Evaluating the performance of solar chimney power plant

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Abstract:

Growing global energy demand has become worrying due to the fluctuating fossil fuel prices, the damage caused by the use of conventional fuels as the toxic emissions and global warming. Therefore, dependence on alternative and sustainable sources has become a pressing topic. In this paper will review the performance of solar chimney power plant, the parameters that affect on the performance, conversion efficiency and power output for a different collection of prototypes. During this study there are found that power output of the solar chimney power plant is directly proportional to increase of the height of the chimney, specifically when the solar chimney is sloped where the performances is better as well as the conversion efficiency. While increasing the diameter of collector will provide a big heating area which cause a decrease of air density due to rise in the air temperature under the solar collector which lead to increase the flow of driving force and the mass flow rate that causes an increase in the power output. Pressure drop is an important factor for identifying the maximum power output when the solar radiation is a constant which effect on thermodynamic properties. Therefore, the efficiency will increase with increasing the optimal proportion of pressure drop.

Keywords: Driving force; Buoyancy; Conversion efficiency; Solar chimney.

Introduction:

Strong countries' economies have the suspicion about energy supplies of fossil fuels, with consideration the fluctuation of oil, petrol prices, the global warming effects that represent a substantial threat of economic and environment as well [1]. Dependence on alternative and sustainable energy sources has become a pressing issue to reduce dependence on traditional sources that produce a big amount of gas emission as a gas, crude oil and coal, electric power plants that produce big amounts of harms waste that paid the humans of migrate to looking for clean environment [2]. Therefore, many factors encourages using solar energy to obtain clean energy, the solar chimney plants is promising solutions which grow quickly nowadays, as well as, has a lowering maintenance cost, durability of system [3], using the solar chimney system will contribute greatly to reduction of toxic materials, gas emission which has direct impact on the environmental, health and adoption as an alternative green energy source [4], in 1903s,1931s, both of Cabanyes, Gunther could present an investigation about study the concepts of solar chimney power plant and basic description as well [5]. Many researchers and experts have investigated by different models to take advantage of solar chimney power plant technology in the recent years. More theoretical and simulation study has been done to find out the performance of the models [6,7]. The main principle work of solar chimney power plant turn out the solar energy into electric power.
A Solar chimney power plant consists of three main components: a solar collector as a circular transparent which raising of the ground by certain height with different collector radius [8], generally the roof of solar collector made of glass or plastic sheet, after collecting solar radiation which will rising the air via the temperature, where the air density between inside the system and the environment is different, it less than inside the system at a same height [9], chimney that fixed at the center of collector as a circular tower by various heights the cylindrical structure of the chimney is made of transparent glass or sometimes from plastic film. By the chimney the air heated will flow towards the turbine and goes to the atmosphere [8-11], turbine that located center of solar chimney at the base, running by airflow that comes by buoyancy which supplier of air heated inside the solar collector [12]. Solar radiation is represented as a major source to work solar chimney power plant [10]. Power produced of solar chimney power plant depend on the amount of solar radiation falling [13], that influenced with weather conditions around the year [14], by a convert kinetic energy to electric energy due to the difference in pressure that resulting of differing air density between the system and the environment after warming the air under roof collector which lead to affect buoyancy which work as driving force [15-18], efficiency of solar chimney power plant depended on size of system and the efficiency is increasing, when the size or dimensions of system increasing [19]. However, to achieve high conversion efficiency that requires increasing height of solar chimney and collector area. Furthermore, a gigantic solar chimney will contribute to raising the conversion efficiency by rising driving force, volumetric flow toward huge turbines and lowering in the energy cost [20]. Therefore desert regions are most suitable for building the solar chimney power plant where the land probably free and the solar radiation is available [12].

