

Performance Analysis of a Solar Chimney Power Plant for Different Geographical Locations of Saudi Arabia

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In this study, a detailed performance analysis was conducted by analysing the energy model of solar chimney power plant. The developed model was used for five locations (cities) in Saudi Arabia for a comparative study. The selected cities were Jubail (East), Arar (North), Umluj (West), Sharurah (South) and Shaqra (Central). The solar irradiation, sunshine hours, ambient temperature and atmospheric pressure was used to determine the output power, efficiency, and other performance parameters for the chosen size of plant. The data analysis showed that the highest annual average solar irradiation was at Sharurah (551W/m^2) and the lowest for Jubail (456W/m^2). The highest and lowest average ambient temperatures were found at Sharurah (303K) and Umluj (301K). Study reveals that annual average efficiency for Jubail is highest followed by Umluj. Furthermore, the output power, energy efficiency, variation of floor and air temperatures and pressure across turbine and chimney, variation of the mass flow rate and, the turbine inlet velocity are reported for all the months during the year for the selected five cities of Saudi Arabia.

Keywords: Solar Chimney Power Plant (SCPP), Energy, Modelling, Saudi Arabia.

1. INTRODUCTION

Solar energy is a clean, abundant, and freely available source of energy and is most suited for locations, which are not yet connected to the power grid. Main applications of solar energy utilization include solar thermal and solar photovoltaic based power generation, solar water heating, solar cooling, to name a few. Nowadays, solar chimney power plants (SCPP), also known as Solar Updraft Towers (SUT), are being designed, developed, and optimized for electrical power generation, though still in infancy stage. It is a technology, which is capable of producing power from low temperature solar heat. The solar radiation from the sun heats the air beneath a wide greenhouse like roofed collector structure surrounding the central base of a tall chimney tower and create an updraft of the lighter hot air through the chimney. In simple words, solar chimneys use radiant energy from the sun to create hot airflow capable of running wind turbines to generate electricity. A typical photo of the SCPP is shown in Figure 1. Around the globe, research efforts are being made to study the operational characteristics, flow field, energy conversion processes, and the structural aspects of such power plants.

Taller chimneys are needed for better efficiency of such plants [1]. Solar chimney is emerging as a reliable renewable energy application and attracting attention of

engineers and scientists to address the current energy crisis. Solar chimneys are innovative passive design components that utilize solar energy to build up stack pressure and enhances the efficiency for residential space heating and cooling, Monghasemi and Vadiie [2]. Solar chimney efficiency is around 2%, but is a promising technology for converting sun's energy to electricity, [3]. A SCPP can produce monthly average 1–2 MW electric power over a year with 350 m high chimney and 1000 m collector diameter [4]. Keeping competitive cost and achieving optimal performance of the plant is still a challenge in the success of this technology [5]. The shape of the chimney influences the plant performance [1]. Generally, solar chimneys for power generation are cylindrical with almost constant cross sectional area throughout [6–11]. For chimney efficiency the enhancement, optimization of its size and shape is an important research area.

Kasaean et al. [12] provided a review of the experimental, analytical, simulation studies, the solar chimney applications, hybrid systems, case studies and identified technological gaps and suggested future research avenues. Muhammad and Atrooshi [13] applied CFD to model the heat transport in collector and chimney areas and reported data for 180 cases in 15 groups for collector size, chimney height, diameter; and another 130 cases in 12 groups for collector height of matching dimensions.

From this development, now it is possible to make decision on consistency of dimensions of chimney plants. Xu and Zhou [14] carried out simulations of divergent-chimney solar power plants (DSPPs) by changing chimney's outlet-to-inlet area ratios (COAR) over a wide range and obtained maximum power of 231.7 kW at

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COAR = 8.7. Ćocić and Djordjević [15] used one-dimensional flow model to obtain the values of physical properties such as velocity, temperature, pressure, and air density in collector and the chimney considering compressible flow. The model results tested on existing plants (Manzanares and Enviromission) showed good agreement between the two.



