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An experimental study on the thermal performance of a solar chimney with different dimensional parameters

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ABSTRACT

For optimizing solar chimney power plant (SCPP) and also reaching to new experimental data, a pilot setup consisting of a chimney with 3 m height and 3 m collector diameter was constructed. Two main effective parameters including absorber material and geometric dimensions were analyzed using thermal and velocity data. In this paper, the main purpose is obtaining new experimental data in these new dimensions. The obtained data will be utilized in our future after studies for achieving a structural dimensional formulation of SCPPs. In fact, there is no comprehensive formula for achieving a precise relationship between the geometric parameters of the SCPPs. The dimension analyses show that the collector entrance distance of 6 cm has the best performance and the corresponding amounts of the chimney diameter and the chimney height are 10 cm and 3 m, respectively. Also, aluminum absorber has more heat transfer rate than iron one and the maximum fluid temperature difference between the collector and the ambient is 27 °C. The maximum air velocity of 1.7 m/s was recorded inside the chimney. In comparison to the chimney with 2 m height, this was about 55.3% higher.

1. Introduction

The concept of the solar chimney process was introduced by Hanns Gunther in 1931 [1] and according to those studies the first prototype consisted of a chimney height of 195 m was constructed in Manzanares in 1982. Haaf et al. and Schlaich [2,3,and4] investigated the Manzanares pilot. After that, many studies have been carried on this subject by scientists and researchers. Backstrom and Gannon [5] analyzed equations in terms of turbine flow for Solar Chimney Power Plant (SCPP).

For the purpose of doing experimental works and temperature measuring, several solar chimney pilots have been constructed around the world. Akbarzadeh et al. [6] proposed and analyzed experimentally the concept of combining a salinity gradient solar pond with a chimney to produce power. Zhou et al. [7] built solar chimney power setup consisted of an air collector 10 m in diameter and an 8 m tall chimney. Ghalamchi et al. [8] constructed a SCPP pilot with 3 m collector diameter and 2 m chimney height, and also evaluated the temperature distributions and air velocity in different conditions [9].

Zhou et al. [10] investigated an alternative method of heat transfer from seawater under the collector of a SCPP. Koonsrisuk et al. [11] proposed the constructal-theory for the geometry of a SCPP, and determined the ratio height/radius and maximum power. Bernardes and Backstrom [12] carried out numerical simulations to study the performance of SCPP and the volume flow and the turbine pressure drop are used as independent control variable. Sangi et al. [13] conducted a more detailed numerical analysis of a SCPP and presented a mathematical model based on the Navier–Stokes.

Also there are several studies on heat storage and control strategies of SCPP. Bernardes and Zhou [14] evaluated the SCPP performance to adverse solar radiance conditions. They modeled mathematically a solar chimney including irregular boundary conditions and proposed simple optimization procedure to calculate the maximal power. In addition, Bernardes and Zhou [15,16] analyzed the heat storage physical process in SCPP collector taking into account the transient heat transfer in different conditions and the results showed that water bags keep the soil warm and gypsum helps to break heat peaks. Bernardes and Weinrebe [17] presented study to estimate power output of SCPP as well as to

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Nomenclature

A	Area (m^2)
D	Diameter (m)
h	Convective heat transfer coefficient ($W/m^2.K$)
Cp	Specific heat capacity (J/kg.K)
$\dot{m}$	Mass flow rate (kg/s)
P	Pressure (Pa)
T	Temperature (K)
u	Velocity in the radial direction (m/s)
V	Quantity of velocity vector (m/s)
v	Velocity in the axial direction (m/s)
ρ	Density (kg/m^3)
g	Gravitational acceleration (m/s^2)
H	Height (m)
r	radius (m)
x	horizontal coordinate, m
y	vertical coordinate, m
z	axial coordinate, m
Subscripts	
a	Ambient
e	Earth
c	Collector
ch	Chimney
in	Inlet
o	Outlet
f	Fluid

examine the effect of various ambient conditions and structural dimensions on the performance output. Bernardes et al. [18] analyzed some available heat transfer coefficients applicable to SCPP collectors. Beerbaum and Weinrebe [19] analyzed the potential and the cost-effectiveness of centralized and decentralized SCPP in India. Nasirivatan et al. [20] investigated effect of the corona wind on the natural convection at absorber of a SCPP experimentally and their result indicated the amount of heat transfer increased more than 14.5%.

