Design and experimental test for solar chimney power plant: case study in Riau Province, Indonesia

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Abstract. Solar chimney is an energy generator that utilizes solar thermal energy. The working principle air is heated in the solar collector, the increased temperature causes downward pressure, and the air density becomes reduced to create a buoyance force or air moving upward through the chimney. This research aimed to investigate the theoretical design in determining dimension of solar chimney and experimental data test. The solar chimney made with collector roof area of 1.3225 m² with clear glass as thick as 5 mm. Chimney is made from PVC pipe with 83 mm inner diameter and high 193 cm. The material of solar chimney made of aluminum pipe. Experimental data was taken on March 2017 from 11:00 AM to 15:00 (3 PM). The design power output was 0.03 watt and the actual values ranged between 0.0133 watt and 0.0317 watt. The design of chimney inlet air velocity was 2.15 m/s while the actual value varied from 1.4 m/s to around 2.2 m/s. These results show that the design is able to assess the potential of solar chimney system in Riau Province.

1. Introduction
Nowadays, refer to the increasing rate of environmental pollution and limitation on fossil fuel resources, the use of sustainable energy seems to be inevitable and an absolute necessity for the world. Recently the impact of environmental pollution caused by fossil fuels is one of huge concern. Solar chimney is the energy generation that utilizes solar thermal radiation energy. This energy generator consists of a solar collector and a tower or chimney placed at the center of the collector. Solar energy is used to heat the air inside the solar collector. The air flow to the chimney is formed due to the temperature difference outside and inside the collector. On a scale power plant kinetic energy in the form of speed from the high air to the chimney is used to drive the wind turbine coupled to the generator which will generate electricity.

The greatest advantage of solar thermal energy compared to other energies because it is clean without pollution environment, and its abundant availability in the world. Indonesia as the part of the world is a region which has a considerable intensity of solar thermal radiation. Compared with the monthly rate energy production of 126.83 kWh per day which has been built in Manzanares, Spain, the capacity of energy production in Riau Province, Indonesia almost doubled with 202.72 kWh per day [1]. Another fact, Riau Province, Indonesia also get sun radiation intensity with 6.06 kWh per m² in March [2]. This is a potential for Riau Province to utilize the heat of solar energy into a clean energy source.
Solar chimney is one of the energy generation that utilizes solar thermal radiation energy. This energy generator consists of a solar collector, a tower or chimney placed at the center of the collector and turbine. The speed from the high air to the chimney is used to drive the wind turbine coupled to the generator which will then generate electricity. To design a large-scale solar chimney power plant, it is necessary to ensure that the power plant works as expected. Some of the part needs to prepare like: height chimney, collector area, the intensity of solar radiation, the height of collector roof, heat storage material and others. Therefore, this study aims to design a prototype of solar chimney with experimental test in Riau Province, Indonesia.

2. Mathematical model
Solar chimneys are energy plants that use solar radiation to raise air temperature, buoyancy of warm air to accelerate the flow of air throughout the system. The main parts of the solar chimney are shown in figure 1.

![Figure 1. Dimension of solar chimney [3].](image)

The air gets hot as a result of the greenhouse effect under a transparent roof (collector). Because the roof is open at the edges, the buoyancy of hot air forms a continuous flow from the edge of the roof to the chimney. A turbine is placed on the passage of the air stream to convert kinetic energy from the air flowing into electrical energy. Based on the scheme of figure 1, the increasing temperature can be estimated from the energy equation in the roof section as shown in equation (1) – (6).

\[
\dot{m}c_p(T_2 - T_1) + \frac{1}{2} \dot{m}(V_2^2 - V_1^2) = q' A_r
\]

\[
\dot{m} = \rho A_{ch} V
\]

\[
\dot{m}c_p\Delta T = q'' A_r
\]

\[
T_2 = T_1 + \frac{q' A_r}{m c_p}
\]

\[
q'' = \alpha l - U\Delta T
\]
\[ \Delta T = \frac{\alpha l}{mc_p \Delta r + U} \]  

(6)

The efficiency collector \( \eta_{coll} \) can be expressed using equation (7) and (8).

\[ \eta_{coll} = \frac{q'}{I} \]  

(7)

\[ A_r = \frac{mc_p \Delta T}{\eta_{coll} I} \]  

(8)

Without the turbine, maximum airflow velocity \( V \) is reached and all pressure differences are used to accelerate the air so that it becomes kinetic energy as shown in equation (9) and (10).

\[ P_{tot} = \frac{1}{2} m V^2 \]  

(9)

\[ V = \sqrt{2gH \frac{\Delta T}{T_a}} \]  

