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Feasibility of Exploiting a Solar Chimney Power Plant in Qom Province

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ABSTRACT

A solar chimney is a kind of power plant that converts solar energy into electricity. Independent of specific maintenance and overhaul, these systems are capable of generating electricity for the long-run and are suitable for those countries with abundant solar radiation. This paper first explains how a solar chimney power plant operates and then presents details on computational equations for the calculation of a solar power plant's power. Lastly, the feasibility of installing a solar chimney power plant in Qom, according to the solar radiation data in Qom province, will be explored. To this end, the study extracts the local data on solar radiation from the world's valid resources in different time intervals.

Then, using the equations that are associated with solar chimney power plants, it calculates the power rate obtainable from the installation of a power plant in the area of concern. The extracted data show that Qom province has excellent potential for the installation of solar power plants. The computations display that the maximum generated power is related to a chimney with a height of 400m and a pressure difference of 155Kpa, and the minimum power is related to a chimney with a height of 45.2m and a pressure difference of 20Kpa.

Keywords: Solar Chimney Power Plant, Mathematical Modeling, Solar Energy, Generation Power, Qom Province.

1. INTRODUCTION

Concerning the limitations of non-renewable energy resources and environmental problems stemmed from their irregular consumption, the use of new energies such as solar energy is reckoned as one of the necessities of modern society. One simple and principle method for generating electricity, reducing produced heat, and infusing natural coolness is the employment of a solar chimney [1].

1.1 History of Using Solar Chimney Power Plants

In 1981, the world's solar power plant unit was built in Manzanares in Spain [2]. This primary sample, which was fabricated and installed for experimental purposes, transferred electric energy to the network from 1986 to 1989 and was also applied for data measurement. The chimney of this power plant had a length of 194.6m and a diameter of 10m, and the diameter of its collector was 122m. The air velocity created in the chargeless conditions inside the chimney was almost 15m/s. Although this sample was generating very small power amounting to 50KW, it proved the usability of a solar chimney power plant and its governing interactions [2].

1.2 Description of a Solar Chimney Power Plant System

On the whole, a solar chimney power plant operates by two general known principles, including the greenhouse effect and buoyancy force. This power plant comprises three main parts: a collector, chimney and turbine [3, 4].

1. Solar collector: The hot air required for a solar chimney is created by the greenhouse phenomenon in an enclosure, which is covered by plastic or glass and is some meters distant from the ground. Of course, the height of the covered area increases in the vicinity of the chimney base so that the movement direction of airflow perpendicularly changes with the least friction. The formation of the greenhouse space, along with its inner heated air, lead the air, which is impressed by the buoyancy force, to move upward inside the tower with a fixed velocity (concerning the gradual increase in its height, the air velocity is almost constant along the collector).

2. The chimney or high tower placed at the center of the solar collector plays the role of a thermal motor in the power plant. The pressure difference between input and output air gives rise to density difference, which depends on the temperature difference between the chimney inlet and outlet and moves the air inside the chimney. The upward air-intake velocity is almost proportionate with an increase in the air temperature inside the collector and tower height, and its power is also proportional to the volume, resulted from the tower height and collector surface.

3. The turbine, which is placed in the tower base and resembles a hydroelectric power plant, usually employs chambered turbines to convert static pressure into rotational energy.

If an extra capacity for heat storage is required or if the power plant is aimed to be used during nights, black water conduits placed inside the collector on the ground can be utilized. These conduits are covered in a way that the evaporation of water from them is impossible. The output power of the solar towers can be explained by the product of input solar energy and the efficiency that is related to the collector, tower, and turbine.

2. EQUATIONS GOVERNING COMPUTATIONS OF SOLAR POWER PLANTS

The analysis of the power plant-related equations is carried out by a hypothesis-based theoretical model. 1. Air is the ideal gas. 2. Only is the buoyancy force considered in a chimney.

2.1 Temperature-Related Computations in Different Parts of System [1, 6]

The air temperature inside the collector is calculated as below:

$T\infty\ (H) = T\infty in - \gamma\infty\ h$ (1)

Where T∞in is the air temperature inside the collector, and γ∞ is the rate of changes in the atmospheric air temperature. Since the changes in the kinetic energy of air are insignificant, the air moves upward as much as dh. The fluid temperature inside the chimney equals the fluid temperature exported from the collector. The air temperature inside the collector T(H) is calculated by the below equation:

$T\ (H) = T\infty in + \frac{gh}{C_p} + \left(\frac{\pi G\eta coll}{C_{pm}}\right)$ (2)

$R^2 coll$

T∞in is the air temperature inside the collector, g is the gravitational constant, h is the inner height of the collector, G is the solar irradiation rate, and Rcoll and ηcoll are the collector radius and its efficiency, respectively. The results obtained from Equations 1 and 2 are similar.

2.2 Pressure Difference in Different Parts of the System

The pressure difference between the chimney inlet and the ambient is calculated by the below equation:

$\Delta P = g \int 0H(\rho\ \infty(h) - \rho(h))dh$ (3)

Where g is the gravitational acceleration of air, and ρ ∞ (h) and ρ(h) are air densities per inner and outer height of the chimney, respectively. The P and Cp of air in different temperature ranges are computed by the below equations (reference temperature; Tf=300k) [5-7].

$\rho = 1/16 - 0/0035\ (Tf - Ti)$ (4)

$Cp = 1/007 - 0/00004\ \Delta P$ (5)

ΔP is calculated by the composition of the Equations 3 and 4 as follows:

$\Delta P = 0.0035g\int_0\ H\ (T(h))dh$ (6)

ΔP is calculated by the Equations 2 and 8 as below:

$$\Delta P = 0.0035gH\left(\left(\left(\frac{\pi G\eta coll}{C_{pm}}\right)R_{coll}{}^2\right) - \left(\frac{gh}{2C_p}\right) + \frac{1}{2\gamma\infty H}\right) \quad (7)$$

The pressure difference is usually created due to the friction (ΔPf) inside the chimney, input loss (ΔPin), output kinetic energy loss (ΔPout), and ΔPt, which is related to the kinetic energy transfer from the turbine. Thus, Equations 8, 9, 10, and 11 are expressed as below:

$\Delta\ P = \Delta\ Pt + \Delta\ Pf + \Delta\ Pin + \Delta\ Pout$ (8)

$\Delta\ P = f + \frac{L}{D}\frac{1}{2}\rho v^2$ (9)

$\Delta\ P = \varepsilon_{in}\frac{1}{2}\rho v^2$ (10)

$\Delta\ P = \varepsilon_{out}\frac{1}{2}\rho v^2$ (11)

According to the observations of the researchers, the pressure loss coefficient (or the friction coefficient of the chimney wall) equals f = 0.00842. Furthermore, the inlet loss coefficient is ε_{in} = 0.056, which is due to the inlet angle and the height of the collector roof, and the outlet kinetic energy loss coefficient is ε_{out} = 1.058 [10-13]. The mass flow rate of the air crossing through the chimney is m and is computed by the below equation:

$$m = \rho_{in} A_c V_{in} \quad (12)$$

Where A_c is the chimney area (airflow transmission section), ρ_{in} is air density inside the chimney, V_{in} is airflow velocity inside the chimney, and U is the total heat transfer coefficient from the chimney airflow to atmospheric air. It is calculated as below:

$$U = \frac{1}{\frac{1}{Ur}+\frac{\delta}{\gamma}+\frac{1}{U\infty}} \quad (13)$$

Where δ is the wall thickness of the chimney, γ is the heat transfer coefficient of the concrete used for the wall, U_∞ is the heat transfer coefficient between the chimney wall and the ambient, and Uf is the heat transfer coefficient between the chimney wall and fluid.

2.3 Maximum Height

The maximum height of the chimney is calculated according to the collector radius as below:

$$H_{max} = \frac{C_{pm}}{U\pi D}\ln\left(\left(\frac{\pi^2 UDG\eta_{coll}R_{coll}{}^2}{C_{pm}(g-\gamma\infty C_p)}\right)\right)+1 \quad (14)$$

Where D is the diameter of the chimney.

2.4 System Power

The electric power produced by the turbine generator (P_{out}) is computable as below:

$$Pout = \boldsymbol{\eta}_{tg}\, \Delta p\, VA_c \quad (15)$$

Where η_{tg} is the efficiency coefficient of the turbine generator. According to studies, it maximally reaches 80% in the best conditions. V is the input air velocity, and Ac is the chimney area (airflow transmission section).

