Applied Energy xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

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

A telescopic divergent chimney for power generation based on forced air movement: Principle and theoretical formulation

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HIGHLIGHTS

- A new power generation concept based on forced updraft air in a divergent chimney.
- A theoretical model was developed to investigate the forced updraft system.
- A self-sustained updraft is reached when air velocity reaches a threshold value.
- No external mechanical work is needed when the forced updraft reaches steady state.
- The extractable energy has an exponential relationship with the chimney heights.

ARTICLE INFO

Article history:
Received 31 October 2013
Received in revised form 24 March 2014
Accepted 26 April 2014
Available online xxxx

Keywords:
Forced air movement
Divergent chimney
Renewable energy

ABSTRACT

We present a new renewable energy technology concept for electricity generation based on an upward momentum created by a balanced forced air movement, which is initiated by an air blower, inside a telescopic divergent chimney constructed with adiabatic materials and equipped with a gas turbine. A theoretical model based on the principles of mass and energy conservation, and continuity was developed to investigate the forced air flow inside the system using a criterion defined as the difference between ambient pressure and static pressure at the outlet aloft of the chimney. The model results indicated that, as the air flow increasing to reach a threshold, there exists a steady state when the pressure difference equals to zero. At this state, a constant air flow velocity is attended such that the system becomes stable and the action of the blower is no longer required. In this condition, there is a non-linear relationship between the threshold velocity and the pressure difference with the geometry of the chimney, the installed load and ambient conditions are important dependent variables. With the estimated threshold velocity for chimneys from 15 to 150 m, the steady-state distributions of velocity and energies (internal, potential, kinetic, enthalpy and extractable mechanical energy) at five cross-sections of the chimney were evaluated. The maximum velocity is found at the section with the minimum area, where maximum mechanical energy can be extracted. The maximum velocity can reach ∼45 m/s in a 100-m high chimney. The extractable energy is found to have an exponential relationship with the chimney heights. The novelty of the concept is that when the air is forced to reach a threshold velocity in the system, the air can maintain a steady state without further supply of driving power.

1. Introduction

This aim of this paper is to introduce a new device that produces energy through a telescopic divergent chimney that transforms internal energy of air into mechanical energy by forced air movement and subsequently electricity. This chimney system is structurally quite similar to the solar chimney power plant (SCPP), which is a device for transferring heat to mechanical energy then

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http://dx.doi.org/10.1016/j.apenergy.2014.04.086
0306-2619/

Nomenclature

g	gravity acceleration (m/s^2)
h	enthalpy per unit of mass (kJ/kg)
$H_{chimney}$	chimney height (m)
Ht	total energy per unit of mass (kJ/kg)
$\dot{m}$	mass flow rate (kJ/s)
P	power (kW/kg)
p	pressure (Pa)
Q	heat (kJ)
R_d	vertical temperature gradient (K/m)
R_g	gas constant (J/(kg K))
A	cross area (m^2)
T	temperature (K)
U	threshold velocity (m/s)
u	velocity (m/s)
z	altitude (m)
I	internal energy per unit of mass (kJ/kg)

Greek

α	angle of the arc of the bending duct (degree)
ρ	air density (kg/m^3)
γ	specific heat ratio
ζ	energy loss coefficient
λ	D'Arcy–Weisbach friction coefficient
θ	dip angel of the chimney wall (degree)

Subscript

0	the ambient on the ground
alt	the ambient at altitude
a/b/c/d/e	duct cross-sections
f	friction
loss	energy loss at the turbine

to electricity but with a straight chimney [1–3]. The first prototype of SCPP was operated in Manzanarès of Spain from 1982 to 1989 and it showed that it is possible to produce electricity power using natural thermal convection [1,2]. The convective air flow of the SCPP is created by the temperature difference of warm air heated by solar radiation at ground surface and the ambient temperature of the air aloft of the chimney [4–7]. It is structured with a straight chimney, a huge canopy on the ground level, a turbine and a generator [8,9]. Research investigations revealed that the output efficiency of the solar tower is highly dependent on the height of chimney and the acreage of the heat-collecting canopy [10,11].

