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Simulation and optimization of geometric parameters of a solar chimney in Tehran

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ABSTRACT

An analytical and numerical study for geometrical optimizing of a solar chimney prototype at University of Tehran was performed. A fundamental mathematical model that describes the flow was presented, and the performance evaluation of solar chimney was simulated with operational and geometric configurations. The numerical predictions were validated through comparison with the experimental data of the solar chimney pilot which was constructed in height of 2 m and collector radius of 3 m. The results show that, the collector inlet of 6 cm, the chimney height of 3 m, and the chimney diameter of 10 cm were the best alternatives for the constructed solar chimney pilot. It is found that the velocity magnitude can be raised to 4–25% in different cases; also the analysis indicated that the height and diameter of the chimney are the most important physical variables for solar chimney design.

1. Introduction

The primarily concept of the solar chimney power technology was introduced by Hanns Gunther in 1931 [1]. The first prototype consisted of a chimney height of 195 m and collector with a radius of 120 m was constructed in Manzanares in 1982. Haaf et al. and Schlaich [2–4] investigated the initial studies and presented the results of Manzanares pilot including energy balance, design criteria, and cost analysis. Pasumarthi and Sherif [5,6] and Padki and Sherif [7] evaluated some of the earliest studies on the thermo-fluid and developed a mathematical model of the environment and geometry effects of a solar chimney. Yan et al. [8] proposed numerous analytical investigations to predict the flow in the solar chimney power plant (SCPP). After that, more and more research and experimental studies have been carried out around this subject. The overall performance analyses and turbine efficiency of SCPP were conducted by [9–11]. Bernardes et al. [12] developed a numerical model of a SCPP and compared results with experimental data from the pilot plant at Manzanares. Zhou et al. [13] evaluated the optimal chimney height for maximum efficiency for Manzanares prototype. The results showed that, the optimal chimney height and the maximum power output of Manzanares were 615 m and 102.2 kW, respectively.

Bilgen and Rheault [14] proposed a system of solar chimney for power generation at high latitudes and reported the performance of the system. Pretorius and Kröger [15] evaluated the governing heat transfer equations for SCPP. Theodor et al. [16] analyzed the ratio of turbine pressure drop to pressure potential for SCPP. Some dimensionless variables were presented by Koonsrisuk and Chitsomboonin [17] in a small-scale solar chimney. They used water and air as two fluids for the modeling study and showed that air is more suitable than water to be the working fluid in the solar chimney. In another work, they used their dimensional analysis with engineering intuition and combined eight primitive variables into one dimensionless variable [18]. Fluri and Von Backström [19] proposed several layouts for a turbo generator, and also evaluated the performance of these layouts using analytical models and optimization techniques.

So far, some experimental studies have been carried out and several solar chimney pilots in different sizes were constructed [20–27]. In those researches, the influence of geometrical and climatic parameters on the solar chimney performance was evaluated and temperature distributions in whole system were reported. Fluri et al. [28] presented several cost models for large-scale solar chimney power plants. Petela [29] presented a thermodynamic modeling of solar chimney power plant using the concept of mechanical exergy.

Researchers carried out several studies on optimization of various parameters of solar chimney. Zhou et al. [30] carried out an analytical study of solar chimney performance and investigated

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Nomenclature

D	diameter (m)	Pr	Prndtle
h	convective heat transfer coefficient (W/m^2 K)	β	thermal expansion coefficient
$\dot{m}$	mass flow rate (kg/s)	σ	Prndtle number
P	pressure (Pa)	g	gravitational acceleration (m/s^2)
T	temperature (K)	H	height (m)
u	velocity in the radial direction (m/s)	x	horizontal coordinate, m
V	quantity of velocity vector (m/s)	y	vertical coordinate, m
v	velocity in the axial direction (m/s)		
ρ	density (kg/m^3)	*Subscripts*	
C_1	constant for the turbulence model	a	ambient
C_2	constant for the turbulence model	t	turbulent
C_μ	constant for the turbulence model	A	absorber
ϵ	epsilon	c	collector
k	turbulence kinetic energy	ch	chimney
κ	Karman constant	in	chimney inlet
I	initial turbulence intensity	f	fluid
G_k	generation of turbulence kinetic energy		
G_b	generation of turbulent kinetic energy that arises due to buoyancy		

the optimum combination of chimney and collector dimensions. In another work, Zhou et al. [31] presented a new concept for producing energy by integrating a solar collector with a mountain hollow. This system can save a great amount of construction materials for constructing a chimney structure and reduce the energy cost which is needed for commercial solar chimney thermal power plants.