2.5 System Efficiency

The total efficiency of energy conversion is explained by P_{out}.

$$\eta = \frac{P_{out}}{\pi R_{coll}{}^2 G} \quad (16)$$

Where Rcoll and G are the radius of the collector and rate of solar radiation, respectively. According to its different components, the total efficiency of the power plant is computed by the below equations:

$$\eta_{tot} = \eta_{coll}.\ \eta_{ch}.\ \eta_{tg} \quad (17)$$

$$\eta_{coll} = \frac{Q}{A_{coll}G} \quad (18)$$

$$\eta_{ch} = \frac{gH}{C_p T_i} \quad (19)$$

Where η_{tot} is the total efficiency of the power plant, η_{coll} is the collector efficiency, η_{ch} is the chimney efficiency, Q is heat transfer to the collector, H is the chimney height, and T_i is the input temperature to the chimney.

3. VALIDATION AND ANALYTICAL RESULTS

To investigate the validity of the computational results of the mathematical equations presented in this paper, we conducted the power plant computations for the solar chimney power plant in Manzanares and compared the computation results with the real power of this power plant. The dimensions of the power plant in Manzanares are as below:

Table 1. Manzanares Power Plant Dimensions

parameters	value
Chimney Height	194.6 m
Chimney Inlet Section Radius	5.08 m
Collector Radius	122 m

This power plant has generated electric energy with the 50KW power. If the power plant under investigation is modeled by the equations explained in this paper, it will have a power of $48\left(\frac{kWh}{m^2}\right)$. The comparison of these two powers shows that the presented computational equations can be employed with an acceptable error percentage.

Table 2 includes the solar irradiation data extracted from the Joint Research Center of Europe and Photovoltaic Geographic Information System Site [15-17] for the considered area in this study. These data include solar irradiation, such as irradiation over the horizontal surface of the collector (Hh), optimal irradiation according to the inclination angle of the collector to the ground (Hopt), solar irradiation with a 90° angle to the collector H(90), and optimal irradiation according to the inclination angle of the collector to the ground and its inclination direction (DNI), in the varying months of the year and annual mean related to the Qom Province. As observed, the maximum mean irradiation on the horizontal surface of the collector is achieved in June at the outset of the summer. Likewise, the minimum value of the mentioned parameter relates to December at the beginning of winter. Concerning the desirable irradiation on the collector surface, we can state that it is maximal in August and minimal in December. The results for December is similar in both irradiations; however, concerning the maximum radiation rate, the difference between these two associates with the inclination conditions of the collector in the status of desirable irradiation, i.e., the collector is positioned in the ground in such a way that it can maximally exploit solar irradiation. Another parameter under investigation is the 90° irradiation angle of the Sun relative to the collector surface. The maximum and minimum values of this parameter relate to October and June, respectively. Respecting the rate of direct perpendicular irradiation, we can assert that the maximum and minimum values relate to June and January. These results show that the rate of solar irradiation is variable in different months and with regard to the inclination conditions of the collector. In months with maximum irradiation, the power generation reaches its maximum value due to an increase in the air temperature inside the collector [18, 19].

Table 2. Horizontal, Optimal, normal, and 90° Irradiation of Sun for Geographical Specifications of Qom Province (m Northern, "33'50°52 Eastern, 34°38'23"935: Altitude)

Month	H_h	H_{opt}	H (90)	DNI
Jan	2870	4490	4390	4160
Feb	3980	5610	4820	5300
March	5310	6380	4370	5890
April	5990	6230	3150	5720
May	7200	6790	2580	6590
June	8080	7220	2150	8110
July	7910	7270	2400	7690
Aug	7400	7440	3190	7750
Sep	6360	7350	4440	7500
Oct	4760	6380	5080	6170
Nov	3210	4870	4580	4520
Dec	2700	4470	4570	4290
year	5490	6210	3800	6150

The monthly mean values of irradiation and solar reflection along with the monthly mean values of temperature and wind velocity for Qom province are illustrated in Table 3. These data were extracted from references [15-17], which include solar irradiation information. The maximum and minimum mean values are related to summer (July) and winter (December). These results pursue the same trend regarding solar reflection, and July and January, respectively, allocate the maximum and minimum temperature to themselves.

