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Review on the Enhancement Techniques and Introduction of an Alternate Enhancement Technique of Solar Chimney Power Plant

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Abstract: Due to the low plant efficiency associated with Solar Chimney Power Plant, there is a need for the plant performance enhancement. This study presents the enhancement techniques of solar chimney power plant. It reviews previous works that had been done in performance enhancement of solar chimney power plants. It also, introduces an alternative approach to enhance the solar chimney performance by hybridizing the solar operation mode and waste heat energy from flue gas. The new idea is to convert the waste thermal energy in the flue to useful thermal energy in a Solar Chimney Power Plant collector. It is another form of waste heat energy recovery and utilization method.

Key words: Energy recovery, solar chimney, flue gas, enhancement

INTRODUCTION

Solar energy finds its applications in domestic hot water systems, solar distillation of sea and brackish water, water pumping, drying of agricultural produce, solar industrial process heat, space heating and cooling (passive and active design), daylighting, solar refrigeration, building integrated photovoltaic systems and solar electrical power generation. Electric power can be generated by direct conversion of sunlight to electricity using photovoltaic or indirect conversion using solar thermal systems. Solar thermal systems for electrical power generation include parabolic trough systems, central receiver systems, dish-stirling engine systems and solar chimney power plant.

Operational principles of the solar chimney power plant: A solar chimney power plant, SCPP is a solar thermal power plant that uses greenhouse principle (solar air collector) and buoyancy effect created by a chimney to generate a solar induced convective flow which drives pressure staged turbogenerator(s) to generate electricity. A traditional solar chimney power plant consists of a circular transparent canopy or roof raised a certain height above the ground, with a chimney/tower at its center as shown in Fig. 1. The chimney at the center houses one or more turbogenerators located at its base. Ambient air from the surrounding enters the system at point 0 (Fig. 1) along the circumference of the collector roof and the ground. Radiation from the sun penetrates the collector roof and strikes the ground surface and the heated ground in turns heats the adjacent air from the ambient temperature to warm air temperature at the collector outlet - point 1, Fig. 1.

The warm air underneath the collector moves toward and up into the central chimney as a result of buoyancy and pressure difference between the ambient air and the warm air inside the plant. The kinetic energy in the warm air is converted to electrical energy using turbogenerator(s).

In 1981, the German structural engineering company, Schlaich Bergermann and Partners (SBP) proposed, designed, built, and tested a SCPP in Manzanares, Spain. The plant has a collector diameter of 240 m and a chimney of 195 m high with 10 m diameter. It is the largest constructed Solar Chimney Power Plant to date designed to produce 50 kW electricity (Fluri, 2008). After an experimental phase the prototype plant fed the Spanish grid in fully automated operation from July 1986 to February 1989 during a total of 8611 h (Schlaich, 1995). The nominal power output of an economically viable plant is three to four orders of magnitude higher than the result of the Manzanares plant but the results from Manzanares show that this concept is a possible alternative to conventional power plants (Fluri, 2008). Considering the result of the experiment on the SCPP in Manzanares and different research models developed so far, SCPP total efficiency is still below 2% and depends largely on the chimney height and the collector area (Elizabeth, 2006).

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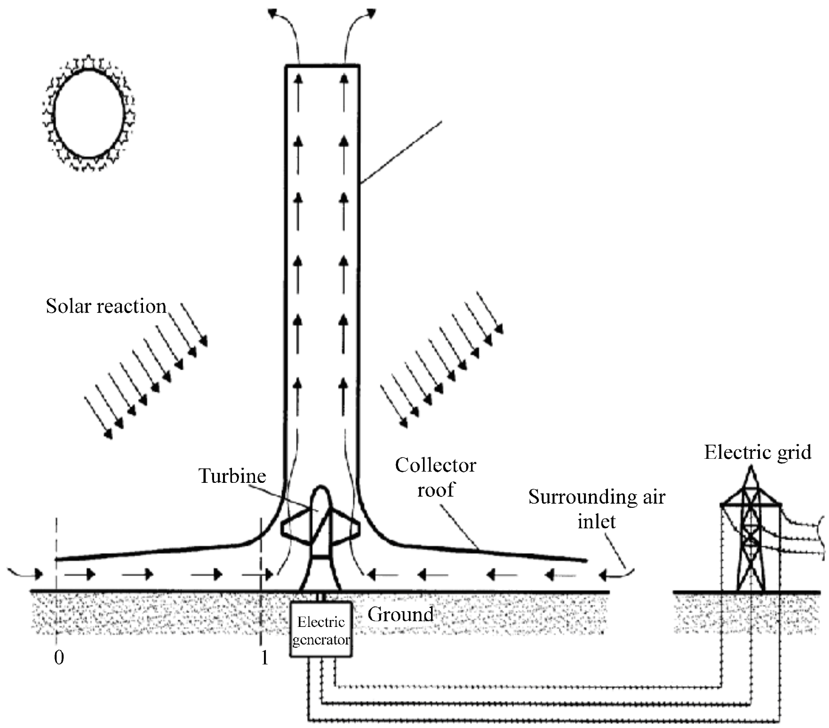

