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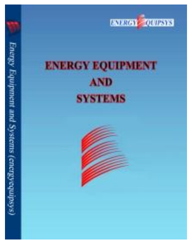

Numerical simulation of a solar chimney power plant in the southern region of Iran

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ABSTRACT

Three-dimensional numerical simulations are performed to investigate the effects of pressure drop across the turbine and solar radiance on the performance of a solar chimney power plant (SCPP). The SCPP system expected to provide electric power to a city is located in southern region of Iran (city of Lamerd, Fars province). Its dimensions are similar to the Manzanares prototype (built in Spain, 1970s). The results demonstrated that the SCPP can provide up to 40–200 KW of power, depending on the season. It was found that the turbine pressure drop and the solar radiation had significant effects on the first and second law efficiencies.

Keywords: Solar Chimney Power Plant, Turbine Pressure Drop, Performance Analysis, South of Iran, Output Power.

1. Introduction

Solar energy is a clean and renewable energy source, which is of interest to many researchers. A solar chimney power plant (SCPP) system is one of the practical applications of solar energy. Figure 1 shows a typical SCPP system, with three components: a solar collector to collect solar radiation, a wind turbine to generate electric power, and a chimney. The solar chimney concept was originally proposed by an engineer from Spain, Isidoro Cabanyes, in 1903. The prototype solar chimney power plant was built in Manzanares, Spain in the late 1970s [1]. The height of the chimney, the diameter of the chimney, and the radius of the collector were about 195 m, 107 m, and 5 m respectively. Focusing on the Manzanares prototype SCPP, Haff et al. [2] analyzed the energy balance, system costs, and the energy generation of an SCPP system. Considerable investigations have been conducted to demonstrate its effectiveness ([3], [4], and [5]). These investigations showed that solar energy has a vital role in the design and construction of an SCPP system. Larbi et al. [6] analyzed its performance in Adrar, the southern area of Algeria. They reported that the SCPP system could provide up to 140 to 200 KW of electricity during a year. They revealed the effects of solar radiation, the ambient temperature, the chimney height, and the collector diameter on electricity production. Sangi et al. [7] examined a numerical simulation of an SCPP system, based on the Manzanares prototype SCPP, and modeled the system, using the standard k-ε turbulence model. They showed that the numerical results are in good agreement with the experimental data. Li et al. [8] investigated the effects of the collector diameter and the chimney height on the power output of an SCPP system, theoretically. The authors demonstrated that there is an optimum magnitude for the collector diameter to achieve

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the maximum power output, but there is no limitation for the height of the chimney tower. Xu et al. [9] also examined numerical simulations on the airflow, heat transfer, and power output characteristics of an SCPP system, similar to the Manzanares prototype. They revealed that energy loss in the system increases with an increasing mass flow rate of the airflow. Energy and exergy analysis of an SCPP system were performed by Maia et al. [10]. They showed that as the dead state temperature decreases, the exergy losses decrease, while the thermal efficiency increases. The geometrical effect on the airflow behavior, through a solar chimney, was investigated by Lebbi et al. [11]. They revealed that the geometry of the chimney tower has a vital role on the performance of an SCPP system, due to an increase or decrease in the mass flow rate. Lee et al. [12] identified the optimal configuration of a solar chimney, experimentally. They used an organic Rankine cycle to generate electricity and demonstrated that the maximum outlet air temperature is approximately 125°C. The influence of air humidity on the performance of an SCPP system is studied numerically by Sudprasert et al. [13]. They found that the overall air temperature in the case of moist air is higher than that in the case of dry air.

