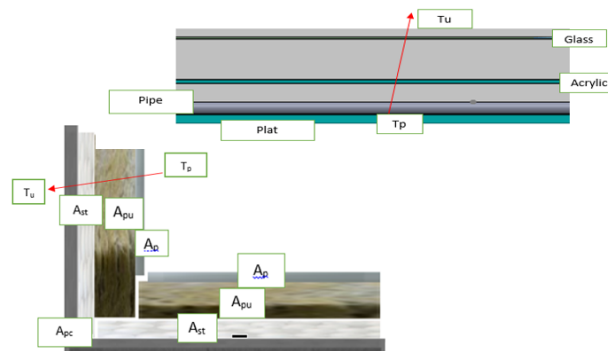
Figure 7. Scheme of heat loss on the bottom and top side

Wasted energy in the collector is calculated on each side of the collector, namely the collector's side, bottom, and side. The energy wasted on the side of the collector is caused by conduction heat transfer from the absorber plate to the insulator, to the collector's frame, and conduction from the collector's frame to the environment as shown in Figure 9. With 97,820 watts of energy loss coming out, loss from the wall of 2,273 watts and losses below the collector reached 32,989 watts. The energy received by the collector can be determined by calculating the radiation energy reaching the collector multiplied by the efficiency factor due to the slope of the collector. Radiation energy that reaches the collector is calculated based on actual data obtained from thermocouple measuring devices on Hobo.
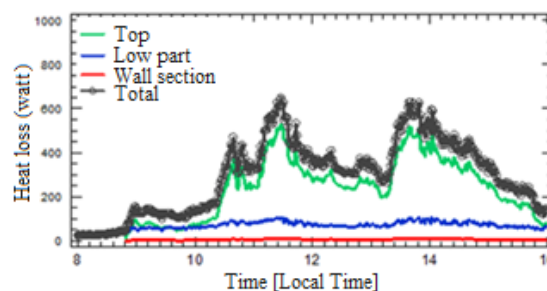

Figure 8. Heat loss of the collector during the experiment

Based on Figure 8, it can be seen that the highest heat wasted during the testing on the collector's upper side occurred at 12.00 until 13.00 West Indonesian Local Time. Meanwhile the minimum heat is wasted from the side of the collector and below the collector. This is directly proportional to the temperature value of the absorber plate which reaches its highest temperature at almost the same time. By paying attention to the heat graph that was wasted during this test, we can know how much energy is wasted on the top, side, bottom and total sides of the experiment, using the equation below to find out the total energy.

$$Q_{out} = Q_{wall} + Q_{down} + Q_{top} \qquad\qquad (27)$$

In which Q_{Out} is the transfer of heat wasted into the environment which is limited by a black plate attached to the collector's solar coincide with polyurethane and Styrofoam. The outside of the solar collector is used aluminum to wrap the side and bottom of the solar collector that is in direct contact with the surrounding environment. The total energy loss out of the environment reached 133083.03 watts.

4. Conclusion

From the results of the analysis and testing by adding thermal insulation of flat plate type solar collectors, the energy achieved was 8,798,634 j/m^2. With theefficiency level of 69% with energy losses coming out from the upper side of 97,820 watts, the loss of 2,273 watts of wall and losses below the collector reached 32,989 watts with a toll of energy losses reached 133083.03 watts. Therefore, it can be concluded that by using 3 cm thick Styrofoam and Polyurethane as insulators installed on all sides of the collectorexcept the upper side is very effective to reduce the loss of energy coming out to the environment, asthose materials have low thermal conductivity value to be able to isolate the energy in the solar collector.

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