Figure 1. A typical photo of a solar chimney power plant

Koonsrisuk [16] investigated the performance of a conventional and a sloped SCPP based on second law of thermodynamics and demonstrated that efficiencies of both the systems increased with the increasing height. The sloped system was found thermodynamically better than the conventional plant. An unsteady comprehensive and a streamlined unsteady mechanism models was used to analyse the energy conversion and transmission of the system for SCPPs, [17]. Results showed positive and negative correlations between the chimney height and power quality factor and collector radius and the power quality factor; respectively. Performance of SCPPs is highly site dependent due to dependence on solar radiation intensity and sunshine duration. This requires specific site dependent design and accordingly, Cao et al. [18] used TRNSYS to simulate the performance of SCPPs and stated that power generation was more dependent on solar irradiation intensity than ambient temperature.

A multi-objective optimization technique was employed to find optimum configuration of chimney plant based on power output and capital cost [19]. Results showed that the output power increased linearly with solar irradiation while decreased slightly with increase in ambient temperature. A hybrid renewable energy system consisting of waste-to-energy and solar chimney power plants was analysed in terms of energy, exergy, exergoeconomic, and environmental impact through parametric study [20]. Results demonstrated that the best exergy efficiency and total cost rate were 7.56% and 406.8 \$/h. The system exergy efficiency was higher during night and the product cost low during the day. Maia et al. [21] reviewed and reported major technologies used for solar desalination and evaluated the relevant approaches for the usage of solar chimneys for water treatment. Performance of a laboratory scale solar chimney (diameter = 0.3 m, length = 12 m, air collector diameter = 11 m, and height = 0.65 m) was investigated using thermal phase change material [22]. Results showed that with thermal storage materials (water and paraffin) the productivity increased by 9% and 20% and energy yield by 6.2% and 22%, respectively; compared to the case without absorber.

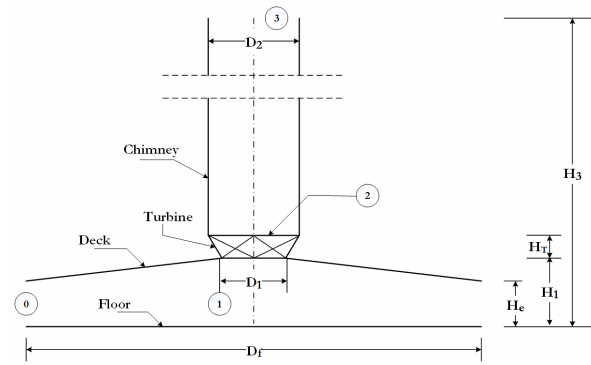


Figure 2. A schematic diagram of an SCPP

Cost models were presented for main components (collector, chimney, and power unit) of a SCPP and pointed out that previous models may have underestimated the initial and levelised cost of energy of large-scale SCPPs [23]. It was shown that carbon credits significantly reduce the levelised cost of energy for such a plant. Tan and Wong [24] determined the effect of air speed and internal heat load on the thermal performance of the chimney ducts and classroom's interior both experimentally and computationally. Their results showed that high air speed >2.00 m/s improved the airflow within the chimney duct. However, the significant drop in air speed is noticed for solar irradiance intensity of >700 W/m².

A 50-kW pilot SCPP was constructed in Manzanares, Spain [25] and experimental results showed that the chimney concept is technically viable but low overall efficiency of < 0.1% [26]. For improved the efficiency, larger plants with chimney heights of 1000 m or more were proposed [9]. Khanal and Lie [27] conducted experiments on inclined passive wall chimney model with a uniform heat flux on the active wall and reported that the inclination angle of passive wall did not have visible effect on temperature distribution across the air gap width and chimney height.

Table 1. The dimensions of the SCPP under evaluation [28]

Geometric Parameter	Dimensions (meter)
D_f	240
D_1	16.970
D_2	17.86
H_1	4.243
H_e	0.300
H_3	195

However, the inclination angle strongly affected airflow velocity across the air gap width. Liu et al. [29] studied the induced chimney effect in a solar hybrid double wall with chimney gap width-to-height ratios between 1:10 and 3:5. Experimental data indicated lowest temperature existed in the air gap and varied with air gap width. The average air velocity increased with the radiation intensity and showed high value with decreasing chimney gap width. However, the induced mass flow rate enhanced with both the radiation intensity and the chimney gap width. The temperature difference between the chimney inlet and ambient reached to 26.3°C in a pilot plant having 3 m collector diameter and 2 m chimney height [30]. The output power increased with

reduction of inlet size and a maximum air velocity of 1.3 m/s was found in the chimney, while velocity was around zero at collector entrance.