Fig. 1: Schematic overview of the solar tower principle (Nizetic *et al*., 2008)

Thermal waste in flue gases: Exhaust gas heat losses are unavoidable part of operating any fuel-fired furnace, kiln, boiler, oven, or dryer. In fuel-fired furnaces, air and fuel are mixed and burned to generate heat, and a portion of the heat is transferred to the heating device and its load. When the energy or heat transfer reaches its practical limit, the spent combustion gases are removed from the furnace via a stack to make room for a fresh charge of hotter combustion gases. These exhaust gases still hold considerable thermal energy which is exhausted to the atmosphere as waste heat. According to Al-Kayiem *et al*. (2009) flue gas exhausted from thermal power plants contains more than 50% of the fuel thermal energy. Waste heat from flue gases can be classified base on the source and the exhaust gas temperature as high temperature, medium temperature or low temperature heats as shown in Table 1 to 3 (Arvid, 2009). Considerable economic advantage can be achieved by utilizing the waste heat energy from flue gases, which under normal circumstances would have been let out as heat loss (www.em-ea.org). The utilization of this waste heat will reduce the heat in the gas before being exhausted to the atmosphere. Besides considering flue gas for use in this application of hybrid solar chimney (Romero, 2007), on their presentation in AIChE Chicago Symposium-2007, show that flue gases waste heats have been utilized in applications such as combined cycle turbo expander system for solar, biomass and geothermal plants.

Table 1: High temperature range waste heat sources (Arvid, 2009)

Types of Device	Temperature (°C)
Nickel refining furnace	1370-1650
Aluminium refining furnace	650-760
Zinc refining furnace	760-1100
Copper refining furnace	760- 815
Steel heating furnaces	925-1050
Copper reverberatory furnace	900-1100
Open hearth furnace	650-700
Cement kiln (Dry process)	620-730
Glass melting furnace	1000-1550
Hydrogen plants	650-1000
Solid waste incinerators	650-1000
Fume incinerators	650-1450

Table 2: Medium temperature range waste heat sources (Arvid, 2009)

Types of Device	Temperature (°C)
Steam boiler exhausts	230-480
Gas turbine exhausts	370-540
Reciprocating engine exhausts	315-600
Reciprocating engine exhausts (turbo charged)	230-370
Heat treating furnaces	425-650
Drying and baking ovens	230-600
Catalytic crackers	425-650
Annealing furnace cooling systems	425-650

Table 3: Low temperature range waste heat sources (Arvid, 2009)

Source	Temperature (°C)
Process steam condensate	55-88
Cooling water from Furnace doors	32-55
Bearings	32-88
Welding machines	32-88
Injection molding machines	32-88
Annealing furnaces	66-230
Forming dies	27-88
Air compressors	27-50
Pumps	27-88
Internal combustion engines	66-120
Air conditioning and refrigeration condensers	32-43
Liquid still condensers	32-88
Drying, baking and curing ovens	93-230
Hot processed liquids	32-232
Hot processed solids	93-232

Similarly, some industries have started the energy recovery of flue gases for economic and environment purposes. For example, in a study sludge industry, in addition to the incinerator, a natural circulation water tube boiler is used to effectively recover steam from the waste heat of the flue gas (Phubalan, 2004). Nouri *et al.* (2006), studied energy recovery in wastewater treatment plant to lower operation costs and the results showed that by optimization of methane production and energy consumption in different units of the plant, it is possible to provide 97% of plant electrical energy from the waste heat, consequently the amount of recoverable energy in combined engine of heat and power (CHP) system's wasted energy was about 35478 kJ day^{-1}.