2. Comparison between performance of conventional and sloped solar chimney power plants:

Conception to build up a mathematical model of sloping solar chimney that supporting by a mountainside was a new idea in 1931, where would occupy vast space reach to thousands of meters without any technical limitations that leads to improve conversion efficiency and make build gigantic vertical chimney is easy [21], avoiding selecting the regions that have bad weather as a high wind, dust storms and heavy hailstorms [22]. Therefore, building a solar chimney power plant with a floating chimney that attaching on the mountainside is a proposal to solve the issue of bad weather [23], some of the experts proposed a floating solar chimney to avoid disadvantages in the conventional solar chimney power plant as an expensive construction cost, technological restrictions and external restrictions as an earthquake [24]. A many studies have conducted for comparison the behavior both of a floating chimney fixed on a mountainside, and the conventional solar chimney power plant. Where a simulation have conducted on a sloped solar chimney power system that is designed to supply electricity to villages in Northwest China by 5 MW. The study focused on the behavior of some parameters such as pressure, increasing the temperature of airflow, efficiency of the system and solar collector. The results indicate that the sloped solar chimney system has better performances, especially in spring and autumn Season figure (1) shows most of parameter values increase by March, September while values decrease in July and November. Generally, the parameters of the system were symmetrical and stable and the overall efficiency was low, although the solar radiation was abundant [5], according to specific topography to know if it’s useful for stable electricity cost and desert regions. The chimney designed as a floating chimney fixed on a mountainside segment as shown in a figure (2). To resist the air flow and strong dust storms [23], the segments of chimney designed to be curved and used wires with small bases to attach the chimney on the mountainside and the feature of the solar chimney is can be extended to thousands of meters [21]. Performance evaluation of this model finds out the power obtained can meet the overall electricity consumption in China with higher energy conversion efficiency comparison with a concrete vertical chimney [2].

Another A study has conducted on two sorts of the solar chimney power plants, first one fixed at high latitudes which build with a slope of mountain hills, for three locations selected in Canada and the second has fixed at...
the southern locations to horizontal. Where the thermal performance of the first plant reaches to 85%, output of plant well as and that is considered a sufficient comparison with the second plant and the total thermal performance for both of plants was less than 0.5%. For a mathematical model that designed for MATLAB platform [25], increasing the height of the chimney is a great advantage that will contribute to decrease the pressure at the turbine and the properties of the diameter of the collector which considered as important factors at design of solar chimneys that will decrease the cost as well as civil engineering problems [26]. According to the comparison was made for conventional solar collector of solar chimney power plant that shown in the figure (3) with the sloped solar collector of solar chimney power plant [27], by using the second law of thermodynamics, which has a vastly acceptance as robust tool for measuring the behavior and performance of the solar chimney plants [28], with an entropy generation number of the 5-MW plants that suggested for these systems to identify the effects of height chimney by two systems. Results show a contrast between the minimum entropy generation and the maximum second law efficiency, which will increase with increasing of the chimney height. While at change pressure and temperature for both of them, found that the sloped solar chimney power plant is better than conventional solar chimney power plant at thermodynamically [29], performances of sloped solar collector are higher, specifically at high altitudes and when it's build at along the hillside [23].

![Fig. 1. Fluctuation the values of parameters during the months.](image1)

![Fig. 2. Floating solar chimney fixed on a mountainside.](image2)
3. Effect of the height of chimney on the system performance:

3.1. Power output:

According to the theoretical model for analysis of chimney height that was conducted for solar chimney power plant, to analysis the maximum chimney height and convection to achieve the greater power output as well to avoid negative buoyancy at a higher temperature of surrounding and affect it on another chimney. In the figure (4) shows that the larger collector radius will increase the power output significantly, convection and the height of chimney plays basic role to achieve a maximum power output [30]. However, many theoretical and experimental investigations have conducted on models and to gain a great amount of power converted efficiently that need a huge solar chimney [31], [8], during study the economic feasibility indicators for solar chimney power plant, by used the simulation model conducted in Cyprus and Spain. Found that the chimney of height was one of the important factors which effect on the power generation [32], height of the chimney was the main factor by increasing the electricity producing, figure (5) shows the influence of the height of the chimney on the electricity produced and the chimney efficiency [33] To achieve the maximum power and conversion efficiency must take in considering the optimal chimney height for a limited collector [34], where the conversion efficiency and generated capacity increases depending on the height of the chimney [35]. Maximum chimney height will effect on convection that contribute avoid negative buoyancy and increase power output [30], where there is relationship directly proportional between increase solar collector size and the height of chimney with power output.
3.2. Conversion efficiency:

Based on a theoretical model that has been verified to study the behavior of a limited solar collector to gain the highest conversion efficiency by determining the effect both of the optimal chimney and maximum chimney height on the conversion efficiency. When the height of the optimal chimney with maximum chimney height are equal leads the conversion efficiency reach to maximum value [30], [37]. There is a direct relationship between the height of the chimney and efficiency, this influence is clear in the figure (6) shows that the efficiency increases when the chimney height, where the gradual increase in the height of the chimney accompanied by a clear increase in efficiency [36]. The chimney outlet one of the parts that will affect the energy loss of the system relative to the solar radiation received, where energy loss is increasing with the solar radiation at the chimney outlet while the energy loss is decreasing with pressure drop due to decrease the air flow rate which leads to lowering the energy conversion efficiency [38]. Some modifications could make to the design of the solar chimney to obtain effective power, such as use rubber as a floor of collector, for the roof used double glazing glasses with lowering the collector height of 1.3 m. All that contributes to improve produced power to 7 kW and decrease cost of electrical energy production depend mainly on increasing with length of the chimney [39]. According to proportional static pressure distributions for various solar radiations indicate that the minimum values of proportional static pressure find at down part of solar chimney where both of airflow and pressure are great. Which means obtain more of axial work transmitted of the air pressure potential energy and gain a great amount of electricity energy produced which leads to increasing conversion efficiency of solar chimney system [40].

Despite all the theoretical analysis on the performance of the solar chimney is still the power output is directly proportional to the chimney height and the diameter of collector [41]; nevertheless, the conversion efficiency is low if still specific by the thermal performance of a solar chimney power system, but the conversion efficiency rising with increasing the height of the chimney [12].

**Fig. 5. The influence of the height of the chimney on the power produced and the chimney efficiency.**

**Fig. 6. Proportional relationship between height of the chimney and efficiency.**
4. Effect of solar collector area of the system performance

4.1. Solar radiation

Solar irradiation is the main principle of operation the solar chimney power plant and select a geographic location which have sufficient of solar irradiation averages around the year is considered as an important element in the economic feasibility when setting up of solar chimney power plant [36], [42]. A practical prototype has studied in Spain to recognize the relationship between the collector radius, driving force and solar radiation. Found that increasing the collector radius will increase the air temperature inside that lead to the reduction of the air density and this occurs when solar radiation is constant. Subsequently, the relative static pressure will be affected by these factors and increases as well [18], maximum power produce via solar chimney power plant will increase with increasing the collector radius, Which leads to density drop due to warming the air under the solar collector which made the flow of driving force toward the chimney is natural [4], as a resulting of rising of temperature at various heights that generate a large amount of warm air will drive by buoyancy towards drives turbine to generate electricity [30]. Mathematical models have been created to study the effect amount of solar radiation on characteristics of heat transfer and air flow with an energy storage layer. According to the simulation results found that increasing of solar radiation will increase the capacity of the storage layer, static pressure, decreasing while velocity inside the system, increase significantly and the average temperature at the chimney outlet will increase as well. The density of the air is different between inside the system and the environment, as a result of that the conviction will affect by buoyancy which in turn affects driving force [31]. Numerical simulations have been studied of two-dimensional steady-state of the solar chimney system to find out the behavior of the solar collector, solar chimney, turbine and energy storage layer. Where found that the solar radiation has a big effect on pressure drop across the turbine, energy lack of the system due to the large of heat flow at the chimney outlet, increase canopy of collector will cause energy loss due to pressure drop at the turbine and solar radiation as shown in a figure (7) where the energy loss will increase sequentially with pressure drop [18, 44].

Fig. 7. Increase the effect size for the collector on the pressure drop and energy loss.

