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Natural convection enhancement in an asymmetrically heated channel-chimney system

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ABSTRACT

In this paper, a numerical study is performed in order to analyze the effect of adding a chimney to a vertical open channel. The channel is heated asymmetrically at uniform heat flux while the chimney is symmetric and wider than the channel. The thermal and dynamic aspects of the channel-chimney system (T chimney) are studied by varying the width and the height of the chimney while the aspect ratio of the channel is kept fixed. The main objective of this work is to determine the optimal geometric parameters of the chimney: the expansion ratio B (chimney width normalized by the channel width) and the extension ratio Er (chimney height normalized by the channel height), that maximize the mass flow rate (G) and the average Nusselt number (Nu_a). More than four hundred numerical simulations have been carried out at modified Rayleigh numbers ranging from 10^2 to 5×10^4 (laminar regime). The computations allowed the identification of three types of system responses. The flow structure and the pressure field were also analyzed to elucidate why the increase of the chimney width can improve or deteriorate the mass flow rate and the heat transfer. Finally, appropriate correlations have been proposed for determining the optimal configurations and the corresponding enhancement of the mass flow rate and the heat transfer coefficient.

1. Introduction

Laminar natural convection in vertical channels has been widely studied experimentally and numerically because of their occurrence in many technological applications such as solar collectors, passive ventilation of buildings, cooling of electronic equipment and nuclear reactors.

To enhance the limited performances of the heated vertical channel, several modified configurations have been proposed. Some authors added straight adiabatic extensions in the upstream and downstream channel [1,2]. Others have placed internal objects, as auxiliary plates [3,4] or obstructions [5,6].

One of the most attractive modified channel configurations is the channel-chimney system. This configuration is obtained by means of the placement of adiabatic extensions downstream of the heated channel. These configurations depend on the Rayleigh number and the dimensionless geometrical parameters, such as the channel aspect ratio, the expansion ratio (chimney width normalized by the channel width) and the extension ratio (chimney length normalized by the channel length). In the following, a review of the numerical and experimental studies on the channel-chimney system is given.

The first research on the “chimney effect” was carried out by Haaland and Sparrow [7]. They investigated natural convection in a vertical channel-chimney system with heat sources situated at the channel inlet. The analysis was carried out numerically by means of the boundary-layer approximation. Oosthuizen [8] investigated a symmetrically heated channel with uniform wall temperature. Numerical results showed that significant increases in heat transfer rate were obtained only with very long adiabatic extensions downstream of the heated channel.

Experimental investigations of natural convection in air, in a channel-chimney system, heated symmetrically at uniform heat flux were carried out in Refs. [9,10]. In Ref. [9], the main results indicate that some optimal configurations of this system can enhance the heat transfer up to 20% and reduce the maximum wall temperature significantly. In Ref. [10], the results are presented in

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Nomenclature

Ar	channel aspect ratio ($Ar = h/b$)
b	channel width (m)
b'	chimney width (m)
B	expansion ratio ($B = b'/b$)
Er	extension ratio ($Er = h'/h$)
g	acceleration due to the gravity (m s^{-2})
G	dimensionless mass flow rate
h	channel height (m)
h'	chimney height (m)
$hconv$	convective heat transfer coefficient (W m^{-2} K^{-1})
Nu	local Nusselt number
Nu_{a0}	average Nusselt number
p	pressure (Pa)
P	dimensionless pressure
Pr	Prandtl number
q	heat flux (W m^{-2})
Ra	Rayleigh number
Ra^*	modified Rayleigh number ($Ra^* = Ra/Ar$)
t	dimensionless time
t'	time (s)
T	dimensionless temperature
u,w	velocity component along (x,z)-direction (m s^{-1})
U,W	dimensionless velocity components
x,z	Cartesian coordinates
X,Z	dimensionless coordinates

Greek symbols

β	coefficient of volumetric expansion (K^{-1})
θ	temperature (K)
υ	kinematic viscosity (m^2 s^{-1})
ρ	density (kg m^{-3})
Δ	difference between two values
α	thermal diffusivity (m^2 s^{-2})
λ	thermal conductivity (W m^{-1} K^{-1})

