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Optimization of effective parameters on solar updraft tower to achieve potential maximum power output: A sensitivity analysis and numerical simulation

Kamel Milani Shirvan [a], Soroush Mirzakhanlari [b], Mojtaba Mamourian [a], Soteris A. Kalogirou [c,*]

[a] Department of Mechanical Engineering, Ferdowsi University of Mashhad, Mashhad, Iran
[b] Young Researchers and Elite Club, Qazvin Branch, Islamic Azad University, Qazvin, Iran
[c] Cyprus University of Technology, Department of Mechanical Engineering and Materials Sciences and Engineering, Limassol, Cyprus

HIGHLIGHTS

- The performance of solar updraft power plant is numerical simulated.
- A sensitivity analysis is performed to obtain the potential maximum power output.
- The best angle of collector roof is zero.
- The power output to collector gap, reduces as gap, tower diameter and collector angle increase.

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ABSTRACT

In this paper, an axisymmetric 2-D numerical simulation and sensitivity analysis are carried out to obtain the potential maximum power output in a solar updraft tower power plant. The geometrical dimensions of the physical model of the studied solar updraft tower are based on the prototype installed at Manzanares. The sensitivity analysis is performed by utilizing the Response Surface Methodology. The effects of various parameters on the maximum potential power output of the solar updraft tower power plant are investigated and include the entrance gap of collector ($2\ m \le CG \le 6\ m$), tower diameter ($5\ m \le DT \le 10\ m$), tower height ($200\ m \le HT \le 220\ m$) and collector roof inclination ($0° \le \theta \le 5°$). It is found that the potential maximum power output enhances with the tower diameter and height, and reduces as the entrance gap of collector is increased. Additionally, the sensitivity analysis revealed that the sensitivity of the potential maximum power output to (CG), reduces as (CG), (DT) and (θ) are increased. Moreover, its sensitivity to (DT) reduces as (DT), (θ) and (HT) are increased but increases with (CG). It is also found that to maximize the potential maximum power output, the effective parameters must have the values of CG = 2 m, DT = 10 m, HT = 220 m and $\theta = 0°$.

1. Introduction

The increase of global energy demand has led to a considerable growth in the depletion rate of the fossil fuel sources and while these sources are environmental damaging and nonrenewable, finding a technology to exploit cleaner and renewable energy sources has become a subject of interest for many researchers such as Kalogirou et al. [1], Liu et al. [2], Zare [3], Ashuri et al. [4] and Moreno et al. [5]. Among these clean and renewable sources, solar energy is the most plentiful, and can provide a significant amount of energy for different energy consuming areas [6]. One of the possible options for utilizing solar energy effectively is the solar updraft tower, which can convert the solar thermal energy into electricity and was first proposed by Schaich in 1978 [7]. It is normally equipped with three components; a solar collector and the ground under it, covered by black tubes filled with water to absorb and store the solar radiant energy; a tall cylindrical structure called tower in the center of the collector; and a turbine generator/s at the base of the tower [8,9]. It should be noted that earlier on the tem "solar chimney" was used, subsequently modified to "solar updraft tower". Although the earlier expression is used in most of the papers reviewed in this section the new terminology is shown here as adopted by the scientific community. The benefits

* Corresponding author at: P.O. Box 50329, Limassol, Cyprus.
E-mail address: soteris.kalogirou@cut.ac.cy (S.A. Kalogirou).

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of this relatively new system are that there is no fossil fuel consumed. No requirement for cooling water and minimum maintenance requirement [10–15].

