Environmental Engineering

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Recent Advances in Fluid Dynamics with Environmental Applications

Springer

Environmental Science and Engineering

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ISSN 1863-5520 ISSN 1863-5539 (electronic)
Environmental Science and Engineering
ISSN 1431-2492
Environmental Engineering
ISBN 978-3-319-27964-0 ISBN 978-3-319-27965-7 (eBook)
DOI 10.1007/978-3-319-27965-7

Library of Congress Control Number: 2016937508

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Preface

Fluid dynamics has had significant advances in recent years as a result of the current vertiginous development of computational power. This expansion has nowadays enabled the implementation of numerical high-resolution simulations as never before. For instance, fluid dynamic cosmological simulations are presently being run using up to 10^{12} particles, and turbulence simulations with up to 10^{11} mesh elements. Experimental advances are also present. Just to mention, some computer methods to reconstruct the topography of a liquid's free surface have been developed in recent times bringing into play high-definition digital images. With these tools, phenomena like wave turbulence or wave breaking are at the present being investigated. The development of different computer architectures offers now the possibility to work out fluid dynamics equations with alternative methods. Recent simulations with Smoothed Particle Hydrodynamics have been done using both multicore architectures and GPUs. The advantage of this approach is that the method is meshless, so it is suitable for modeling systems with moving and irregular boundaries.

Today the Mexican fluid dynamics community is involved in the research of novel topics using the advancements mentioned above. To name but a few topics, we draw attention to the studies in microfluidics and their relation to real problems like secondary oil recovery, while—in a different vein—studies in the field of magnetohydrodynamics are now being conducted on the mutual conversion of mechanical and electromagnetic energy.

The papers included in this book are selected contributions of two meetings held in Mexico during 2014. The first one was the Spring School "Enzo Levi" on May 12–13, 2014. The second event was the Annual Meeting of the Division of Fluid Dynamics of the Mexican Physical Society on November 18–20, 2014. In both meetings, an important fraction of the Mexican community working on fluid dynamics gathered, including students, researchers, and lecturers of several institutions from all over Mexico. We are pleased to acknowledge the contributions and attendance of all colleagues of the institutes and universities that were present in one or both meetings. Among several institutions we would like to mention: UNAM, CINVESTAV, CICESE, IPN, UAM-A, ININ, and UNACH.

The 2014 "Enzo Levi" Spring School was hosted by the recently created Aeronautical University of Querétaro (UNAQ). This university was established with the aim to provide technical assistance to the aeronautical industries located in the Mexican state of Querétaro.

The number of participants attending the "Enzo Levi" conference was approximately 150. During this meeting, a total of 11 lectures were delivered by renowned scientists from Mexico and abroad. The topics covered by the lectures were diverse: waves produced by ships, aerogenerator designs, drag reduction in planes, turbulence at low temperatures, fluid mechanics in cosmology, and in coastal systems, among other topics. Of the lectures delivered during the meeting, some of them stand out. We would like to mention those given by Jens Sorensen, a distinguished professor of the Technical University of Denmark. His first lecture dealt with aerodynamic principles and then was centered on renewable energy, in particular on how to increase wind power. His second lecture was devoted to wind farms and the problems associated with the wakes produced by turbines. Marc Rabaud from the University Paris-Sud delivered two lectures on the wakes produced by fast boats and small obstacles, respectively. In the first case, the gravity is relevant while in the second case both gravity and capillarity are involved. With respect to aeronautics, Fausto Sánchez Cruz, from the University of Nuevo León, spoke about the development of winglets to reduce the drag on aircrafts and on the modifications of the wing end to dissipate or attenuate the wingtip vortices. In a succeeding lecture, Hugo Carmona Orvañanos spoke about the Coanda effect and its application to the reduction of the takeoff length. Enrico Fonda from New York University spoke on two aspects of turbulence, namely, experiments at low temperatures to attain high Reynolds numbers and on vorticity in superfluids. The lecture by Jorge Cervantes from Instituto Nacional de Investigaciones Nucleares (ININ) concerned fluid dynamics in the frame of cosmology in which relativistic and non-relativistic effects were reviewed. Finally, Erick Lopez Sanchez from UNAM spoke on numerical simulations of vortices in tidal induced flows in a channel flushing to the sea.