Table 3. Monthly Mean Values, Air Temperature, and Wind Velocity for the Geographical Specifications of Qom Province (m Northern, "33'50°52 Eastern, 34°38'23"935: Altitude)

Month	$G\left(\frac{\mathbf{kWh}}{\mathbf{m^2}}\right)$	Diff $\left(\frac{\mathbf{kWh}}{\mathbf{m^2}}\right)$	T(C)	Wind$\left(\frac{m}{s}\right)$
Jan	98.2	28.6	4.3	0.6
Feb	114.2	34.7	7.9	1.1
March	152.2	57.8	14	1.4
April	179.9	67.2	18.9	1.59
May	218.7	75.7	25.1	1.69
June	230.4	71.4	30.1	1.39
July	231.3	73.8	33.2	1.6
Aug	221	59.4	32.1	1.3
Sep	180.7	47.9	26.8	1
Oct	141.4	42.5	25.5	0.8
Nov	104.4	26.1	11.8	0.8
Dec	87	27	6	0.5
year	1959.7	612.1	19.2	1.1

Figures 1 and 2 illustrate the graphs related to the total solar irradiation (G) in the dusty sky, the total solar irradiation in the clear sky (Gc), normal irradiation on the collector surface in the dusty sky (DNI), and normal irradiation in the clear sky (DNIc) in different hours of February for Qom province. As the graphs show, the best solar irradiation for power generation occurs in the hours between 8 A.M. and 4 P.M. This quantity reaches its maximum value at noon (about 12 o'clock). The regional information associated with these Figures was extracted from references 15-17.

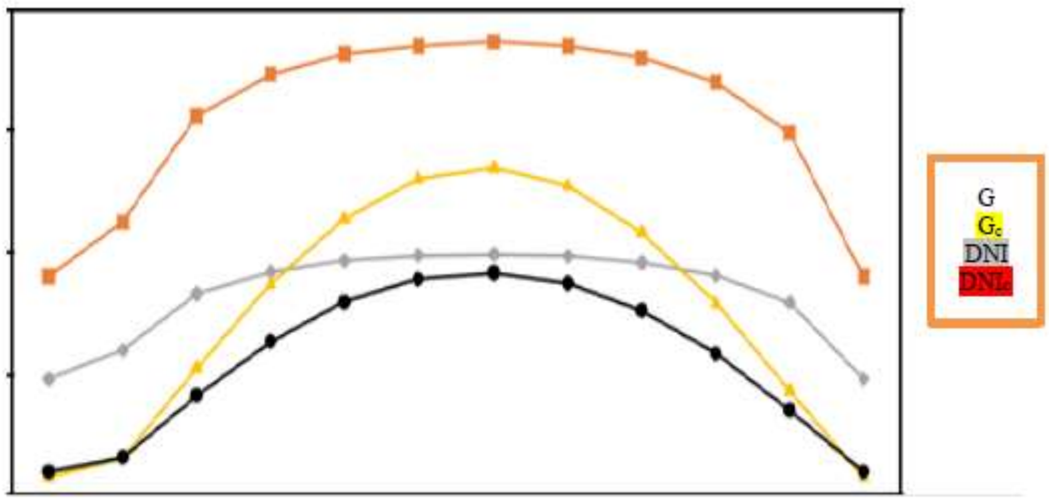

Figure 1. Solar Irradiation Rate in Different Hours of Day in February for Qom Province