In this study, a simple description of the solar chimney pilot which is constructed was presented. Next, the variable effective parameters were introduced and finally, the experimental data in different conditions were rendered and discussed.

2. Model description (energy balance)

The technology of SCPPs is not new in power generation sector. Air is warmed by solar radiation under a low circular transparent collector open at the periphery. As hot air is lighter than cold air, it rises up the chimney tower. At last, the air flow out the tower through the chimney exit. In the other words, the radiation heats fluid of collector, which is then forced by buoyancy forces to move as a hot wind through special turbines to generate electrical energy. Thus solar radiation causes a constant updraft of fluid in the chimney.

According to this, the governing equations of physical 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.

Continuity equation:

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

Energy equation:

$$\rho c_p\left[\frac{1}{r}\frac{\partial}{\partial r}(rTu)+\frac{\partial}{\partial z}(Tv)\right]=\frac{1}{r}\frac{\partial}{\partial r}\left(rw\frac{\partial T}{\partial r}\right)+\frac{\partial}{\partial z}\left(w\frac{\partial T}{\partial z}\right)+\frac{1}{r}\frac{\partial}{\partial r}(rPu)+\frac{\partial}{\partial z}(Pv)\,\Phi \tag{2}$$

By assuming one-dimensional and steady flow, the mass flow rate is obtained as following:

$$\dot{m}=\rho A V_{in} \tag{3}$$

The following expression of the velocity for the fluid is obtained with substituting the flow area into Eq. (3):

$$V_{in}=-\frac{\dot{m}}{2\pi r H_c \rho} \tag{4}$$

The energy balance of the warm air inside the collector and chimney is expressed as:

$$\rho_{in}C_p V_{in}H_{ch}\frac{\partial T_f}{\partial r}=h_c\left(T_f-T_c\right)+h_e\left(T_f-T_e\right) \tag{5}$$

In the collector energy equation, convective heat transfer is considered for every contact surface. Surface temperatures are desired for the integration of Eq. (5). At first, initial values for surface temperatures and heat transfer coefficients are assumed. Therefore, the temperature of the fluid (T_f) can be derived by integration of Eq. (5), assuming constant values for the air density and substituting V_{in} from Eq. (4) into Eq. (5):

$$T_f(r)=\frac{1}{2}\left[T_c+T_e+(2T_a-T_c-T_e)e^{\frac{2\pi h}{C_p \dot{m}}\left(r^2-r_0^2\right)}\right] \tag{6}$$

3. Solar chimney prototype

3.1. Chimney and structure

A pilot experimental solar chimney power setup consists of the air collector 3 m in diameter and 3 m height chimney was built. Because of the resistance to heat transfer, a 3 m polycarbonate pipe with diameter of 20 cm and thickness of 4 mm was applied for making the chimney. Polycarbonate sheets have a balance of useful features including excellent toughness, very good heat resistance, fair chemical resistance, transparent, and are fairly UV resistant [21]. The structure made by 15 pieces of 2 × 1 steel profiles and the schematic of that is shown in Fig. 1 and the size of different parts is shown in Table 1.

3.2. Collector

The numerical studies on the collector slope for this set-up was carried out before by the authors, and the results demonstrated that zero angle of collector is the most appropriate option for the solar chimney pilot [22]. So, zero angle for collector is the best choice. Low Iron soda-lime glass were selected for top layer of collector. For these reasons, 8 spices of a circle glass with thickness of 3 mm were applied for making the collector roof.

Steel and wood have the economic price and the appropriate