During the 2014 "Enzo Levi" Spring School, the UNAQ local organizer arranged an open house event where participants visited the aeronautical school premises including laboratories, test workshops, and toured around various airplanes donated to the institution for student training. This experience allowed visitors and local participants, researchers, and students of different institutes to establish fruitful academic links in the vibrant field of applications of fluid mechanics to aerodynamics.

The annual meeting of the Mexican Division of Fluid Dynamics was held during three days at the recently established Mesoamerican Centre for Theoretical Physics in Tuxtla Gutierrez, Chiapas, a state located south of the country. This conference was attended by approximately 250 participants. Conference activities included: oral sessions, a gallery of fluid motion and open lectures on fluid mechanics aimed at an audience of informed non-specialists in the specific topic of the talk.

Prominent scientists from Mexico and other countries delivered lectures on new trends in fluids dynamics. In relation to the contents of lectures, Tomas Bohr, from the Physics Department of the Technical University of Denmark, talked on the analogy between quantum mechanics and the behavior of a bouncing drop on the surface of a vibrating fluid. Yves Couder from the University of Paris Diderot also commented on the mentioned analogy. Tomas Bohr made a critical review of the double slit experiments. In a succeeding lecture, Joseph Niemela of the International Centre for Theoretical Physics (ICTP) gave a talk on experiments in turbulence for high Reynolds and Taylor numbers, which conveys to a better understanding of this phenomenon. For its part, Chantal Staquet from Joseph Fourier University in France talked about the statistical properties of internal waves in the ocean, their nonlinear interactions, and their importance in geophysical flows. Another lecture concerning waves was given by Francisco Ocampo Torres from CICESE, a research institute located at the Baja California Peninsula, in the north of Mexico. He spoke about the interactions between the ocean and the atmosphere, with emphasis on the surface waves and their role in the oceanic and atmospheric circulation. It is also important to mention the talk given by Nicolas Mujica from the University of Chile, related to a vibrating granular material and the occurrence of phase transitions. Finally, Vadim Kourdioumov of Centro de Investigaciones Energéticas, Madrid, gave a lecture on the propagation of flames in narrow channels. Some of these lectures have been included in this book.

The book contains review and research papers, covering a wide spectrum of topics in fluid dynamics. It is divided into four parts, each one having papers based on invited lectures and a selection of works presented in the annual 2014 meeting. The first part is devoted to vortices and circulation phenomena. It contains contributions like vortices produced by deformable objects (a flexible plate and a flexible cylinder). Three papers treating some applications to aerodynamics, for example, structures generated behind flapping foils or the study of the Coanda effect to increase the lift of airplanes. The part includes also a paper about the vortices created in tidal induced flows and two papers on the technique known as Background Oriented Schlieren. Finally, a paper of the crossflow in a non-isothermal open cavity is included. The second part is entitled "Environmental Applications". This part includes experimental and numerical investigations of the modeling of hydrodynamic processes in lagoons, offshore, and in atmospheric systems in Latin American countries such as Colombia and Mexico. In addition, the part includes a paper on fractals and rainfalls and other one on the evaluation of a cooling system. The third part is devoted to the fluid–structure interaction. In this part there are papers on magnetohydrodynamics, microfluidics, applications to the automotive industry, and an introduction to novel techniques like the fractional Navier–Stokes equation. There are in addition papers on the formation of Rayleigh jets, the trajectories of water and sand jets, the flow of viscoelastic fluids, and so on. In this part of the book there are contributions that reflect some of the new trends of the research developed by the Mexican community of fluid dynamics. The last part is entitled "General Fluid Dynamics and Applications". In this part a relevant paper of Tomas Bohr is included which deals with the analogy between a bouncing drop and quantum mechanics. There are also two papers on astronomical applications of fluid dynamics, namely the dynamics of novae and the X-ray outflow in active galactic nuclei. This part contains a paper written by Nicola Mujica and Rodrigo Soto on the dynamics of non-cohesive granular media. Other papers deal with fundamental problems such as heat propagation or the use of new computing capabilities. Such is the case of a paper in which the method of Smoothed Particle Hydrodynamics is programmed to run in parallel using GPUs and multicore architectures.