In recent years, several models and methods have been presented by various researchers to study the performance, efficiency, electrical power and thermal and dynamic processes of the solar updraft tower and its parts. Lee et al. [16] have carried out an experimental investigation on the effects of several effective parameters on the solar updraft tower. They concluded that the highest outlet temperature of air in solar updraft tower is 125 °C and heat collecting efficiency is about 65%. An investigation of a coupled geothermal cooling system with an earth tube and a solar collector enhanced solar updraft tower has been performed by Yu et al. [17]. They found that the airflow to the system increases during the daytime, generated by using an enhanced solar collector solar updraft tower due to the stronger solar intensity. Liu and Li [18] investigated the thermal performance of a solar updraft tower with and without the use phase change material (PCM) experimentally. They concluded that a solar updraft tower with PCM has less air flow during charging period but more during discharging period in comparison with the one without PCM. Ming et al. [19] estimated the temperature and pressure fields of the air in a solar updraft tower power plant. Fei et al. [20] estimated the design characteristics of a combined geothermal– solar updraft tower. A simulation on an inclined solar updraft tower power plant has also been performed by Fei et al. [21]. Li and Liu [22] also performed an experimental investigation of the thermal performance of a solar updraft tower combined with phase change material (PCM). The results revealed that, the absorber surface temperature changes, for the three different heat fluxes investigated, and they are the same during the phase change transition period; however, the PCM does not fully melt in the cases of 500 W/m^2 and 600 W/m^2. A simplified analytical method for evaluating the optimal ratio of turbine pressure drop in solar updraft tower has been presented by Nizetic and Klarin [23]. The results showed that the turbine pressure drop ratios are in the range of 0.8–0.9. Ghalamchi et al. [24] have presented an experimental investigation on optimizing the thermal performance of a small size solar updraft tower by considering different dimensional parameters. They found that the solar updraft tower plant with collector entrance distance of 6 cm, updraft tower diameter and height of 10 cm and 3 m, respectively, has the best performance. An experimental and numerical investigation on predicting a solar updraft tower performance under varying geometrical features has been carried out by Imran et al. [25]. The optimum updraft tower inclination angle to obtain the maximum rate of ventilation is found to be 60°. Guo et al. [26] have studied a 3-D numerical simulation of solar updraft tower by considering the solar radiation, solar load, and turbine models. They also found that the power output of the solar updraft tower plant is insensitive to ambient temperature. A mathematical investigation on solar updraft tower has been presented by Hamdan [27] using an updraft tower discrete model. He simplified the analytical model by a constant density assumption, but this simplification resulted in over prediction of the power generation. Additionally, in this paper, the tower height, collector radius, solar irradiance, and turbine head are considered as the necessary parameters for solar updraft tower design. Ming et al. [28] carried out a numerical investigation to analyze the characteristics of flow and heat transfer of the solar updraft tower power plant system which had an energy storage layer. Experimental and numerical investigations have been carried out on a novel solar updraft tower by Shahreza and Imani [29]. They used intensifiers to enhance the heat flux on the system with a detailed rotational pattern study. Wibing et al. [30] have presented a new model to investigate costs and advantages of reinforced concrete solar updraft towers. Fasel et al. [31] carried out a numerical study on solar updraft towers. In this paper, they have presented in detail a particular case and considered the scale comparisons and thermal instabilities evaluations. Other interesting investigations and simulations have been presented by Kasaeian et al. [32], Patel et al. [33], DeBlois et al. [34], Gholamalizadeh and Mansouri [35], Hu et al. [36], Zhou et al. [37], Koonsrisuk and Chitsomboon [38,39], Li et al. [40], Zhou et al. [41,42], Li [43], Bernards and Zhou [44] and Xu at al. [45].

According to the literature review and to the best knowledge of the authors, despite the importance of the power output in solar updraft towers, a numerical investigation and sensitivity analysis of effective parameters on power output in a solar updraft tower has not yet been considered. Therefore, a sensitivity analysis is needed to evaluate the effects of critical parameters, including entrance gap of collector, tower diameter, tower height and inclination of collector on the potential maximum power output of a solar updraft tower. In this paper the sensitivity analysis of these parameters is done using the Response Surface Methodology (RSM). Current investigation aims to obtain the optimal conditions to enhance the potential maximum power output of a solar updraft tower in order to provide a useful guideline for researchers in this field. In general, the motivation in this article is based on the investigation of optimal conditions and also sensitivity analysis of the potential maximum power output, using the Finite Volume Method (FVM) and RSM models.

2. Mathematical formulation

2.1. Problem statement

A typical solar updraft tower consists of a solar collector and a tower which increases the energy level of the air due to the greenhouse effect. The collector which is a cavity with one inlet and one outlet receives solar energy and converts it to thermal energy by increasing the temperature of the air. The tower converts this thermal energy to kinetic energy and moves the warm air toward its exit due to density reduction, buoyancy effect (conversion of the thermal energy to kinetic energy) and the taper shape of the tower (chimney) which increases the velocity of the air that move toward the center of the collector [8,9]. Finally, the warm air escapes through the tower at the base of which a turbine is used to convert the speed of the air into electricity. The schematic diagram and the boundary conditions considered for the solar updraft tower studied is presented in Fig. 1. It must also be noted that the geometrical dimensions of the physical model of studied solar updraft tower are based on the Manzanares prototype.

To formulate the model some assumptions are made as follows:

- Wind effect in the ambient environment is not considered.
- The ground surface boundary condition is assumed to be no-slip with constant heat flux. Additionally, the heat flux from the ground surface is 800 W/m^2, assuming constant heat flux from the sun absorbed by the ground.
- The emissivity of the collector roof and absorber are 0.85 and 0.90, respectively.
- Collector diameter (CD) is considered to be 122 m.
- The convective heat transfer coefficient is assumed to be 5 W/m^2 K.
- The properties of the fluid are assumed to be constant in all formulations, except for the term of the buoyancy formulation, and to present negligible compressibility effects. Thermal conductivity, dynamic viscosity and specific heat for the working fluid are 0.0263 W/m K, 1.875×10^{-5} m^2/s and 1.007×10^3 J/kg K, respectively. Additionally, the fluid density is considered to change linearly with temperature according to the following empirical relationship: