Simulation of solar chimney power plant with an external heat source

Azeemuddin Islamuddin, Hussain H Al-Kayiem and Syed I Gilani

Department of Mechanical Engineering, Universiti Teknologi Petronas, Malaysia

Email: hussain_kayiem@petronas.com.my

Abstract. Solar chimney power plant is a sustainable source of power production. The key parameter to increase the system power output is to increase its size but the plant cannot operate during night hours. This study deals with simulation work to validate results of pilot plant at Manzanares and include the effects of waste heat from a gas turbine power plant in the system. The effects show continuous night operation, a 38.8 percent increase in power at 1000 W/m^2 global solar irradiation at daytime and 1.14 percent increase in overall efficiency.

1. Introduction

Solar chimney power plant runs truly on renewable energy source that is the sun. Many parts of the world that have flat land properties and receive massive amount of solar radiation, can be utilized for such system. It can work under diffuse solar radiation and is durable and require less maintenance. The system has three main components a) collector b) chimney and c) turbine. The collector absorbs heat energy from solar radiations, the air inside the collector moves due to buoyancy effects and finally reaches the center of the chimney with a certain velocity. The turbine located there rotates by extracting the kinetic energy of the air. Finally this kinetic energy is converted to electric power. One of the drawback of this system is that it cannot operate during night hours. Although previous researches have shown by using means to make it work at night. In this study, a simulation is carried out that not only shows night operation of the plant but also power output enhancement and efficiency. The simulation includes the effects of exhaust gases from a nearby gas turbine power plant on the system that originally operates only on solar energy.

A detailed numerical analysis was carried out by Roozbeh [1], showing with increasing solar radiation values, the power increases. Simulation with energy storage layer for different solar radiations was carried out by Tingzhen [2], which resulted that heat loss from the storage medium increases with increase in solar radiations. According to Bernardes [3], the power output can be increased by increasing chimney height, collector area and transmittance. Another study by Jiakuan [4], show that power output of power generating system increases with global solar radiation intensity, collector area and chimney height. It also concluded that the larger the chimney height, the greater would be the driving force in air. The use of water storage system in collector was presented by Kreetz [5], his study indicated a continuous day and night operation of the solar chimney power plant.

The main purpose of this research is to model the system so that it will work at night and also enhance the power output. The results of Manzanares pilot plant were validated by simulating a mathematical model. Later, the effects of exhaust gases were incorporated with the mathematical model. This simulation uses ANSYS Fluent to calculate the heat transfer effects of exhaust gases on the system.
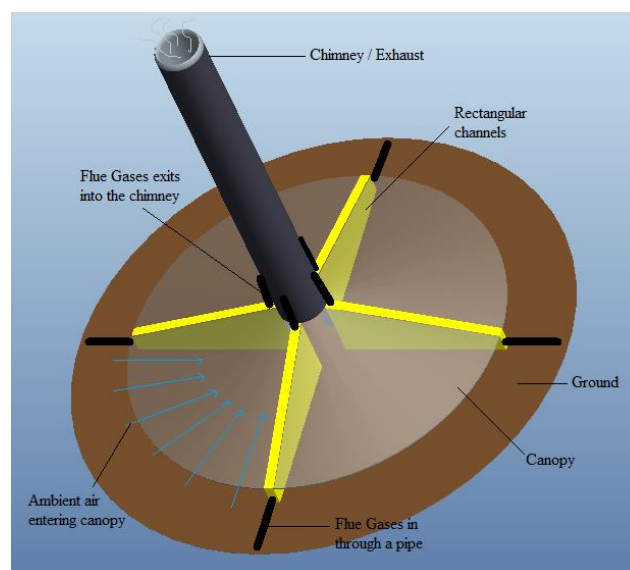
2. Proposed model

A model was needed to implement the exhaust gases effect into the classical solar chimney power plant. The proposed model consists of hollow rectangular channels beneath the collector cover. The orientation of these channels depend upon the equally divided circular collector (360 degrees) by the number of channels (in this study four, each at 90˚). The exhaust gases are passed into the channels by means of pipes and exits into the chimney base. Inside the channels the gases released through pipe holes. The walls of the channel becomes hot and a heat transfer mechanism takes place between the walls and the air flowing beneath the collector cover. Consequently, the air will gain more kinetic energy and thus increasing the power output through the turbine. The exhaust gases after useful energy transferred to the collector air, are allowed to escape through upper pipes located at the extreme end of the channels top and then into chimney as shown in Fig.1.

Table 1. Channel and exhaust gas specifications.

	Parameter	Value
Channel	Material	Carbon steel
	Length	117 m
	Thickness	0.015 m
	Inner width	0.17 m
	Height at collector inlet	2 m
	Height at collector outlet	6 m
Exhaust gas	Fuel	Natural gas
	Mass flow	24.5 kg/s (each channel)
	Temperature	643.15 K

The assumptions that were taken into account to utilize the exhaust gases in the system are as follows,
a. The exhaust gases from the turbine exit are just at the inlet of the channels.
b. The temperature of these gases at the inlet of channels is the exit temperature of the gas turbine.
c. The mass flow rate of these gases is equally distributed into the channels i.e. mass flow rate from the exit of the turbine divided by number of channels.

Figure 1. Schematic diagram of proposed model.

