International Information and Engineering Technology Association
Advancing the World of Information and Engineering

International Journal of Energy Production and Management
Vol. 8, No. 2, June, 2023, pp. 81-87
Journal homepage: http://iieta.org/journals/ijepm

Experimental Evaluation of a Hybrid Inclined Solar Chimney for Power Generation

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https://doi.org/10.18280/ijepm.080204

Received: 6 January 2023
Accepted: 30 March 2023

Keywords:
energy recovery, flue gas, hybrid solar chimney, inclined solar chimney, integrated solar system, waste to energy

ABSTRACT

The intermittent nature of solar energy is a problem for power demand-supply. In particular, power generation by a solar chimney is insufficient due to low efficiency and interrupted power production. In the current research, an experimental model of an inclined solar chimney is integrated with an external heat source to develop a hybrid solar chimney. The developed hybrid solar chimney utilizes the exhaust flue gas from a lab-scale experimental gas turbine. The exhaust gases from the gas turbine were supplied through a passage underneath the absorber plate of the solar chimney. The absorber plate is modified into a heat exchanger by adding extended surfaces in the flue passage. Furthermore, the hybrid system is experimented outdoors to utilize solar irradiation, and a burner produces the hot gases. Experimental measurements have been carried out in three different cases. The investigated system performance to produce power is enhanced by 91.0% by integrating the inclined solar chimney with an external heat source at an average temperature of only 88.0℃. The results show that the mean enhancement in the air temperature rise of the hybrid mode is 33% compared to the solar mode; this considerably improves the solar chimney performance. The proved concept of the hybrid inclined solar chimney could be adopted in existing thermal power plants to recover the heat losses in the flue gases.

1. INTRODUCTION

Solar chimneys are practically used for the ventilation of spaces and are proposed to be power generation technology. The concept of solar updraft power for generation by a pilot scale of a solar chimney power plant is not yet applied. The only pilot plant used for the proof of concept is the one implemented in Manzanares–Spain, to produce 50 kW power. After that, many researchers have attempted to improve the observed low efficiency and address the interrupted power generation at night and on cloudy days. The current research aims to investigate a hybrid solar chimney integrated with an external heat source. The selected model of an inclined solar chimney was modified to operate with solar and flue gas supplied from an external thermal system. The results demonstrated huge improvement in the system operation whereby the performance indicator by the hybrid operation is improved by 91.0%. Also, it is possible to operate the system at night using flue gas as a thermal energy source.

1.1 Inclined solar chimney

Attempts have been reported to replace the circular solar air collector with an inclined rectangular collector to form an inclined solar chimney (ISC). Al-Kayiem et al. [1] reported an early rudimentary attempt at developing an experimental evaluation of an ISC model integrated with a flue gas source from an experimental gas turbine using an S-rotor for power generation. Chikere et al. [2] introduced a new ISC configuration that includes a double slope rectangular collector. The first half is inclined at 15° and the second is inclined at 45° relative to the horizontal plane. At the same time, Panse et al. [3] suggested a geometry of ISC that could be constructed over the side of a mountain, on which maximum solar insolation is incident throughout the year. The chimney and the collector merge to make the structure stable, cost-effective and easy to construct. They developed a mathematical model considering the total energy balance, which predicts the emerging air draft's temperature, velocity and kinetic power for some chosen values of other parameters.

Detailed mathematical modeling of the energy balance of ICS integrated with flue gas is reported by Al-Kayiem et al. [4]. They presented mathematical and numerical results and concluded that when the flue temperature is increased from 605 K to 843 K, the performance is enhanced by 75%, indicating that this is a highly effective system performance parameter.

1.2 Description of hybrid solar chimney

Hybrid solar chimney power plant (SCPP) integrates the traditional SC with another heat source to enhance the combined system's power production. The idea of hybrid SCPP is presented schematically in Figure 1. Rahbar and Riasi [5] proposed two novel hybrid configurations for the conventional SCPP. The first solar chimney model was integrated with transparent PV panels, while the second was integrated with transparent PV panels and saline water desalination. A comparison of the obtained results shows that the collector and plant efficiencies of the second model notably exceeded those of the conventional and the first models, where the collector efficiency surpassed the traditional and the first model by 26.13% and 21.92%, respectively. Aurybi et al. [6, 7] and Al-Kayiem et al. [8] proposed another approach to hybrid SC using a new concept that combined a solar chimney with waste external heat sources to enhance the performance of the traditional SCPP. A significant enhancement in the solar chimney performance and a continuous full-day operation were achieved by installing a thermal channel between the canopy and the ground.