Why SCPP: The SCPP has some advantages for electric power generation and also some disadvantages when compared to other energy systems. Many of these factors had been mentioned by Pretorius (2007).

Advantages:

- SCPP utilize beam and diffuse radiation
- The construction materials (mainly glass and concretes) for SCPP are relatively inexpensive and readily available
- The plant does not require any renewable fuels in order to operate and does not produce any emission
- The plant operates using simple technology. Except for possibly the turbo generator, solar chimney power plant technology will not become outdated easily
- SCPP does not require any cooling water
- It has low maintenance cost
- The plant has a long operating life (at least 80 to 100 years)
- It is suitable anywhere in the tropics even in desert areas as solar radiation is a very reliable input energy source

Disadvantages:

- n order to become economically viable, the plant has to be built on a very large scale
- The plant output is not constant throughout the day or year
- The construction of the plant requires large quantities of materials and thereby causing logistic problems regarding the availability and transportation of the materials
- No structure of the scales that are proposed for an economically viable solar chimney power plant has been built before now
- The efficiency of the solar chimney power plant is still below 2% and depends mainly on the height of the chimney and area of the collector

The main objective of this study is to present a review of the techniques suggested by other investigators to enhance the performance of the SCPP techniques. Then the study introduces an alternate enhancement technique which employs a combination of solar and waste heat from flue gas. Multiple goals in this case will be achieved. First is enhancement of the SCPP collector heat transfer to the hot air in the greenhouse and consequently improve the plant efficiency. Second is to reduce the flue gas temperature before exhausting it to the atmosphere.

LITERATURE REVIEW ON SCPP ENHANCEMENT

In order for solar energy to supply a significant proportion of the energy required by mankind, it is generally believed that it will be necessary to provide efficient means for its energy conversion. For wide use of renewable energy technology such as solar power systems, the technology should be simple, reliable and accessible to the technologically less developed countries that are sunny and often have limited raw material resources. It should be based on environmentally sound production from renewable or recyclable materials. The energy produced should be affordable to the consumers. The solar chimney meets these conditions and this is enough reason to further develop this form of solar energy utilization, up to large, economically viable units. The performance of SCPP is a product of the collector efficiency, chimney efficiency and turbine efficiency ($\varsigma_{lant} = \varsigma_{ollector} * \varsigma_{himney} * \varsigma_{urbine}$).

Many research works have been done in modeling mathematically the performance of SCPP collector. An analytical model was presented by Schlaich, (1995). Some numerical models have been presented by

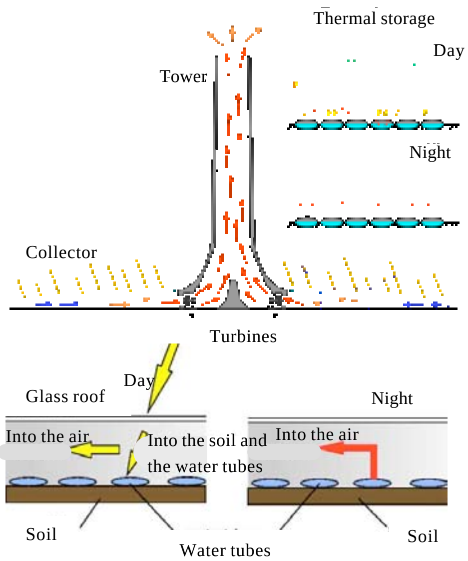

Fig. 2: Water-filled tubes as heat storage in SCPP (Bernardes, 2004; Schlaich *et al*., 2005; Wikipedia, Oct. 2009)