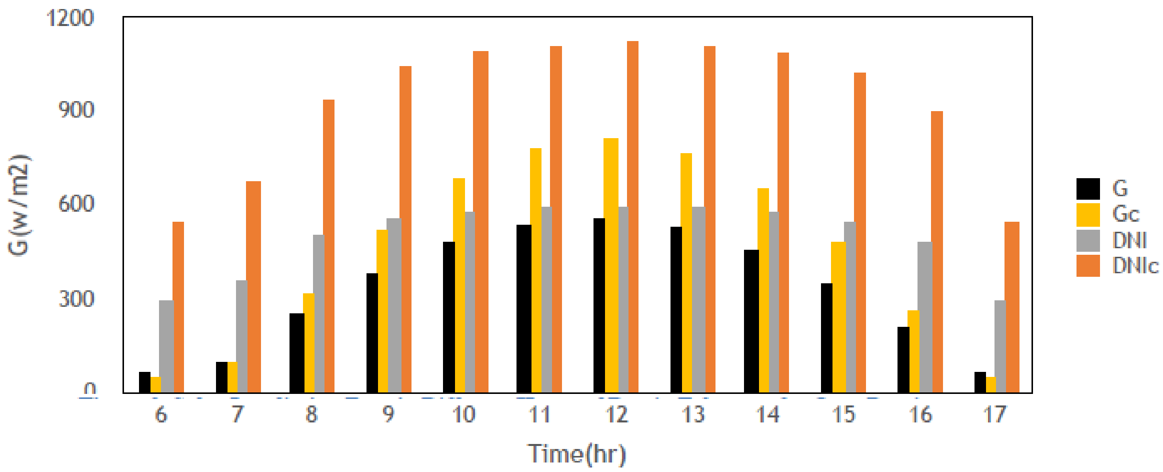

Figure2. The amount of sunlight at different times of the day in February for Qom province

As Figure 2 illustrates, Qom province can extensively use solar irradiation in February from 8 A.M. to 4 P.M. It means it can use solar irradiation for 8 hours during a day. This rate does not become smaller than $500\left(\frac{kWh}{m^2}\right)$ and it reaches $1100\left(\frac{kWh}{m^2}\right)$ around noon in its best condition. This proper irradiation potential is a good reason for the suitability of employing a solar chimney system. Figure 3 and 4 display the graphs related to the total solar irradiation

(G) in the dusty sky, total solar irradiation in the clear sky (Gc), normal irradiation on the collector in the dusty sky (DNI), and normal irradiation in the clear sky (DNIc) in the different hours of a day in July. These values show that the solar irradiation rate reaches its maximum value at 12 o'clock at noon in July. The comparison of Figures 3 and 5 denotes that the G and GC irradiation rates increase in July compared to February; however, DNI and DNIc irradiation decrease. It is because these values depend on the different meteorological conditions. The regional information associated with these figures wwas extracted from references [15-17].

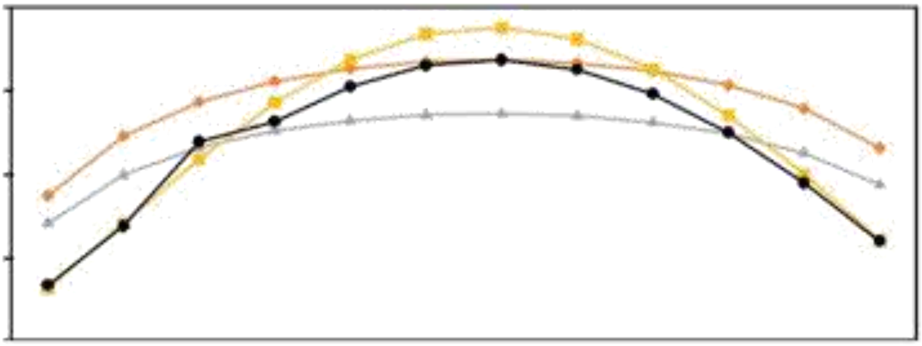

Figure 3. Solar Irradiation Rate in Different Hours of a Day in July for Qom Province

