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Performance parameter evaluation, materials selection, solar radiation with energy losses, energy storage and turbine design procedure for a pilot scale solar updraft tower

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ABSTRACT

Performance investigation of a prototype of solar updraft tower (SUT) power plant is carried out in this study. The diameters of the solar collector and chimney are of the 3.5 and 0.6 m respectively. The objective of this work is to investigate the performance of SUT and to tabulate all the inputs and estimated parameters with the materials of a SUT power plant. All the three main components' (turbine, solar collector and a chimney) process parameters are estimated and discussed. Appropriate materials are discussed and selected for solar collector, chimney, turbine and heat storage materials. Solar beam, diffuse and global radiation are estimated to analyze the performance of collector cover. Energy losses in solar collector cover and transmissivity estimations are performed to calculate theoretical energy collected in solar collector. Pressure drop inside the chimney is estimated and from that the actual power output of the turbine is calculated. The quantity of heat storage materials needed is evaluated in terms of both mass and volume. Theoretically the maximum velocity of air is achieved at the chimney base and is 2 m/s. The maximum overall efficiency of the plant is estimated as 0.0028%. The maximum theoretical power output of the plant is 0.633 W.

1. Introduction

Power generation using solar energy is an attractive alternate solution nowadays. There are two ways the power can be generated by solar energy: through photo-voltaic cells and by solar thermal generator. Solar updraft tower (SUT, also called solar chimney power plant) is also one of the key solutions to the today's predominant energy challenges. Unlike conventional power generating stations (such as thermal power plants), solar chimneys do not require cooling water. A solar chimney consists of three main components, namely, solar collector, a chimney and a power generating unit – turbine.

Solar chimney converts only a small percentage of the collected solar energy into electricity. However it can be overcome this disadvantage by making a cheap, robust construction with low maintenance costs [1,2]. The concept of solar chimney technology was first introduced in 1931 [2] and after consequent studies the first Spanish prototype SUT having a chimney height (H_{ch}) of 195 m and a maximum electricity generation of 50 kW was built and commissioned in Manzanares, Spain in 1982. This work concluded that effective electricity production is possible with the application of large scale (up to 400 MW) solar power plants [2]. Once this setup was made then the electricity can be produced without any further cost as it has no running cost. One of the other important fact is that it is eco-friendly comparative to other fossil fuel plants. These factors inspired to develop this complete data of SUT.

Preliminary experiments were carried out by Haaf [3] in a solar chimney power plant. This work discussed and analyzed about the thermal energy balances, solar collector efficiency, various pressure losses and turbine losses with reference to a twenty four hour period. The current status of knowledge such as physical process, experimental and theoretical study and cost evaluation for the solar chimney power plant has been reviewed by Zhou et al. [4]. Descriptions of other types of solar chimney power technology were also mentioned in this work.

The physical process of a large scale SUT was evaluated by Pretorius and Kröger [5]. This work incorporated the new convective heat transfer coefficient correlation and found that the annual power output of the system reduced up to 11.7%. It was also found that the annual power output increases by 3.4% by selecting better glass material for collector. Simulations were conducted and it was concluded that the results for energy storage materials such as lime stone and sand stone gave similar results to that obtained for granite.

A 2-D numerical model was developed by Shrivan et al. [6] to

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Nomenclature

A	solar azimuth angle (°)
A_c	collector surface area (m^2)
b	width of the blade section (m)
B	number of blades
C_{opt}	chord length (m)
C_p	specific heat of the air (kJ/kg K)
C_L	coefficient of lift
C_D	coefficient of drag
D	diameter (m)
D_Y	the day of the year
F_L	lift force (N)
F_D	drag force (N)
g	acceleration due to gravity (m/s^2)
H	distance between the absorber plate and the collector cover (m)
h_w	wind loss coefficient (W/m^2 K)
h_L	linearized radiation coefficient (W/m^2 K)
hc	convective heat transfer coefficient (W/m^2 K)
H	height (m)
K	thermal conductivity (W/m·K)
L	latitude (°)
L′	colatitude (°)
m_r	mass of the rocks (kg)
n	number of days after the vernal equinox
N	number of rotations per minute (rpm)
r	radius of blade segment from the hub (m)
R	turbine blade tip radius (m)
S	the solar constant (W/m^2)
T	temperature (°C)
U_t	overall heat loss coefficient (W/m^2·K)
v	velocity (m/s)
v_1	free stream velocity (m/s)
V_r	volume of the rocks (m^3)
w	relative wind speed (m/s)
Z	solar zenith angle (°)