Gannon and Backstrom (2000), Pretorius and Kroger (2006), Hedderwick (2001) and Bernardes (2004). According to Bernardes (2004), the collector accounts for more than 50% of the investment cost and about 50% of the overall system losses. Therefore improving the collector performance offers a big potential in making the SCPP cost competitive and viable source of commercial power generation (Seow, 2008), on the invention of the idea of hybriding solar energy with flue gas showed that the collector performance can be enhanced using heat recovery method. Similarly, in order to predict the total performance of SCPP, various mathematical models have been developed since the early 1980s by Gannon and Backstrom (2000), Schlaich *et al*. (2005), Haaf *et al*. (1983), Pasumarthi and Sherif (1998), Pastohr *et al*. (2003) and Pretorius and Kroger (2006). As much as these models may vary in their approach and computational implementation, they share very important trends. In all the above mentioned models, the power output increases with the height of the chimney and the collector area and they all show a large daily and seasonal fluctuation of power output.

Schlaich (1995) shows that for an economically viable Solar Chimney Power Plant, the chimney height is 950 m high with a diameter of 115 m. Schlaich *et al*. (2005) used analytical model in presenting a simplified theory of SCPP, results from designing, building and operating a small scale prototype in Spain were presented (practical experience). In their analysis, it was found that

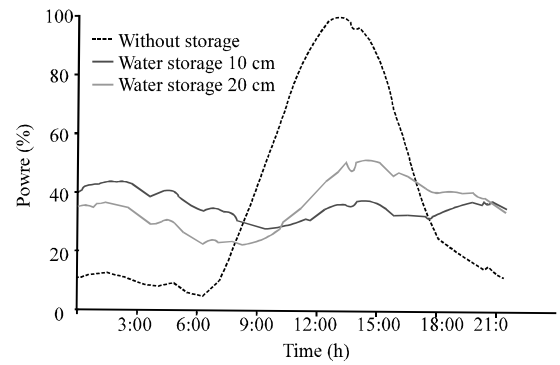

Fig. 3: The effect of the capacity of the thermal storage (water tubes) on power output with respect to time (Bernardes, 2004; Schlaich *et al*., 2005)

the efficiency of a solar chimney power plant increases with the chimney height and the collector area, therefore such plants have to be large enough to become cost competitive.

In Kreetz (1997) introduced the concept of water-filled tubes under the collector roof for thermal energy storage. Bernardes (2004) investigated the possibility of using water-filled tubes on the collector floor as heat storage device and finds that its hence, increases the power output after sunset.

The technique is shown in Fig. 2 and 3. In the day (h of sunshine) the heat from the sun heats up the water in the water-filled tubes and the heat transferred to the water is stored. At night when the air in the greenhouse starts to cool down, the water inside the water-filled tubes releases the heat energy that it has store during the day.

Comparing this technique (water-filled tubes) with the ground, showed that the heat transfer between water tubes and water is much higher than that of ground surface and the soil layers underneath since the heat capacity of water is about five times higher than that of soil (Bernardes, 2004; Schlaich *et al*., 2005). This helps to smooth out the heat requirement for the generation of warm air to drive the turbine and generate electricity for 24 h.

The heat storage capacity is a function of available daily insulation and the water depth/content of the tubes. For 5 to 20 cm depth range of water in the tubes, it was found that the higher the depth/volume of water, the higher the available heat energy stored and the smoother the power generated throughout the day and the daily fluctuations (power drop in the night and early morning) are reduced. But, as can be expected, the peak power output is reduced to about 50% of the normal output without thermal storage medium. This shows that some of the energy from the sun is absorbed by the water in the tube (Fig. 3).