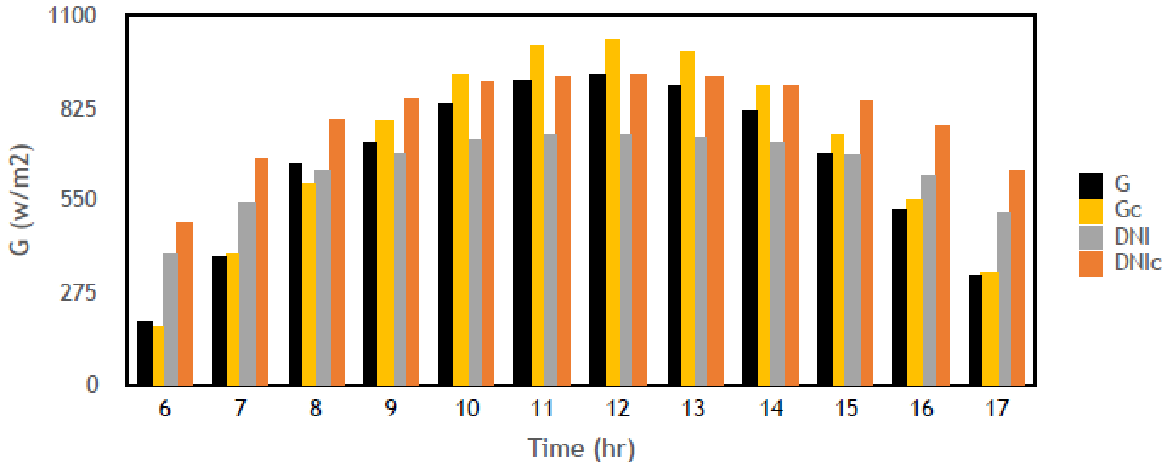

Figure 4. Solar Irradiation Rate in Different Hours of a Day in July for Qom Province

As considered in Figures 1, 2, 3, and 4, the extracted results for solar irradiation in Qom province show that this region has a very high potential in exploiting solar energy, solar systems, and electric energy generation. Using the equations presented in section 2, we deal with the computations that are related to the different components of the sample solar power plant in Qom province. Figure 5 illustrates the changes in the tower height of the solar chimney in varying temperature differences between its inlet and outlet. As observed, as the temperature difference increases, the height also increases, and vice versa.

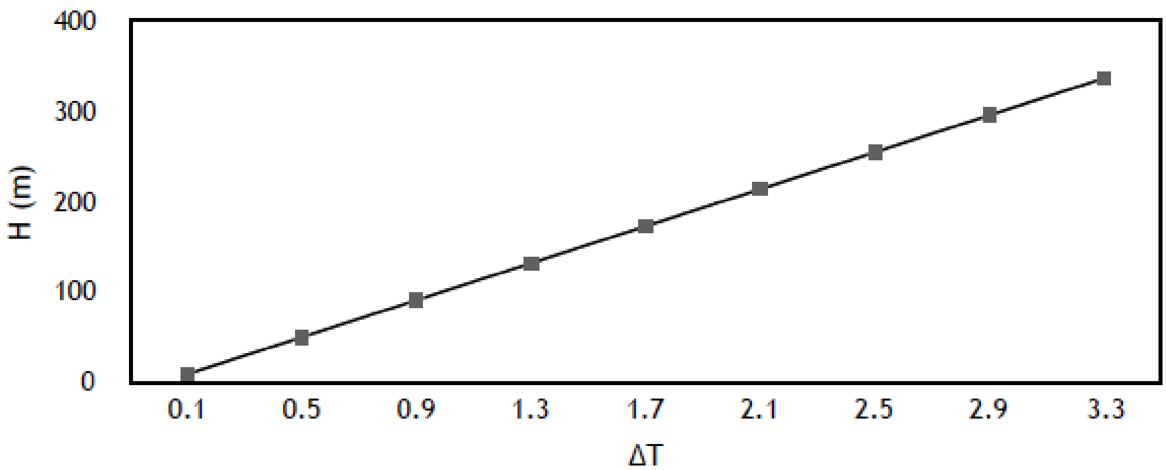

Figure 5. Changes in the height of the solar chimney based on the temperature difference in its inlet and outlet in the weather conditions of Qom province

Pressure changes in the different heights of the tower are displayed in Figure 6. As observed, an increase in height increases the pressure difference between the inlet and outlet of the chimney. These two values have a direct relationship with each other. This Figure has been inferred from Equation 7, in which the height magnitude is variable, and the G value is measured at 213.3 KWh in July and 87KWh in December in Qom province. The collector radius is 50m, the inlet section radius of the tower is 5m, and the mass flow rate of the input air to the tower is different according to the wind velocity in the two months, and the collector efficiency is considered at 0.95 based on the researchers' studies.