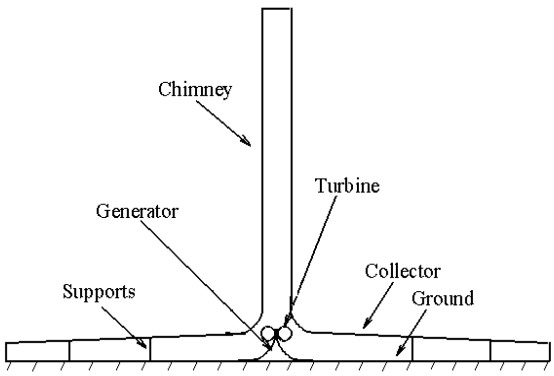

Fig. 1. A schematic representation of an SCPP system

Iran is close to the equator and receives a lot of solar energy. The annual average radiation is about 1825 kWh/m², which is about 2500 times the power consumed in the country. Iran's southern regions receive about 2200 kWh/m² per year; therefore, the use of SCPP in these areas is justified. In the present study, the performance of an SCPP system in Lamerd city, located in the southern part of Iran, is investigated numerically. The dimensions of the Spanish prototype [1] were selected. The effects of the turbine pressure drop and solar radiation on the upward velocity and outlet temperature are studied for different months. Moreover, the monthly average performance of the SCPP system is analyzed under different conditions, based on the first and the second law efficiencies.

2. Governing equations

The governing equations for air flow through the system, including continuity equation, Navier-Stokes equations, and energy equation can be written as follows:

Continuity equation:

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x_i}(\rho u_i)=0 \qquad (1)$$

Navier-Stokes equations:

$$\frac{\partial}{\partial t}(\rho u_i)+\frac{\partial}{\partial x_j}(\rho u_i u_j)=-\frac{\partial p}{\partial x_i}+\frac{\partial \tau_{ij}}{\partial x_j}+\rho g_i \qquad (2)$$

Energy equation:

$$\frac{\partial}{\partial t}\left(pc_pT\right)+\frac{\partial}{\partial x_i}\left(pc_pu_jT\right)=\frac{\partial}{\partial x_i}\left(k\frac{\partial T}{\partial x_i}\right)+\tau_{ij}\frac{\partial u_i}{\partial x_i}+ \beta T\left(\frac{\partial T}{\partial t}+u_i\frac{\partial p}{\partial x_i}\right) \qquad (3)$$

where ρ is the density, u is the velocity, p is the pressure, and T is the temperature. B denotes the thermal expansion coefficient and τ is the stress tensor.

For the natural convection heat transfer, the Rayleigh number, $Ra = g\beta\Delta TH^3/(\alpha\nu)$, is used to determine the fluid flow regime. Here, H is the height of the collector, α is the thermal diffusion coefficient, and υ is the kinematic viscosity. It is found that the Rayleigh number for the present case is higher than the critical value, 10^9 , which means that the fluid flow regime in the system is turbulent. Hence, the standard κ-ε model is used to simulate the turbulent air flow:

$$\frac{\partial}{\partial t}(pk)+\frac{\partial}{\partial x_i}(pku_i)=\left[\left(\mu+\frac{\mu_i}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right]+G_k-p\varepsilon \qquad (4)$$

$$\frac{\partial}{\partial t}(p\varepsilon)+\frac{\partial}{\partial x_i}(p\varepsilon u_i)=\frac{\partial}{\partial x_i}\left[\left(\mu+\frac{\mu_i}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_i}\right]+ \frac{\varepsilon}{k}\left(C_{1\varepsilon}G_k-C_{2\varepsilon}\varepsilon\right) \qquad (5)$$

where G_K is the generation of turbulence kinetic energy, due to the mean velocity gradient. Turbulent viscosity is defined as $\mu_t = C_\mu \rho k^2 / \varepsilon$. The constants for the above equations are as follows:

$C_{1\varepsilon} = 1.44$, $C_{2\varepsilon} = 1.92$, $C_\mu = 0.09$, , $\sigma_\varepsilon = 1.3$

3. Numerical method

The governing equations for the turbulent air flow in the current SCPP system are solved by the finite volume method, using ANSYS FLUENT 15. Convection terms are discretized, using the upwind second order scheme. Also, an algorithm called SIMPLEC is used for coupling the velocity and pressure fields. Numerical simulations are performed, based on the following assumptions: 1) Environmental conditions are constant. 2) Three-dimensional simulations are done upon neglecting the effects of the altitude angle of the sun. 3) The chimney wall is assumed to be isolated. 4) The Boussinesq approximation is assumed to be valid for the density variation of the air. 5) Collector surface reflection coefficient is equal to 0.8. 6) A reverse fan is considered as the turbine.

4. Results and discussions

4.1. validation

To validate the numerical method used for our simulations, the current results are compared with the numerical results of Xu et al. [9]. Fig. 2 shows the averaged velocity of the chimney outlet, as a function of the turbine pressure drop for a solar radiation of 600 w/m². This figure demonstrates that the exit velocity decreases with an increase in the turbine pressure drop. It is observed that our results are in good agreement with the results of Xu et al. [9].

