International Journal of Heat and Mass Transfer 128 (2019) 794–806

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Investigation on optimization of the thermal performance for compressible laminar natural convection flow in open-ended vertical channel

Deboprasad Talukdar *, Chung-Gang Li, Makoto Tsubokura

Graduate School of System Informatics, Kobe University, Kobe 657 8501, Japan

ARTICLE INFO

Article history:
Received 13 April 2018
Received in revised form 2 September 2018
Accepted 8 September 2018

Keywords:
Laminar natural convection
Compressible flow
Numerical simulation
Optimum thermal performance
Optimal channel aspect ratio
Open-ended vertical channel

ABSTRACT

The present paper focuses on the optimization of the thermal performance for compressible laminar natural convection flow induced under high-temperature difference in an open-ended vertical channel by optimizing the channel inter-plate spacing using numerical simulation. The present investigation is conducted for a wide range of Rayleigh number (Ra) 10^4 to 10^7 in channel heated asymmetrically by uniform surface temperature with air (Pr 0.72) as working fluid. Several values of channel gap between plates, new modified preconditioned all-speed Roe scheme along with dual time stepping technique and modified Local One-dimensional Inviscid (LODI) relations as channel inlet and outlet boundary conditions suitable for compressible laminar natural convection is employed for the current simulation. Heat transfer rate in terms of average Nusselt number is obtained for all Rayleigh number and channel aspect ratio is obtained. Variation of thermal and velocity profiles, the variation of average Nusselt number and mass flow rate into the channel for the combination of each Rayleigh number and channel aspect ratio is reported. From the results obtained, a correlation for optimum aspect ratio with Rayleigh number which maximizes the heat transfer within the channel is presented.

1. Introduction

Phenomena of heat transfer by natural convection in open-ended vertical channels are applied in numerous practical applications like air ventilation within building utilizing solar energy, cooling of nuclear reactors and heat management in electronic equipment. Extensive research of natural convection in vertical channel and associated configurations [1–10] have been conducted in the past.

Burek and Habeb [11] and Chen et al. [12] carried out an experimental investigation using the solar-chimney model with uniform heat flux for varying channel aspect ratio. Lu et al. [13] conducted experimental research in laminar natural convection in a vertical channel with large aspect ratio configuration similar to coolant flow passage in plate type nuclear fuel reactors. But these investigations do not stress upon the fact of the existence of optimum aspect ratio for maximizing the heat transfer inside the channel. Through numerical investigation of laminar natural convection flow, Silva and Gosselin [14] obtained results for optimum aspect ratio for maximum thermal performance for asymmetrically heated L and C shaped channel. In their study, it was pointed that when the aspect ratio (channel gap to height ratio) is smaller than the optimum aspect ratio, the chimney effect is pronounced and fluid temperature reaches the wall temperature before the end of the channel. So, heat transfer towards the upper side of the channel is very small. Whereas, the chimney effect decreases and boundary layer flow takes place when the aspect ratio is greater than the optimum value. This phenomenon put emphasis on the existence of an optimum aspect ratio for optimum heat transfer. Zamora and Kaiser [15] investigated optimum wall-to-wall spacing in a symmetrically heated solar chimney-shaped channel on laminar and turbulent flows for a wide range of Rayleigh number. This study found that an optimum aspect ratio for maximum heat transfer and for maximum mass flow rate is different and pointed out that optimization of thermal performance and dynamic performance is not possible simultaneously. This behaviour can be pointed out due to changing flow pattern with increasing aspect ratio. Morrone et al. [16] numerically investigated optimum plate separation in an I-shaped vertical channel by additionally introducing large reservoir spaces at the channel extreme. Correlation of optimum values for aspect ratio as a function of Grashop number was presented from the investigation. The investigations in

* Corresponding author.
E-mail addresses: 141x704x@stu.kobe-u.ac.jp (D. Talukdar), cgli@aquamarine.kobe-u.ac.jp (C.-G. Li), tsubo@tiger.kobe-u.ac.jp (M. Tsubokura).

https://doi.org/10.1016/j.ijheatmasstransfer.2018.09.034
0017-9310/

Nomenclature

T_0	ambient fluid temperature (K)
T_w	hot wall temperature (K)
ΔT	temperature difference (K)
P	pressure (Pa)
P_0	ambient fluid pressure (Pa)
Pr	Prandtl number
Ra	Rayleigh number
Nu_x	local Nusselt number
$\underline{Nu}$	average Nusselt number
m_x	mass flow rate (kg/s)
H	height of channel (m)
L_0	length of channel section upstream to- heated surface (m)
L	length of heated surface (m)
W_d	channel inter-plate spacing (m)
W_d/L	channel aspect ratio
N_x	number of grids in x coordinate
N_y	number of grids in y coordinate
x, y	Cartesian coordinates (m)
u, v	velocities in x and y direction (m/s)
R	gas constant (J/kg/K)
g	acceleration due to gravity (m/s^2)
M_{ref}	Mach number ($\sqrt{(g\beta\Delta TL)/(\gamma RT_0)}$)
M_{local}	local Mach number