(10)

The coefficient losses at top collector can be expressed in equation (11) - (16).

\[ U_t = (h_w + h_{rs}) \]  

(11)

\[ h_w = \frac{k}{L} Nu \]  

(12)

\[ h_{rs} = \frac{\sigma \varepsilon (T_1 + T_2) (T_1^2 + T_2^2) (T_1 - T_2)}{(T_1 - T_{\infty})} \]  

(13)

\[ Nu = 1 + 1.44 \left[ 1 - \frac{1708 (\sin 1.8 \beta)^{1/6}}{Ra \cos \beta} \right] \left[ 1 - \frac{1708}{Ra \cos \beta} \right]^{1/3} + \left[ \left( \frac{Ra \cos \beta}{5830} \right)^{1/3} - 1 \right]^{1/3} \]  

(14)

\[ Ra = \frac{g \beta' \Delta T \lambda^3}{\nu a} \]  

(15)

\[ T_s = T_{\infty} \left[ 0.711 + 0.0056 (T_{dp} - 273.15) + 0.000073 (T_{dp} - 273.15)^2 + 0.013 \cos (15t) \right]^{1/4} \]  

(16)

Meanwhile for the equation of losses coefficient under collector is shown in equation (17).

\[ \frac{1}{U_B} = \frac{l_1}{k_1} + \frac{l_2}{k_2} + \frac{l_3}{k_3} \]  

(17)

All are above those equations taken from [4].

3. Method of design

To define the design dimension of solar chimney, first we have to decide several assumptions, where the solar radiation determined after calculation is 918 W/m² while ambient temperature \( T_a \) is 30 and dew point temperature \( T_{dp} \) is 25.7°C. For the coefficient losses of collector \( U \), 14 W/m² K. The collector installed in this solar chimney is glass which its emissivity \( \varepsilon_c \) is 0.9 and ground absorptivity is \( \alpha \), 0.98, while emissivity of ground absorber \( \varepsilon_p \), is 0.88. In order to achieve 50 m watt power without turbine dimension of glass 115 cm x 115 cm (available dimension in Indonesia market), meanwhile different temperature between inlet and outside \( \Delta T \), 37 C. With those above equations found the required air velocity based on equation (9) is 2.15 m/s. The height of the required chimney based on
equation (10) is 1.93 m. The chimney diameter is 0.086 m which calculated based on equation (2). Collector height taken 6 cm based on experimental test conducted by [5] and it was the best height.

Clear glass applied as collector with thickness 1.5 mm is good material for its transmissivity value 0.9. The dimension of clear glass was selected considering availability of collector material in the local market. The points of measurement were adjusted for temperature inlet collector, plat absorber, inlet chimney and ambient utilized by Advantech 4718. Krisbow KW06035 anemometer was chosen to collect data for air velocity of chimney inlet. The data collected for every 15 minute from 10:00 AM until 15:00 (03:00 PM).

4. Result and discussion

4.1. Radiance intensity in Riau Province

Daily solar radiations of direct and diffuse for clear sky day were calculated based on a mathematical models equation from [6], due to solar irradiance instrumental very expensive so that these approach equations are matched. In other hand this value has to be determined to calculate air mass flow rate and power output. The solar irradiance in Riau Province is shown in figure 2.

![Solar Irradiance in Riau Province](image)

Figure 2. Solar irradiance in Riau Province.

The peak solar irradiance is 918 W.m\(^{-2}\) occurred in 12:00 and this intensity larger than other country such as Manzanares, Spain which only 800 W.m\(^{-2}\), because this region located in the equator line.

4.2. Solar chimney dimension

The whole equations above used to design the prototype of solar chimney. There several parameters to be as assumption such as the power 30 mWatt, diameter of clear glass 1.15 m and differential temperature of ambient and plat absorber as 37 °C. To calculate coefficient of losses at top collector side by its value 12.4 W.m\(^{-2}\) K and also there are many parameters found by all above equations such as \( h_a = 2.28 \) W.m\(^{-2}\) \( h_e = 10.14 \) W.m\(^{-2}\).K with \( \text{Nu} = 5.1 \) and \( \text{Ra} = 284686 \). Hopefully by these values can helps in solar chimney’s design.

