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Research Paper

Numerical–analytical assessment on Manzanares prototype

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HIGHLIGHTS

- Sensitivity CFD analysis was performed with respect to available radiation.
- 1-D simplified form of N.S. equations was solved analytically.
- CFD and analytical data were compared against the available experimental values.

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ABSTRACT

In this study an appropriate expression to estimate the output power of solar chimney power plant systems (SCPPS) was considered. Recently several mathematical models of SCPPS were derived, studied for a variety of boundary conditions, and compared against CFD calculations. An important concern for modeling SCPPS is the accuracy of the derived pressure drop and output power equation. To elucidate the matter, axisymmetric CFD analysis was performed to model the solar chimney power plant and calculate the output power for different available solar radiation. Both analytical and numerical results were compared against the available experimental data from the historical Manzanares power plant. We also evaluated the fidelity of the assumptions underlying the derivation and present the output power characteristics of Manzanares prototype under a range of solar irradiation, mass flow rate and collector efficiency. This research provides an approach to estimate the output power with respect to available radiation to the collector.

1. Introduction

Although the idea of the SCPP can be traced to the early 20th century, practical investigations of solar power plant systems started in the late 1970s, around the time of conception and construction of the first prototype in Manzanares, Spain. This solar power plant operated between 1982 and 1989 and the generated electric power was used in the local electric network [1–3].

The basic SCPP concept (Fig. 1) demonstrated in that facility is fairly straightforward. Sunshine heats the air beneath a transparent roofed collector structure surrounding the central base of a tall chimney. The hot air produces an updraft flow in the chimney. The energy of this updraft flow is harvested with a turbine in the chimney, producing electricity. Experiments with the prototype proved the concept to be viable, and provided data used by a variety of later researchers. A major motivation for subsequent studies lays in the need for reliable modeling of the operation of a large-scale power plant. The Manzanares prototype had a 200 m tall chimney and a 40,000 m^2 collector area. With respect to the distinguished rise of R&D budget on renewable energy [5], study and evaluation the different aspects of SCPP seem beneficial and vital. Proposals for economically competitive SCPP facilities usually feature chimneys on the scale of 1 km and collectors with multiple square kilometer areas.

Padki and Sherif [6] used the results from the Manzanares prototype to extrapolate the data to large scale models for SCPP. In 1991, Yan et al. [7] developed an SCPP model using a practical correlation. They introduced equations including air velocity, air flow rate, output power, and thermofluid efficiency. Von Backström and Fluri conducted a numerical study to determine the optimum ratio of pressure drop of the turbine as a fraction of the available pressure difference required to achieve the maximum power [8]. They noted that this ratio might lead to overestimating the flow passage in the plant and also designing a turbine without a sufficient stall margin. In other recent works, the SCPP concept involving an inflatable tower was examined, with all parts of the power plant modeled numerically [9–11].

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Nomenclature

Variables

A	cross-sectional area (m^2)
A_r	cross-sectional area of the collector ground (m^2)
g	acceleration due to gravity (m/s^2)
h	height (m)
$\dot{m}$	air mass flow rate (kg/s)
p	pressure (N/m^2)
$\dot{W}$	flow power (W)
q	heat transfer per unit mass (J/kg)
q''	heat flux (W/m^2)
R	air specific gas constant (J/kg K)
T	temperature (K)
ρ	density (kg/m^3)
u	velocity (m/s)
c_p	specific heat capacity (J/kg K)

Subscripts

i	inlet
o	outlet
c	collector
t	tower
m	mean
∞	ambient air
$turb$	turbine
atm	atmospheric

Abbreviations

CFD	computational fluid dynamics
EOS	equation of state
SCPPS	solar chimney power plant system
RHS	right hand side
M&S	modeling and simulation

To find the maximum power, different atmospheric pressure and temperature boundary conditions were applied for various tower heights and atmospheric lapse rates [12,13]. Theoretical analysis to study the effect of pressure drop in the SCPP turbine was performed by Koonsrisuk and Chitsomboon [14]. The optimal pressure drop ratio was found numerically and analytically by Xu et al., around 0.9 for the Manzanares prototype. This investigation can be applied as an initial estimation for various SCPP turbines [15].

Earlier modeling efforts [9] showed a keen sensitivity of the predictions of SCPP output to boundary conditions, in particular, pressure. Numerical simulations require careful validation and verification, and for that, analytical models are indispensable. A theoretical model was recently developed [16] to model the combined performance of the solar collector, chimney, and turbine. Here we will examine some of the assumptions and derivations in this model and present an alternative formulation for the energy equation. We will perform M&S of the Manzanares prototype and compare the computational results against the available experimental values and our analytical analysis data. This comparative study is carried out for different solar radiation based on available experimental data.

2. Analytical study

2.1. Collector

Solar Chimney Power Plants provide a reliable and conceptually straightforward way of energy generation from the solar irradiation [14,17]. A solar collector is the main and only component of this power plant to accumulate the available solar energy to heat up air in a greenhouse. The air escapes the collector through a tall chimney which connects the warm air flow of the collector with the cooler air above the ground. The temperature difference induces the natural convection, and turbine at the outlet of collector harvests the energy of the air flow. To model the collector, the simplified one dimensional mathematical analysis was performed to clarify the details. The analytical correlation will be applied later to compare the CFD results against it. To derive the equations, we start from the collector. It is assumed that the flow through the collector is one-dimensional, steady-state, and compressible. Let us disregard the friction and assume the total heat from the solar irradiation is absorbed within the air filling the collector. For this thermal-fluid analysis, the mass conservation satisfies:

$$\frac{dA}{A}+\frac{d\rho}{\rho}+\frac{du}{u}=0 \quad \text{(Continuity)} \tag{1}$$

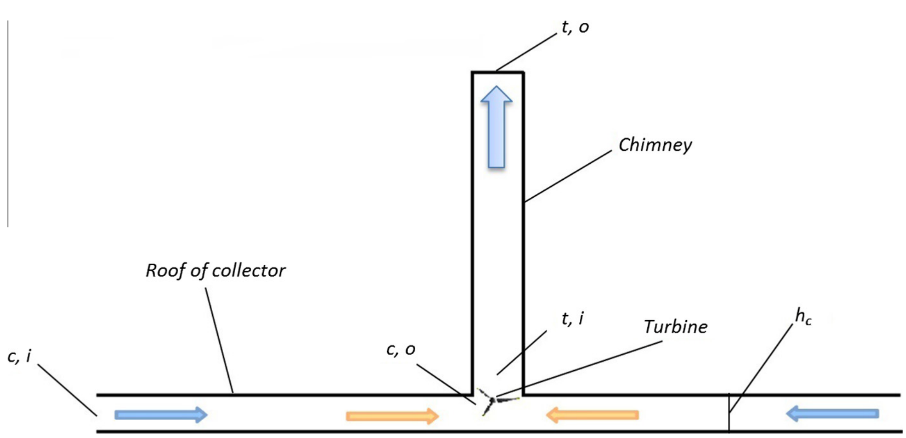

Fig. 1. Schematic of SCPP with the applied variables and subscripts in the present analysis.