Investigation of the effects of ambient temperature and dimensional parameters on the performance of solar chimney power plants

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Abstract
In this study, the influence of ambient temperature is investigated on the performance of solar chimney. Dimensional analysis is performed to find the dimensionless variables for the purpose of predicting the solar chimney performance. A mathematical model was developed and validated with the experimental data of an experimental pilot. By using this model, it is shown that the ambient temperature has an adverse effect on the SCPP output. For this purpose, a solar chimney with 7.4 m chimney height, 0.6 m chimney diameter, 8 m collector diameter, and 0.2 m mean collector height was built. By using the Buckingham Pi theory, a dimensionless variable was obtained, and its value was correlated using the experimental data. The investigation of the system performance using this dimensionless variable shows that the output power increases with a third-order polynomial relation through increasing the size of SCPP, and with a linear relation through increasing the solar insolation. In the other word, when the size of the system and solar insolation increase, the output power of the solar chimney rises. The variation of the air velocity versus daytime shows maximum area from 11:00 a.m. to 1:00 p.m.

Keywords: solar chimney; SCPP performance; dimensional analysis

Received 6 March 2016; revised 7 May 2016; editorial decision 29 May 2016; accepted 28 March 2017

1 INTRODUCTION

According to the International Energy Outlook’s report [1] in 2001, the energy consumption, especially the oil-related energies is increasing steadily in the world. Also, almost 86% of these energies are supplied from fossil fuels, 6.6% from nuclear energy, 6.7% from hydro-electric power plants and just 0.8% from other renewable energy resources. So it is clear that most of the energy demands of human beings are extracted from the underground natural resources. It is concluded that the world economy is highly dependent on the nonrenewable resources, and there is so much concern about the availability of the fossil fuels in the underground resources in the future. On the other hand, the greenhouse gas emission is an important issue in burning the fossil fuels which causes the climatic change and global warming phenomena. Also, burning the fossil fuels has other costs, such as pollution of air and water, health problems for individuals, acid rain, destruction of forests and destruction of animal habitats [2]. So energy production through clean and green sources has been paid attention owing to high energy consumption and environmental emission [3], and a further target of 20% of renewables has already been set for 2020 [4]. Obviously, using these energies such as solar energy reduces the environmental hazards significantly. The renewable energies including hydropower, biomass, wind, photovoltaic (PV) and solar thermal are currently used. These studies about renewable sources are supposed to be carried out in Iran more than before. The amount of insolation incident on the earth’s surface depends on many factors like location, time of the day, the inclination of the surface, declination, and weather [5]. On the
other hand, almost half of Iran is in the areas with the insolation higher than 2200 (kWh/m²) and the other half has the insolation between 1950 and 2200 (kWh/m²) which shows that Iran has a high potential for constructing solar power plants [6].

Photovoltaic energy conversion is considered as one of the most promising renewable energy technology which has the potential to contribute significantly to a sustainable energy supply and to mitigate greenhouse gas emissions [7].

The solar heat which concentrated and absorbed by a collector is utilized in solar thermal power systems to drive a heat engine/generator and produce electric power [8], also the solar energy can be used directly in many ways. In a particular way, the sunlight contacts on a solar thermal collector and then an adsorbent surface is warmed; the obtained thermal energy is transferred by the process fluid. We can even say; the solar chimney power plants convert the solar thermal energy to the kinetic energy of fluid and subsequently to mechanical work in the turbine. A solar chimney power plant system consists of three main parts: a solar collector, a chimney and a turbo-generator which are named as the Solar Aero-Electric Power Plant (SAEP). The energy source for the power generation is the horizontal solar radiation which is transferred through a transparent cover collector and a portion of this radiation is trapped by the greenhouse phenomena. This part uses the solar radiation to rise the temperature of the air and then the buoyancy of warm air causes making the air stream flow through the system.

Solar technologies have had an important place for researchers in the last few years. Many authors worked on the various solar technologies and their applications, and some of them are reviewed in the following. Singh et al. [9] studied experimentally on the performance of a hybrid photovoltaic thermal (PVT) flat plate collector (FPC) solar still. They observed that the proposed system could meet potable water requirement as well as electricity requirement. Rajoria et al. [10] investigated the performance evaluation of building integrated photovoltaic thermal (BiPVT) system. Kalogirou [11] investigated possible solutions of PV and STS integration on the building roofs and facades. He quantified the advantages of integration and gave suggestions to address the possible problems created. In the recent years, remarkable attention is drawn to Stirling engine because of their advantages such as high efficiency and also using many resources like biomass, fossil fuels and solar energy as the heat source. Numerous studies have been done on the coupling of Stirling engines to solar collectors in the case of optimization and thermodynamic analysis by researchers [3, 12–15].

