International Journal of Heat and Mass Transfer 55 (2012) 6077–6089

Contents lists available at SciVerse ScienceDirect

International Journal of Heat and Mass Transfer

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

Numerical investigation of transient natural convection in a vertical channel-chimney system symmetrically heated at uniform heat flux

Assunta Andreozzi [a], Bernardo Buonomo [b], Oronzio Manca [b,*]

[a] Dipartimento di Energetica, TErmofluidodinamica applicata e Condizionamenti ambientali, Università degli Studi di Napoli Federico II, Piazzale Tecchio 80, 80125 Napoli, Italy
[b] Dipartimento di Ingegneria Aerospaziale e Meccanica – Seconda Università degli Studi di Napoli, Real Casa dell'Annunziata, Via Roma 29, 81031 Aversa, CE, Italy

ARTICLE INFO

Article history:
Received 16 January 2012
Received in revised form 7 June 2012
Accepted 9 June 2012
Available online 4 July 2012

Keywords:
Transient natural convection
Vertical channel chimney
Thermal design
Laminar flow
Numerical simulation

ABSTRACT

In the present numerical investigation, a transient numerical analysis for natural convection in air, between two vertical parallel plates (channel), heated at uniform heat flux, with adiabatic parallel plates downstream (chimney), is carried out by means of the finite volume method. The analyzed transient problem is two-dimensional and laminar. The computational domain is made up of the channel-chimney system, and two reservoirs, placed upstream the channel and downstream the chimney. The reservoirs are important because they simulate the thermal and fluid dynamic behaviors far away from the inflow and outflow regions. Results are presented in terms of wall temperature and air velocity profiles. They are given at different Rayleigh number and expansion ratios (chimney gap/channel gap) for a fixed channel aspect ratio (channel height/channel gap) equal to 10 and extension ratio (channel-chimney height/channel height) equal to 2.0. Wall temperature profiles over a period show the presence of overshoots and undershoots. The comparison among the maximum wall temperatures shows that the simple channel is the most critical configuration at steady state condition, but it is the best configuration during the transient heating at the first overshoot. As indicated by the temperature profiles, average Nusselt number profiles over a period of consideration show minimum and maximum values and oscillations before the steady state. Stream function fields allow to observe the development of fluid dynamic structures inside the channel-chimney system, particularly how and when the cold inflow is present and develops.

1. Introduction

Natural convection between heated vertical parallel plates is a physical system frequently employed in technological applications, such as thermal control in electronic equipments, nuclear reactors, solar collectors and chemical vapor deposition reactors and it has been extensively studied both experimentally and numerically [1–5]. The need to improve heat transfer in natural convection explains the reason behind the discovery of find new configurations or to analyze standard configurations to carry out optimal geometrical parameters for a higher heat transfer rate and transient behaviors for a suitable thermal design [2,6–19]. A very simple method, which allows for improvement of the chimney effect and consequently heat transfer rate in vertical channels and other configurations, is that of placing parallel adiabatic extensions downstream heated configurations [20].

Several investigations on vertical channel-chimney systems have been accomplished as recently reported in [3,14,18]. Subsequently a short review of the numerical studies on adiabatic extensions downstream of a heated channel is reported.

The first research on the chimney effects was accomplished by Haaland and Sparrow [20]. A vertical channel with point source or distributed heat source situated at channel inlet was investigated. The analysis was carried out by means of the boundary layer approximation. A numerical study on the natural convection in an isothermal vertical parallel-plates with straight adiabatic downstream extensions was carried out in [21]. The boundary layer approximation was employed. A numerical investigation on unheated chimney attached to a vertical isothermal tube was accomplished in [22]. The effect of the chimney diameter, which is larger than the tube diameter, was analyzed for the first time. The problem was examined by numerically solving the full elliptic governing equations on an enlarged computational domain, containing the tube-chimney system. The vertical chimney-channel system was studied numerically and experimentally in [23]. The parallel walls of the channel were isothermal and the unheated extensions had various length and width. The numerical solution of the full elliptic form of the governing equations was obtained by means of a finite element discretization on a computational domain equal to the channel-chimney system. The computations were carried

---

* Corresponding author. Tel.: +39 0815010217; fax: +39 0815010204.
E-mail addresses: assunta.andreozzi@unina.it (A. Andreozzi), bernardo.buonomo@unina2.it (B. Buonomo), oronzio.manca@unina2.it (O. Manca).