Koonsrisuk et al. [32] evaluated the height to radius ratio for maximum mass flow rate of the solar chimney. Bernardes and Von Backstrom [33] presented the optimum ratio of turbine pressure drop to pressure potential. The results showed that the optimum ratio is between 0.67 and 0.97, and point to note that it is not constant during the whole day. Afriyie et al. [34] proposed a new system of chimney-dependent solar crop dryer and carried out the parametric studies. According to the results, the optimum inlet collector area to exit chimney area ratio for this set-up was around 4:1.

Chergui et al. [35] analyzed thermo-hydrodynamic parameters consist of the heat transfer process and the fluid flow in the collector under some operational conditions. Xu et al. [36] carried out numerical study on air flow, heat transfer and power output parameters of a SCPP. Cao et al. [37] designed a sloped solar chimney plant consisting of a chimney with the height of 252.2 m. The results showed this system has a better efficiency in spring and autumn. Ming et al. [38] proposed different mathematical models for the collector, the chimney and the energy storage layer and also, analyzed the effects of solar radiation on the energy storage layer. Panse et al. [39] introduced a new system which is called inclined solar chimney, also developed a mathematical model including the total energy balance.

Hamdan [40] presented a mathematical model for steady state airflow inside a SCPP using Bernoulli equation with buoyancy effect, and showed that the chimney height, the collector radius, the turbine head, and the solar irradiance are essential parameters for the design of solar chimneys. Fasel et al. [41] investigated numerically SCPPs using ANSYS Fluent. Their model was verified by considering a large range of scales with tower heights between 1 m and 1000 m. Koonsrisuk [42] carried out a comparison between the conventional SCPP and the sloped SCPP using second law analysis, and the results revealed that the sloped SCPP is thermodynamically better than conventional SCPP for some configurations. Afriye et al. [43] developed a simulation procedure describing the drying process within a chimney-dependent solar crop dryer. Patel et al. [44] worked on optimization of the geometry of the major SCPP components using a CFD software to improve the flow characteristics inside the SCPP. Zou et al. [45] proposed an optimization scheme for solar enhanced natural draft dry cooling tower design, also presented detailed cost model. Li et al. [46] analyzed the cost and benefit of a reinforced concrete SCPP, and showed that this system have very good application prospect.

In this study, a simple mathematical model including the flow details within the collector was presented. Next, the description of the constructed solar chimney and methodology of CFD models are expressed. Finally, the theoretical predictions from the models are discussed and compared with experimental results.

2. Governing equations

2.1. Fundamental equations

A typical solar chimney power plant consists of a solar collector and a chimney whose function is to increase the energy level of the air by greenhouse effect. The air flow is driven by the buoyancy effect due to the vertical column of hot air. Accordingly, the governing equations of axisymmetric mathematical model describe the movement of the flow. The properties of fluid are assumed to be constant in all formulations, except in the term of buoyancy formulation and negligible compressibility effects. The fluctuation of wind effects was neglected, therefore the time term was considered steady. The solar radiation is uniform vertical and, also radiation heat transfer among the walls of SCPP in the model was negligible. The basic governing equations are presented as followings:

Continuity equation:

$$\frac{1}{r}\frac{\partial}{\partial z}(r\rho u)+\frac{\partial}{\partial z}(\rho v)=0 \tag{1}$$

Navier–Stokes equations:

$$\frac{dp}{dr}=\frac{\partial}{\partial r}\left[2\mu\frac{\partial u}{\partial r}+\mu'\nabla\cdot\vec{v}\right]+\frac{\partial}{\partial z}\left[\mu\left(\frac{\partial u}{\partial z}+\frac{\partial v}{\partial r}\right)\right]+\frac{2\mu}{r}\left(\frac{\partial u}{\partial r}-\frac{v}{r}\right) \tag{2}$$