Ahmed and Hussein [9] reported experimental investigation results of ISC integrated with PV panels. Similar experimental work was carried out in Kuwait, as reported by Hussam et al. [10] who, however, extended the work to visualize the flow field inside the ISC using numerical simulation and reported their results in the study [11].

The literature demonstrates some advantages of designing the solar chimney in an inclined orientation. On the other hand, hybridization is a promising method to overcome the issue of interrupted power generation by the solar chimney. Accordingly, the current study aims to investigate a hybrid inclined solar chimney, which is integrated with a flue gas source as a secondary energy input, while the main source is solar energy. The developed system has been investigated under three operational modes, namely, flue gas mode, solar mode and hybrid flue-solar mode.

2. EXPERIMENTAL PROGRAMME

The experimental model selected for this study is a modified inclined SC.

2.1 Experimental model and modifications

A schematic of the system is presented in Figure 1. The system consists of a thermal absorption unit, a power unit, and a chimney unit. The first modification is imposed on the absorber plate, while the second is imposed on the collector section. The thermal absorption unit receives and converts the solar radiation during the solar and hybrid modes and transfers heat to the ambient air flowing inside the airflow passage. During flue operation and hybrid modes, the thermal absorption unit receives thermal energy from the solar at the top surface and the hot flue gas at the bottom.

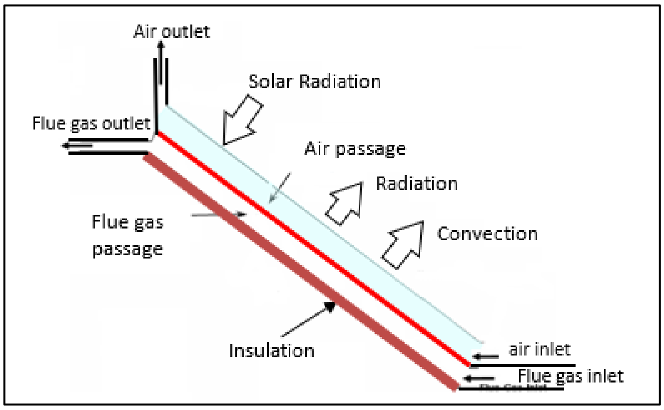

Figure 1. Schematic of the hybrid inclined solar chimney with flue gas source

This unit was modified from a plain flat plate absorber to a heat exchanger by adding extended surfaces at the backside by installing straight fins. The addition of the straight fins in the flue gas passage enhanced the heat transfer rate from the hot flue gases to the thermal unit by increasing the heat transfer area. The finned Aluminium thermal plate is fabricated in the university with limited cost and facilities, and thus the design is fairly simple. Nine angled Aluminium plates, 0.04 m-high and 1.5 m-long, are attached to the thermal unit at the bottom surface. The absorber plate and a perspex cover bound the upper air flow passage. The solar absorber surface is coated with non-glossy dark-colored paint aiming to achieve maximum absorptance, α, and minimum re-emittance, ε, so that the ratio of performance factor, α/ε is a maximum. Black chrome on the cupper has been selected because it has a high-performance ratio of 7.92. Also, it is locally available and cheap compared to black Nickel or black Chrome on copper. The unit is 1.0 m-wide perpendicular to the air and flue flowing direction and 1.5 m-long in the flow direction inside the thermal absorption unit, as shown in Figure 2.

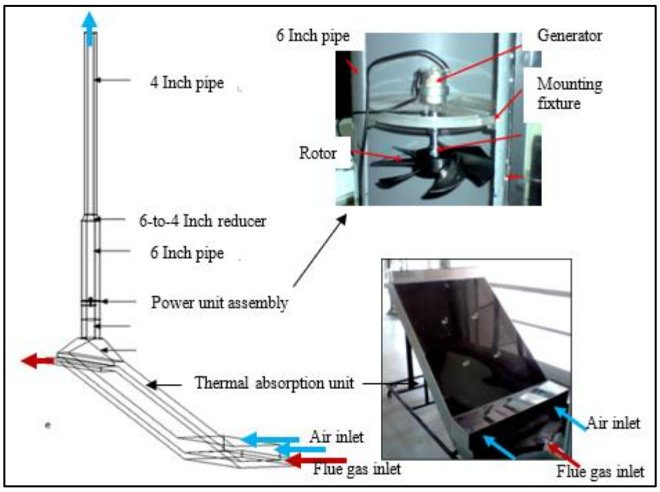

Figure 2. The layout of the hybrid inclined solar chimney shows the layout, the thermal conversion unit and the power generation unit

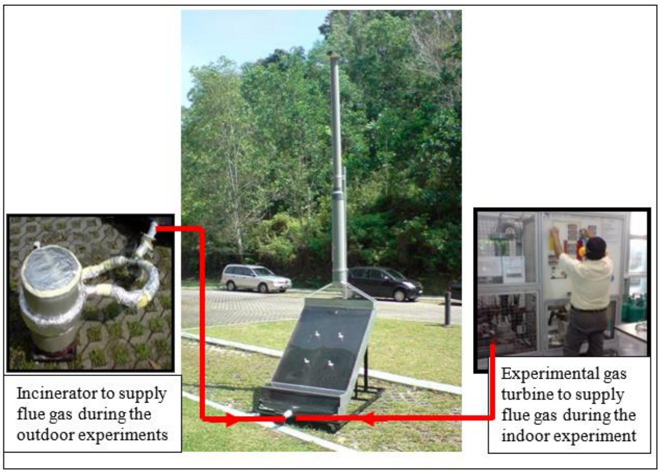

Figure 3. Outdoor experimental setup

The flue gas flows underneath the heat exchanger plate and exhausts to the ambient, while the air flows in the upper passage and moves up in the chimney unit. The chimney unit is fabricated in a conical shape. It is attached to the air outlet section at its bottom and reduces in size to the that its top in a 6 inch-diameter circular exit. A 6 inch-diameter PVC pipe with a 1.0 m-diameter is fixed to the conical part, and then a 4 inch-diameter PVC pipe of 2.0 m height is attached to the 6 inch pipe by a PVC reducer. A power generator unit is fabricated and mounted inside the 6 inch PVC pipe to extract the power from the wind, comprising a perspex supporting fixture that holds the wind rotor perpendicular to the flow air stream. The rotor is connected directly to a DC motor to produce electric power.

During the indoor experiments, operation mode 1, an experimental gas turbine was utilized for the hot flue gas supply. During the outdoor experiments, operational modes 1 and mode 2, a small incinerator was used to produce and supply the hot flue gas. Figure 3 shows the physical model and the flue gas supply units.

2.2 Operational modes

Three different modes were investigated in the current research. The operational condition of each mode is described below.

i. Flue gas operational mode: The experiments have been carried out inside the thermal research Lab for the flue gas operational mode. An experimental gas turbine was utilized to supply the flue gases to the solar chimney. During the flue mode operation, the exhausted gases from an experimental gas turbine are guided to flow underneath the heat exchanger plate of the thermal unit. Some technical problems have affected this operational mode due to the limited operational time of the gas turbine as it was not possible to continue running the gas turbine for more than 20 minutes due to technical problems with the air compressor of the gas turbine.
ii. Solar operational mode: a few basic configurations of the solar model related to the sun must be noted:

- Latitude and longitude of the experiment site.
- Model orientation (compass).
- Weather forecast.
- Local time forecast for sunrise and sunset.

The experiment was conducted at the Universiti Teknologi PETRONAS, Malaysia, which has a latitude of 4° 25' 1" North of the Equator and a longitude of 100° 58' 58" East of the Prime Meridian on the world map. The model's orientation depends highly on the coordinates of the model on the globe and the experiment's timing. The solar mode experiment was performed in August. The model was installed facing the south to avoid shadowing by the tall chimney. A solar calculator was used in the analysis of acquired data, and the declination of the sun on the day of the experiment (21 Aug. 2019) was a positive 12 degrees.

iii. Hybrid operational mode: The experiments were carried out for the hybrid operational mode using a biomass burner to supply the flue gases, as the connection to the gas turbine was impossible. The gas-to-gas burner was designed, fabricated and evaluated as described by Yassen et al. [12]. The flue gas supply was controlled to be constant from 9 am until 4 pm to ensure that the experiments simulated the environment. The biomass burner was functional before 9 am to ensure constant flue gas temperature throughout the experiment. Charcoal was used as an alternative to a biomass fuel source due to its long-lasting burning effect. The flue gas temperature from charcoal burning was around 100°C.

