Energy and Buildings 43 (2011) 3696–3703

Contents lists available at SciVerse ScienceDirect

Energy and Buildings

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

Heat transfer and mass flow correlations for ventilated facades

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ARTICLE INFO

Article history:
Received 15 April 2011
Received in revised form
27 September 2011
Accepted 3 October 2011

Keywords:
Ventilated facade
Natural convection
Nusselt number
Mass flow rate
CFD

ABSTRACT

Natural convection heat transfer and mass flow phenomena in ventilated facades are numerically investigated in this work. The study focuses on the determination of accurate results in terms of correlations for the average Nusselt number at each of the two walls of the ventilated facade and for the mass flow induced in the cavity, as functions of the descriptive geometrical and thermal parameters, covering the laminar region with modified Rayleigh numbers $Ra_b{}^*$ ranging from 10^0 to 10^5. Comparison with available experimental data and numerical results is first presented to validate the validity of the numerical procedure. Then correlations are proposed for the heat and the mass flow in symmetrically and asymmetrically heated channels. These correlations are developed as a contribution for the thermal models of ventilated facades, in which the accurate determination of heat transfer coefficients and induced mass flow rates are of great importance to establish the energetic performances of the element.

1. Introduction

The implementation of ventilated facades in buildings has been the object of broad application especially in recent years, due to its advantages in terms of thermal performance and energy savings among others related to aesthetics, noise protection or flexibility in construction, among others. In the summer period, the shading of the external wall combined with the induced air flow due to natural convection into the heated cavity, causes a reduction of the heat loads of the adjacent rooms.

There are many publications in which thermal models of ventilated facades are studied with different assumptions for the calculation of the convective coefficients and the induced mass flow. Balocco [1], defined a complete model of the element in which a steady state energy balance is applied to a control volume and basic equations are solved with a finite element code with an iterative procedure, calculating at each element of the channel height, the surfaces and air mass temperatures. The Nusselt number inside the channel is calculated using an expression that only depends on the Reynolds and the Prandtl numbers. Marinosci [2], experimentally and numerically investigated the thermal behavior of a rainscreen ventilated facade. The model of the test building was created by using the simulation program ESP-r, which is a transient simulation program based on the finite volume technique. The convective heat transfer is computed by using the Alamdari–Hammond correlations, as a function of the difference between the surface and the room air temperatures and the surface height. Ruiz [3] developed a transient thermal model of a ventilated facade based on the finite differences method. The Nusselt number in the cavity is calculated using Sparrow's correlation, as a function of the aspect ratio and the Rayleigh number based on the height of the channel.

These different assumptions have great importance in the thermal performances of ventilated facades and affect to critical aspects like the peak cooling load, air temperature and surface temperatures, as concluded in Ref. [4].

The evaluation of ventilated facades energy performances requires a detailed thermofluid-dynamic analysis of the ventilated channel and an accurate calculation of the heat transfer coefficients and the induced mass flow. Laminar free convection phenomena in vertical channels have been widely studied for many years and a large number of experimental and numerical works published on laminar natural convection exist, studying different geometries and boundary conditions at the walls of the channel (uniform temperature or heat flux). Most of these works are focused on the study of the average Nusselt number and only a few of them also consider the flow rate. Elenbaas [5] was a pioneer in the detailed study of the thermal characteristics of symmetrically heated vertical channels. Using a semiempirical analysis, he obtained the average Nusselt number as function of a modified Rayleigh number, $Ra_b{}^*$, and confirmed his results with experiments. Different numerical studies can be found in the literature using diverse strategies that are in good agreement with Elenbaas results, like Bodoia and Osterle [6], Bar-Cohen and Rohsenow [7], Rohsenow et al. [8] or Sparrow et al.

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doi:10.1016/j.enbuild.2011.10.002

Nomenclature

b	channel width (m)
L	channel height (m)
b_{dom}	computational domain width (m)
L_{dom}	computational domain height (m)
C_P	specific heat of air at constant pressure (J kg^{-1} K^{-1})
g	gravitational acceleration (m s^{-2})
Ra_b	Rayleigh number (Eq. (1))
Ra_b^*	modified Rayleigh number (Eq. (2))
r_t	temperature ratio parameter (Eq. (3))
Nu	average Nusselt number (Eq. (4))
M	nondimensional mass flow rate (Eq. (5))
$\triangle T$	temperature difference, K (Eq. (6))
Nu_y	local Nusselt number
Pr	Prandtl number
q_m	mass flow rate (kg s^{-1})
T	temperature (K)
Q	heat flux (W)
h	convective heat transfer coefficient (W m^{-2} K^{-1})
UWT	uniform wall temperature
CFD	computational fluid dynamics