The book is aimed at senior and graduate students, and scientists in the field of physics, engineering, and chemistry that have an interest in fluid dynamics from the experimental and theoretical points of view. The material includes recent advances in experimental and theoretical fluid dynamics and is adequate for both teaching and research. The invited lectures are introductory and avoid the use of complicated mathematics.

The editors are grateful to the institutions that made possible the International Enzo Levi Spring School 2014, and the XX National Congress of the Fluid Dynamics Division of the Mexican Physical Society, particularly the Consejo Nacional de Ciencia y Tecnología (CONACYT), the Sociedad Mexicana de Física (SMF), the Aeronautical University of Queretaro (UNAQ), the Mesoamerican Centre for Theoretical Physics in Tuxtla Gutierrez, Chiapas, the Universidad Nacional Autónoma de México (UNAM), the ESIME of the Instituto Politécnico Nacional (IPN), Cinvestav-Abacus, the Universidad Autónoma Metropolitana-Azcapotzalco (UAM-A), and the Instituto Nacional de Investigaciones Nucleares (ININ).

Mexico City
January 2016

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Contents

Part I Vortex and Circulation Phenomena

Part II Environmental Applications

Part III Fluid–Structure Interaction

Part IV General Fluid Dynamics and Applications

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Part I
Vortex and Circulation Phenomena

Numerical Study of the Cross Flow in a Non-isothermal Open Cavity

G.E. Ovando-Chacon, S.L. Ovando-Chacon, J.C. Prince-Avelino, A. Rodriguez-León and A. Servin-Martínez

Abstract In the present work, the laminar steady state fluid dynamics and heat transfer, in a two-dimensional open cavity with a cross flow due to a secondary jet injected at the top wall, are analyzed. The numerical study is carried out for a Reynolds number of 500 with different Richardson and Prandtl numbers. A hot plate is provided on the bottom of the cavity which generates the heating of the fluid. In order to investigate the effect of the length of the plate two different plate sizes are considered. The governing equations of continuity, momentum and energy for incompressible flow are solved by the finite element method combined with the splitting operator scheme. It is studied the streamlines and isotherms inside the cavity and it is analyzed the average Nusselt number, the average temperature and the outlet temperature as a function of the Richardson and Prandtl numbers. It is observed that the Prandtl and Richardson numbers play a major role in the thermal and fluid behavior of the flow inside the cavity with a cross flow. Moreover the results indicate that a secondary jet injected at the top wall enhances the average Nusselt number.

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J. Klapp et al. (eds.), *Recent Advances in Fluid Dynamics with Environmental Applications*, Environmental Science and Engineering, DOI 10.1007/978-3-319-27965-7_1

1 Introduction

The numerical simulation of the flow in an open cavity with heat transfer is an important issue in many technological processes. Madadi et al. (2008) evaluated the optimal location of discrete heat source placed inside a ventilated cavity. Oztop et al. (2011) numerically examined the steady natural convection in an open cavity filled with porous media. Radhakrishnan et al. (2007) reported experimental and numerical investigation of mixed convection from a heat generating element in a ventilated cavity. Zhao et al. (2011) analyzed the characteristics of transition from laminar to chaotic mixed convection in a two-dimensional multiple ventilated cavity. Najam et al. (2002) presented the simulation of mixed convection in a T form cavity, heated with constant heat flux and ventilated from below with a vertical jet. Mamun et al. (2010) studied the effect of a heated hollow cylinder on mixed convection in a ventilated cavity. Mahmoudi et al. (2010) numerically examined the effect of the inlet and the outlet locations on the mixed convection flow and on the temperature field in a vented square cavity. Deng et al. (2004) investigated the laminar mixed convection in a two-dimensional displacement ventilated enclosure with discrete heat and contaminant sources. The main aim of this numerical investigation is to study the complex interaction of a cross flow with a perpendicular jet inside an open cavity in presence of a heating surface.

