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One-dimensional analysis of compressible flow in solar chimney power plants

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ABSTRACT

A novel theoretical approach for the calculation of the buoyancy driven air flow in all constitutive parts (entrance to collector, collector, turbines, collector-to-chimney transition section and chimney) of a solar chimney power plant is presented in the paper. It consists in the use of one-dimensional model of flow. The flow in the collector and the chimney is considered as compressible, while the flow in entrance to collector, turbines and collector-to-chimney transition section is treated as incompressible. Differential equations that describe the flow in the collector and in the chimney, together with algebraic equations that describe the flow in other parts of the plant are simultaneously solved. As a result, distribution of basic physical quantities, like velocity, temperature, pressure and density, in the collector and the chimney are obtained. The model is tested on two solar chimney power plants: well known Manzanares plant and Enviromission plant. The obtained results are in good agreement with measured results from Manzanares plant known in literature, together with predicted values of turbine power and turbine pressure drop for Enviromission plant. In addition, dimensional analysis of the model equations is performed and the results for mass flow rate, available turbine power, chimney height, etc. are presented. These results can be used as reliable prediction of the performance of solar chimney power plants.

1. Introduction

Development of energy systems which can provide clean and sustainable energy is one of the most important tasks nowadays. One example of generating this kind of energy is solar chimney power plant (SCPP) which relies on natural driving force, i.e. energy from the Sun. The solar energy transforms first into mechanical energy and then into electrical one. The process of producing energy in solar chimney power plant has been a topic of intensive research in previous decades, especially in the last decade.

Schematic representation of solar chimney power plant is shown in Fig. 1. It has three essential elements: collector, chimney and turbines. The collector consists of a transparent roof and the ground on the collector floor. The roof of the collector is directly exposed to solar radiation. Since it is made of transparent material, radiation heats the ground. This creates the greenhouse effect, so the air under the collector roof is heated. Due to the buoyancy effect, continuous air flow in the collector is established, directed from the perimeter to the center of the collector where chimney is located. This thermal and kinetic energy of the air is used to generate electricity via one or several turbines. Turbines can be placed horizontally at the base of the chimney, or vertically. Detailed analysis about performance of turbines in different configurations can be found in Fluri and Von Backström (2008).

There have been a lot of theoretical research of air flow in solar chimney power plants. Pretorius (2004), Pretorius and Kröger (2006) and Pretorius (2007) present one-dimensional conservation equations for air flow in collector and chimney derived from conservation principles for elementary control volume. Solving these equations simultaneously with draught equations, Pretorius (2007) evaluates the performance of a large scale solar chimney power plant. Bernardes et al. (2003) develop comprehensive algebraic model which describes the performance of solar chimneys. Authors used their model to estimate power output of solar chimney power plant as well as to examine the effect of various ambient conditions and structural dimensions on the power output. Koonsrisuk and Chitsomboon (2013) also develop algebraic model to estimate the performance of solar chimney power plants, and they investigate the optimum ratio between the turbine extraction pressure and available driving pressure. They also use dimensional analysis to evaluate turbine power output.

The flow inside the chimney is treated analytically by Von Backström and Gannon (2000) and by Von Backström (2003), by

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Nomenclature

A_{coll}	area of collect or (m^2)
$\widetilde{D}$	dimensionless diameter of collector
$\widetilde{D}_1$	diameter to height ratio of collector
$\widetilde{H}$	dimensionless collector height
$\widetilde{S}$	characteristic dimensionless parameter of collector
d	chimney diameter (m)
D_1	collector outer diameter (m)
D_2	collector inner diameter (m)
F	Froude number
f	Darcy friction factor in collector
f_g	Darcy friction factor for collector ground
f_r	Darcy friction factor for collector roof
g	gravitational acceleration ($g = 9.81\ m/s^2$ x)
H	collector height at arbitrary position (m)
H_1	height of collector inlet cross-section (m)
H_4	height of chimney inlet cross-section (m)
H_5	height of chimney outlet cross-section (m)
I	heat from solar irradiation (W/m^2)
K_m	overall efficiency parameter of solar chimney power plant
M	Mach number
m	standard atmosphere lapse rate ($m = 6.5 \times 10^{-3}$ K/m)
N_G	turbine output power (W)
P	dimensionless pressure
p	local pressure (Pa)
p_0	total pressure (Pa)
p_a	atmospheric pressure at zero level in still air (Pa)
Δp_t	turbine pressure drop (Pa)
P_m	turbine hydraulic power (W)
R	gas constant of air ($R = 287.15$ J/(kg K))
r	radial coordinate (m)
S	total amount of heat received by air in collector (W/m^2)
s	entropy per unit mass (J/kg)
T	local temperature (K)
T_0	total temperature (K)
T_a	ambient temperature at zero level in still air (K)
V	dimensionless velocity
v	local velocity (m/s)
X	dimensionless coordinate
Y_m	turbine work per unit mass (J/kg)
Z	dimensionless coordinate
$\dot{m}$	mass flow rate (kg/s)

Greek symbols

η_{coll}	collector efficiency
η_t	turbine efficiency
γ	ratio of specific heat capacities ($\gamma = 1.4$ for air)
λ	Darcy friction coefficient in chimney
ρ	local density (kg/m^3)
ρ_0	total density (kg/m^3)
ζ_1	entrance loss coefficient in collector
ζ_m	intake loss coefficient of bell mouth

Abbreviations

SCPP	solar chimney power plant
1-D	one-dimensional

Subscripts

1, 2, 3, 4, 5	cross-section denotations
a	atmospheric conditions at zero level
ch	chimney
$coll$	collector

employing one-dimensional model of flow. They express logarithmic differentials of characteristic physical quantities in terms of the local value of the Mach number and draw important conclusions concerned with the effect of compressibility. They also discuss the possible effect of cross-section area variation upon the flow in the chimney, and in particular upon the energy loss at the exit cross-section. Zhou et al. (2009) develop numerical model including three-dimensional Navier-Stokes equations to evaluate

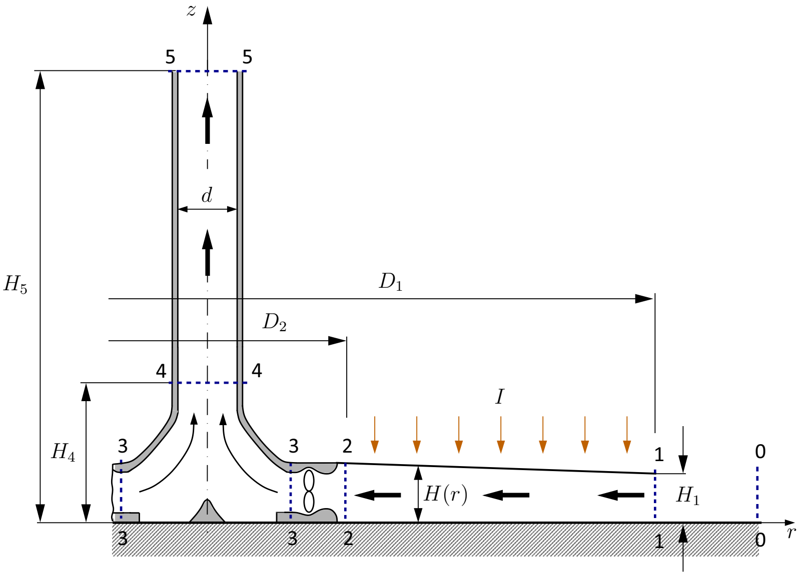

Fig. 1. Axi-symmetric view of characteristic geometrical parameters and sections of the flow, in which turbines are placed horizontally.