The Kingdom of Saudi Arabia is heading towards diversifying its energy mix portfolio by adding wind, solar photovoltaic, and solar thermal based power generation. Efforts are also being made to supplement these renewable sources of energy through hydro energy storage, building integrated photovoltaic and solar water heaters, and solar chimney power plants as well. This study aims at studying the performance of solar chimney plants (height = 195 m and floor diameter of 240 m) for five cities in Saudi Arabia for possible deployment in the near future.

2. WORKING PRINCIPLE OF A SOLAR CHIMNEY POWER PLANT (SCPP)

Solar thermal technologies are the basis of proper operation of SCPP. However, the main disadvantage of this technology is that it is less efficient. Being a cost effective and clean source of energy generation, it is feasible. In SCPP, the natural updraft of hot air is driven through the chimney. It consists of mainly three components, an energy conversion device (solar energy absorber, known as greenhouse), a chimney at the centre of the greenhouse, and a wind turbine installed inside the chimney.



Figure 3. Locations for comparative study 1. Jubail, 2. Arar, 3. Umluj, 4. Sharurah, 5. Shaqra

This arrangement allows the conversion of sun's radiant energy into electrical energy in two steps. First, the collector transforms radiant energy into thermal energy (greenhouse effect) which heats the air. The design of

the collector facilitates the heated airflow radially towards the chimney from all directions. Next, updraft flow of lighter air in the chimney upwards tend to operate the wind turbines installed in the chimney, depending on the cut-in-speed of the wind turbine and the velocity of the airflow and produce electricity using a generator.

2.1 Geometric Modeling

The proposed model consists of a deck made of glass at an inclination and is raised above the ground level (AGL). The cover traps the radiation emitted from the ground surface. Thus, the ground below the deck cover becomes hot. Figure 2 depicts a line diagram of the SCPP evaluated in the present work. The air enters the collector through *point 0* with a gap of height H_e . The collector floor under the cover has a diameter of D_f . The slope of the deck is inclined to ensure constant radial cross-sectional area for radial airflow. The constant radial cross-section implies the following (Equation (1)):

$$\pi \times D_f \times H_e = \pi D_1 \times H_1 = \pi \times D_1^2 / 4. \quad (1)$$

The known values of H_e and D_f allow the determination of the inlet turbine diameter and height at *location 1* using the Equations (2) and (3):

$$D_1 = (4 \times D_f \times H_e)^{\frac{1}{2}} \prod_{i=1}^n X_i. \quad (2)$$

$$H_1 = D_1 / 4. \quad (3)$$

Radiation from the floor heats the air from *state 0* to *state 1*. Heated air expands in the turbine reaching *state 2*. Turbine inlet and outlet diameters are D_1 and D_2 and are related by Equation (4). von Backström and Gannon [31] suggested the area ratio between the inlet and exit of turbine to be 0.8 to 0.9, which implies that the diameter ratio of inlet to exit vary from 0.90 to 0.95.

In the present case, the height of the turbine is H_T ; ($H_1 + H_T = H_2$). Air, after expansion leaves the SCPP through the chimney opening, which has a height of H_3 . Although the chimney height H_3 can vary between 10.5 and 22 times of the outlet diameter of the turbine. However, Zhou et al. [32] stated that the maximum power that can be obtained from a SCCP must have a chimney height of 19.15 times the outlet diameter of the turbine. The dimensions of the SCPP model evaluated in this study are those described by Petela [28] and are provided in Table 1.

Table 2. Yearly average meteorological data for selected cities

City	Latitude (°N)	Longitude (°E)	Yearly Average		
			Irradiation (W/m ²)	Ambient Temperature (K)	Atmospheric Pressure (Pa)
Jubail	26.904	49.763	455.83	300.02	101030.80
Arar	31.028	40.906	481.56	296.18	94685.00
Umluj	25.004	37.274	493.96	300.54	101039.20
Sharurah	17.476	47.086	550.61	302.63	92885.00
Shaqra	25.173	45.142	500.65	300.29	92400.83

