Energy Conversion and Management 138 (2017) 638–650

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

A moist air condensing device for sustainable energy production and water generation

Tingzhen Ming [a,*], Tingrui Gong [b], Renaud K. de Richter [c], Yongjia Wu [d], Wei Liu [b,*]

[a] School of Civil Engineering and Architecture, Wuhan University of Technology, No. 122, Luoshi Road, Wuhan 430070, China
[b] School of Energy and Power Engineering, Huazhong University of Science and Technology, Wuhan 430074, China
[c] Tour-Solaire.Fr, 8 Impasse des Papillons, F34090 Montpellier, France
[d] School of Mechanical Engineering, Virginia Polytechnic Institute and State University, Blacksburg 24060, USA

ARTICLE INFO

Article history:
Received 7 October 2016
Received in revised form 20 January 2017
Accepted 6 February 2017

Keywords:
Solar chimney
Output power
Turbine
Freshwater
Performance
Efficiency

ABSTRACT

A solar chimney power plant (SCPP) is not only a solar thermal application system to achieve output power, but also a device extracting freshwater from the humid air. In this article, we proposed a SCPP with collector being replaced by black tubes around the chimney to warm water and air. The overall performance of SCPP was analyzed by using a one-dimensional compressible fluid transfer model to calculate the system characteristic parameters, such as chimney inlet air velocity, the condensation level, amount of condensed water, output power, and efficiency. It was found that increasing the chimney inlet air temperature is an efficient way to increase chimney inlet air velocity and wind turbine output power. The operating conditions, such as air temperature and air relative humidity, have significant influence on the condensation level. For water generation, chimney height is the most decisive factor, the mass flow rate of condensed water decreases with increasing wind turbine pressure drop. To achieve the optimum peak output power by wind turbine, we should set the pressure drop factor as about 0.7. In addition, increasing chimney height is also an efficient way to improve the SCPP efficiency. Under ideal conditions, the system total efficiency of a SCPP with a height of 3000 m can be up to nearly 7%.

1. Introduction

1.1. Background

Energy and water are two essential items in our lives. As the population increases and living standard improves, the global energy demand will increase continuously. A report shows that total world energy consumption rises from 549 quadrillion British thermal units (Btu) in 2012 to 815 quadrillion Btu in 2040, with an increase of 48%. Particularly in China and India, account for more than half of the world's total increase in energy consumption over the 2012 to 2040 projection period [1]. Fossil fuels continue to provide most of the world's energy, which have arisen about the corresponding environmental cost, especially for greenhouse gas (GHG) emissions, exacting a heavy toll on human health [2]. On the other hand, the freshwater shortage is emerging as one of the most critical global issues. In China, large areas, especially in North and West China, are experiencing a severe dryness, and the total national water shortage in 2030 is predicted to be nearly 200 billion m^3 with more than 25% for domestic needs [3]. In addition, due to global warming and other extreme climatic phenomena, like the El Nino Phenomena, the droughts are getting more and more serious. The demand for providing sustainable freshwater is increasing.

Given the depletion of resources and increasingly growing environmental problems, people and governments would turn their attention to clean and renewable solar energy. As it is well known that China is rich in solar energy resource, the annual average sunshine time in most areas is more than 2000 h and the total annual radiation is nearly 1500–1800 kWh/m^2, providing favorable conditions for the full development of solar technologies [4].

The idea of solar chimney power generating technology was first put forward by Schlaich et al. [5] in 1978. Shortly after that, in 1983, the German government and a Spanish electricity company jointly built the world's first solar chimney power plant (SCPP) in Manzanares, Spain. The experimental SCPP had a chimney 194.6 m in height and 5.08 m in radius, a collector 122.0 m in radius, and a peak output power of 50 kW. This prototype was fully tested and validated till 1989. Haaf et al. [6,7] gave some experimental results and a scientific description of this SCPP proto-

* Corresponding authors.
E-mail addresses: tzming@whut.edu.cn (T. Ming), w_liu@hust.edu.cn (W. Liu).

http://dx.doi.org/10.1016/j.enconman.2017.02.012
0196-8904/

Nomenclature

A	chimney cross-section area [m^2]
c_p	specific heat capacity [J/(K kg)]
d	chimney diameter [m]
d_s	moisture content in per kilogram air [kg/kg (dry air)]
f	friction factor
g	gravitational acceleration, 9.8 [m s^{-2}]
H	chimney height [m]
$\dot{m}$	condensed water in per kilogram air [kg/kg]
$\dot{m}_{total}$	mass flow rate [m^3/s]
n	wind turbine pressure drop factor
p_v	water vapor partial pressure [Pa]
p_s	saturated water vapor partial pressure [Pa]
p_z	pressure at some height [Pa]
s	water content in per cubic meter [kg/m^3]
t	Celsius temperature [°C]
T_0	heated air temperature at the chimney entrance [K]
T_z	temperature at height being z m [K]
v	specific volume [m^3/kg]
V_z	vertical velocity [m/s]
V_0	velocity at the inlet [m/s]
V_l	condensed water velocity [m/s]
Z	vertical height [m]
P_e	system total output power [W]
P_{e1}	wind turbine output power [W]
P_{e2}	hydraulic turbine output power [W]
V	the inlet volume flow rate of airflow [m^3/s]
Q_{air}	thermal energy absorbed by airflow inside the tubes [W]