In the case of solar chimney technology, Leonardo da Vinci [16] designed the first solar chimney, using the warm air from a chimney to move a device. In 1903, Cabanes [17] provided the first proposal for using solar chimneys for power generation and called it as ‘solar engine’. In this system, an air heater was attached to a house with a chimney. Inside the house, a kind of wind propeller was placed for the purpose of electricity production. In 1926, Dubos proposed to the French Academy of Sciences the construction of a Solar Aero-Electric Power Plant in North Africa which was placed on the slope of a high height mountain. The author claims that an ascending air speed of 50 m/s could be reached in the chimney [18]. The first outstanding action for the SCPP development is referred to the prototype structure in 1982 in Manzanares, Spain. Haaf [19] disclosed the preliminary test results including the energy balances, the collector efficiency values, the pressure losses due to the frictions and the losses in the turbine section for the Manzanares power plant.

Dai et al. [20] studied the effective parameters like the chimney height, the collector diameter, the solar insolation, the ambient temperature and the turbine efficiency on the performance of solar chimney power plants. They showed that the ambient temperature has a negative effect on the chimney performance. Zhou et al. [21] investigated the performance of a solar chimney in Qinghai-Tibet where there are abundant solar radiation and low atmospheric temperature. To carry out the analysis of SCPP, they considered a 100 MW reference SCPP. They found that SCPP if built on the plateau can produce twice more power than an SCPP built on the same latitude of other regions. Larbi et al. [22] studied the performance of a solar chimney power plant in the southwestern region of Algeria theoretically. The obtained results show that the generated power depends on some parameters such as the solar irradiance, the ambient temperature, the height of the tower and the surface of the collector. Also, they found that the ambient temperature has a positive effect on the generated power but not as much as the solar irradiance. It means that the ambient temperature has little impact on the performance of the system. In 2011, Kasaedian et al. [23] investigated the effects of the climatic parameters on the performance of a solar chimney pilot. For this purpose, a solar chimney pilot with 10 m collector diameter and 12 m chimney height was built on the campus of University of Zanjan. The air velocities were variable according to the chimney-collector temperature difference and a maximum air velocity of 2.9 m/s was achieved. Also, they found that the larger collectors and the higher chimneys would make much more power. Sangi [24] studied the performance of SCPP theoretically to examine the effect of various ambient conditions and structural dimensions on the power generation in some parts of Iran. Sangi found that the capacity of power generation was dependent on various ambient conditions and structural dimensions such as solar irradiation, ambient temperature, chimney height and collector diameter. Asnaghi and Lajevardi [25] in 2012 examined the SCPP performance in 12 cities of Iran. Their results show that the ambient temperature and the solar radiation have a positive effect on the generated power. Haghighi and Maerefat [26] designed a solar chimney (SC) and earth-to-air heat exchanger (EAHE) to face the thermal need of flat buildings. They found the design of SC and EAHE which reveal better performance. Also, their investigation shows that the system performance depends on solar radiation, outdoor air temperature, the heating demand of room, the soil temperature, as well as the configuration of both the SC and the EAHE.

In the case of dimensional analysis, Koonsrisuk and Chitsomboon [27] performed a numerical analogy analysis in a solar chimney power plant. The dimensionless variables were...
used in the study of flow in a small-scale solar chimney and the suitable working fluid was examined for the better solar chimney performance. Their results show that air is more suitable than water to be utilized as the working fluid. In the other study, they investigated the dynamic similarity between a prototype and its models, while they used the same solar heat flux, because it’s hard to conduct an experiment using dissimilar heat fluxes with different physical models [28]. They concluded that, to achieve the same conditions of solar thermal flux, the radius of the collector roof of the model and original samples should be dissimilar, while the other parameters must be similar (partial similarity). In 2009, Koonsrisuk and Chitsomboon [29] used a dimensional analysis which established a dynamic similarity between a prototype and its scaled models to combine eight primitive variables into only one dimensionless variable. They also have examined three configurations of the solar chimney including the models with complete geometric similarity, partial similarity and without similarity.

According to what have been studied before regarding the effect of ambient temperature on the performance of the solar chimney, different results have been observed. In some studies including the work of Dai et al. [20] and Zhou et al. [21], the negative effect of this parameter on the power plant is shown. From another side, Larbi et al. [22] and Asnaghi and Lajevardi [25] claimed against what Dai and Zhou had stated in their results. So, one of the aims of this research is distinguishing the right claim about the parameters as mentioned earlier. Using dimensional analysis also taking the advantages of the sample experimental results, we can obtain a proper correlation for the SCPP power output. This correlation can be utilized for investigating the system performance in a variety of dimensions. Unlike the previous works about the dimensional analysis, we would like to calculate the amount of the dimensionless figures which have been validated with experimented data, the effects of the collector efficiency, the solar thermal energy losses and also the local and frictional losses are involved in the obtained dimensionless number.

2 EXPERIMENTAL SOLAR CHIMNEY SET-UP

In this study, for investigating the performance of solar chimney power plant, a pilot-scale solar chimney was built. The chimney height was 7.4 m, and 5 degrees was chosen for the collector angle. Other sizes of this pilot are presented in Table 1, and Figure 1 shows a photo of the solar chimney pilot.