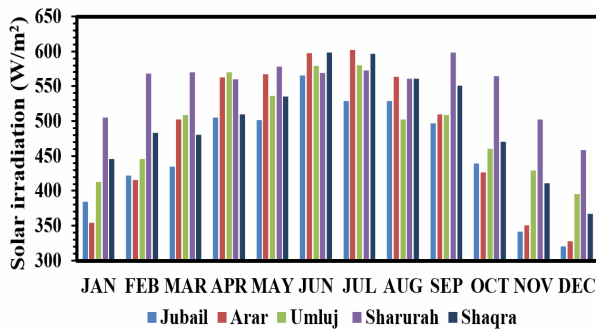


Figure 4. Variation of solar irradiation

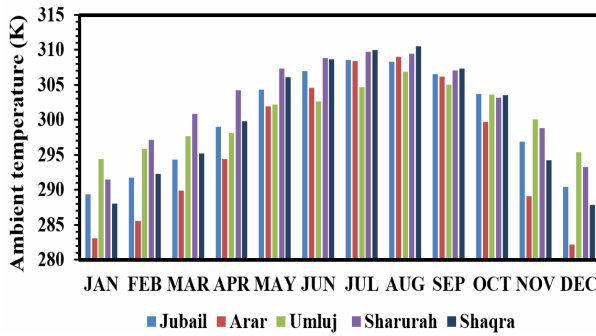


Figure 5. Variation of ambient temperature

$$D_2 = D_1 / 0.95 . \quad (4)$$

2.2 Energy Modelling

The energy conservation principle is applied to model each section of the SCPP. Energy rate components are described by E . Six energy rate balance equations (based on the control volume approach) for floor surface, collector air, collector, turbine, chimney, and air in the chimney are used [28] and are presented here with few modifications.

$$E_{S-f} = E_{f-a} + E_{f-d} \quad (5)$$

$$E_{f-a} + E_{d-a} + E_{a0} + E_{w0} + E_{p0} = E_{a1} + E_{w1} + E_{p1} \quad (6)$$

$$E_{S-f} + E_{a0} + E_{w0} + E_{p0} = E_{a1} + E_{w1} + E_{p1} + E_{d-sky} + E_{d-amb} + E_{d-ch} \quad (7)$$

$$E_{a1} + E_{w1} + E_{p1} = E_{a2} + E_{w2} + E_{p2} + E_{power} \quad (8)$$

$$E_{a2} + E_{w2} + E_{p2} + E_{d-ch} = E_{a3} + E_{w3} + E_{p3} + E_{ch-amb} + E_{ch-sky} + E_{ch-gr} \quad (9)$$

$$E_{a2} + E_{w2} + E_{p2} = E_{a-ch} + E_{a3} + E_{w3} + E_{p3} \quad (10)$$

The energetic efficiency of an SCPP is described by Equation (11).

$$\eta_{energy} = \frac{E_{power}}{E_{S-f}} * 100 \quad (11)$$

The modifications include addition of kinetic, potential and enthalpy energy terms for air at the entrance of SCPP (i.e., inlet). Floor temperature, deck temperature, temperature of air at the inlet and outlet of turbine,

temperature of chimney and the temperature of air at the outlet of chimney are the 6 unknown temperatures. In conjunction, 6 simultaneous system of equations are needed to obtain the 6 unknowns as shown in Equations (5)-(10).

Moreover, an inconsistent equation to determine the temperature of chimney and temperature of air at the outlet of chimney is used in Petela [28]. Hence, a modified Equation (10) is obtained from the energy balance of air flowing through the chimney to determine the temperature at the outlet of chimney. A detailed explanation to determine each of the term can be obtained from Petela [28] and Hussain and Al-Sulaiman [33].

3. RESULTS AND DISCUSSION

The input geometric parameters and dimensional specifications of the SCPP under evaluation are given in Table 1. The monthly average metrological input data of irradiance, ambient temperature and atmospheric pressure are depicted in Figure 4, Figure 5 and Figure 6 respectively and the corresponding yearly average data points are summarized in Table 2, along with the latitude, longitude, and annual mean meteorological data for the chosen cities. The physical locations of these cities are depicted in the map shown in Figure 3.

The energy balance equations were simultaneously solved using engineering equation solver (EES) software. The output provided the theoretical final power output and the theoretical efficiency. In addition, the monthly variation of the temperature of the floor and air, pressure across turbine and chimney, mass flow rate, and inlet velocity of the turbine during the year 2017 are reported for the chosen cities.