4.2. Effect of solar radiation

The effects of solar radiation and pressure drop across the turbine, on the temperature, have been shown in Fig. 3, for four seasons. It should be noted that we used the average amount of solar radiation in each season. It is observed that the chimney outlet temperature increases as the turbine pressure drop increases. This is due to an increase in the turbine pressure drop, which further decreases the air mass flow rate, through the system. Therefore, the available time for heat transfer from the collector surface to the air flow, increases. Fig. 4 confirms that the chimney outlet velocity decreases as the turbine pressure drop increases. It is notable that the air flow velocity and air temperature of the chimney outlet increase with the ambient temperature (solar radiation) for constant values of the turbine pressure drop.

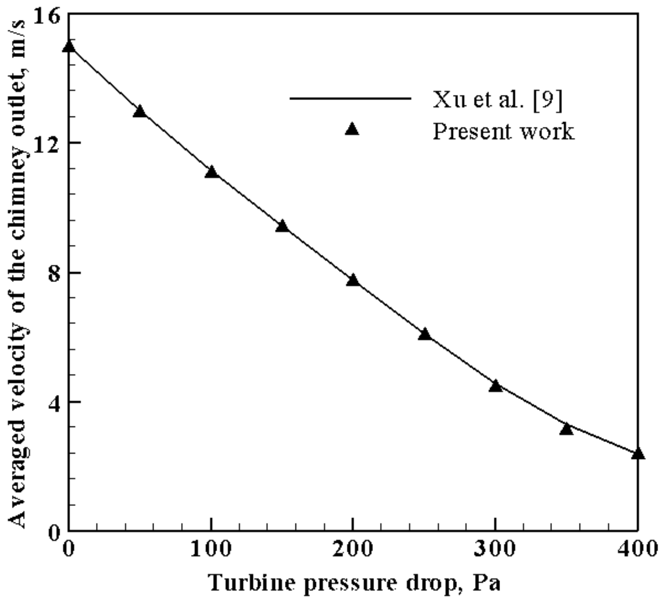

Fig. 2. The averaged velocity of the chimney outlet versus the turbine pressure drop for a solar radiation of 600 w/m².

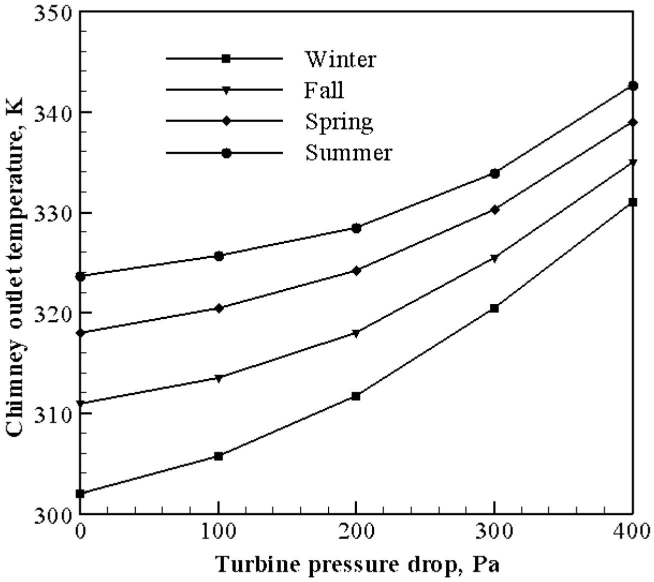

Fig. 3. The temperature of the chimney outlet versus turbine pressure drop for different seasons.