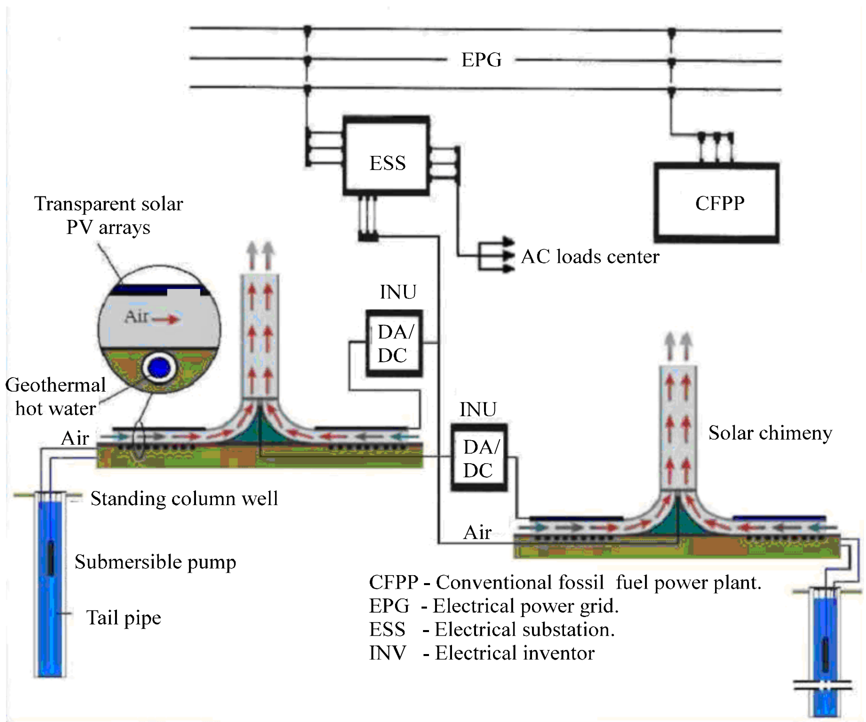

Fig. 4: Hybrid Geothermal/PV/Solar Chimney Power Plant (Hussain, 2007)

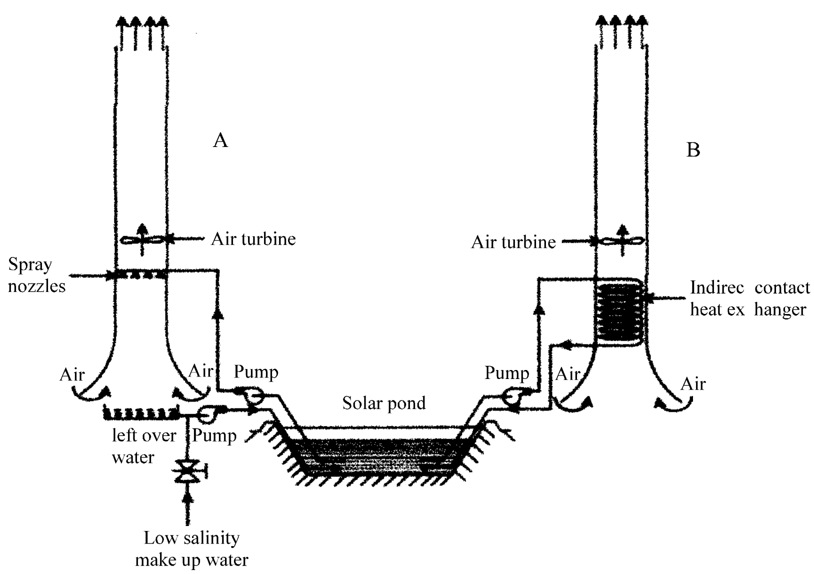

Fig. 5: Concepts for combining a chimney with a solar pond to generate power (Akbarzadeh *et al*., 2009)

Hussain (2007) has proposed Hybrid Geothermal/Solar Chimney Power Plant and Hybrid Geothermal/PV/Solar Chimney Power Plant for prospective SCPP in the south region of Libya. The technology for this hybrid system can be described from the diagram (Fig. 4), geothermal hot water is pumped and circulated through pipes embedded on the soil surface under the collector roof thus hating up the adjacent air to generate artificial wind (hot air stream) that turns the turbine. The Hybrid Geothermal/PV/Solar Chimney Power Plant is similar to Hybrid Geothermal/Solar Chimney Power Plant but includes PV as auxiliary energy converted and an inverter which convert the DC power generated by the PV to AC power to enhance the power generation (Fig. 4). In the two proposed hybrid systems, submersible pumps are required and in the Hybrid Geothermal/PV/Solar Chimney Power Plant, PV cells and inverters are included. The use of pumps will contribute to higher running cost; reduce the expected power generation as most of the power generated will be consumed by the pumping system. The pumping system will need constant maintenance and change of worn out parts. Similarly, the Hybrid Geothermal/PV/Solar Chimney Power Plant includes PV and inverters which will contribute to the initial total cost of the plant making the initial investment high.