2.3 Long-Term Variation of Meteorological Parameters used for Performance Evaluation

For performance evaluation of the proposed SCPPs at the chosen cities, the long-term ambient temperature, atmospheric pressure, and solar irradiation data is used as input to the model. The monthly mean values of solar irradiation intensities, over entire data collection period, are illustrated in Figure 4 for all the cities used in this study. At Sharurah, the higher intensities are observed during entire year compared to other locations and always remained above 450 W/m² (Figure 4). At Jubail, Arar, Umluj, and Shaqra; the radiation intensities are found to be increasing from January until June and July and then followed a decreasing trend towards the end of the year. Overall, the highest annual mean of 551 W/m² is observed at Sharurah in the southern region of the Kingdom and followed by 501 W/m² in Shaqra, which is situated in the central region. However, the minimum irradiation intensities with annual average of 456 W/m² are observed in Jubail, located in the eastern coastal region of the country.

Overall, lower temperatures are observed in the month of January and an increasing trend from January until June, July, and August and then a decreasing towards the end of the year (Figure 5). A shift of one month in peak, the peak values of ambient temperatures

(July-August) is observed relative to the solar irradiation (June-July) intensities (Figure 4 and Figure 5). Highest annual mean temperature occurred at Sharurah (303 K) followed by Umluj (301 K), and Arar (296 K).

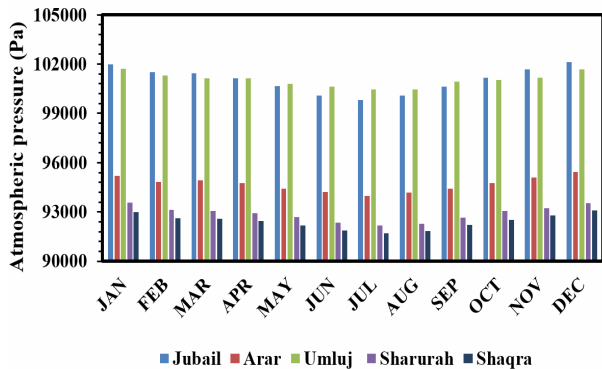


Figure 6. Variation of atmospheric pressure

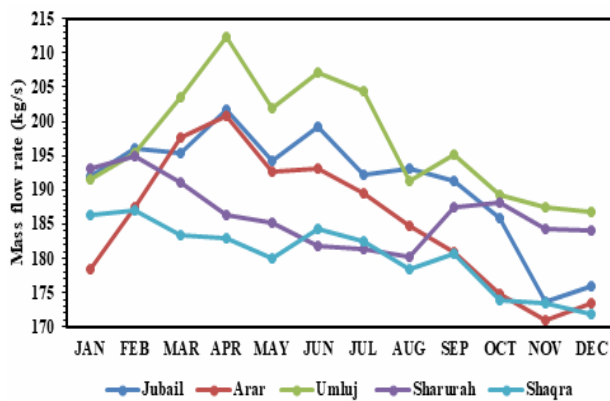


Figure 7. Variation of mass flow rate in SCPP

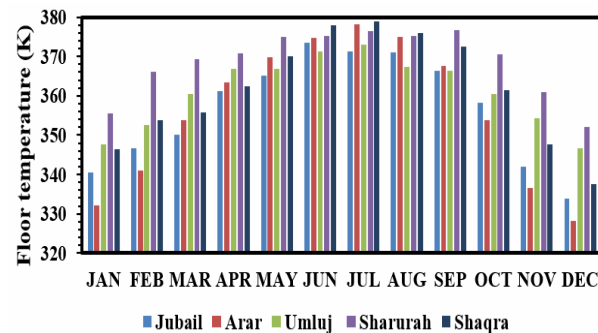


Figure 8. Variation of floor temperature

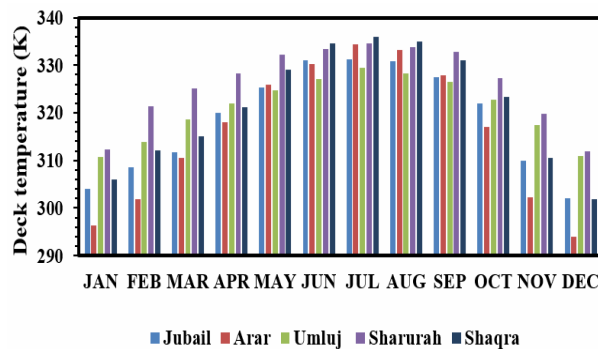


Figure 9. Variation of deck temperature

The monthly mean values of the atmospheric pressure at all the sites chosen for the present study are shown in Figure 6. Overall, higher values of pressure are observed in the wintertime and the lower during