2 Problem Formulation

A sketch of the enclosure configuration studied is shown in Fig. 1. 2D numerical simulations are carried out inside an open square cavity ($H/W = 1$) with a cross flow due to a secondary jet injected at the top wall. The main fluid enters from the lower left side wall and leaves the cavity through the upper right side wall. The Reynolds number ($Re = U_m W/\nu$), based on the velocity of the main inlet flow U_m and the width W of the cavity, studied in this investigation is $Re = 500$ for different Richardson and Prandtl numbers. In order to induce the buoyancy effect, a hot plate is located on the bottom of the cavity which generates the heating of the fluid. Two different lengths W_p of the plate are considered. The main entrance and exit of the cavity are fixed to $h = 0.25\ W$, meanwhile the inlet of the jet on the top wall is fixed to $a = 0.05\ W$.

The governing equations for a non-isothermal incompressible steady state flow, in a two-dimensional domain Ω, are given as:

$$-\frac{1}{\mathrm{Re}}\Delta\mathbf{u}+\mathbf{u}\cdot\nabla\mathbf{u}+\nabla p=RiTj \text{ in } \Omega, \tag{1}$$

$$\nabla\cdot\mathbf{u}=0 \text{ in } \Omega, \tag{2}$$

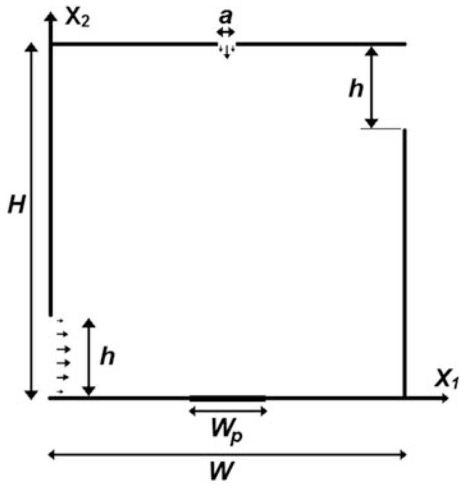

Fig. 1 Geometry of the open cavity with a cross flow due to secondary jet injected at the top wall

$$-\frac{1}{Pe}\Delta T+\mathbf{u}\cdot\nabla T=0 \text{ in } \Omega, \tag{3}$$

In the above equations $\boldsymbol{u} = (u_1, u_2)$ is the velocity vector, being u_1 and u_2 the horizontal and vertical velocity components, respectively; ν is the kinematic viscosity, p is the pressure, T is the temperature and j is the vertical unitary vector. In the governing equations, the Richardson number, Reynolds number and Peclet number are defined as follow:

$$Ri=g\beta W(T_h-T_c)/U_m^2, \quad \mathrm{Re}=U_w W/\nu, \quad Pe=\mathrm{Re}\,\mathrm{Pr}, \tag{4}$$

where g is the gravity, β is the compressibility coefficient, T_h is the hot temperature, T_c is the cold temperature. No slip boundary conditions ($u_1 = u_2 = 0$) were established in all the walls of the cavity and adiabatic walls ($\partial T/\partial n = 0$) were supposed except in the bottom wall where the heating takes places. The temperatures of the jet and main inlet flows are fixed to $T = T_c$, meanwhile the temperature of the isothermal heater plate is fixed to $T = T_h$. The non-dimensional values of this temperature were $T_c = 0$ and $T_h = 1$. The boundary conditions of the main inlet flow were $u_1 = U_m$, and $u_2 = 0$. On the outlet flow was imposed $\partial u/\partial n = 0$.