4.2. Driving force:

Natural convection works as a driving force toward the chimney due to different air density that occur at the same height into the system where the cumulative buoyancy lead to a big pressure variation between the system and the environment resulting to that heated air, increasing rapidity to the chimney [14], when the chimney height is increasing, the buoyancy difference will influence by driving force which it is greater than the friction losses and this occur because the chimney height [45]. Driving force increases depends on value of relative static pressure is increasing with decreasing the air density, which are influenced by several factors as an increase in collector area, an increase in the amount of the solar radiation, rises up the air temperature inside the system and the chimney height, which have an effect on the driving force by increase the quantity...
of mass flow rate then the driving force as in a figure (8) increasing the amount of falling solar radiation on a large of the solar collector area to creation a big different in the air density which effect on the pressure drop and increasing the driving force [19], [46]. However, increasing both of collector area for a harvest as the largest amount of solar radiation and a high huge chimney to be suitable for harboring a big turbine, which contribute to increase the driving force [12], [47] other studies found that the temperature difference at the collector outlet and the environments that might reach until 24.1°C is enough to generate the driving force [48]. The pressure drops by the turbine will affect on driving force, suppose that the driving force had transformed into kinetic energy where the flow rate is unpractical and the power output of a solar chimney power system is large [49].

**Fig. 8. Effect collector radius on driving force.**

### 4.3. Pressure drop:

Pressure drop at the turbine one of the most important parameters that should considered at the solar chimney design [30]. Many researchers have found that the pressure drop for the turbines are depending on the flow rate and pressure drops at both of turbines and solar chimney power plant was the nearest to the flow rate [19], lowering flow rates will effect the power output of the system and increasing flow rate make both of temperature is rising at the collector and pressure drop at the turbine goes down [50]. By comparison conducted between solar chimney power plants and sloped a solar chimney power plants found that there are three factors can effects on pressure change as an increasing the heat addition toward the collector, reduction of flow area by the collector and friction which have a simple effect [29], pressure drop across the turbine, diameter of collector which contribute increase the power output when the size of collector increase and the height of chimney are the important parameters should take in consideration at design [9], increasing the solar radiation intensity will increase the differential pressure of transition section of the collector. In a figure (9) the pressure has negative value in all of system section that because the outer air are flowing inside the system as a circular flow. Therefore, a big value of differential pressure can obtain between top of solar collector and the chimney bottom, which the system energy can derived from it [51].

Pressure distribution in the solar chimney power plant has a large effect on the mass flow rate and consider as an important to analyze the solar chimney system and for finding the suitable ratio of pressure drop cross the turbines to predict the volume of energy produced of solar chimney power plant [52], [40], where static pressure into the solar collector will increase with flow direction and this disagreement with flow theory [18], which proved that the relative static pressure into a solar collector will decrease with the flow direction depending on Bernoulli equation which considered not suitable to get the pressure difference by the solar collector [53], [9]. While the investigation has conducted to 3D numerical simulations to define the optimal
ratio of pressure drop across the turbine. Found that the optimal ratio is changed with the intensity of solar radiation and effect on the pressure drop. Thus affected on the overall efficiencies of the system as shown in a figure (10) where overall efficiency of the system will increase with increasing the optimal ratio of pressure drop due to the amount of radiation received. Therefore, increase of solar radiation and flow losses will proportional to the square of the air velocity, that requires use more pressure difference to control the loss of flow [54].

Therefore, pressure drop has become an important factor that of identifying the maximum power output when the solar irradiation is constant, where some studies point out the optimal value of the pressure drop across the turbine which has been suggested is 0.7-0.9, there is not unified value, or it will differ at other authors [55], [56], while both of the draft and power output will be affected by pressure drop as well [57]. Other numerical simulation models have been verified to determine the effect of relative static pressure on the performance of the system. Where found that decreasing the relative static pressure will contribute to increase the velocity inside the system. [18]. Based on Spanish prototype that have been investigating that applied the impulse turbine, which, depending on the pressure and velocity at a solar chimney. Where pressure drop will affect on velocity of air flow where the velocity lowering significantly by pressure changes [38]. A theoretical model was investigated to find out the relationship the pressure drop and certain flow rate at the solar chimney power plant after subtracting flow losses of the system drive force [58]. At analysis the numerical model of turbine to find out the pressure jump into the turbine section by simulation, where could divide the pressure difference produced at the chimney base and the ambient into two components, one of them is a static the other is a dynamic, where causes losses at the turbine section and other losses occur due to friction [19].