summer period. It is evident from the data that highest atmospheric pressure values are observed at Jubail and Umluj being situated at the Arabian Gulf coast. The pressure values are seen to be significantly low at Arar, Sharurah, and Shaqra compared to Jubail and Umluj sites with lowest magnitudes at Shaqra. The annual mean value of atmospheric pressure was highest at Jubail and Umluj (101,039 Pa and 101,030 Pa) the lowest at Shaqra (92,400 Pa). A seasonal variation is evident in the values of atmospheric pressure, Figure 6.

2.4 Performance Evaluation of Proposed SCPPs

The above-described mathematical model equations were used to estimate the performance of the proposed solar chimneys at different locations in Saudi Arabia, theoretically. It is well known that the mass flow rate depends on the air density, which varies directly with the atmospheric pressure. It is evident from Figure 7, that the highest monthly mean values of mass flow rate are observed at Umluj where the atmospheric pressure was the highest during the year (Figure 6). The annual mean value of mass flow rate at this site is 197 kg/s. The next high values of mass flow rate are noticed at Jubail (191 kg/s) while lowest at Shaqra (180 kg/s). Higher mass flow rates are observed during summer months compared to wintertime. It is due to the fact that during the summer months the irradiance intensity is higher and the rate of change of density in collector is more which increases the velocity of air in the collector, as it is evident from Figure 11. Although the density is inversely proportional to temperature, but mass flow rate is dependent on atmospheric pressure and velocity of air in the collector, so higher mass flow rates are observed during warmer months.