3 ANALYTICAL METHOD

In this paper, the energy equations of solar chimney power plants have been modeled using a simplified mathematical model, and then this model is validated by using experimental results that are obtained from the pilot sample to find the effects of ambient temperature on the performance of solar chimney power plants. In the models, the accuracy of the results is reduced with increasing the number of the assumptions. At the worst conditions, we can expect of the simplified model that just shows the trends of the input and output parameters. The aim of this paper is to provide a model to investigate the effect of temperature on the performance of solar chimney power plants. So, all the energy equations on which the ambient temperature effects are considered. The ambient temperature effects on the energy loss from the collector roof and chimney to the ambient and the sky, the chimney performance and the velocity of airflow inside the chimney. So using this model provides good results for reaching the specified purpose. A schematic of the considered solar chimney power plant is shown in Figure 2.

The energy analysis is performed based on the energy conservation equation. Also, the equations of mass and momentum conservation are used to find some of the variables in the energy equation. The solar insolation that reaches on the collector is divided into three parts. Most of this insolation transfers through the collector because of its high transparency.
coefficient, and small amounts are absorbed or reflected by the collector roof. The amount of the transmitted insolation is absorbed in the bottom layers, so they find temperature increasing. The latter one, which has short wavelength, is reflected to the sky. The heated ground causes increasing temperature of the inlet airflow and radiating the energy to the collector roof. It is assumed that the air inside the chimney doesn’t have any heat transfer to the walls; thus, the losses by the chimney are ignored in the energy equation. The energy balance equations in the solar chimney power plants are as follows:

\[ E_S = E_{r,\text{trans}} + E_{r,\text{ref}} + E_{r,\text{abs}} \]  

\[ E_f = E_{fa} + E_f \]  

\[ E_{r,\text{abs}} + E_{fr} = E_{ra} + E_{rar} + E_{in} + E_{rch} \]  

\[ E_{ach} + E_{rch} = E_{ach} + E_{cha} + E_{chr} \]  

The input solar energy to the system is obtained by the following equation; where \( G \) is the solar insolation (W/m²) and \( A_c \) is the collector area (m²).

\[ E_S = G \times A_c \]  

The achieved energy by the collector roof is given by:

\[ E_f = \tau_r \alpha_f \times E_S \]  

where \( \tau_r \) is the transparency coefficient of the collector and \( \alpha_f \) is the absorption coefficient.

The amount of the solar energy which is absorbed by the roof contains the direct insolation from the sun and the energy which is reflected from the bottom of the collector (Equation 7).

\[ E_{r,\text{abs}} = \alpha_r \times E_S + \alpha_r \tau_r (1 - \alpha_f) \times E_S \]  

The energy conservation equation for the airflow in the solar collector is according to Equation 8:

\[ E_{fa} + E_{ra} = m c_p (T_{co} - T_i) \]  

In the above equations, \( \alpha \) is the absorption coefficient, \( m \) is the air mass flow, \( c_p \) is the specific heat capacity of air at constant pressure and \( T_c \) and \( T_o \) are the air temperatures in the input and output of the collector, respectively.

The air mass flow rate is obtained by the following equation. Here, \( \rho_{co} \) is the air density at the collector output (chimney input), \( A_{ch} \) is the internal area of the chimney and \( V_{ch} \) is the air velocity at the base of the chimney (maximum velocity).

\[ m = \rho_{co} A_{ch} V_{ch} \]  

The maximum velocity is calculated using Equation 10 that is based on the principles of momentum conservation. By the Boussinesq condition, except in the buoyancy term, the density changes are negligible.

\[ P_{co,1} - (1 + \xi) \frac{\rho V^2}{2} - \int_{0}^{H_{ch}} \rho g dz = P_{co,4} \]  

In which \( P_0 \) is the air pressure in the input and output of the solar chimney and \( \xi \) is the pressure losses from the input to the output of the system. The pressure difference is given by Equation 11 which is converted to Equation 12, after placement in Equation 10.

\[ (P_{co,1} - P_{co,4}) = \int_{0}^{H_{ch}} \rho_{co} g dz \]  

\[ \frac{P_{co} - \rho}{\rho} g H_{ch} = (1 + \xi) \frac{V^2}{2} \]  

With using the Boussinesq condition, the maximum velocity reads as:

\[ V_{ch} = \sqrt{\frac{2 g H \beta}{(1 + \xi) (1 - T_0/\beta)}} \]  

where \( \beta \) is the Thermal expansion coefficient (for ideal gases: \( \beta = \frac{1}{T_0} \approx \frac{1}{T_i} \)).

**The convection heat transfers:**

- The collector bottom to the airflow: in which \( T_{bE} \) and \( T_{aE} \) are the average temperature of the collector’s bottom and the airflow through the collector, respectively.

\[ E_{fb} = h_{fb} A_c (T_{bE} - T_{aE}) \]  

- The collector roof to the airflow: where \( T_{rE} \) is the average temperature of the collector roof.

\[ E_{fr} = h_{fr} A_c (T_{rE} - T_{aE}) \]
The collector roof to the ambient: where $T_\infty$ is the ambient temperature.

$$E_{R\infty} = h_\infty A_c (T_{E} - T_\infty)$$  \hfill (16)

It is understood from the above equation that the ambient temperature is effective in the heat transfer from the collector roof to the ambient. The convection coefficient ($h$) is described for different streams in the following equation. The heat transfer coefficients from the collector roof and bottom to the air are assumed to be equal ($h_{fa} = h_{ra}$). Although the airflow is caused by the buoyancy effect, forced convection mechanism is considered for calculating the heat transfer coefficient. Here due to the higher temperature of the roof than the air, the heat transfer is accrued from the roof to the ambient. For calculating the heat transfer coefficients for the collector roof, two parallel horizontal plates are considered, and the airflow in the collector is assumed as a flow between two parallel plates. The heat coefficient for the turbulent stream is obtained by the Gnielinsky equation [30]:

$$h_{ra} = \frac{(f/8)(Re - 1000)Pr}{1 + 12.7(f/8)^{1/2} (Pr^{2/3} - 1)} \left( \frac{k}{d_h} \right)$$  \hfill (17)

where $f$ is the coefficient of friction, $Re$ is the Reynolds number, $Pr$ is the Prandtl number, $k$ is the thermal conductivity of air and $d_h$ is the hydraulic diameter which is introduced as:

$$d_h = 2H_c$$  \hfill (18)

The Reynolds number is calculated by using the average radial velocity of the air inside the collector ($u_{ave}$):

$$Re = \frac{\rho_{av} u_{ave} d_h}{\mu_{av}}$$  \hfill (19)

where $u_{ave}$ is given by:

$$u_{ave} = \frac{1}{R_c - R_{ch}} \int_{R_{ch}}^{R_c} \frac{m}{2\rho\pi r H_c} dr = \frac{m}{2\rho \pi (R_c - R_{ch}) H_c} \times \ln \left( \frac{R_c}{R_{ch}} \right)$$  \hfill (20)

The coefficient of friction for a smooth surface in the transition or turbulent flow regimes is calculated by [31]:

$$f = (1.82 \log_{10} Re - 1.64)^{-2}$$  \hfill (21)

The air heat transfer coefficient is given by the following equation, in which $u_{wind}$ is the wind velocity [32].

$$\hat{h}_\infty = 5.7 + 3.8 \times u_{wind}$$  \hfill (22)

The radiation heat transfers:

- From the collector’s bottom to the roof

$$E_{fr} = \sigma A_c (T_{E}^4 - T_{ch}^4) = h_{fr} A_c (T_{E} - T_{ch})$$  \hfill (23)

where $h_{fr}$ is the radiation heat transfer coefficient for two flat plates (due to the high ratio of the collector diameter to its height), which is calculated by Equation 24.

$$h_{fr} = \sigma \frac{(T_{fr}^4 + T_{ch}^4)(T_{E}^4 + T_{fr}^4)}{\frac{1}{\varepsilon_f} + \frac{1}{\varepsilon_r} - 1}$$  \hfill (24)

- From the collector roof to the chimney’s outside surface

$$E_{rch} = \varepsilon_r \varphi_{rch} \sigma (A_c - A_{ch}) (T_{E}^4 - T_{ch}^4)$$  \hfill (25)

- From the collector roof to the sky

$$E_{rs} = \varepsilon_r \varphi_{rs} \sigma (A_c - A_{ch}) (T_{E}^4 - T_{sky}^4)$$  \hfill (26)

where $\varepsilon$ is the emissivity coefficient of the collector roof and the collector’s bottom, $\sigma$ is the Stefan-Boltzmann constant, $\varphi$ is the shape factor and $T_{sky}$ is the sky temperature which is calculated by the Swinbank equation for a clear sky [33].

$$T_{sky} = 0.0552 \times T_{\infty}^{0.5}$$  \hfill (27)

According to the above equation, the ambient temperature effects on the heat radiation from the collector roof to the sky.

The following assumptions are considered:

- The material which is used to cover the collector roof is almost completely transparent to the solar insolation (for short wavelength, the transmissivity is 85%). This coating absorbs a small amount of solar insolation (absorptivity 10%) and reflects the rest (5%). The emissivity for the longer wavelength radiations which are released from the collector’s bottom is assumed to be 0.9 ($\varepsilon_r = 0.9$). The transmissivity of the collector cover for the long wavelength insolation is very low, and therefore the radiation of the collector’s bottom to the sky is negligible.
- The absorptivity of the collector’s bottom is assumed 0.65.
- The absorptivity of the chimney wall is assumed 0.9 ($\varepsilon_{ch} = 0.9$) and the Chimney wall is thin, so there is no temperature gradient in the thickness of the chimney.
- The temperature distribution of inside the collector is assumed to be linear.
- The air properties including Prandtl number, viscosity, density, etc. are calculated in the average air temperatures.
- The air is considered to be transparent to the insolation ($\varepsilon_{in} = 1$, $\varepsilon_{out} = 1$) and thus, only the convection causes warming the air in the collector.
- The local losses and the coefficient of friction for the airflow are ignored.