2.3 Experiment strategy

The required variables to predict the system performance were measured at various operational modes. Air inlet and outlet temperatures, flue gas and outlet temperatures, and absorber plate temperature have been measured using thermocouple wires type J. A Solari meter is used to measure solar irradiation, and a digital tachometer is used to measure the rotational speed of the wind turbine. The absorber plate temperature was measured using two thermocouples fixed on the upper surface at the thermal unit's inlet and outlet of the air passage. The air velocities at the inlet and outlet were measured by a portable hot wire connected to a digital anemometer.

The properties of the measuring instruments are presented in Table 1. The installed power unit cannot produce measurable outputs due to the low flow rate that cannot rotate the wind turbine properly.

Table 1. Measuring instrumentations of process variables and their specifications

Variable	Instrument	Specification
Angular velocity	Optical Tachometer	Accuracy ±0.3% of rdg ±1RPM ±30 RPM Operation range: 60 - 10000 RPM
Absorber plate temperature	Thermocouple wires type-K	Accuracy: ±0.75%
Air inlet and outlet velocities	TPI 565 Hotwire Anemometer	Accuracy ±5% of reading ±3 digits
Air inlet and outlet temperatures	Portable thermocouple probe type K	Accuracy: ±0.75%
Solar intensity	Light/Solari meter	Accuracy: ±5% of the measurement

The measurement locations in the system are shown in Figure 4.

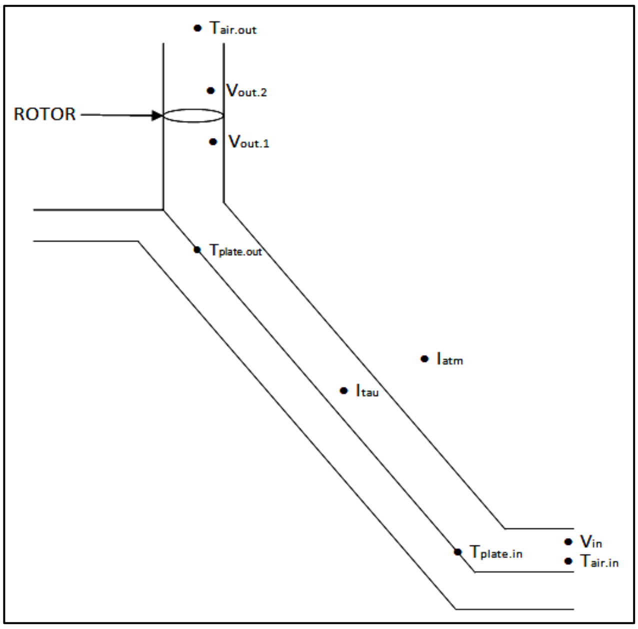

Figure 4. Locations of the process variables measurements

3. RESULTS AND DISCUSSION

Three operational modes have been investigated in the current study, including flue gas mode, solar mode and hybrid mode. The analysis presented in this section consists of experimental measurement results and comparisons between different design assumptions. Comparison between the cases is based on air, gas and absorber plate temperatures and the performance indicator (P.I.) proposed by Al-Kayiem et al. [8] defined by

$$P.I. = \dot{m}\Delta T_{air} \qquad (1)$$

where, $\dot{m}$ is the mass flow rate.

3.1 Analysis of operational modes

The three tested modes were implemented in two locations. The first mode was applied inside the gas turbine laboratory, where an experimental gas turbine setup was utilized. The other two modes applied outdoors, since solar radiation is then required.

3.1.1 Flue gas mode results

The absorber plate temperature increases after the start of the gas turbine. Figure 5 shows the thermal behaviour of the system, including the absorber plate and air temperature rise. Five data points were recorded at 5 minutes intervals after starting the gas turbine. From the limited 20 minutes experiment, the maximum air temperature difference is a massive 26.5°C. Figure 5 also shows the temperature differences of the updraft air across the inclined collector due to the thermal supply to the absorber through the absorber plate. A significant increase in the air temperature may reduce the solar chimney size or enhance efficiency. It could be concluded that using the hot gases resources assists the solar in operating the system early in the morning when the solar energy is insufficient to allow the solar chimney to produce electric power at low intensity.

