Energy Conversion and Management 113 (2016) 189–200

Contents lists available at ScienceDirect

Energy Conversion and Management

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

# Freshwater generation from a solar chimney power plant

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ARTICLE INFO

*Article history:*
Received 22 November 2015
Accepted 26 January 2016

*Keywords:*
Solar chimney
Freshwater
Precipitation
Effectiveness

ABSTRACT

A modified solar chimney power plant is presented which is not only a solar thermal system able to achieve output power but also is able to extract freshwater from the air. This solar chimney power plant has no greenhouse canopy which is replaced by a collector made of black tubes around the chimney to warm the water and air. The effectiveness of this engineering structure is analyzed in comparison to natural precipitation at nine cities in China; one-dimensional compressible flow and heat transfer mathematical model has been developed to describe the moist air which cools down along the chimney and condenses above the lifting condensation level. The recovery of water is a partial duplication of natural atmospheric convection processes because of the unstable environment lapse rate. The results showed that there is often a high-strength positive correlation between the natural precipitation and the water production by this modified solar chimney power plant in those cities, Water production by the device in the conditions of the study can produce up to $37.9 \times 10^6$ tons of water per year in Guangzhou, and $29.7 \times 10^6$ tons of water per year in Chengdu, the correlation coefficient is even up to 0.875. Moreover, this device is more efficient in arid regions, might increase the rainfalls and enhance the regional water cycle. The amount of potable water produced by this modified solar chimney power plant is remarkable and might be able to benefit to several millions of people.



## 1. Introduction

### 1.1. Background

Water is an essential item in our lives and promotes civilization. Freshwater shortage is emerging as one of the most critical global resource issues. In China, large areas especially in the North are experiencing a spate of dryness, and even a total national shortage in 2030 is predicted to be nearly 200 billion $m^3$ with more than 25% for domestic needs [1]. On the other hand, due to global warming and other extreme climatic phenomena, like the El Nino Phenomenon, the droughts are getting more and more serious. The demand for the sustainability of current freshwater is increasing.

To fight global warming, Ming et al. [2] suggested that several types of engineering structures are able to transfer heat from the Earth surface to the upper layers of the troposphere, thus could cool down the Earth by controlling atmospheric convection, enhancing outgoing longwave radiation to the outer space. One of the devices proposed to transfer surface hot air several kilometers higher, a solar updraft chimney variant was mentioned. A solar chimney power plant (SCPP) usually comprises of three main components: the chimney (for stack effect), the solar collector (the greenhouse, for greenhouse effect) and turbines (power conversion unit, driven by airflow to produce carbon-free electricity). A comprehensive review of scientific literature on SCPP was provided by Zhou et al. [3]. Whereas in the early days Haaf [4] gave some experimental results and a scientific description of the SCPP prototype built in Manzanares, Spain. This experimental plant, with a 194.6 m high chimney and a radius of 5.08 m was built in 1981/82, with a peak output of 50 kW. This prototype was fully tested and validated till 1989.

### 1.2. Literature review

Koonsrisuk [5] compared the performance of the conventional solar chimney power plant and the sloped solar chimney power plant based on second law analysis. Meanwhile, a single dimensionless similarity variable for the solar chimney power plant was proposed by Koonsrisuk and Chitsomboon [6]. Kraetzig [7] described and formulated the thermo-fluid dynamics including all physical processes in the SCPPs to evaluate the energy harvest by them. Bernardes and Backström [8] studied the performance

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http://dx.doi.org/10.1016/j.enconman.2016.01.064
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 ($ms^{-2}$) |
| $H$ | chimney height (m) |
| $L$ | latent heat (J/kg) |
| $\dot{m}$ | condensed water in per kilogram air (kg/kg) |
| $\dot{m}_{total}$ | mass flow rate ($m^3$/s) |
| $p$ | pressure (Pa) |
| $p_v$ | 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 some height (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) |
| $C$ | atmospheric scale height (m) |
| $R_g$ | ideal gas constant (J/(kg K)) |