3 Numerical Solution of the Model and Results Validation

Numerical simulations are conducted for the laminar flow inside an open cavity for the Reynolds number of *500* with Richardson and Prandtl numbers ranging between *0.01* and *10*. A 2D geometry is used (see Fig. 1) and several types of meshing are included in order to obtain independent results from the numerical parameters. The governing equation are solved with the finite element method combined with the operator splitting scheme, see Glowinski (2003). The convergence analysis is done for three different meshes with resolution of 25050, 27200 and 30080 elements. An analysis of the temperature profiles on the middle horizontal and vertical lines indicates that the largest difference of the results between the meshes of 25050 and 27200 is 8.5 %, while the maximum difference of the results between the meshes of 27200 and 30080 is 1.0 %. The analysis is also done for the velocity components, for all cases the worst relative error between the meshes of 27200 and 30080 is less than 1.0 %. The whole simulations presented in this paper are performed for a cavity with 30080 elements.

4 Results and Discussions

Figure 2 shows the streamlines, for $W_p = 0.10$. For the lowest Richardson number a strong jet is observed from the entrance to the exit of the cavity, above this diagonal jet three vortices are formed as a result of the boundary layer detachment from the surface driven by the fluid motion that crosses the cavity and its interaction with the flow of the secondary jet injected at the top wall, further a clockwise vortex is formed at the bottom left corner of the cavity. As the Richardson number is increased the strength of the diagonal stream decreases, for $Ri = 1.0$ and $Pr = 0.01$ only two vortices can be observed due to the circulation of the fluid injected at the top inlet. For the natural convection regime $Ri = 10$ with $Pr = 0.01$, a strong circular vortex is formed, which occupies the whole of the cavity. Increasing the Prandtl number to $Pr = 1.0$, it is observed that three vortices tend to form above the main stream, however when the Prandtl number is increased to Pr = 10 and natural convection regime dominates, these vortices merge to form only one vortex above of the main stream which moves from left to right and then rises toward the outlet of the cavity. For the lowest Richardson number, the velocity field remains without changes as the Prandtl number is increased, however as the Richardson and Prandtl numbers are increased different configuration of the streamlines are formed, as a result of the buoyancy effect.

Figure 3 shows the streamlines, for $W_p = 0.75$. For forced convection regime the distribution and number of vortices inside the cavity are independent of the length of the heating plate and the thermal properties of the fluid, see left panels of Figs. 2 and 3. For $Ri = 1.0$, the size and distribution of the vortices depend on the length of the heating plate, see middles vertical panels of Figs. 2 and 3. For $Ri = 10$, the number and size of the vortices tends to change with the variations of the length of the heating surface as the Prandtl number is increased. On both cases, $W_p = 0.10$ and 0.75, it can be observed that the secondary jet tends to mix totally with the main stream in the natural convection regime due to the buoyancy effect.

Figure 4 shows the isotherms, for $W_p = 0.10$. For all cases, it can be seen that the temperature contours are clustered around the heater, a hot temperature region tends to grow up toward the inside of the cavity due to the thermal plume rises above of the heater and the heat fluxes from this one to the interior part of the cavity