Greek symbols

Δ	difference or increase
κ	specific heat ratio
ρ	density [kg/m^3]
ρ_H	air density at the exit of the chimney [kg/m^3]
γ	latent heat [J/kg]
ε	the entrance and exit losses factor
η_1	the efficiency of wind turbine
η_2	the efficiency of hydraulic turbine
η_{sys}	system efficiency

Subscripts

0	chimney inlet
H	chimney outlet
l	water liquid
s	saturated state
v	water vapor

type. A comprehensive review of scientific literature on SCPP was also provided by Zhou et al. [8].

Ming et al. [9] proposed several types of engineering structures that were able to transfer heat from the Earth's surface to the upper layers of the troposphere, thus could cool down the Earth by increasing atmospheric convection, enhancing outgoing long wave radiation to the outer space. The solar updraft chimney, one of the devices proposed to transfer surface hot air several kilometers higher was introduced. A SCPP is comprised of three main components, the chimney (for stack effect), the solar collector (the greenhouse), and turbines (power conversion unit, driven by airflow to produce CO_2-free electricity). Moreover, the performance of a SCPP [10], such as the effect of the energy storage layer [11], turbines [12], ambient crosswind [13], and chimney shape [14] on thermo-fluid dynamics and power output were also studied via numerical method for the purpose of theoretical analysis.

The research group led by Sherif [15,16] developed comprehensive mathematical models to analyze the influence of miscellaneous parameters of a SCPP, such as ambient conditions and structural dimensions, on the temperature and output power of the solar chimney. They concluded that the output power of a solar chimney was directly proportional to the air temperature difference attained in the collector and the mass flow rate of air, appropriate enhancements could help to increase the overall chimney output power. Besides, three types of experimental prototype were built by them in Florida, with the chimney shape, collector construction, and an energy storage layer performance being taken into consideration.

Koonsrisuk and Chitsomboon [17] proposed a dynamic similarity variable between a SCPP prototype and its scaled models, thus could simplify the experimental study of SCPP and cut expense. Maia et al. [18,19] developed a numerical model of the turbulent flow inside a solar chimney to evaluate the influence of geometric configurations and operational variables on the flow behavior. It showed that the height and diameter of the chimney were the most significant variations in the flow behavior. The energy and exergy analysis of the airflow inside a solar chimney were also carried out. Patel et al. [20] studied the effect of geometric parameters to optimize the configuration of SCPP. Krätzig [21] developed a mathematical model to analyze the thermo-fluid mechanical processes of SCPPs and to evaluate their power/energy harvest performance. Nia and Ghazikhani [22] studied the heat transfer characteristics of a SCPP numerically using passive flow control approach. Fasel et al. [23] developed a numerical model using CFD method to investigate the fluid dynamics and heat transfer of SCPPs. Cao et al. [24] suggested that the TRNSYS can also be used as a convenient tool to simulate the performance of SCPPs.

In order to evaluate the performance of SCPP, researchers found that the ratio of the pressure drop across the turbine to the total driving pressure is much significant. Most investigators have assumed that the optimum ratio is 2/3 [7,25–27]. Koonsrisuk and Chitsomboon [28] found that with a constant driving pressure, the optimum ratio of the turbine extraction pressure to the driving pressure was 2/3 and it was a function of the plant size and solar heat flux. Bernardes and Backström [29] and Hedderwick [30] indicated that the optimum ratio was not constant during the day and it is dependent of the heat transfer coefficients in the collector. Nizetic and Klarin [31] concluded that the turbine pressure drop factors were in the range of 0.8–0.9 by using a simplified analytical approach. Guo et al. [32] indicated that the solar radiation and ambient temperature had obvious effect on the optimum turbine pressure drop ratio by an analytical approach and numerical simulations, and the optimum ratio of the Spanish prototype varies from 0.90 to 0.94 under normal climate conditions.

Since Schlaich et al. [33] introduced the SCPP, with a good overview of the technology, many researchers tried to find conceptual devices more efficient. Koonsrisuk et al. [34,35] proposed a solar chimney system with a sloped collector. When comparing the conventional SCPP with the sloped solar chimney power plant (SSCPP) based on the Second Law of Thermodynamic analysis, results showed that SSCPP was thermodynamically better than conventional SCPP in some configurations. Meanwhile, they developed a