*Greek symbols*

| | |
|---|---|
| $\Delta$ | difference |
| $\kappa$ | specific heat ratio |
| $\rho$ | density (kg/$m^3$) |
| $\rho_H$ | air density at the exit of the chimney (kg/$m^3$) |
| $\varepsilon$ | the entrance and exit losses factor |

*Subscripts*

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

for the heat transfer coefficients of Pretorius and Kroger [9] by theoretical simulations, each subjected to two power control schemes. Fasel et al. [10] simulated the performance of SCPP by using ANSYS Fluent and an in-house developed Computational Fluid Dynamics (CFD) code. To decrease the negative influence of ambient crosswind on the SCPPs performance, Ming et al. [11] simulated a blockage wall built a few meters in front of the collector inlet by numerical simulation. Ferreira et al. [12] studied the feasibility of a solar chimney for food drying. Maia et al. [13] performed an analytical and numerical study of the influence of geometric dimensions and materials on the flow behavior in a solar chimney, the energy and exergy analyses were also carried out [14]. Patel et al. [15] studied the effects of various geometric parameters on a SCPP to evaluate its performance. Cao et al. [16] studied a sloped solar SCPP in Lanzhou, which presented technical and practical support for SCPP. Ninic and Nizetic [17] studied the possibility of developing and making use of the availability of warm, humid air in the atmosphere. Nizetic et al. [18] analyzed the feasibility of SCPPs as an environmentally acceptable energy source for small settlements and islands in the Mediterranean region. Nizetic and Klarin [19] evaluated the factor of turbine pressure drop in SCPP by a simplified analytical approach. Pasumarthi and Sherif [20] studied the performance characteristics of solar chimneys both theoretically and experimentally by a demonstration model, the overall results were encouraging [20].

Since Schlaich et al. [21] introduced the SCPPs, with a good overview of the technology, many researchers have been trying to find conceptual devices which operate in a more effective fashion. Zou et al. [22] proposed the hybrid cooling-tower-solar-chimney system, which could generate electricity and dissipate waste heat simultaneously. A device called Solar Cyclone was introduced for accomplishing the separation of water from surface air by Kashiwa and Kashiwa [23]. There is an expansion cyclone separator for condensing and removing atmospheric water in the chimney, with the central temperature below the dew point. If it works, the fresh water can be collected and this cycle is sustainable, but the efficiency is unclear, and should be determined in further studies.

The construction cost of an SCPP could be approximately broken down as follows: 25% for the chimney, 5% for the turbines and 70% for the collector [24]. Thus for cutting down expenses, Bonnelle [25] proposed a variant SCPP with no collector, similar to the "energy tower" also described by Bonnelle.

In addition, Papageorgiou [26] studied solar chimney technology without solar collector with floating chimney. As the solar collector received thermal energy by the sunlight irradiation to create warm air, it is evident that the heat is necessary for solar chimney operation, but these researchers found that the air humidity and condensation in the chimney can increase the updraft velocity, thanks to the latent heat released inside the chimney, thus the solar collectors could be omitted. In addition, they suggested that the solar chimney power plant placed in humid areas, near the sea, could generate more power output than that placed in arid areas.

Zhou et al. [27] investigated a combined solar chimney system for power generation and seawater desalination. One-dimensional compressible flow model was developed to compare the performance of the classical SCPP system and the combined solar chimney system for power generation and seawater desalination. They found that due to the fact that an important amount of heat is used as latent heat for water evaporation, decreasing the working air temperature, the power output of the combined system is less than that of the classical system. Moreover, a revenue analysis carried out found that the critical chimney height depends on the price level of fresh water and of electric power.

### *1.3. Research in this article*

In this paper, a modified solar chimney power plant with no greenhouse canopy was proposed; the collector being replaced by twisted black tubes filled with hot water to warm the air entering the chimney and to keep the relative humidity percent identical to ambient. Then, a one-dimensional compressible flow and heat transfer mathematical model was developed to investigate the effectiveness of freshwater generation by this unique engineering structure. Later, the natural precipitations at nine cities in China were compared to effectiveness of freshwater generation by this unique engineering structure.

## 2. System mechanism and prototype

### *2.1. System mechanism*

Starr and Anati [28] proposed an artificial construction within a vertical tube of 3 km height with a radius of 50 m, which they