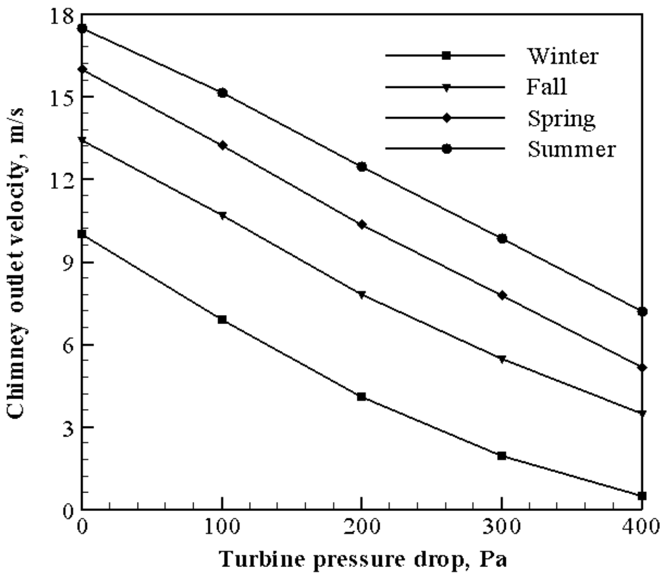

Fig. 4. The velocity of the chimney outlet versus turbine pressure drop for different seasons.

The power generated by the turbine is calculated by the following equation:

$$W_t = \eta_t.\Delta p_t.V_{chi}.A_{chi} \quad (6)$$

Where, η_t represents the efficiency of the turbine, V_{chi} is the air velocity in the chimney outlet, and A_{chi} is the area of the chimney outlet. It is assumed that the turbine efficiency is equal to 80%, which is less than the optimized data. The area of the chimney outlet is about 78.53 m^2, based on the Manzanares prototype dimensions. Fig. 5 shows the turbine output power as a function of the turbine pressure drop for different seasons. At a constant turbine pressure drop, as the solar radiation increases, the air volume flow rate increases due to the buoyancy force, resulting in an increase in the output power of the system. On the other hand, it is observed that there is an optimum output power in each season. This is due to the fact that low a turbine pressure drop has more significant effects, as the volume flow rate (the air flow velocity) decreases. The optimal values of the pressure drop across the turbine are 185, 300, 360, and about 400 PA for different seasons. It is notable that as the solar radiation increases (for example, in the summer season), the optimal value of the turbine pressure drop increases.

4.3.First and second law analysis

To investigate the thermal performance of the SCPP system, it is necessary to calculate its thermal efficiency. Guo et al. [14] expressed the overall efficiency of an SCPP system by ignoring the aerodynamic losses:

$$\eta_o = C_1.C_2.V_{chi}.\Delta T - \frac{1}{2}C_1V_{chi}^3 \quad (7)$$

Where, $C_1 = \rho A_{chi}/(A_{coll}G)$ and $C_2 = gH/T_0$. A_{coll} represent the area of the collector and G is the global radiation. Here, T_0 is the temperature of the dead state as a datum value.

The overall efficiency of the SCPP system was calculated, using the current simulations, as shown in Fig. 6. As we expected, the solar radiation has a significant effect on the overall efficiency and the pressure drop across the turbine. The figure shows that the maximal overall efficiency occurs at an optimal amount of the turbine pressure drop in each case. It should be noted that the overall efficiency of the Spanish prototype was less than 0.2% under different conditions. The overall efficiency of the SCPP system, under current solar radiations, is slightly more than that of the Manzanares prototype, especially for higher solar radiations, due to neglecting the flow losses.

To determine the SCCP second law efficiency, we need to define the availability:

$$\psi = h - T_0 s \quad (8)$$

where, h is the enthalpy and s is the entropy.
The second law efficiency or the rational efficiency is defined as follows:

$$\eta_{\text{II}} = \frac{W_a}{\psi_i - \psi_o} \quad (9)$$

Here, W_a is the actual network and $\psi_i - \psi_o$ represents the maximum network that can be achieved.

Figure 7 shows the effects of solar radiation and the turbine pressure drop on the second law efficiency. As solar radiation increases, the rational efficiency increases. It is indicated that the maximum useful work available from the cold flow is less than that available from the hot stream. In other words, the irreversibility or the exergy loss reduces with an increase in the temperature at which the heat is transferred. Moreover, it is observed that the second law efficiency does not have an optimal value. As the turbine pressure drop increases, the rational efficiency increases.