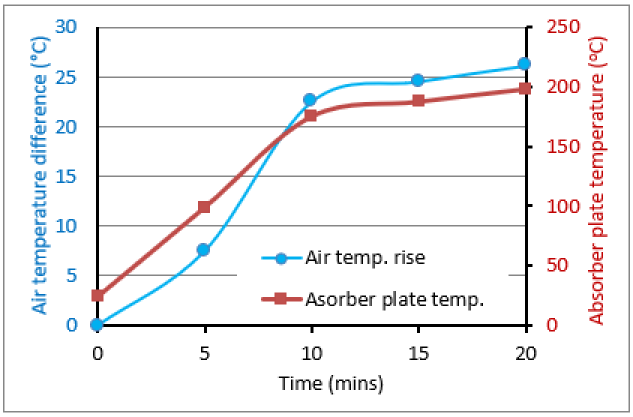

Figure 5. Thermal results in terms of air temperature rise and absorber plate temperature

Figure 6 shows the measured air velocity at the chimney base. As the flue gas temperature became higher, the increase in the kinetic energy of air was fast, and the air velocity reached 0.75 m/s just 20 minutes after starting. The maximum velocity of updraft air was 0.8 m/s, which is a very encouraging result for a lab-scaled hybrid solar chimney. A longer testing period than 20 minutes is not possible due to technical issues in the gas turbine unit. The unit is meant for teaching purposes and cannot continue operating for more than 20 minutes due to the limitation in the compressed air supply. This finding is practically significant. Using flue gas to operate the system before sunrise would significantly enhance the system's performance and start the power production in the early morning. If the supply of flue gas is continuous, in that case, there is no interruption in the power production and the production increases when the solar radiation reaches the absorber surface. The results show a significant contribution of the flue gas to enhance the solar chimney performance. This has also been demonstrated by Al-Kayiem et al. [8] in their study of the normal circular solar chimney integrated with flue gases.

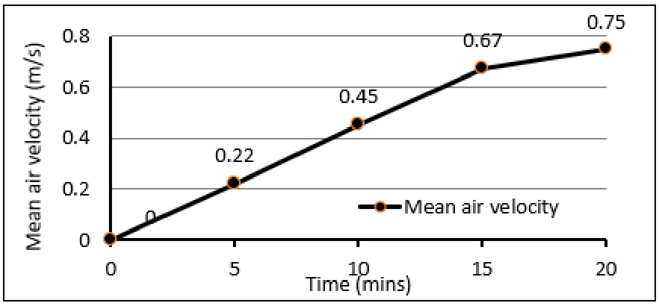

Figure 6. Measured mean air velocity inside the chimney

This study can mimic the actual environment where the hybrid solar chimney could be installed in power plants in the future. If it is assumed that the gas turbine can provide constant flue gas for a longer period, the increased temperature and velocity can maintain the electricity production during the night as well as in a cloudy and rainy environment.

3.1.2 Solar mode results

After all the precautions discussed in the previous section were taken, the results were acquired and tabulated in Table 2. The analysis of the measured solar irradiation is shown in Figure 7. There is considerable reduction in the power values after transmission through the perspex cover. There is a massive loss, with an average of 29%, of solar radiation throughout the 8 hours (9 am till 4 pm) ex, due to the 4 mm thick Perspex. The reduction in the transmitted solar power could be less if glass is used instead of perspex.

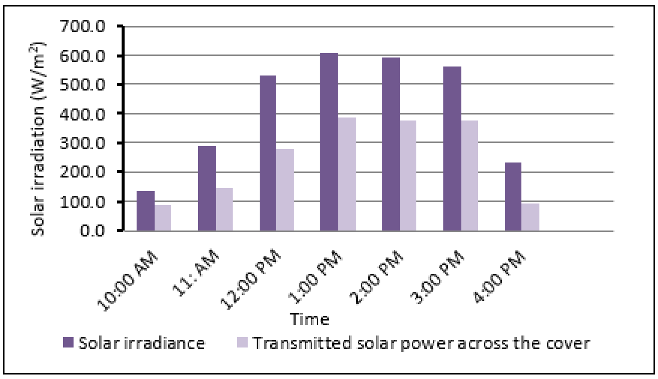

Figure 7. Measured values of the solar irradiance before and after transmissivity through the thermal unit cover

The thermal analysis of the solar operational mode is presented in Figure 8. This figure shows the measured solar irradiance, the absorber plate temperature, and the air temperature rise. The increase in air temperature inside the thermal unit follows the trend of the absorber plate temperature, which is a result of the absorbed solar radiation by the absorber plate. Until 11:00 am, air gained a small amount of thermal energy from the absorber. The air temperature rise becomes considerable after 11:00 am. Consequently, the air velocity in the chimney base increases. The maximum recorded air temperature rise is 9.8°C at around 2:00 pm. The measured velocity at the chimney base is the highest at this time.