Greek symbols

β	volumetric expansion coefficient (1/K)
μ	dynamic viscosity (Ns/m^2)
ν	kinematic viscosity, μ/ρ (m^2/s)
γ	specific heat ratio
ρ	density (kg/m^3)
ρ_0	ambient fluid density (kg/m^3)
γ_d	grid density constant

Superscripts

k	artificial time stepping iteration count
n	physical time stepping iteration count

Subscripts

i	grid index in stream-wise direction
j	grid index in wall normal direction
L, R	left and right cell interface value

[14-16] have been conducted with the incompressible fluid and Boussinesq approximation along with constant fluid properties.

Lee et al. [17] in an experimental investigation of the solar chimney for optimal heat collection pointed that, although many research has been directed towards investigating performance related to the indoor comfort of building through solar chimney model, however, few studies have been devoted in the higher temperature range (> 120 °C). A review article by Narasimham [18] for natural convection cooling of electronic equipment pointed that modern-day electronic packages have to cope with temperature difference typically exceeding 90–100 °C. For such practical and high-temperature difference (> 30 K) engineering applications of natural convection, investigations using governing equations without Boussinesq approximation produces accurate solutions as pointed out by Gray and Giorgini [19]. Also, Zamora et al. [20] showed that that the effect of not considering fluid property variable with temperature could be significant in terms of accuracy of the solutions. Quere et al. [28] highlighted that natural convection flow induced under high-temperature difference becomes compressible with direct coupling between continuity, momentum and energy equation through the equation of state and temperature dependent viscosity and thermal conductivity of the fluid. Under such considerations, numerical investigations with compressible flow solver become necessary. In [29], modified preconditioned All-speed Roe scheme was shown to be competent and accurate for numerical investigation of compressible natural convection flow with the large temperature difference.

Numerical investigation of natural convection flow in channel-chimney system by Brangeon et al. [30] highlighted the importance of choosing local pressure boundary conditions at the inlet and outlet section of open channel since the induced flow through the channel depends on the combined effect of buoyancy forces generated and pressure difference existing between the inside and outside of channel. Additionally, the mass flow rate and velocity at inlet and outlet are not known prior to the simulation. Pressure calculated based on local flow velocity representing the local Bernoulli boundary condition was shown to achieve improved results than that obtained using global boundary conditions (pressure calculated based on assigned mass flow rate) at the inlet and outlet section of the channel. Similar kind of global boundary condition at inlet and outlet was considered in [15] and study in [16] adopted extended large domain at the open boundaries. Fu et al. [27] proposed modified local one dimensional inviscid (LODI) relations as non-reflecting boundary conditions suitable for an open boundary applicable in compressible natural convection flow through a channel. Such boundary condition does not require any prior information of the flow at the inlet and outlet but calculated based on local flow conditions and also would not allow the acoustic waves induced by the compressibility of flow to be reflected at the inlet and outlet.

Chenoweth and Paolucci [31] concluded in their study of natural convection under large temperature difference that the velocity and temperature field strongly depends on the temperature difference parameter ($\varepsilon = (T_H - T_c)/(T_H + T_c)$) although the average Nusselt number being independent of the parameter. Also, it is concluded that extrapolation of any result obtained under Boussinesq approximation with an intention to be used for cases with large temperature difference might lead to considerable risk. Hence, based on literature review it can be noted here that the current investigation of optimizing thermal performance in natural convection induced under high temperature difference ($\Delta T = 110$ K) through an open-ended vertical channel holds significance in view of practical engineering applications and not addressed before in referred literatures [14–16].

This paper focusses on the objective to maximize the thermal performance parameterized in terms of average Nusselt number for compressible natural convection induced under high-temperature difference in an open-ended vertical channel by optimizing the channel aspect ratio (ratio of channel inter-plate spacing and length of the heat source). The current study is presented for the whole range of steady laminar flow $10^4 \leq Ra \leq 10^7$ and for a fixed temperature difference of 110 K. The channel is heated asymmetrically with a partial section of one wall maintained at a uniform surface temperature and all other walls considered adiabatic. The global constraint used in the simulation is the total height of the channel (H) and the length of the channel (L_0) upstream of the heated surface. The length of the heat source is only increased in dimension with increasing Rayleigh number.