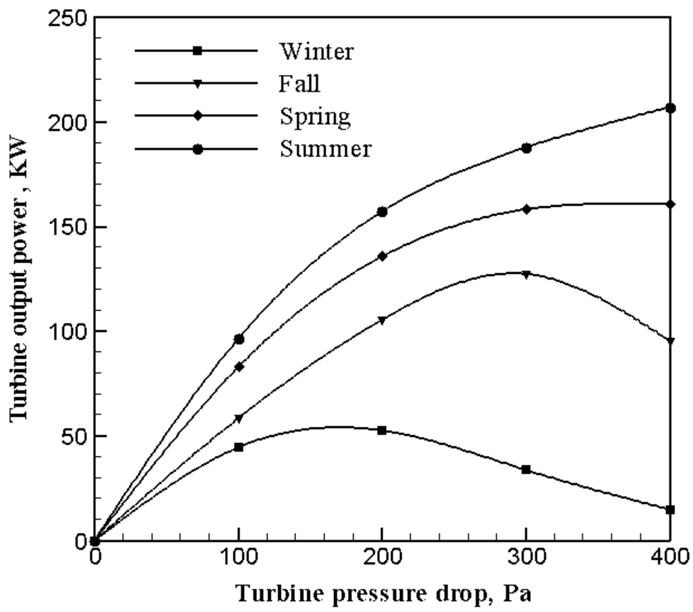

Fig. 5. Turbine output power versus turbine pressure drop for different seasons.

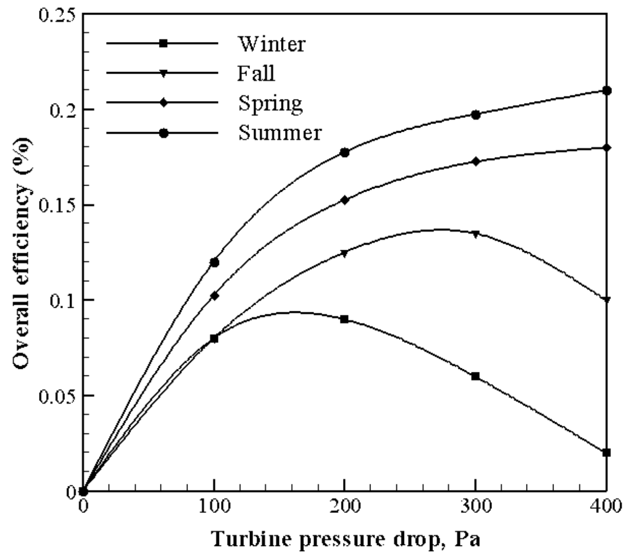

Fig. 6. Overall efficiency versus turbine pressure drop for different seasons.

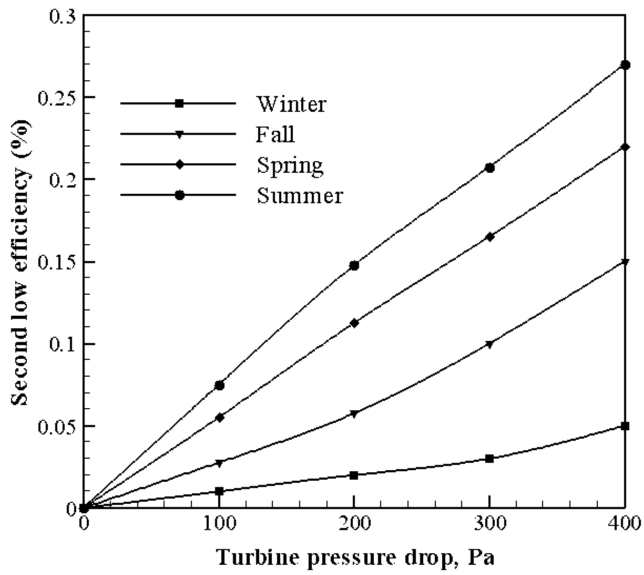

Fig. 7. Second law efficiency versus turbine pressure drop for different seasons

5. Conclusions

In the present work, the performance of an SCPP system in the southern region of Iran has been studied, using three-dimensional simulations. The SCPP system expected to provide electric power to a city, located in southern region of Iran. Its dimensions are similar to the Manzanares prototype. The results demonstrated that the SCPP system can provide up to 40–200 KW of power, depending on the season. It was found that the temperature and the velocity of the chimney outlet are affected by the pressure drop and solar radiation, significantly. As the ambient temperature (or solar radiance) increases, the outlet temperature and the outlet velocity increase at a constant turbine pressure drop. Our results revealed that there is an optimal value of the turbine output power and the overall efficiency, under different amounts of turbine pressure drop. However, the second law efficiency increases with an increase in the turbine pressure drop.

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