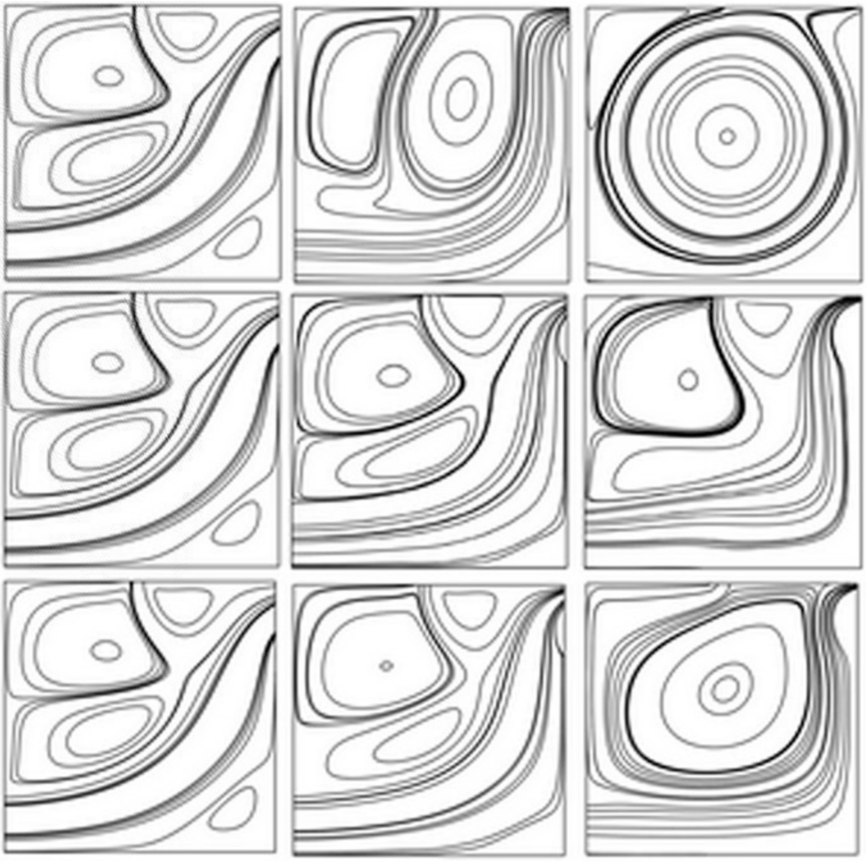

Fig. 2 Streamlines for $W_p = 0.10$. Top: $Pr = 0.01$. Middle: $Pr = 1.0$. Bottom: $Pr = 10.0$. Left: $Ri = 0.01$. Middle: $Ri = 1.0$. Right: $Ri = 10.0$

heating the fluid located at the neighborhood of the heat source. For the lowest Prandtl number the isotherms elongates toward the whole part of the cavity due to the thermal diffusion regime, however as Prandtl number is increased the contours tend to elongate from the heater toward the exit of the cavity due to the cooling of the fluid as a result of the flow motion that crosses the cavity.

Figure 5 shows the isotherms, for $W_p = 0.75$. Due to the increase in the length of the heating plate, the fluid inside the cavity remains hotter than the previous case. The contours tend to intensify as a result of the more energy injected. For low Richardson numbers the temperature contours are affected by the forced convection regime, however for the highest Richardson number the contours tend to follow the behavior of the streamlines, as the Prandtl number is increased, driven by the natural convection regime. For both lengths of the heating surface, a perturbation of the main isotherms at the central part of the top wall is observed due to the injection of cool fluid. For low Prandtl number the isotherms of the secondary jet are