Symbols

α	angle of attack (°)
β	turbine blade pitch angle (°)
ξ	collector slope angle (°)
δ	solar declination (°)
ε_A	absorber plate emittance
ε_g	collector cover emittance
λ	turbine blade tip speed ratio.
υ	kinematic viscosity of air (m^2/s)
ρ	reflectance
ρ_a	density of the air (kg/m^3)
Ψ	the azimuthal collector orientation (°)
σ	Stephan-Boltzmann constant (W/m^2 K^4)
σ_s	solidity ratio
θ	the obliquity angle (°)
τ	the clearness index
ω	rotational speed of the turbine (rpm)
ω_s	the hour angle at sunset and sunrise (°)

Subscripts

a	ambient
A	absorber plate
c	cover
ch	chimney
g	glass transition
h	hot air
m	glass melting
max	maximum

estimate the maximum power output from the SUT power plant. The design data were used from the recently erupted plant from Iran. The effect of entrance gap of the collector, chimney diameter, chimney height and inclination of collector roof on maximum power output was studied. The optimized parameters were identified through this numerical work.

Tian and Zhao [7] discussed the most recent growths and advancements in solar thermal energy applications. A brief review has been done over solar collectors and various thermal energy storage systems. They concluded that photovoltaic thermal collectors gave the best overall performance among the various non-concentrating type collectors. This work also suggested that the molten salts are the best choice for high temperature thermal energy storage applications because of their wide properties such as density, thermal conductivity and specific heat.

A similar type of overview is given by Schlaich et al. [8]. This work described the price evaluation for a large scale solar chimney power plant. It explained the results of a newly designed power plant in Spain. Technical and economic issues which were related to the upcoming commercial solar power plants were also discussed. An experimental investigation was carried to check the functioning of a small scale solar tower turbine by von Backström and Gannon [9]. The inlet guide vanes provided in their setup were meant to enhance the pre-whirl of air which reduces the turbine exit kinetic energy at diffuser inlet. The turbine developed in the setup produced 85–90% total-to-total efficiency and 87–90% total-to-static efficiency.

The performance of different airfoil structures such as symmetric and cambered of standard three blade vertical axis wind turbine was examined by Durrani et al. [10] through CFD numerical simulation. The impact of thickness of blade, camber, turbulent flow intensity and the effect of various turbulence models were discussed for acquiring the overall most beneficial turbine blade design configuration. Similarly a mathematical model for SUT was developed by Gitan et al. [11] and Guo et al. [12] and they found the optimized slope angle of a tilted collector. The mathematical model was compared with an experimental result and good agreement was noticed.

A divergent chimney was proposed for SUT power plant by Hu et al. [13]. A numerical model was developed with different configuration of divergent chimney with other variable parameters of area ratio and divergent angle. They concluded that the performance of the divergent chimney was much higher than the straight chimney. Similarly a mathematical model was developed for the performance analysis of SUT by Maghrebi et al. [14] for a sloped chimney.

An elaborated experimental study was carried out by Ozgen et.al [15] in order to investigate the thermal performance of three categories of double flow solar air heaters having aluminium cans under different operating conditions. They concluded that the double flow air channels are more efficient than the single flow channel over or under the absorber plate. Similar studies have been performed with artificial neural networks (ANN), wavelet neural network (WNN) [16] and least squares support vector machine (LS-SVM) [17]. Finally it was concluded that WNN was an excellent method for prediction of thermal performance of the system. Similar investigation of greenhouse heating using various renewable energy sources under different climatic conditions was reported by Esen and Yuksel [18].

From the literature survey it is noticed that quite a few prototypes of SUT power plant have been developed [8,9]. Some studies explained the SUT components such as turbine [15–22] and chimney [2,3]. In few