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Constructal solar chimney configuration

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ABSTRACT

In this study, we describe the constructal-theory search for the geometry of a solar chimney. The objective is to increase the power production over the area occupied by the plant. The ratio height/radius, maximum mass flow rate and maximum power under the constraints of a fixed area and volume are determined. We find that the power generated per unit of land area is proportional to the length scale of the power plant. The analysis is validated by a detailed mathematical model. Pressure losses are reported in terms of the dimensionless length scale of the system, and are illustrated graphically. They indicate that the pressure drop at the collector inlet and at the transition section between the collector and chimney are negligible, and the friction loss in the collector can be neglected when the svelteness (Sv) of the entire flow architecture is greater than approximately 6.

1. Introduction

The solar chimney is a power plant that uses (1) solar radiation to raise the temperature of the air and (2) the buoyancy of warm air to accelerate the air stream flowing through the system. The main features of the solar chimney are sketched in Fig. 1. Air is heated as a result of the greenhouse effect under a transparent roof (the collector). Because the roof is open around its periphery, the buoyancy of the heated air draws a continuous flow from the roof perimeter into the chimney. A turbine is set in the path of the air current to convert the kinetic energy of the flowing air into electricity.

In 1981 a solar chimney prototype of 50 kW and chimney height nominally at 200 m was built in Manzanares, Spain. The plant operated from 1982 to 1989, and was connected to the local power network between 1986 and 1989 [1]. This project demonstrated the viability and reliability of the solar chimney concept. Since then, numerous investigations have been conducted to predict the flow in solar chimneys. Generally, it was found that the electricity yielded by a solar chimney is in proportion with the intensity of global solar radiation, collector area and chimney height. Based on a mathematical model, Schlaich [1] reported that optimal dimensions for a solar chimney do not exist. However, if construction costs are taken into account, thermoeconomically optimal plant configurations may be established for individual sites. Pretorius and Kröger [2] showed numerically that the power generation is a function of the collector roof shape and inlet height. Maia et al. [3] carried out a simulation study and found that the height and diameter of the chimney are the most important geometric dimensions for solar chimney design. Zhou et al. [4] reported the maximum chimney height in order to avoid negative buoyancy, and the optimal chimney height for maximum power output. They found that the maximum height and the optimal height increase with collector radius.

A common feature in these findings is that the plant efficiency is very low, and that it increases with the plant size. Consequently only large-scale plants, in which the chimney heights are 1000 m or more, were proposed in the literature. In the 1990s, a project in which a solar chimney power plant with the capacity of 100 MW was proposed for construction in Rajasthan, India, but was not built. Its collector had a radius of 1800 m and a chimney height and diameter of 950 m and 115 m, respectively [5]. The Australian government planned to build a 200 MW commercial plant with a 1000-m high concrete chimney. Recently, the plant was downsized to 50 MW and a 480-m high chimney [6], because the construction and safety of such a massive structure poses significant engineering challenges.

The work described in this paper was stimulated by the quest for fundamental principles for improved designs, and focuses on the generation of shape and structure in the pursuit of global performance of the flow system. It is based on constructal theory [7].

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Nomenclature

A	horizontal area, m^2
A_c	cross-sectional area, m^2
A_r	roof area, m^2
$C_{1,2,3,4}$	constants
c_p	specific heat at constant pressure, J kg^{-1} K^{-1}
D	tower diameter, m, Fig. 1
f	friction factor
g	gravitational acceleration, m s^{-2}
H	tower height, m, Fig. 1
h	roof height, m, Fig. 1
K_{inlet}	collector inlet loss coefficient
M	Mach number
$\dot{m}$	mass flow rate, kg s^{-1}
q''	solar heat flux, W/m^2
R	ideal gas constant, J kg^{-1} K^{-1}
R	roof radius, m, Fig. 1
Sv	svelteness number, Eq. (40)
T_0	atmospheric temperature, K
U	velocity, m s^{-1}
V	volume, m^3
$\dot{W}$	flow power, W
z	Cartesian coordinate in vertical direction