Greek letters

β	thermal expansion coefficient (K^{-1})
υ	kinematic viscosity (m^2 s^{-1})
α	thermal diffusivity (m^2 s^{-1})
ρ	density (kg m^{-3})
κ	thermal conductivity (W m^{-1} K^{-1})

Subscripts

o	ambient
h	hot
c	cold
ch	channel
sim	obtained by simulation
dom	computational domain
isot	isothermal

[9], to cite some of them. Olsson [10] made a literature review of the symmetrically heated channel case, in order to investigate correlations for the average Nusselt number and the flow rate, suggesting new formulas based on asymptotic estimations and adaptation to data available in the literature. Gan [11] investigated solar heated open cavities, including solar chimneys and double facades, using a commercial CFD package to predict buoyant air flow and flow rates in the cavities.

Velocity and pressure values at the inlet and exit sections of such open cavities are not known a priori in case of pure natural convection. To overcome this dilemma of two unknown but dependent quantities, either the value of velocity or pressure (or their derivatives) can be assumed at the inlet and exit sections of the channel, or a relation between these two variables. Another possibility to overcome this difficulty is to consider an extended computational domain well beyond the physical configuration, imposing the boundary conditions far from the heated surfaces where undisturbed atmospheric pressure condition can be applied. Kheireddinein [12] considered such an extended domain. On the other hand, numerous computational works only consider a pre-entrance region and a post-exit region in order to reduce the computational domain. Kettleborough [13], Nakamura et al. [14] and Naylor et al. [15] have, as an example, reported results for the uniform wall temperature condition (UWT) including a pre-entrance region but not a post-exit region. A post-exit region was included in the investigations of Chang and Lin [16], Ramanathan and Kumar [17], Shy et al. [18], Morrone et al. [19], Campo et al. [20], and Morrone [21]. As the calculated average Nusselt number and the flow rate can be greatly influenced by the size of these computational domains, it is important to perform a size independence study of these domains.

Moreover, the local Nusselt number and the flow rate induced in the channel have not been studied as widely as the global Nusselt number. Some works can be found in the literature that report results for the local Nusselt number, like Anwar [22] and like Ayinde et al. [23] for the mass flow rate, who obtained velocity profiles experimentally, using particle image velocimetry (PIV) system. Some authors obtained these results through a purely numerical approach like Kaiser et al. [24], Olsson [10], Nakamura et al. [14] or Naylor et al. [15].

Due to the different temperatures conditions between the interior and the exterior of a building, a ventilated facade is, most of the times, asymmetrically heated. Contrary to the symmetrically heated case, only a few articles can be found in the literature for asymmetrically heated channels with different constant temperatures that focus on the heat transfer separately at each wall. Roeleveld et al. [25] numerically studied this problem including a "pre-entry" plenum and obtained correlations for the average Nusselt number at each of the walls. They obtained the average Nusselt number at the cold wall from a heat balance using a correlation for the average Nusselt number at the hot wall and an existing correlation for the overall channel convective heat transfer, but no attention was paid in their study to the mass flow induced in the channel.

The above literature review indicates that further investigations are required to obtain complete sets of results, for the different Nusselt numbers at both channel walls and also for the induced mass flow rate. Therefore, the objective of the present study is to investigate the heat and mass flow induced by natural convection in isothermal symmetrically or asymmetrically heated ventilated facades and to derive appropriate correlations for these quantities. This is presented in this paper as a first step for laminar flow conditions, with modified Rayleigh numbers $Ra_b{}^*$ ranging from 10^0 to 10^5.

2. Problem formulation and solution procedure

2.1. Problem formulation

The ventilated facade geometry and the variables of interest are shown in Fig. 1. An open cavity is formed between the interior construction (typically including some thermal insulation) and the exterior skin, which could be made of different materials like ceramic, stone or metal. This finite channel of height L and spacing b is formed by two isothermal surfaces at temperatures T_h (hot) and T_c (cold), while the ambient outdoor temperature is T_o.

The buoyancy induced flow in the channel is supposed to be unidirectional so $T_h \geq T_c \geq T_o$. When T_h and T_c are equal, the channel is symmetrically heated and otherwise the channel is asymmetrically heated. Due to heat transfer between air and the surfaces of the channel, a buoyant flow is induced in the channel. Due to boundary conditions at the walls, the heat flux at the hot wall is always from the wall to the air but at the cold wall, the heat can either be transferred from air to the cold wall or to the cold wall to air, depending on the local temperature difference.

The characteristic parameters of the problem are the Rayleigh number based on the width, Ra_b, the average modified Rayleigh