3. Governing equations

The mass flow rate of air entering the collector is evaluated as,

$$\dot{m} = \rho_{in} V_{in} A_{in} \tag{1}$$

Where, ρ_{in} is air density, V_{in} inlet velocity and A_{in} is the inlet area.
The actual useful heat gain by the collector is given by [6],

$$Q_u = A_{coll}[S - U_L(T_g - T_{amb})] \tag{2}$$

Where, S is the heat absorbed by the collector, A_{coll} is the exposed collector area to solar radiations, U_L is the overall heat transfer coefficient, T_g and T_{amb} is the ground and ambient temperature respectively. The heat transfer coefficient for ground to collector air is given by [3],

$$h_{c,g-air} = \frac{0.2106 + 0.0026 V_{in}\{\frac{T_m \rho}{\mu g(T_g - T_{fm})}\}^{1/3}}{\{\frac{\mu T_m}{(T_g - T_{fm})g\rho^2 C_p k^2}\}^{1/3}} \tag{3}$$

Where,
$h_{c,g-air}$ = convective heat transfer coefficient from ground to collector air.
T_{fm} = mean temperature of air.
T_m = mean temperature of T_g and T_{fm}.
C_p is air specific heat, μ is air dynamic viscosity, k is air thermal conductivity and g is gravitational acceleration.
Similarly, for cover to collector air,

$$h_{c,c-air} = \frac{0.2106 + 0.0026 V_{in}\{\frac{T_m \rho}{\mu g(T_{fm} - T_c)}\}^{1/3}}{\{\frac{\mu T_m}{(T_{fm} - T_c)g\rho^2 C_p k^2}\}^{1/3}} \tag{4}$$

Where,
$h_{c,c-air}$ = convective heat transfer coefficient from canopy to collector air.
T_m = mean temperature of T_c and T_{fm} , T_c is the cover temperature.
The maximum power output from the turbine is calculated as [7],

$$P_{out} = \frac{2}{3}\frac{\{\rho_{ch,in} A_{ch} V_{ch,in} H_{ch} g(T_{c,out} - T_{amb})\}}{T_{amb}} \tag{5}$$

Where, $\rho_{ch,in}$ is the air density at chimney inlet, $V_{ch,in}$ is the air velocity at the chimney inlet and A_{ch} is the chimney inlet area. The velocity at chimney inlet is given by [8]

$$V_{ch,in} = \sqrt{2gH_{ch}\frac{(T_{c,out} - T_{amb})}{T_{amb}}} \tag{6}$$

H_{ch} is chimney height and $T_{c,out}$ is collector outlet temperature. The grid power can be found if the turbine efficiency (which is normally ranging between 50 to 90 percent) and efficiency η_f (that include the frictional losses) is taken into account.

4. Validation and results

The simulation was run in two parts, 1) Solar mode 2) Hybrid mode (referred here as the proposed model). Manzanares pilot plant was used as reference plant in the simulation. Solar mode resulted power

output of 47.8 KW and 12.8 m/s updraft velocity at 1000 W/m^2 global solar irradiation. This is the validation of mathematical model with Manzanares pilot plant results. In hybrid mode, the heat transfer effects in the system were calculated by using ANSYS Fluent software. The geometry from the proposed model was used consisting of collector section with two channels only. The final results show a 38.8 % increase in power at 1000 W/m^2. The average day efficiency of the hybrid system resulted as 1.25 % compared with 0.11 % of solar mode. The power comparison (Fig. 2) shows that during night hours solar mode delivers negligible power which is due to some heat energy released by the collector that is had absorbed during the daytime. A significant power value can be seen when the plant is running on hybrid mode. Besides, during the daytime it also enhances the power. Power output largely depends upon the temperature and pressure differences between the ambient and collector outlet respectively as represented by eq. (5). The trend of collector pressure difference follows same as that of power (Fig. 3).
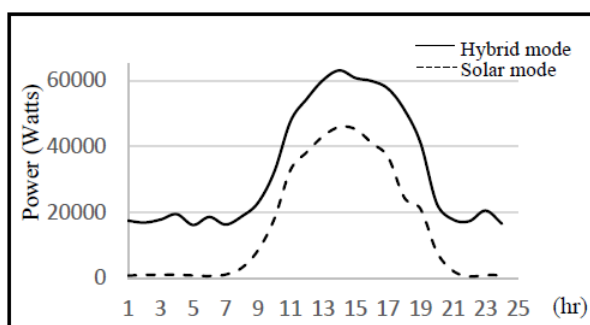
Figure 2. Power comparison between solar and hybrid mode
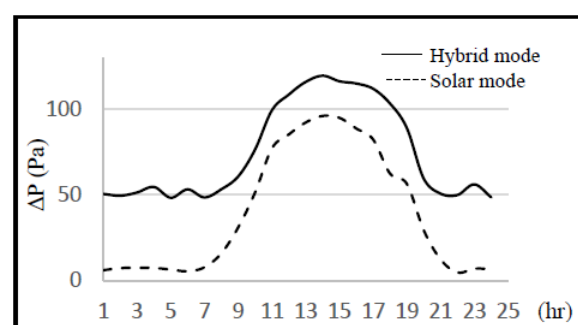
Figure 3. Collector pressure drop comparison between solar and hybrid mode

5. Conclusion

An enhancement technique to improve the performance of the solar chimney power plants has been investigated by mathematical simulation. The simulated model was validated by comparing the results with the operational results of Manzanares pilot prototype plant. The proposed model which based on charging heat to collector air has shown considerable enhancement in the performance. The system under the new proposed thermal hybrid technique becomes able to deliver electricity all around the day.

References

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