4.3. Absorber and collector

The selected heat absorber floor material is an aluminum plate with a thickness of 0.02 mm and is dyed black to maximize the absorption of solar radiation the aluminum is better of reflectivity value than stainless steel plate. The position of solar chimney made from aluminum hollow 1x1 or 23 mm x 23 mm and 5 mm, in other hand the clear glass is selected as collector's roof with its transmissivity value 0.9, whereas high roof collector is 0.06 m this is the best height of inlet collector. The view of frame collector and absorber is shown in figure 3.
4.4. Chimney

PVC pipe is selected as chimney material is selected due to its low conductivity thermal as well as it considered to be adiabatic system inside chimney. From equation (10) it is found that the height of chimney 2 m while the air mass flow rate 0.013 kg/s. The adiabatic system of chimney will create the pressure drop from the inlet into outlet of chimney, by these the force buoyancy occurred. The cross wind ambient measured around 5 – 8 m/s therefore need a rope to tie the chimney. Inner diameter of chimney supposed to be 0.083 which has constant diameter. Figure 4 shows the result of solar chimney design (a) side-view of solar chimney design (b) top-view over solar chimney (c) solar chimney.

The experimental was conducted in the yard of Universitas Muhammadiyah Riau on March 21, 2017. Which graphical represented latitude 0.49989036° and longitude 101.41544804°, where 27 m above sea level based on Google maps. Data collected for every 15 minutes from 11:00 AM to 14:00 (02:00 PM). The measuring instrument used thermocouple K type, and an anemometer placed at the base of the chimney. The measured data are ambient air temperature, air temperature at the bottom of chimney, heat absorber plate temperature, and air velocity at the base of chimney. The data is then analyzed to obtain power without turbines by using equation (9).
4.5. Absorber insulation
In order to isolate heat losses comes from the bottom of basement into atmosphere, it is necessary utilizing aluminum foils, Styrofoam and carpet by their thickness 2 mm, 7 mm and 20 mm respectively, while the aluminum also become support the equipment of solar chimney. Figure 5 depicts how the system isolated.

![Diagram of insulation materials](image)

**Figure 5.** The composition of material insulation.

By these above isolators the heat only flow over the plate and going into chimney inlet, even though there are still not still good isolator to be applied.

4.6. Result test
After manufacturing and assembling the solar chimney by its instrumental measurement figure 6 illustrates temperature of ambient, plat and chimney inlet. It indicates that the highest temperature of plate 57.8 °C occurred in 11:00 AM while the maximum temperature inlet chimney also at that time. It concludes that temperature chimney inlet was effected by absorber temperature.

![Graph illustrating temperature changes](image)

**Figure 6.** The graph relationship between ambient, chimney inlet, plat and time.

From the graph in figure 6, the differential temperature between ambient and plat really significant and will lead to higher power output. The ambient wind influenced the experimental test involved to power fluctuation. Hence the effect of wind velocity also caused by ambient wind velocity. The air velocity inlet chimney graph is shown in figure 7.
Fig 7. Graphic trend line time versus air chimney inlet velocity.

From the graphs in figure 7, the air velocity inlet chimney starts in 10:00 until 15:00, the air velocity tends to increase and stops at 11:30 because there is cross wind ambient moving over plat absorber that is why absorber become colder and after 12:00 rises again until 13:30 and then decreased because of ambient temperature dropped. The highest air velocity inlet chimney is 2.2 m/s in 11:30 meanwhile the lowest air velocity 1.4 m/s happened in 10:00.

Fig 8. The power output without turbine.

The measured power output without turbine is shown in figure 8. Based on the measurement, temperature and air velocity, the resulting power without turbine reaches 0.0317 Watt at 13:30. And the lowest is 0.0133 Watt at 10:00. Data collected 23, 26 and 28 August 2017. The change of power caused by air velocity and temperature at the base of the chimney varies, in this study observed due to various factors such as ambient cross wind going into the collector that would increase the solar chimney's power. By this condition also enlarge the coefficient loss of collector.

It is clearly seen that the power output along with the parameters which are homogeneous to the power like velocity inlet chimney, mass flow rate approaches their peak almost always at mid-day approximately as supposed because at that time solar radiation becomes maximum due to its position.
5. Conclusion
Solar chimney that has been made has height of the chimney is 200 cm, the size of the collector roof is 115 cm x 115 cm, the inner diameter of the chimney is 8.3 cm, the collector roof height is 6 cm. Material insulation selected are very satisfactory even the efficiency of collector 41%. In the data analysis, solar chimney produces the lowest power 0.0133 Watt and the highest 0.0317 Watt. Average power generated is 0.020 W. The design power output was 0.03 Watt and the actual values found ranged between 0.0133 Watt and 0.0317 Watt The design of chimney inlet air velocity was 2.15 m/s while the actual value varied from 1.4 m/s to around 2.2 m/s. These results show that the design is able to assess, with a fairly good with experimental and Riau province has great prospect to generate electricity by solar chimney system.

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