### 4 DIMENSIONAL ANALYSIS

To achieve the dimensionless variable ($s$) for the purpose of investigating the flow in the solar chimney, the dimensionless variable ($s$) is achieved by using the Buckingham Pi method. At
first, the governing parameters in the system are obtained using the energy, mass and momentum conservation equations. These primitive parameters are \( V_{ch}, G, \beta, g, c_p, D, \) \( H, D_h, \) and \( \rho, \) which are the velocity in the chimney (m/s), the solar insolation (W/m²), the coefficient of volumetric thermal expansion (1/K), the gravity (m/s²), the specific heat capacity at constant pressure (J/(kg K)), the collector diameter (m), the chimney height (m), the chimney diameter (m) and the air density (kg/m³), respectively. For making the parameters dimensionless, the below stages were followed:

Stage 1: in the first step, by the combination and grouping the primitive parameters, the following new variables are proposed and the number of variables is reduced to five:

\[
A_{ch} = \frac{\pi D_{ch}^2}{4} \tag{28}
\]

\[
A_c = \frac{\pi D^2}{4} \tag{29}
\]

\[
m = \rho A_{ch} V_{ch} \tag{30}
\]

\[
P = \frac{1}{2} m V_{ch}^2 \tag{31}
\]

\[
m \Delta T = \frac{G A_c}{c_p} \tag{32}
\]

Stage 2: in the second stage, the combination of the basic dimensions of which the primitive variables are formed is presented. The fundamental dimensions are the mass (M), length (L), time (t) and temperature (θ).

Stage 3: in the third stage, the primitive variables are expressed in the terms of the fundamental dimensions:

\[
\frac{1}{2} m V_{ch}^2 : M L^2 t^{-3}, H_{ch} : L, g : L t^{-2}, \beta : t^{-1}, \frac{G A_c}{c_p} : M t^{-1} \theta
\]

Stage 4: the number of the dimensionless variables is calculated at this stage. Following the Buckingham’s Pi theory, \( n \) minus \( m \) is the number of the dimensionless variables; where \( n \) is the number of the variables and \( m \) is the number of the fundamental dimensions. Here, \( n \) and \( m \) are taken as five and four, respectively. Therefore, one dimensionless number will be achieved.

Stage 5: in this stage, the repetitive variables are selected. According to the primitive variables \( \frac{G A_c}{c_p}, g, \beta, H_{ch} \) are chosen.

Stage 6: finally the main dimensionless variable can be obtained at this stage. The dimensionless variable may be calculated by combining the governing equations or by the following method:

\[
P \times g^a \times \beta^b \times H_{ch}^c \times \left( \frac{G A_c}{c_p} \right)^d = M^0 L^q T^0 \theta^0 \tag{33}
\]

\[\rightarrow a = b = c = d = -1\]

And therefore, the dimensionless variable is given as:

\[
m = \frac{1}{2} \rho A_{ch} V_{ch}^3 \tag{34}
\]

\[g \beta H_{ch} \left( \frac{G A_c}{c_p} \right) = \text{Const.} = C \]

Which is constant and its value is obtained by the experimental measurements results. The numerator is the kinetic energy in the chimney which is related to the output power and the interpretation of the denominator is given as follows:

\[
\frac{G A_c}{c_p} = \dot{m} \Delta T = \rho A_{ch} V_{ch} \Delta T \tag{35}
\]

\[
\beta = -\frac{1}{\rho} \left( \frac{\partial p}{\partial T} \right)_p \approx \frac{1}{\rho} \left( \frac{\Delta p}{\Delta T} \right) \tag{36}
\]

\[\rightarrow g \beta H_{ch} \left( \frac{G A_c}{c_p} \right) = \left( \Delta \rho \psi \right) V_{ch} \tag{37}
\]

The terms in the parentheses \( \left( \Delta \rho \psi \right) \) show the resultant of the buoyancy force and the weight force which cause the air flowing inside the chimney. The multiplication of these terms by the velocity shows the generated power due to the buoyancy force of the airflow through the chimney. Koonsrisuk and Chitsomboon [29] achieved a similar dimensionless variable in their study but they didn’t modify the variable and considered it’s amount as one. For using this variable for large power plants, the complete similarity law between the model power plant and the pilot must be used. The complete similarity means the geometric, kinematic and dynamic similarity. Due to the constancy of the system, the kinematic similarity exists but it is required to maintain the geometric similarity for all the dimensions so that the dimensions shall be scaled up with a similar level; in other words, the following equation must be satisfied:

\[
r = \frac{H_{ch,m}}{H_{ch,p}} = \frac{D_{ch,m}}{D_{ch,p}} = \frac{H_{c,m}}{H_{c,p}} = \frac{D_{c,m}}{D_{c,p}} \tag{38}
\]