Instead of the straight chimney design which is commonly used in the SCPP, the new device adopts a divergent structure [12] constructed with adiabatic materials. Different from the natural thermal convection in the straight chimney, which will not be able to reach an efficiency of 1% of the incident solar radiation [13], the divergent chimney operates with an air movement artificially initiated by air blowers or other devices. This air flow is called forced air movement in this paper. When it starts to operate, the air blowers pull the air into the chimney with a certain speed. As the flow velocity increases to a threshold value, the whole system reaches a steady state in which the air flow stays almost at a constant speed without the action of the blowers any more. The chimney using forced air movement does not require the heat-collecting canopy or solar radiation for heating the air. Thus, it is a new technology for electricity generation and this technology is less dependent on ambient conditions, especially sunlight than the solar tower.

2. Conceptual design and operation

For easy understanding, the telescopic divergent chimney is expressed in a 2-D structure as shown in Fig. 1. The device is structured with a ground-level circular canopy for collecting air from the ambient environment, which is directed by a blower through cambered ducts to the inlet of a telescopic chimney situated at the center of the canopy. The chimney is constructed by adiabatic materials with the smallest diameter at the bottom where a turbine and a generator are located, from which the chimney is divergent upwards. At the top, the chimney is connected to a hull which is separated into six radial spans leading air into the ambient atmosphere and is covered by a dome.

With the structure, there are 5 important cross-sections in the chimney. The vertical Plane A is the cross-section of the inlet where air blowers generate a forced air flow into the chimney. The Plane B is horizontal and close to the bottom side of the turbine, while the Plane C is parallel to Plane B and near the upper side of the turbine. Noted that the virtual turbine is assumed to have no geometrical parameters; that is, the Plane B and C share the same diameter and altitude. The Plane D is the last horizontal cross-section of the divergent chimney. The Plane E is an extension of the hull of the chimney. It is separated into six radial spans leading air into the ambient atmosphere.

3. Formulation of the problem

3.1. Assumptions

Given the 2-D structure and operating process, we build up a theoretical model based on the assumptions below:

(I) In air flow with low Mach number (<0.3) (i.e. with low flow velocity), the air is usually considered as an incompressible gas [14]. Our computations through a CFD model indicated

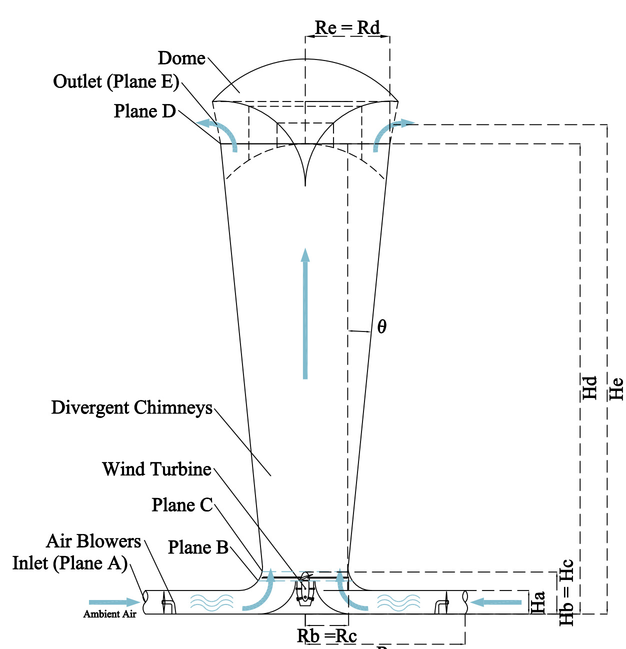

Fig. 1. Schematic illustration of the 2-dimensional structure of a telescopic divergent chimney. The dimensions are for theoretical model setup.

Please cite this article in press as: Chan C-y et al. A telescopic divergent chimney for power generation based on forced air movement: Principle and theoretical formulation. Appl Energy (2014), http://dx.doi.org/10.1016/j.apenergy.2014.04.086