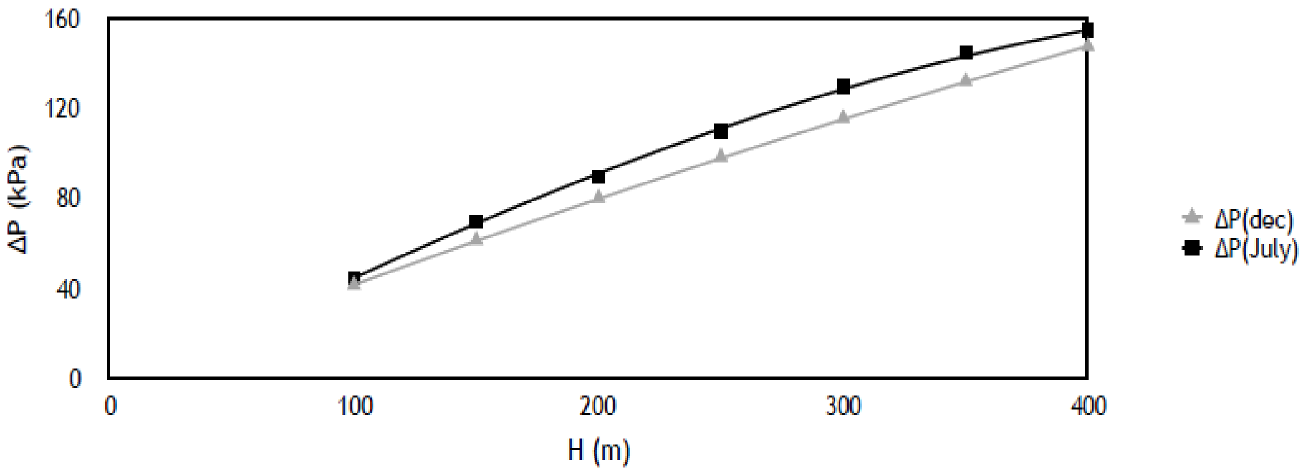

Figure 6. Pressure changes at the inlet and outlet of solar chimney according to the change in the height of a chimney in July and December for Qom province

Figures 7 and 8 show the generation power graph of a solar chimney power plant possessing a turbine with 70 and 80% efficiency in December and July for Qom province according to the pressure difference and varying heights in the tower inlet and outlet. These graphs are inferred from Equations 15, 16, and 17, which display power according to varying pressure differences.

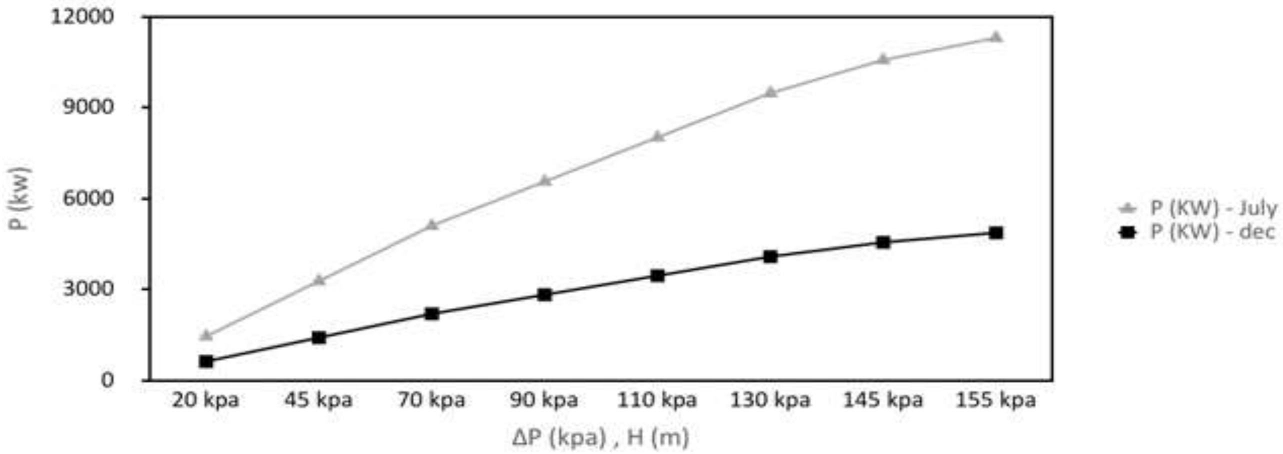

Figure 7. Generation power according to pressure difference and height in solar chimney with 80% turbine efficiency