In Equation 36, the subscript ‘p’ corresponds to the pilot and ‘m’ corresponds to the model. After ensuring about the geometric and the kinematic similarity due to the presence of the dynamic similarity, the obtained dimensionless variables for the pilot and the model are set equal.

\[
\frac{1}{2} \rho A_{ch} V_{ch}^3 \tag{39}
\]

\[g \beta H_{ch} \left( \frac{G A_c}{c_p} \right) \]
5 RESULTS AND DISCUSSION

For estimating the ambient temperature effect on the solar chimney power plant, a mathematical model was provided. This model is solved by the Engineering Equation Solver (EES) software and the results are presented here. For the second part of the work, the dimensionless variable was obtained by using the dimensional analysis. Then, by validating with the experimental data, a correction coefficient between the dimensionless variables is calculated. This coefficient may be used for the bigger power plants and the output power can be calculated if the geometric similarity exists.

5.1 Ambient temperature effects on the performance of the solar chimney

The ambient temperature is an important factor in the performance of solar chimney power plants. In this part, first, the presented model is validated with the experimental data and then the model is used for estimating the ambient temperature effect.

5.1.1 Validating the model

The presented analytical model is compared with the experimental data and the parameters of the pilot are used for solving the model in the EES software. This model possesses coupled and nonlinear equations which the EES software can solve them. The parameters included in Table 1 and the experimental data are used here. These data are given in a sunny day on 6 October 2013. For validating the model, the input air velocity in the chimney section as the indicator of the output power is used. Figure 3 shows the velocity changes versus time in the chimney input for the model and the pilot. As the figure shows, the velocity changes in the model and the experimental pilot are similar. The reason for the difference between the experimental data and the model in the early hours is the delay between the insolation and the air velocity rising in the system, but it is not considered in the model because of the simultaneous solution. Also, due to the low accuracy of the velocity measuring instruments, the experimental data of the velocities are discontinuous. So, according to the incremental and decreasing patterns of the diagram, it can be predicted that the results of the pilot plant and the model could be more consistent.

So it can be concluded that the analytical model is suitable for studying the effect of temperature on the efficiency and the output power of a solar chimney power plant.

5.1.2 Investigation of the ambient temperature effect using the model

After validating the model with the experimental data, for estimating the ambient temperature effect, the efficiency and the power output changes, the analytical model is used. This model is utilized for a constant insolation (800 w/m²) and a temperature between 288 and 318 K. The amounts of different parameters used for the power plant are given in Table 2.

Figures 4 and 5 show the effects of ambient temperature on the efficiency and the output power, respectively. The figures show that the ambient temperature has a negative effect on the efficiency, and the power of the plant and these are decreased by increasing the temperature. It is defined by the model that the ambient temperature influences on the heat losses to the sky and the surrounding. Another reason is that by increasing the temperature, the density difference between the airflows decrease; it means that in the higher ambient temperatures, the density difference and therefore the velocity of the airflow in the system will be less (for the same temperature...
However, in high temperatures due to increasing the losses to the out of the system and reducing the heat transfer from the collector bottom and the collector roof to the air, the same temperature difference between the air inside the system and the ambient would not have occurred. So the temperature difference in the lower ambient temperatures is always more than the higher ambient temperatures.

Table 2. Sizes of the solar chimney power plant (the Manzanares power plant) [34]

| Parameter                  | Size | Unit |
|----------------------------|------|------|
| Chimney height             | 194.6| m    |
| Chimney diameter           | 10.16| m    |
| Collector diameter         | 244  | m    |
| Average height of the collector | 2    | m    |

Figure 4. Effect of the ambient temperature on the generated power.

Figure 5. Effect of the ambient temperature on the efficiency.
For the purpose of determining the effects of the temperature on decreasing of the output power and efficiency of solar chimney power plants, the model results for a plant (whose parameters are shown in Table 3) with a constant insolation (800 W/m²) are given in Table 4. In this table the decreasing percent of the efficiency and output power for different values of temperature (between 300 and 310 K) is specified. The results show that for each unit increasing in the ambient temperature (300 K temperature is considered as a reference), the output power and efficiency are reduced almost one percent.

An important issue is that the ambient temperature is influenced by the solar insolation; however, it depends on other factors like the ground reflectivity. Usually places with the high insolation have the higher ambient temperature, but it is necessary to investigate the insolation effect compared with the ambient temperature effect. In this part, first the qualitative effect of solar insolation on the performance of solar chimney is investigated and next we try to distinguish which of the two parameters including the ambient temperature and insolation is more important. By using the developed model, for a power plant (whose parameters are given in Table 2), the insolation effect is studied for a constant ambient temperature (308 K) and a range of insolation between 600 and 1000 W/m². Figure 6 shows that increasing of the solar insolation has a positive effect on the obtained power of the plant and Figure 7 shows that the insolation doesn’t have any effect on the efficiency of the solar chimney power plant. According to the results that have been published by some researchers, increasing the output power by increasing the solar insolation is more than its reduction by increasing the ambient temperature [22, 24, 25].

