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ScienceDirect
Solar Energy 81 (2007) 1439–1446
SOLAR ENERGY
www.elsevier.com/locate/solener

Dynamic similarity in solar chimney modeling

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Received 15 August 2006; received in revised form 8 January 2007; accepted 20 March 2007
Available online 30 April 2007

Communicated by: Associate Editor S.A. Sherif

Abstract

Dimensionless variables are proposed to guide the experimental study of flow in a small-scale solar chimney: a solar power plant for generating electricity. Water and air are the two working fluids chosen for the modeling study. Computational fluid dynamics (CFD) methodology is employed to obtain results that are used to prove the similarity of the proposed dimensionless variables. The study shows that air is more suitable than water to be the working fluid in a small-scale solar chimney model. Analyses of the results from CFD show that the models are dynamically similar to the prototype as suggested by the proposed dimensionless variables.

Keywords: Solar chimney; Dimensional analysis; Dimensionless variables; Dynamic similarity; CFD; Natural convection

1. Introduction

Solar chimney is a rather new solar technology proposed to be a device that generates electricity in large scale by transforming solar energy into mechanical energy. In other words, it can be classified as an artificial wind generator. The schematic of a typical solar chimney power plant is sketched in Fig. 1. Solar radiation strikes the transparent roof surface, heating the air underneath as a result of the greenhouse effect. Due to buoyancy effect, the heated air flows up the chimney and induces a continuous flow from the perimeter towards the middle of the roof where the chimney is located. Shaft energy can be extracted from thermal and kinetic energy of the flowing air to turn an electrical generator (Schlaich, 1995).

Numerous analytical investigations to predict the flow in solar chimney had been proposed (Gannon and Von Backström, 2000; Haaf et al., 1983; Padki and Sherif, 1988; Padki and Sherif, 1989a; Padki and Sherif, 1989b; Padki and Sherif, 1992; Schlaich, 1995; Von Backström and Gannon, 2000; Yan et al., 1991). There are common features of all these investigations in that they developed mathematical models from the fundamental equations in fluid mechanics. In doing this the temperature rise due to solar heat gain had been assumed to be a reasonable value using engineering intuition. Flows in the roof and the chimney were studied individually without a mechanism to let them interact. Chitsomboon (2001a) proposed an analytical model with a built-in mechanism through which flows in various parts of a solar chimney can naturally interact. Moreover, thermo-mechanical coupling was naturally represented without having to assume an arbitrary temperature rise in the system. The results predicted were compared quite accurately with numerical solutions from CFD.

Experimental study of a full scale solar chimney prototype is very expensive and time consuming since a “small” power plant is of the order of 100 m in height. Small-scale model testing is obviously desirable but a similarity scaling law must first be established. The dimensional analysis methodology focuses on combining the effects of various

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0038-092X/$ - see front matter
doi:10.1016/j.solener.2007.03.003

Nomenclature

A	flow area, m^2
A_r	roof area, m^2
c_p	specific heat capacity at constant pressure, J/(kg K)
g	gravitational acceleration, m/s^2
h_c	chimney height, m
h_r	roof height above the ground, m
$\dot{m}$	mass flow rate, kg/s
q''	insolation, W/m^2
q'''	solar heat absorption per unit volume, W/m^3
r_c	chimney radius, m
r_r	roof radius, m
S	source term
T	absolute temperature, K
t	time, s
V	flow velocity, m/s

Greek symbols

β	volumetric coefficient of thermal expansion, 1/K
γ	specific heat ratio
Π	dimensionless group
ρ	density, kg/m^3

Subscripts

1,2,3,4	position along chimney (as depicted in Fig. 1)
r	roof
c	chimney
ref	reference state

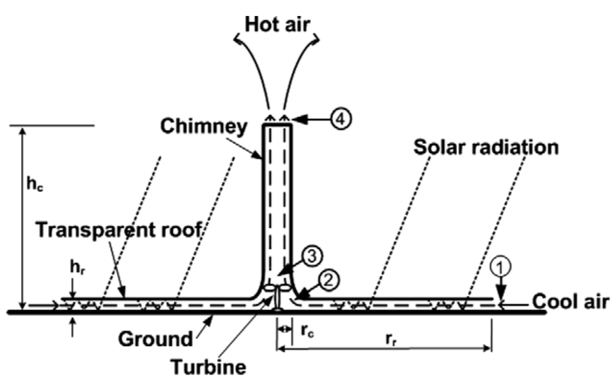

Fig. 1. Schematic layout of solar chimney power plant.

primitive variables into fewer dimensionless variables, thereby scaling the primitive variables to exhibit similar effects on the different physical models. Aside from the scaling law, dimensional analysis also helps reduce the number of independent variables resulting in lesser experimental trials.

To the present time, there has been only one experimental solar chimney plant constructed for testing. This was done in Spain as a result of a joint venture between the German government and a Spanish utility. This pilot plant, with the chimney height and the roof diameter nominally at 200 m, had been running from 1982 to 1989. Theoretical and numerical results must ultimately be validated by experimental findings of model testing. However, the high cost and long time involved in constructing and testing of large scale model stipulates the use of a small-scale experimental plant. This paper proposes to use dimensional analysis methodology to establish scaling law to extrapolate results from small-scale model to the full scale prototype. The characteristic scaling method of (Chitsomboon, 2001b) is used to find the dimensionless variables. Finally, the similarities between the model and the prototype attained by the dimensionless variables are verified by scaling the numerical results obtained from a computational fluid dynamics (CFD) code.

While air is the natural working fluid in the prototype, water is also tested for its suitability as a test fluid in small-scale models. Due to its much higher density water might offer an advantage in small-scale testing as is well known in aerodynamic testing. Some researchers also used water as the working fluid in their small-scale solar chimney models (Chenvidyakarn and Woods, 2005; Khalifa and Sahib, 2002; Spencer, 2001), albeit without mentioning its theoretical advantages, if any.

2. Dimensional analysis

In Chitsomboon (2001a), by synthesizing the conservation equations of mass and energy together with ideal gas relations, the mathematical model for the frictionless, one-dimensional flow in a solar chimney was proposed as,

$$\frac{1}{2}\dot{m}V_1^2\left[\rho_1 - 2\rho_1 A_1^2\int_1^2\frac{dA}{A^3} + \frac{2A_1q''}{V_1c_pT_1}\int_1^2\frac{dA_r}{A^2} + \frac{2\rho_1A_1^2gh}{\gamma RT_1}\int_1^2\frac{dA}{A^3}\right] = \frac{\rho_1ghq''}{c_pT_3}\int_1^2 dA_r \qquad (1)$$

The results obtained from the above model were compared with numerical results from the self-developed CFD computer code (Chitsomboon, 2001a). This CFD code solved the full two-dimensional, compressible Navier–Stokes equations using an implicit finite volume methodology. The test cases investigated represent the solar chimney system with a roof radius of 100 m, roof height of 2 m and chimney radius of 4 m. Two parameters were used in the test: (1) the chimney height, and (2) the insolation. Good agreements between analytical and