Fig. 9. Pressure distribution in system sections.

Fig. 10. Relationship between pressure drop across turbine and the overall efficiency.
4.4. Thermodynamics

4.4.1. Second law efficiency

In thermodynamic interpretations another parameters take considering in the solar chimney power plant as a heat transfer between the components, fluid mechanics and temperature distribution on the surfaces as a chimney or floor [59], [60], to calculate the moist air properties to explain the errors that occur in an enthalpy, specific volume via use the ideal gas relations and according to ASHRAE (2005). Found that the errors will lower with a lowering pressure where reach to less than 0.7%, but at a criterion atmospheric pressure for a temperature of (50 - 50) °C. The second law analysis is an important factor to scale the performance of systems, identify in power generation [28]. A simplified thermodynamics analyses have been conducted to determine the behavior of airflow into the solar chimney, depending on some parameters as a Bernoulli, ideal gas equation and fluid statics as well. The results of analytical indicate to the relationship between second-law efficiency and turbine pressure head were asymmetrically, while there is an increase by a second-law efficiency, gained power which associated with increasing chimney height and/or diameter of the collector as a show in Figure (11), where the increase by power and the second law efficiency is clear with increasing the height of the chimney where the actual thermodynamic efficiency affected positively with the height of chimney [33]. While the power generation is still increasing with increasing the collector diameter as shown in a figure (12) [4], where it can be determined the thermodynamic inefficiencies and locations. As well as ways to improve thermodynamics of the system [27].

![Figure 11](image1.png)  ![Figure 12](image2.png)

**Fig. 11.** Effect height of the chimney on both power and the second law efficiency. **Fig. 12.** Effect collector diameter on power and the second law efficiency.

4.4.2. Thermodynamic cycle analysis:

Thermodynamic analysis is an important factor to analyze the performance of a solar chimney power system and the energy conversion which are subject to the laws of thermodynamic where thermodynamic analysis proves that there is directly proportional between the height of the chimney, the monthly average of overall solar radiation that falling on sloped surfaces, collector dimension and the power generated by the system. For that purpose some solar chimney power system had designed for low latitudes by use horizontal collector systems [23], thermodynamic properties are affected by the quantity of solar radiation, particularly the air density that will change and cause a big pressure difference occurring among the system and the environment but at the same altitude due to the natural convection [61]. Therefore, many researchers depend on thermodynamic cycle analysis to calculate of efficiency, performance of the turbine, the relation between the major variables of the system, chimney friction and the kinetic energy losses of the solar chimney power.
system [62], [63], with considered the thermodynamic cycle via warm air that heating by huge solar collector, where the warm air is considered as a thermodynamic energy moving towards turbines that are directed to the electric generators [1]. In other hand, simplified thermodynamic analysis of the total solar chimney cycle have conducted to study the behavior of pressure drop by the turbine. The results indicate that the ratio of the effective absorption coefficient to the factor of commensurate convective energy lack and the ratio of the pressure drop by the turbine to the overall available pressure drop are parameters that thermodynamic analysis depends on it. [9], [64].

4.5. Mass flow rate:

Generation a maximum power is necessary in solar chimney power plant design to take in consideration the value of mass flow rate that must be optimized with the work of turbines at the constant running of the system [65,40]. The value of mass flow rate affected by several factors as temperature rising inside the collector, pressure drops cross turbines and driving force. Therefore, power output depends mass flow rate where power output decreases at low flow rates, because the high flow losses that occur due to increasing air velocities into the system as shown in a figure (13), Where there is a clear increase in the power output with increasing the mass flow rate [33,49], other parameters such as an increasing the height of the chimney with a constant amount of solar radiation contribute to the increase the mass flow rate [18]. Enhancing mass flow rate is important to increase the power output; furthermore, some additions are used as insert an intermediate absorber with a big base of solar collector diameter where lead that increasing velocity, the air temperature and rising the mass flow rate as well as the total power output [66]. According to the Manzanares prototype the power output that produce with maximum chimney height is not represented maximum power output, in other hand, the average density of air flow is stable inside the chimney due to the small temperature range and increase of chimney height has a positive effect by increasing the flow rate while the pressure difference will reduce as show in a figure (14), the height of chimney has positive effect by increase the mass flow rate and negative effects on the pressure difference [67]. Based on the steady airflow for the analytical model in the solar chimney, the maximize of power produced of the solar chimney power plant depends on the value of mass flow rate with pressure drop at the turbine [68].