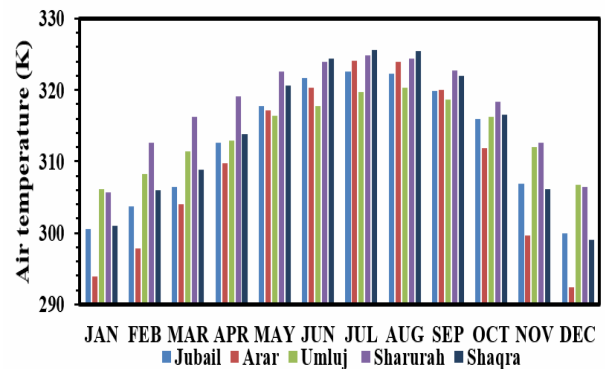


Figure 10. Variation of collector air temperature

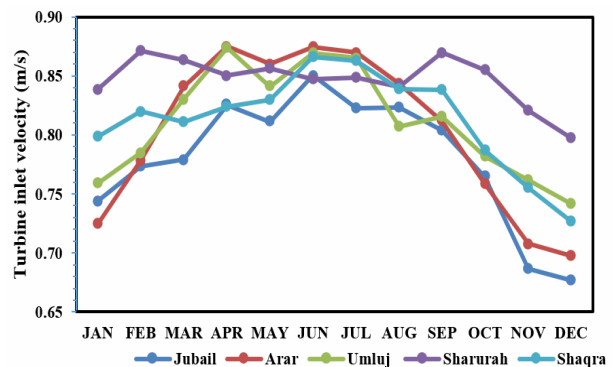


Figure 11. Variation of turbine inlet velocity

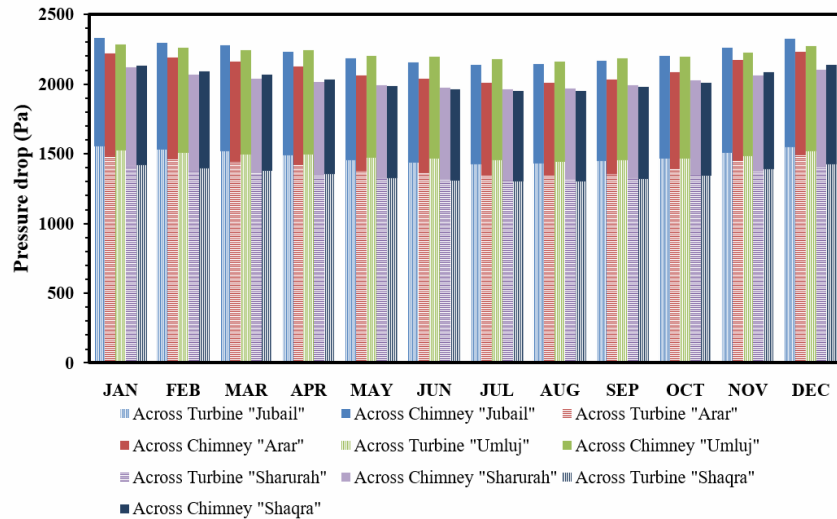


Figure 12. Variation of pressure drop across turbine and chimney

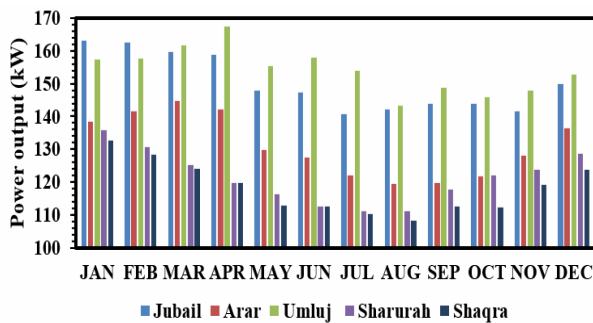


Figure 13. Variation of power output of SCPP

The variation of floor, deck, and air temperatures for all the cities are demonstrated graphically in Figure 8, Figure 9, and Figure 10, respectively. The temperature of the floor is the highest among all the components (deck and collector) of SCPP as radiation is incident upon it, followed by deck and collector air temperatures. The temperatures in these components are higher during the summer months and lower during winter months due to higher solar incident energy and ambient temperatures (Figure 3 and Figure 4). Among all the cities, floor, deck, and collector air temperatures are highest at Sharurah due to higher annual average ambient temperatures of 369K, 326K and 318K, respectively. The lowest annual average values correspond to Arar (356K, 316K and 310K). The turbine inlet velocity observed to be highest in Sharurah city during entire year including the winter months too, as shown in Figure 11. At other location, lower values found during winter months compared those in summertime. An increasing trend seen in the values of turbine inlet velocities at Jubail, Arar, Umluj, and Shaqra from January to July and then a decreasing from July onwards. The seasonal or monthly trends of the turbine inlet velocity follows almost the similar trend as that of incident solar radiation (Figure 4). The highest annual average inlet velocity found to be 0.847 m/s at Sharurah for the proposed SCPP while the minimum of 0.78 m/s at Jubail. The second highest velocity found at Shaqra (0.813 m/s).

Figure 12 presents the variation of pressure difference across the turbine and chimney. The pressure

difference across the turbine and chimney is highest during winter months and lowest in summer months. Among the selected cities, annual average pressure difference across the turbine and the chimney is highest for Jubail with an average of 1484 Pa and 742 Pa, respectively. The average lowest pressure drop of 1351 Pa (across turbine) and 676 Pa (across chimney) is obtained in Shahrurah.

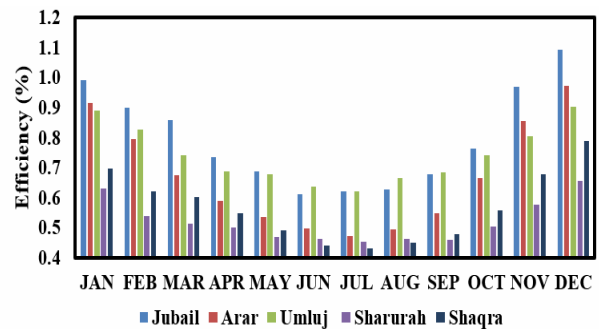


Figure 14. Variation of efficiency of SCPP

The calculated monthly mean power output variation during the year found to be higher in winter months lower in summer months at Arar, Sharurah, and Shaqra and a clear seasonal trend is observed (Figure 13). At Jubail and Umluj a decreasing trend is noticed from January to December in monthly mean power output values. The annual average power output is highest for Umluj (154 kW), followed by Jubail (150 kW) and the least for Shaqra (118 kW). The monthly average power output follows the same trend as that of the pressure (Figure 6). Figure 14 illustrates the variation of efficiency of SCPP over a year for all the selected cities. The yearly average efficiency is highest for Jubail (0.80%) followed by Umluj (0.74%) and the lowest at Sharurah (0.519%). The variation of power output of SCPP follow the same trend as the variation of pressure drop across the turbine and chimney evident from Figure 12.