Greek symbols

β	volumetric coefficient of thermal expansion, 1/K
ΔP	pressure drop, Pa
ΔP_{acc}	acceleration pressure drop, Pa
ΔP_{inlet}	collector inlet pressure drop, Pa
$\Delta P_{junction}$	pressure drop at the collector-to-chimney transition section, Pa
ΔT	temperature difference in roof portion, K
$\epsilon_{junction}$	loss coefficient at the collector-to-chimney transition section
Φ	auxiliary function, Eq. (18)
λ	Lagrange multiplier
ρ	density, kg/m^3
ρ_0	air density at T_0, kg/m^3
$\sum$	quantity proportional to the total power generation rate
τ	fluid shear stress
Ψ	auxiliary function, Eq. (23)

Subscripts

max	maximum
w	wall
x	horizontal passage
y	vertical passage
1	roof inlet
2	roof outlet
3	chimney inlet
4	chimney outlet

In this paper, we show that the configuration of the solar chimney can be determined along with the scaling rules for being able to scale-up and scale-down the design.

2. Geometry

The analysis is based on a simple model in order to demonstrate analytically the opportunity for searching for a constructal configuration if the system architecture is free to morph. Physical details that are neglected are discussed in the concluding paragraphs. The simplified analysis is validated by a more realistic numerical model in Sections 7 and 8.

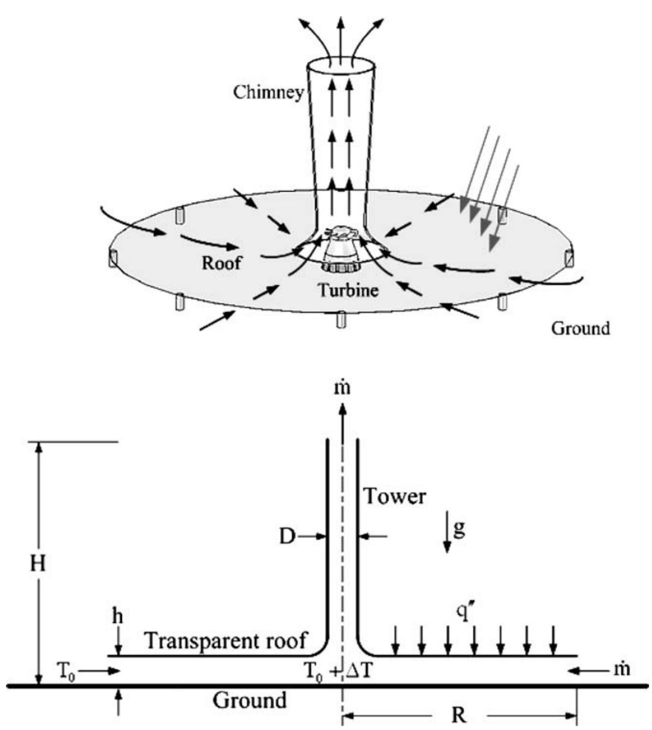

Fig. 1. The main features of a solar chimney.

The system geometry is simplified to a horizontal disc above the ground and a vertical cylinder in the center of the disc. The solar chimney configuration has the four dimensions shown in Fig. 1: D, H, R and h. We assume that the flow is fully developed and turbulent in all the flow passages, and that the friction factors in the vertical tube (f_y) and the horizontal channel (f_x) are approximately constant. The air flow rate ($\dot{m}$) enters at atmospheric temperature (T_0) and is heated with uniform heat flux (q'') as it flows to the base of the chimney, where its temperature reaches $T_0 + \Delta T$. It is assumed that the solar radiation absorbed by the chimney is negligible with respect to the solar heat absorbed by the collector.

3. Pumping effect

The air stream is driven by the buoyancy effect due to the vertical column of hot air (height H, temperature $T_0 + \Delta T$), which communicates with the ambient air of the same height and lower temperature (T_0). The net pressure difference that drives the air stream in the tower is [8]

$$\Delta P = \rho_{T_0} gH - \rho_{T_0+\Delta T} gH = \rho\beta gH\Delta T \tag{1}$$

where ρ is the average air density and β is the coefficient of volumetric thermal expansion.

The pumping effect ΔP is opposed by friction in the vertical tube (ΔP_y) and in the horizontal channel (ΔP_x) and the acceleration due to flow area reduction (ΔP_{acc}). For the vertical tube, the longitudinal force balance is

$$\Delta P_y \pi D^2/4 = \tau_w \pi DH \tag{2}$$

where τ_w is the wall shear stress. The wall shear stress is defined in terms of friction factor as [9]