Another study depends on various values of the solar irradiation to calculate the power output of solar chimney power plant, the mass flow rate where the turbine load has modified at the operating point which lead to decreasing maximum value of pressure drop to match with the mass flow rate and the outcomes obtained depending on proportionality coefficients [69]. Theoretical analysis has conducted to the performance of a solar chimney power system to figure out the flow behavior inside the chimney. Where the tower dimensions (height and diameter) are a directly responsible for the significant changes during the flow behavior into the solar chimney. Moreover, increase the tower dimensions will cause increasing the amount of mass flow rate with lowering the flow temperature [70,71]. A study has been conducted about the influence of tower area change by using software ANSYS-CFX on a solar chimney power plant and comparison with a constant area tower. Where found that use divergent tower contribute to increasing kinetic energy as well as the amount of the mass flow rate, while at a convergent tower the amount of mass flow rate reduce with increases in the velocity at tower top and that causes similar in the kinetic energy with the energy of constant area tower [72], according to other study have conducted about the effect of the ambient crosswind when is weak and strong on the performance of the system by using computational fluid dynamics with (Bernoulli principle). During the study found that the flow field will deteriorate with lowering the power output that occurs when the ambient crosswind was weak. While both of output power and the amount of mass flow rate will increase when the ambient crosswind was strong [73], where a big heating area was created into the collector as a result of reacted little of heated air inside the collector with the ambient temperature which causes a high amounts
of the mass flow rates with velocities [74], the power output will widely increase due to a big heating area in
the collector is created with rising the values of the mass flow rates as well as velocities [75].

Fig. 13. Effect mass flow rate on the power output.

Fig. 14. Relationship the height of the chimney by mass flow rate and pressure difference.

5. Conclusion:
This paper has reviewed the evaluation of performance the solar chimney power plant for different prototypes
to figure out the effect of the main parameters on the performance, conversion efficiency and power output.
Comparison has conducted between sloped solar chimney and conventional on some parameters such as
pressure, the temperature of airflow as well as the efficiency of the system. Where found that the sloped solar
chimney system has better performances than conventional with reduction the cost and civil engineering
problems. Therefore, building a solar chimney power plant with a floating chimney that attaching on the
mountainside is a proposal to solve the issue of bad weather and to resist the airflow, strong dust storms, heavy
hailstorms and an earthquake. Increasing the height of the chimney, the diameter of the collector is a great
advantage that will contribute to increase the performances is better as well as the conversion efficiency and
the power output. Increasing the collector diameter contribute to increase the power output significantly by
providing a big heating area contribute to rise air temperature that leads to decrease of air density and increase
the driving force that which are influenced by several factors as an increase in collector area, the chimney
height and an increase in the amount of the solar radiation.
Height of chimney has an effect on the driving force by increase the quantity of mass flow rate, which decreases to low flow rates due to the high flow losses that occur due to increasing air velocities into the system. Furthermore, maximize of power produced by the solar chimney power plant depends on the value of mass flow rate with pressure drop across the turbine, which affected by increasing the heat addition toward the collector, reduction of flow area by the collector, simple effect of friction. The amount of solar radiation falling affects thermodynamic properties, particularly the air density that will change and cause a big pressure difference occurring among the system and the environment. Moreover thermodynamic analysis depends on the ratio of the pressure drop by the turbine to the overall available pressure drop. Thus, pressure drop across the turbine contribute increase the power output when the collector area increase and height of the chimney is the important parameters take into consideration at a solar chimney design.

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