Now, by determining the effect of the solar insolation and the ambient temperature on the performance of solar chimney power plants, the environmental conditions which are suitable to improve the efficiency of plants can be identified. The areas having a high amount of solar insolation and lower ambient temperature are more suitable for the solar chimney power plants. Generally speaking, to select the appropriate area for solar chimney power plants, various parameters are included (e.g. having high solar insolation, available vacant land, geographical location) but here by using the obtained results, the perspective of the ambient temperature and insolation can be investigated for the solar chimney power plants.

Table 3. Sizes of the solar chimney power plant to determine the ambient temperature effect

| Parameter               | Size  | Unit |
|-------------------------|-------|------|
| Chimney height          | 1000  | m    |
| Chimney diameter        | 40    | m    |
| Collector diameter      | 5600  | m    |
| Average height of the collector | 4    | m    |

Table 4. Effect of the ambient temperature on the performance of solar chimney power plants

| Ambient temperature [K] | Kinetic power [MW] | Decreasing percent | Efficiency | Decreasing percent |
|-------------------------|--------------------|--------------------|------------|--------------------|
| 300                     | 221                | 0                  | 1.122      | 0                  |
| 301                     | 218.8              | 0.995              | 1.110      | 1.07               |
| 302                     | 216.6              | 1.99               | 1.099      | 2.05               |
| 303                     | 214.4              | 2.99               | 1.088      | 3.03               |
| 304                     | 212.3              | 3.94               | 1.077      | 4.01               |
| 305                     | 210.2              | 4.89               | 1.067      | 4.90               |
| 306                     | 208.2              | 5.79               | 1.057      | 5.79               |
| 307                     | 206.2              | 6.70               | 1.046      | 6.70               |
| 308                     | 204.2              | 7.60               | 1.036      | 7.60               |
| 309                     | 202.3              | 8.46               | 1.027      | 8.46               |
| 310                     | 200.4              | 9.32               | 1.017      | 9.32               |

Figure 6. Effect of the solar insolation on the generated power.
impact of ambient temperature can be observed. For example, the environmental and geographical information of several cities in the central and southern parts of Iran which are eligible for solar chimney power plants are used [25].

By using the analytical model, the power output of solar chimney power plants (with the parameters given in Table 2) is calculated for each city, and the results are shown in Table 5. The obtained results show that the power output of the plant in Jahrom and Iranshahr are approximately equal while the annual insolation of Iranshahr is less than Jahrom; that is because of the lower ambient temperature of Jahrom. This case is also true for KhorramAbad and Tabas cities. By comparison between Zanjan and Semnan cities, it is also shown that despite the higher insolation of Zanjan, the generation power of Zanjan is more than Semnan and close to the plant in Tehran. This phenomenon is because of the lower ambient temperature in Zanjan.

### Table 5. Power output for the different regions of Iran with different ambient temperatures and insolation, based on the Manzanares data

| Region    | Output power [KW] |
|-----------|-------------------|
| Bam       | 27.01             |
| Tabas     | 24.71             |
| Jahrom    | 27.21             |
| Zabol     | 26.60             |
| Dashtestan| 26.01             |
| Iranshahr | 27.24             |
| KhorramAbad| 24.50            |
| Sabzevar  | 22.58             |
| Varamin   | 23.36             |
| Yazd      | 25.37             |
| Tehran    | 23.46             |
| Zanjan    | 23.19             |
| Semnan    | 22.98             |

According to the data, the dimensionless variable constant is calculated by using the experimental results and also the dimensionless variable is used to investigate the performance of the solar chimney power plant.

### 5.2 Results of the dimensional analysis

In this part, the amount of the dimensionless variable constant is calculated by using the experimental results and also the dimensionless variable is used to investigate the performance of the solar chimney power plant.

#### 5.2.1 Experimental calculation of dimensionless variable

According to the dimensionless variable obtained in the analytical method (Section 4) and using the experimental pilot data, the dimensionless number is found experimentally. For this purpose, the experimental data are sorted. The results in the mid-day when the solar chimney has more stable performance are separated and averaged. The values are given in Table 6.

According to the data, the dimensionless variable constant is calculated for the pilot. For these data, the numerator or the kinetic output power is equal to 1.357 and the denominator which expresses the power produced by the buoyancy of the airflow is equal to 7.533. Therefore, the dimensionless variable would be: \( \pi = 0.1801 \).

Figure 8 shows the dimensionless variable at different hours for the selected period (09:30 to 14:30). By fitting a line to these data, the dimensionless variable is obtained equal to the previous value.

The dimensionless variable for the maximum solar radiation using the data which corresponds to the maximum value (Table 7) is calculated as \( \pi = 0.1802 \).
The value of this dimensionless variable is calculated for the Manzanares plant in Spain. The size of the plant and the measured data are given in Table 2 and Table 8, respectively. With these data, the dimensionless variable is equal to $\pi = 0.1615$.