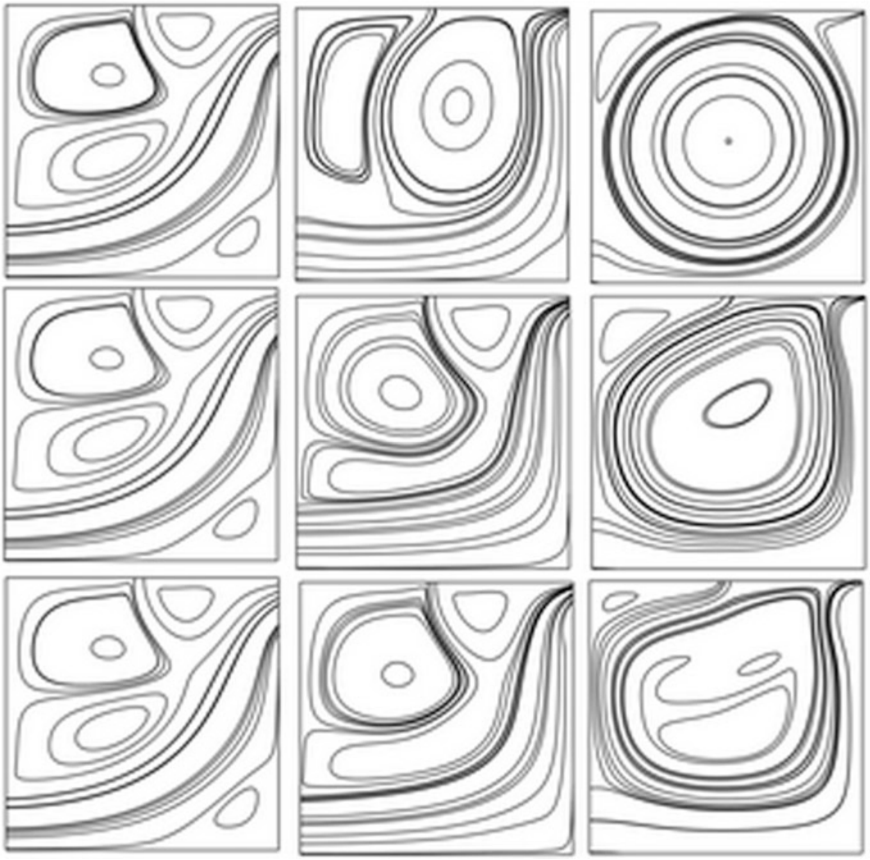

Fig. 3 Streamlines for $W_p = 0.75$. Top: $Pr = 0.01$. Middle: $Pr = 1.0$. Bottom: $Pr = 10.0$. Left: $Ri = 0.01$. Middle: $Ri = 1.0$. Right: $Ri = 10.0$

clustered at the neighborhood of the top entrance, however as the Prandtl number is increased the thermal contours of the secondary jet elongates interacting with the main contours. On the other hand, the temperature gradients increase as the Richardson and Prandtl numbers also increase. The highest temperatures are reached when natural convection and thermal diffusion occurs, meanwhile the lowest temperatures are reached when forced convection and momentum diffusion dominate.

Figure 6 shows the average Nusselt number as a function of the Richardson number for $W_p = 0.1$ (left) and $W_p = 0.75$ (right) with Prandtl numbers in the range of [0.01–10]. For the lowest length of the heater, the average Nusselt numbers are lower than the corresponding values of the highest length of the heater. This variation is increased as the Prandtl increases. Furthermore, for a given Richardson number the Nusselt number increases as the Prandtl number increases, this behavior

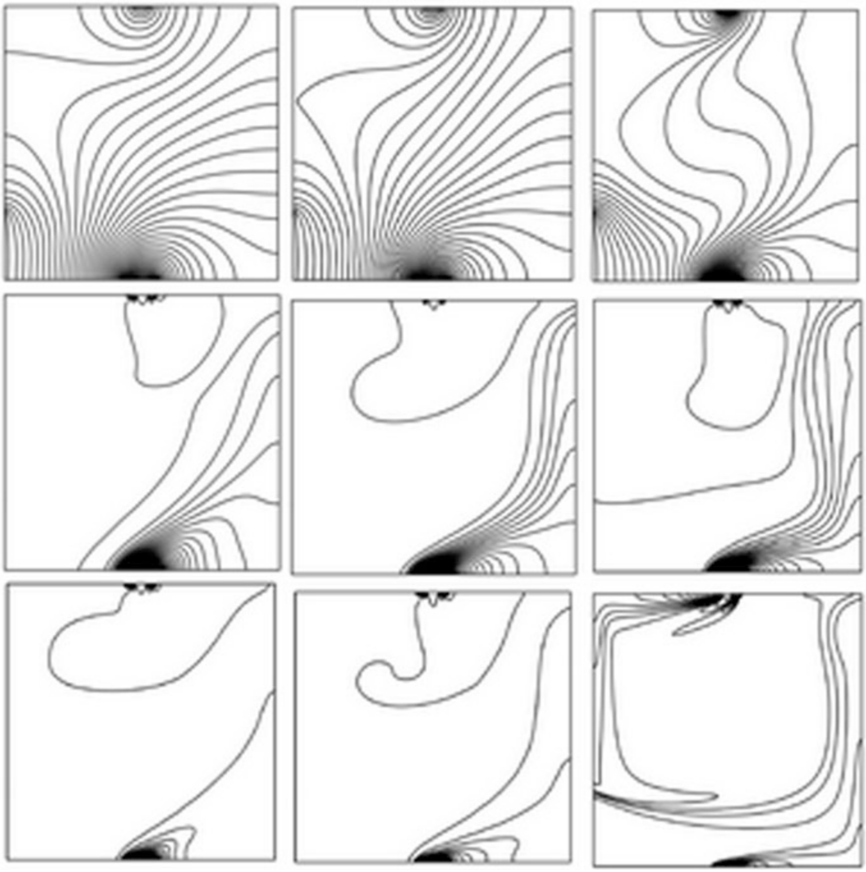

Fig. 4 Isotherms for $W_p = 0.10$. Top: $Pr = 0.01$. Middle: $Pr = 1.0$. Bottom: $Pr = 10.0$. Left: $Ri = 0.01$. Middle: $Ri = 1.0$. Right: $Ri = 10.0$