The trend of absorber plate temperature is not directly proportional to solar irradiation. The highest solar irradiance was measured at 1:30 pm, while the maximum absorber plate temperature, 57.75°C, was recorded at 3:00 pm. The reason is that the absorber plate functions as thermal energy storage. In addition, the ambient air temperature is high after 2:00 pm, and the energy transfer from the absorber to the flowing air is less due to the smaller temperature difference between air and absorber.

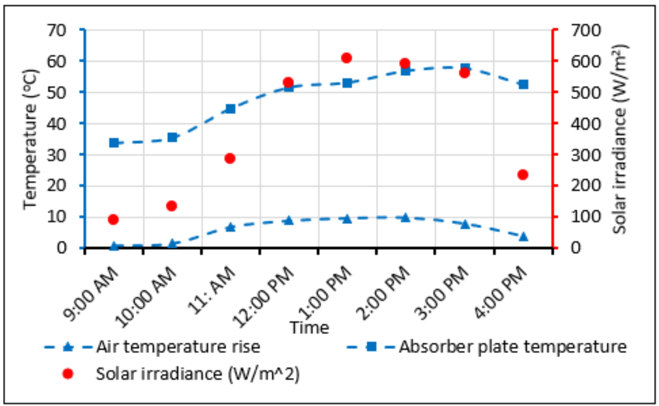

Figure 8. Measurement results of the solar mode showing the solar irradiance, the mean absorber plate temperature and the air temperature rise

The maximum updraft air velocity achieved in this experiment is 0.1 m/s. It is insignificant, but only a lab-scaled model is used in this case. A higher updraft air velocity would be achieved by significantly scaling up the model (increasing the absorber plate area, air inlet, and others).

3.1.3 Hybrid mode results

In the hybrid experiment mode, charcoal generated the flue gases from a biomass burner. The burner could produce a flue gas with a temperature of around 100°C. The experiment was repeated for four days, and the mean results obtained from the measurements are shown in Table 2. The inlet air temperature is the ambient temperature. The mean temperature rise of air in the thermal unit is around 9°C. Temperature measurement of the flue gas shows a considerable reduction in the temperature between the outlet and inlet. This indicates the successful modification of the absorber from a flat plate to a heat exchanger. However, due to the relatively small size of the model, the air velocity is small and cannot rotate the power unit to generate electricity. A larger scale of the thermal unit would enhance the kinetic energy by more thermal energy gain from the solar and the flue gas.

The measurement results of air and flue gas show that the air temperature is higher than the flue gas temperature. The reason is that the flowing air in the upper passage receives thermal energy from the absorber plate, which is 56.45°C. The absorber gained thermal energy from the flue gas and the solar incidence. At 3:00 pm and 4:00 pm, the solar input is dominant and its contribution larger than that of the flue gas.

3.2 Comparison between hybrid and solar modes

The main target of this research is to check the enhancement achieved by integrating solar energy with an external heat source to operate the SCPP. The comparison is presented in Figure 9 in terms of the air temperature rise in solar and hybrid modes. The mean air temperature rises from 9:00 am to 4:00 pm are 9.1°C and 6.1°C for the hybrid and the solar modes, respectively. The mean enhancement in the air temperature rise is 33%, which considerably improves the solar chimney performance.

Another comparison factor is the P.I., in kg·K/s, resulting from the multiplying of mass flow rate by the air temperature change. The estimated P.I. for the hybrid and solar modes is presented in Figure 10. The maximum P.I. of the hybrid mode is 2.925 kg·K/s, while the maximum performance of the solar mode is 0.293 kg·K/s. The mean determined P.I. by operating the system with the hybrid mode is 1.0 kg·K/s, while the mean P.I. by solar mode operation is 0.088 kg·K/s. The ISC performance to produce power is enhanced by 91.0% by integrating the inclined solar chimney with an external heat source at an average temperature of only 88.0°C.