0017-9310/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijheatmasstransfer.2012.06.021

Nomenclature

a	thermal diffusivity, m^2/s
b	channel spacing, m
B	chimney gap, m
g	acceleration due to the gravity, m/s^2
Gr	Grashof number, Eq. (5)
k	thermal conductivity, W/(m K)
L	channel-chimney height, m
L_h	channel plate height, m
L_X	height of the reservoir, m
L_Y	width of the reservoir, m
Nu	average Nusselt number, Eq. (6)
p	pressure, Pa
P	dimensionless pressure, Eq. (5)
Pr	Prandtl number, Eq. (5)
$\dot{q}$	heat flux, W/m^2
Ra	Rayleigh number, Eq. (5)
t	time, s
T	temperature, K
u,v	velocity components along x,y, m/s
U,V	dimensionless velocity components, Eq. (5)
x,y	coordinates, m
X,Y	dimensionless coordinates, Eq. (5)

Greek symbols

β	volumetric coefficient of expansion, 1/K
θ	dimensionless temperature, Eq. (5)
ν	kinematic viscosity, m^2/s
ψ	stream function, m^2/s
Ψ	dimensionless stream function, Eq. (5)
ρ	density, kg/m^3
τ	dimensionless time, Eq. (5)
ω	vorticity, 1/s
Ω	dimensionless vorticity, Eq. (5)

Subscripts

∞	free stream condition
max	maximum value
os	overshoot
ss	steady state
w	channel wall

out using the commercial code FIDAP and the inlet boundary conditions were based on the Jeffrey-Hamel flow. A periodic isothermal vertical channel expanded-chimney was examined in [24]. Each single subsystem channel-chimney was equal to the analyzed configuration in [23]. The full elliptic form of governing equations was numerically solved using the finite element method and the computational domain was a single channel-chimney system and an upstream reservoir.

A numerical study on isoflux channels using the elliptic form of the governing equations was conducted in [25]. A composite I-shaped computational domain was employed in order to obtain a more realistic model. The finite volume technique was employed in the numerical simulation. A numerical simulation of a channel-chimney system was carried out in [26]. The mode and the reason for the deterioration of the "chimney effect" were emphasized. It was connected to the cold inflow at the outlet section and this effect was more prominent at higher Rayleigh number. A parametric analysis extending the previous work given in [26] was carried out in [27]. Thermal management of channel-chimney systems was accomplished in terms of maximum wall temperature, mass flow rate and average Nusselt number. Results showed 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 also proposed. An in depth analysis on fluid motion behaviors in a channel chimney system, taking into account geometrical, fluid dynamic and thermal variables, was accomplished in [18]. The evaluation of the flow separation and reattachment along the adiabatic wall of the chimney was provided. Some guidelines, to evaluate critical conditions related to the beginning of flow separation and complete downflow, were provided as a function 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.

It seems that numerical investigations on transient natural convection in vertical channel have been carried out only for simple channel configurations. A numerical study with the boundary layer approximation was carried out in [28]. Results showed that, for uniform wall temperature, the ratio of the minimum heat transfer to the steady state heat transfer decreases with the length of the channel, and for uniform heat flux, an overheating was observed with maximum transient temperature greater than the steady state value. A transient numerical investigation in an extended domain, which allowed for thermal and fluid dynamic behaviors downstream of the channel, was carried out [29]. The elliptic-type governing equations were solved in a domain with reservoirs upstream and downstream of the channel. The time development of the flow and the thermal structures inside the computational domain were obtained. The thermal transient between the symmetrically heated plates obtained by considering the time variation of the imposed wall heat flux was analyzed in [30]. An open cavity with permeable walls, with all the boundaries open to the surroundings, which considered only one half of the entire domain, was assumed as a computational domain. It was observed that the transient Nusselt number decreases up to the time when convective effects become relevant, then it gradually increases. A numerical investigation on transient numerical analysis, for laminar natural convection in air, between two vertical parallel plates, heated at uniform heat flux by means of the finite volume method, was carried out in [15]. A composite I-shaped computational domain was employed and the simulation allowed to detect the complex structures of the flow inside and outside the channel. Overshoot and undershoot of the wall temperature were observed and for configurations with small aspect ratios, time oscillations in the initial transient regime were observed. Inside the channel conductive and convective regimes as well as an inverse fluid motion were observed and transient average Nusselt number presented oscillations before the steady-state. An interesting suggestion about the thermal design of the channel in natural convection was remarked: temperature overshoots of maximum wall temperature, as limit condition, should be taken into account because these values could be higher than the wall temperatures attained at steady-state conditions.

To the authors' best knowledge, it seems that there are no numerical studies on the transient natural convection in vertical channel-chimney systems though more information on cold inflow and thermal design is very important. The main motivation of the present investigation is to eliminate this lack of knowledge.

In the present study a transient numerical analysis for natural convection in air, between two vertical parallel plates (channel), heated at uniform heat flux, with adiabatic parallel plates downstream (chimney), is carried out by means of the finite volume