Subscripts

0	simple channel
max	maximum value
opt	optimum value

terms of local air temperature measurements inside the system. Different fluid motion regions are also detected inside the chimney. Finally, monomial correlation equations between the local Nusselt number, the modified Rayleigh number and the geometric parameters are proposed. An experimental study on natural convection in a channel-chimney system heated symmetrically and asymmetrically was conducted by Auletta et al. [11]. Correlation equations between dimensionless maximum wall temperature, Rayleigh number and geometrical parameters were proposed.

A numerical simulation of natural convection in a channel-chimney system heated symmetrically at uniform heat flux was performed in Andreozzi et al. [12]. The analysis allowed a comparison between different configurations in order to identify the optimal ones in terms of minimum wall temperature. For the same problem, a parametric analysis is carried out in Ref. [13]. Main results show that the optimal expansion ratio values depend strongly on the Rayleigh number and extension ratio values and slightly on the channel aspect ratio. Correlations for dimensionless mass flow rate, maximum wall temperature and average Nusselt number, in terms of Rayleigh number and dimensionless geometric parameters were presented. In Ref. [14], the authors analyzed the thermal and fluid dynamic behaviors in the channel chimney system, taking into account different geometrical and thermal variables. In this study, the flow separation and reattachment along the adiabatic wall was evaluated. The estimation of critical conditions related to the beginning of flow separation and complete down flow is given in terms of order of magnitude of Rayleigh and Froude numbers. Moreover, it was remarked that the steady-state analysis was not completely able to describe the unstable nature of cold inflow.

For the channel-chimney system with asymmetrical heating, two experimental investigations were carried out by Manca et al. [15,16]. An experimental investigation on air natural convection in an asymmetrically heated vertical channel with a symmetric chimney was carried out in Manca et al. [15]. Results were obtained for different geometrical parameters and wall heat fluxes. Dimensionless maximum wall temperatures and Nusselt numbers were correlated to process parameters. The authors claimed that the addition of downstream unheated extensions improves the thermal performance of the channel for some configurations. Manca et al. [16] conducted experimental study of natural convection in a channel-chimney system where the chimney is geometrically asymmetric (one extension is coplanar to the unheated part of the channel and the distance between the extensions is equal to or greater than the channel width). The comparison between a system with an asymmetric chimney and a system with a symmetric chimney exhibited a similar thermal performance in terms of heated wall temperature profiles.

Extensive parametric studies of the channel-chimney system were performed in previous study, mainly by Auletta et al. [11] and Andreozzi et al. [13]. However, in these investigations the geometric parameters are varied with steps not sufficiently small to detect critical phenomena and determine the optimal configurations. To our knowledge and despite some numerical references carried out for the channel-chimney system heated symmetrically [12,14,17], there is a terrible lack in numerical studies related to asymmetric heating. In addition, in the few experimental work carried out [10,11,15,16], the thermal aspect was dominant and the dynamic behavior of the flow (mass flow rate and flow structure) was practically absent. Indeed, the measurement of the induced mass flow is not easy in this type of problems.

In our paper, a numerical simulation of natural convection in a channel-chimney system (T chimney) is performed. The channel is heated asymmetrically at uniform heat flux while the chimney is symmetric and wider than the channel. Thermal and dynamic aspects of the problem are studied by varying the width and the height of the chimney while the channel aspect ratio is kept fixed. The main objective of this work is to determine the optimal configurations that maximize the mass flow rate and the average Nusselt number and to propose appropriate correlations for these quantities. The flow structure and the pressure field are also analyzed to explain the system responses for different geometrical parameters and various Rayleigh numbers. In particular, we elucidate why the increase of the chimney width can improve or deteriorate the mass flow rate.

2. Problem formulation

Fig. 1 schematically shows the channel-chimney system made up of a vertical channel heated asymmetrically at uniform heat flux (q) and two parallel adiabatic extensions ‘chimney’ placed