Akbarzadeh *et al*. (2009) examined the potential benefit of combining a chimney with a salinity gradient solar pond for production of power in salt affected areas (a case study of northern parts of the state of Victoria in Australia).

In their analysis, they have shown two possible combinations of a SCPP with a solar pond for generation of electricity (Fig. 5). In the technique, heat is removed from the solar pond by extracting hot brine from just below the interface between the gradient layer and the bottom convective zone and pumping it through a water-to-air heat exchanger inside the tower. After delivering its heat, the water is returned to the bottom of the solar pond. The ambient air in the tower is heated and they move towards the turbine where the energy in the moving air is converted by the turbo generator(s) to electricity. The system employs two types of heat exchanger (direct contact and non direct contact heat exchangers). In Fig. 5, tower (A) is a direct contact heat transfer process. In this process, the hot water from the solar pond is pumped up to a height in the tower and the water sprayed all through the surface area of the of the solar tower, the air in the tower gains heat from the hot water, flow up to the turbine by buoyancy principle and losses some of its energy to the turbo generator(s) which converts the kinetic energy into electrical energy. In this process, make up water is required to compensate for the water evaporated as the result of direct contact between air and water. Figure 5, tower (B) shows a non-direct contact heat exchanger, in this process, the hot water is pumped and passed inside a good conductor which extracts and transfers heat from the water to the air insides the solar chimney. The air moving with some acquired energy is used to turn the turbine for power generation.

In analysis of the system described above, it can be found that the efficiency of this system will mainly depend on the diameter and height of the tower because the chimney acts as the greenhouse and also as the tower. It should be noted that the efficiency of a solar chimney power plant depends on the collector diameter, the tower height and the turbine efficiency. In this case, the diameter of the chimney determines the volume of air that would be available for the heating process. Similarly, the use of pumps will drastically affect the amount of power generated as some of the power generated will be channeled to powering the pumping system.

According to Al-Kayiem *et al*. (2009), another approach to facilitate uninterrupted power generation in the absence of intermittent unavailability of solar energy is the use of phase change materials (PCM) which was employed by Sharma *et al*. in their work (Design and development of a solar chimney with built in latent heat storage material for natural ventilation) and Kaneko et al. in their work (Ventilation performance of solar chimney with built in latent heat storage).

AN ALTERNATE ENHANCEMENT TECHNIQUE ON SCPP

Hybrid solar-flue gas chimney: In all considerations, the efficiency of the solar chimney is still very low as compared to the investment cost but it is a very promising technology for environmental friendly and commercial power generation. The problem of ensuring continuous power output or enhancing the efficiency of the solar chimney system has remained a challenge to researchers till date thus this new approach. An alternate enhancement technique has been proposed which utilizes waste heat from flue gas produced from power plants, furnaces and other industrial operations to supplement the solar energy input at the collector to achieve uninterruptible power generation and increase the power output of the solar chimney power plant. Investigation had been done on collector enhancement using flue gas and shown to be feasible (Seow, 2008; Khor, 2009). The schematic side view of a solar flue gas chimney is shown in Fig. 6.

The transparent cover which is made of glass, Absorber plate and insulated back from the greenhouse is named as thermal unit. Solar radiation penetrates through the transparent cover and strike the absorber plate (the heat transfer medium) which is made of good conductor material (aluminum) and painted black to enhance absorbing efficiency. At the flue gas channel, the inlet of the channel is connected to exhaust from experimental gas turbine unit. The hot flue gases discharged from the gas turbine will be passed through the flue gas channel. The heat from the flue gas is transferred to the absorber through the fins attached to the absorber plate. The heat energy gained by the absorber plate from either the solar radiation or the flue gas or a combination of both is transferred to the working