4. CONCLUSION

The present study conducted a theoretical performance analysis of the solar chimney power plants for five cities of Saudi Arabia by using the ambient temperature,

atmospheric pressure, and solar radiation intensity values for the chosen sites. The results are presented in terms of floor, deck, and collector air temperature; pressure drops across turbine and chimney, turbine inlet velocity, power output, and efficiency of the chimney. Highest values of annual mean power output and efficiency are found for Jubail, a near shore location, and the minimum for Shaqra and inland location. Overall, higher values of power output and efficiency are observed during winter months and lower in summer months. Specifically following highlights are worth to provide:

- The floor, deck, and collector air annual mean temperatures are highest at Sharurah (369K, 326K and 318K) and the lowest at Arar (356K, 316K and 310K).
- Annual average pressure drop across the turbine and the chimney is highest for Jubail with an average of 1484 Pa and 742 Pa, respectively and the lowest of 1351 Pa and 676 Pa for Shahrurah.
- The highest annual average inlet velocity is 0.847 m/s at Sharurah for the proposed SCPP while the minimum of 0.78 m/s at Jubail. The second highest velocity is at Shaqra (0.813 m/s).
- The annual average power output is highest for Umluj (154 kW), followed by Jubail (150 kW) and the least for Shaqra (118 kW).
- The yearly average efficiency is highest for Jubail (0.80%) followed by Umluj (0.74%) and the lowest at Sharurah (0.519%).

It is recommended that study should be extended further to find out the effect of chimney height and the collector diameter on the power output and the efficiency of the SCPPs in these cities of the Kingdom.

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NOMENCLATURE

D	Diameter (m)
E	Energy rate
H	Height (m)
I	Solar irradiation
S	Solar insolation
T	Turbine
T _x	Temperature of the component 'x'

Abbreviations

AGL	Above ground level
CFD	Computational fluid dynamics
COAR	Chimney outlet-to-inlet area ratio
CSCPP	Sloped solar chimney power plant
DSPP	Divergent-chimney solar power plant
SCPP	Solar chimney power plant

Subscripts

<i>a</i>	Air
<i>an</i>	Enthalpy
<i>amb</i>	Ambient
<i>ch</i>	Chimney
<i>d</i>	Deck
<i>e</i>	Inlet
<i>f</i>	Floor
<i>gr</i>	Ground
<i>p</i>	Potential Energy
<i>power</i>	Power produced by a Turbine
<i>sky</i>	Sky
<i>s</i>	Sun
<i>w</i>	Kinetic Energy or Velocity
<i>0,1,2,3</i>	State Points

Subscripts representation

<i>x-y</i>	From component x to y
<i>Mn</i>	Mode of energy content (enthalpy, kinetic or potential) at State points (0,1,2,3) E.g., a1 (enthalpy at location 1)

АНАЛИЗА ПЕРФОРМАНСИ СОЛАРНЕ ДИМЊАЧКЕ ЕЛЕКТРАНЕ ЗА РАЗЛИЧИТЕ ЛОКАЦИЈЕ У САУДИЈСКОЈ АРАБИЈИ

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Приказује се анализа перформанси соларне димњачке електране коришћењем енергетског модела електране. Развијени модел је упоредно истражен за пет локација (градова) у Саудијској Арабији: Џубаил (на истоку), Арар (на северу), Умлуј (на западу), Шарурах (на југу) и Шакра (у централној Саудијској Арабији). Соларно зрачење, часови осунчаности, амбијентална температура и атмосферски притисак су били параметри за одређивање излазне снаге, енергетске ефикасности и осталих елемената перформанси електране одабраних димензија. Анализа података је показала да да је годишње просечно соларно зрачење највеће у Шарурахи (551 W/m²), а најмање у Џубаилу (456 W/m²). Највишу и најнижу просечну амбијенталну температуру имали су Шарурах (303К) и Умлуј (301К). Истраживањем је утврђено да Џубаил и Умлуј имају највећу годишњу просечну енергетску ефикасност. Излазна снага, енергетска ефикасност, температурне варијације ваздуха и тла, притисак на турбини и димњаку, варијације у брзини масеног протока и улазна брзина турбине су приказани за сваки месец у години за свих пет градова.