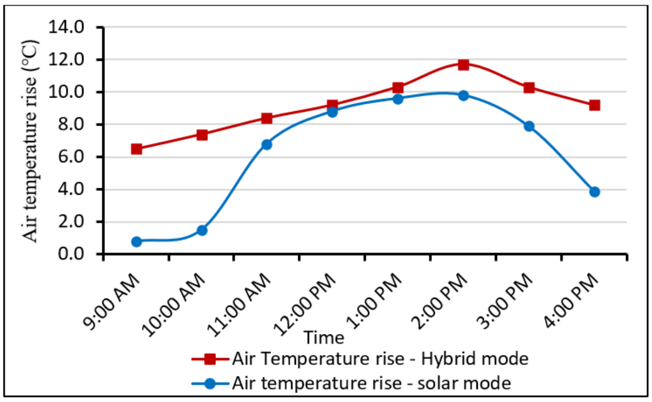

Figure 9. Comparison of the air temperature rise between the solar and hybrid modes

Table 2. Hybrid measurement results in a mean of four days of repeatability

Time →	9:00 am	10:00 am	11:00 am	12:00 pm	1:00 pm	2:00 pm	3:00 pm	4:00 pm
Mean absorber plate temp (°C)	38.75	42.05	53.45	55.95	58.2	63.3	57.25	56.45
Flue gas temp at inlet $T_{gas, in}$	54.6	77	102.1	104.3	100.3	96.4	89.1	84.6
Flue gas temp at exit $T_{gas, out}$	35	35.6	36.5	36.6	40.1	42.3	41.3	39.6
Air temp at inlet $T_{air, in}$	27.0	27.5	28.4	29.3	30.6	30.7	30.9	31.0
Air temp at outlet $T_{air, out}$	34.9	34.9	35.8	38.5	40.5	42.4	41.2	40.2
Mean air velocity in the chimney base	0.0	0.0	0.0	0.1	0.2	0.3	0.1	0.1

The concept of hybrid SCPP is a promising approach for 24/7 power generation, with highly improved energy production performance.

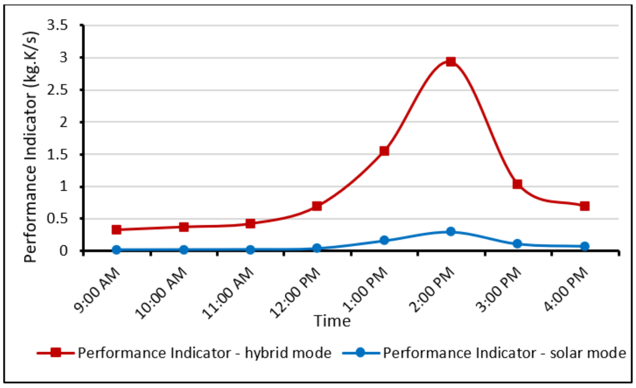

Figure 10. Comparison between the hybrid and solar modes in terms of the performance indicator

4. CONCLUSIONS

An inclined solar chimney for power generation is modified by converting the absorber plate to a heat exchanger that extracts heat from flue gases flowing underneath the plate and the absorbed solar radiation at the top of the plate. The influence of the hybrid approach is evaluated experimentally. The results revealed a high-performance improvement in power production when the inclined solar chimney was integrated with an external heat source. The power production is enhanced by 91.0% by integrating the inclined solar chimney with an external heat source. The mean enhancement in the air temperature rise of the hybrid mode is 33% compared to that of the solar mode. This work proved that the hybrid inclined solar chimney concept could be adopted in existing thermal power plants to recover the heat losses in the flue gases. Such contribution may lead to the reduced size of the solar chimney power plant and increase power production by eliminating solar interruption at night.

It is recommended to extend the investigation of the topic by increasing the collector area, variable flue gas supply and over 24 hours operation to further understand the system performance during the night.

DATA AVAILABILITY

The experimental measurement data and other related materials can be found at Universiti Teknologi PETRONAS UTPedia, site: http://utpedia.utp.edu.my/id/eprint/813/.

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NOMENCLATURE

Symbols

$T_{gas, in}$	Flue gas temp at the inlet
$T_{gas, out}$	Flue gas temp at exit
$T_{air, in}$	Air temp at the inlet
$T_{air, out}$	Air temp at the outlet

Abbreviations

ISC	Inclined solar chimney
P.I.	Performance indicator
SC	Solar chimney
SCPP	Solar chimney power plant