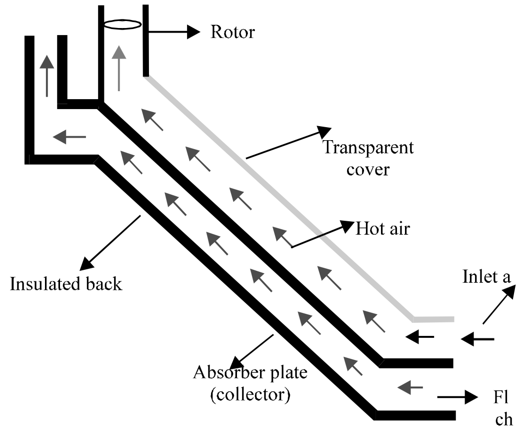

Fig. 6: Schematic side view of a solar flue gas chimney experimental model

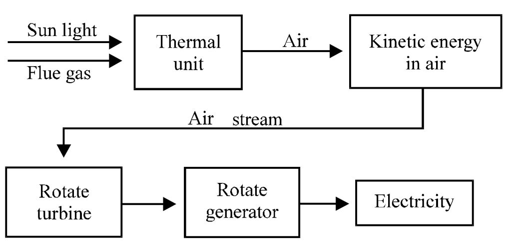

Fig. 7: Energy Conversion Process Block Diagram

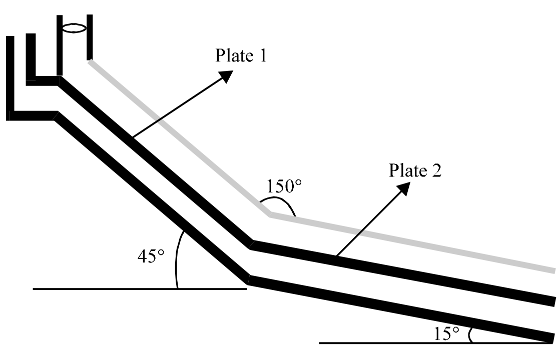

Fig. 8: Design angles of the proposed thermal unit

fluid (air) which is enclosed between the absorber plate and the glass cover. The inlet air is at ambient temperature and atmospheric pressure; a pressure difference and buoyancy effect is created by the heat transfer to the air in the thermal unit which produces air stream, similar to the working principle of a traditional solar chimney. At the top end of the thermal unit is the chimney which creates upwards force (buoyancy) to draw the moving air to the wind rotor situated at the base of the chimney. The hot air stream generated flows through the chimney; the kinetic energy of the moving air stream turns the rotor installed at the base of the chimney to produce mechanical energy which is subsequently converted to electricity by an electric generator. Figure 7 analyses the energy conversion process which is described above.

Thermal unit: The main modification made from a traditional solar chimney to this model is at the thermal unit. In this case an aluminum plate painted black is employed as the collector taking the place of the ground in traditional SCPP. It has two flow channels; above the plate is the air channel housed by a transparent glass, open at the lower end for ambient air inlet; when this air is heated, by the plate, it exits through the chimney which houses a turbine at its base. While underneath the absorber plate is the flue gas flow channel which is housed by a very good insulator (asbestos), channeling the flue gas flow from the exhaust of the gas turbine through the flue gas channel over the fins of the absorber plate (collector) to the exit channel after work (heat transfer to the collector) had been performed.

The first absorber plate (plate 1) is formed at 15° to the horizontal to compensate for the solar mode based on the latitude under consideration (Ipoh Malaysia, 4.57° N) while a second absorber plate (plate 2) is tilted at an angle of 45° to the horizontal and at 150° to the first plate to enhance hot air flow to the tower/chimney, (Fig. 8).

It is expected that the combination of the energy from the sun and the waste heat energy from the flue gas will increase the heat energy available to the collector and hence its performance and the total performance of the SCPP.

CONCLUSION

The performance enhancement techniques of solar chimney power plant have been reviewed and an alternate enhancement technique (solar-flue gas) has been proposed. The alternate technique has the potential of improving the efficiency of the collector and consequently the solar chimney power plant. This alternate approach when employed can reduce the amount of heat that is released to the environment from our daily activities. It is a form of energy saving technique as the energy recovery process will help reduce the fuel consumption in flue gas production plants. So far for the best of the authors, only the mentioned references are dealing with enhancement of solar chimney for power generation application.

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