As can be seen, the variable of the pilot in this study and the resulting variable of the Manzanares are very close to each other. The lower variable of Manzanares plant can be due to the efficiency of the turbine and the incomplete geometric similarity with the pilot in this research. In general, the dimensionless variable obtained from this study can be a proper equation for predicting the performance of solar chimney power plants.

The correction factor obtained in this study is less than the theoretical value (one), whose difference reason is justified with the following statements.

The dimensionless variable has been obtained in the case of assuming that all of the solar radiation is absorbed by the collector. In other words, to obtain the dimensionless variable, the efficiency of the collector is not considered. In general, the collector efficiency is low because the transmission coefficient of the roof and the absorption coefficient of the collector are both less than one. Also, a considerable amount of the absorbed energy by the collector’s bottom is wasted through conduction heat transfer to the ground, and some of this is reflected to the roof. The collector roof gives some of the taken energy to the air beneath the collector, and the rest is lost through convection and radiation heat transfer to the sky and the chimney walls. The collector efficiency is defined by the amount of the solar radiation on the collector which is absorbed by the air flow.

$$\eta_{coll} = \frac{m c_p \Delta T_{coll}}{G \times A_{coll}}$$  \hspace{1cm} (40)

According to the above equation, the efficiency of the pilot collector in this study is about 0.28 and the efficiency of the Manzanares plant collector is 0.32 [36].

Another reason for this difference is related to the velocity of the airflow at the base of the chimney. In the equations that lead to identifying the parameters which effect the performance of the solar chimney power plants, the velocity which is used for the amount of the experimental dimensionless variable is the velocity at the center of the chimney inlet. In fact, the average value of the velocity profile at the inlet of the chimney should be used, which was not possible to be reported due to the measurement equipment. Also, the effect of the local and the frictional pressure drops in the system were not considered, while the pressure drops effects on the measured velocity in the pilot.

### 5.2.2 Performance evaluation using the dimensional analysis

After finding a dimensionless variable for the system, this variable can be used for the larger-scale power plants to predict...
their performance. In this section, by using the obtained dimensionless variable model and the geometric similarity between the model and the experimental pilot, the effects of the plant size and the solar insolation on the performance of the solar chimney are studied.

The changes of the kinetic power of the airflow through the chimney versus the geometric scale are shown in Figure 9. Here, ‘r’ is the ratio of the dimensions of the model to the pilot plant and the solar insolation and the ambient temperature is considered as 1000 W/m² and 310 K, respectively.

According to Figure 9, the equation between the output power and the plant sizes is a third-order polynomial that shows the high effect of the size on the output power. So, the polynomial approximation equation would be as follows:

\[ P_{SCPP}[W] = 2.1 \times r^3 \]  \hspace{1cm} (41)

For the evaluation of the insolation effect on the performance of solar chimney using the dimensionless number, a plant with 100 times scale to the pilot is considered. Figure 10 shows the changes of kinetic energy (the output power) as a function of the solar insolation.

It is clear from Figure 10 that the output power of the solar chimney power plant has a linear relationship with the solar insolation (Equation 42):

\[ P_{SCPP}[W] = 2.1 \times G \left( \frac{W}{m^2} \right) \]  \hspace{1cm} (42)

It should be noted that in the larger-scale plants, it is possible to increase the diameter of the collector to a greater extent and consequently, achieve more power. For example, for a plant which was designed with a chimney height of 1000 meters and 5600 meters collector diameter in Australia [37], a power of 140 MW may be achieved by using the dimensionless variable of this research, but it does not have a high accuracy due to the incomplete geometric similarity.

6 CONCLUSION

In order to investigate the ambient temperature effect and dimensional analysis of solar chimney, a pilot experimental setup was constructed. A mathematical model for SCPP was developed and validated with the experimental data of the pilot. The results show that:

- The air flow velocity reaches at the maximum point of about 2.2 m/s for both the pilot plant and the model at the time between 11 a.m. and 1 p.m.
- The solar insolation has a direct effect on the generated power while it has no effect on the chimney efficiency.
- The areas with a high amount of solar radiation and lower ambient temperature are more suitable for the solar chimney power generation.
- By using the Buckingham pi theory, a dimensionless variable is achieved, and its value is correlated using the experimental data. The amount of this dimensionless variable is 0.18 for the pilot and 0.16 for the Manzanares power plant.
- Investigation of the system performance using this dimensionless variable shows that the output power increases with a third-order polynomial relation through increasing the size of the SCPP, and with a linear correlation through increasing solar radiation.
- When the size of the system and solar radiation increase, the output power of the solar chimney rises.
- At the maximum insolation of 695 W/m² and the collector input temperature of 300.6 K, the collector output

\[ P_{scpp}=1.99955E-11+1.24056E-12r-1.80897E-14r^2+2.1079r^3 \]
temperature, and the air flow velocity were 314.8 K and 2.2 m/s, respectively.

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