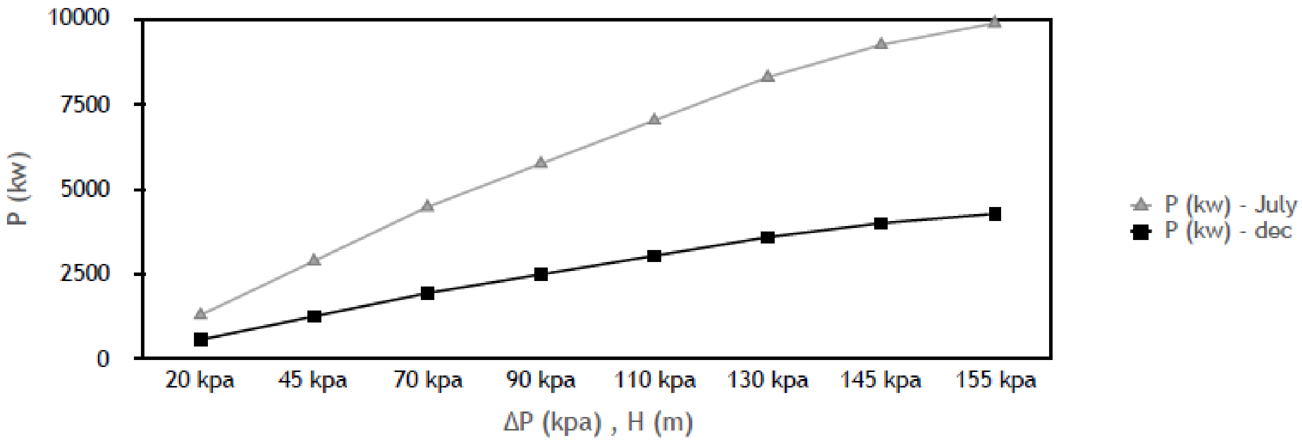

Figure 8. Generation power according to pressure difference and height in solar chimney with 70%
turbine efficiency

As Figures 7 and 8 illustrate, the generation power has direct relationships with pressure difference and height; however, it is completely justified with respect to the definition of a solar chimney. With an increase in height, the pressure difference increases, and, finally, the power increase. The comparison of generation power between July and December shows that the pressure difference increases as the chimney height increases, and;
as a result, the generation power of the power plant increases as well. Graphs 7 and 8 display that the maximum generation power relates to a chimney with a 400m height and 155Kpa pressure difference, and the minimum power associates with a chimney with a 45.2m height and 20Kpa pressure difference, and this generation power is more in July than December. The factor that moves the air inside the chimney upward is the buoyancy force, which is stemmed

from temperature difference, density, and pressure difference. As the pressure difference increases, the air velocity speeds up inside the system, and; consequently, it enters the turbine enclosure faster, and the generation power of the turbine increases [18-20].

4. CONCLUSION

Owing to the high potential of Qom province, the use of solar energy has elevated scientific and economic justification. Solar energy specialists have estimated 300 sunny days during a year for the cities of Iran. This value even increases for Qom province. By comparing annual irradiation mean for the different cities of Iran in this paper, we can perceive that Qom province is one of the best regions for a power plant installation. The meteorological conditions, proper wing velocity, and air temperature (especially for solar chimneys), along with the numerous unused areas, are of the factors that encourage specialists to exploit this system in this province. The extraction of solar irradiation data from global valid resources and their investigation illuminated that the maximum and minimum irradiation rates are associated with the July and December months. These results on the solar reflection follow the same trend. Concerning the direct relationship among the generation power, pressure difference, and chimney height, the pressure difference inside the chimney increases as its height increases, and; as a result, its generation power increases. The maximum generation power is related to a chimney with a 400m height and 155Kpa pressure difference, and the minimum power relates to a chimney with a 45.2m height and 20Kps pressure difference. All in all, regarding the results presented in this paper, Qom province can be recognized as one of the best locations for a solar chimney power plant installation.

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