is observed for both lengths of the heater. This implies that the cooling of the cavity is enhanced when momentum dissipation is augmented. On the other hand, for a given Prandtl number the Nusselt number is increased as the Richardson number is increased, this variation is intensified as Prandtl number increases, this implies that natural convection regime enhances the heat transfer rate inside the cavity.

Figure 7 depicts the effect of the Richardson and Prandtl numbers on the average temperature inside the cavity, for $W_p = 0.1$ (left) and $Wp = 0.75$ (right). For $Ri \leq 1$, the average temperature of the fluid decreased slightly for $Pr = 0.1$, 1.0 and 10 when $W_p = 0.1$, this behavior is also observed when $W_p = 0.75$ for $Pr = 10$ and 1.0, beyond $Ri = 1$, the average temperature increased as the Richardson number increased. Keeping constant the Richardson number, the average temperature is increased as the Prandtl number decreases due to the fact that the thermal diffusivity

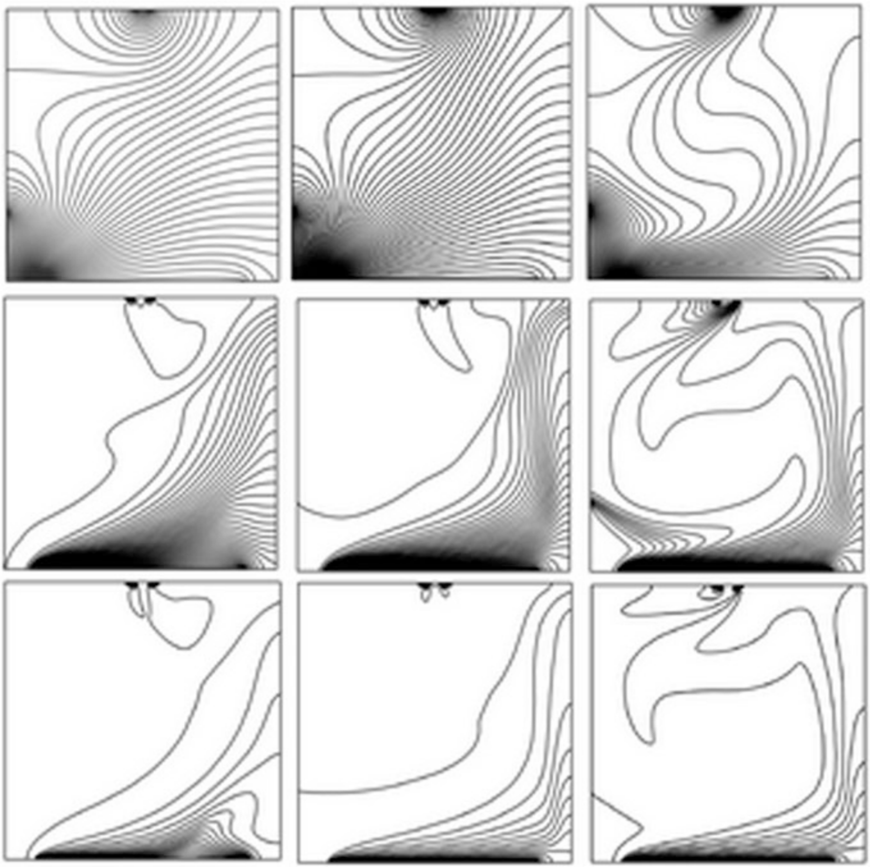

Fig. 5 Isotherms for $W_p = 0.75$. Top: $Pr = 0.01$. Middle: $Pr = 1.0$. Bottom: $Pr = 10.0$. Left: $Ri = 0.01$. Middle: $Ri = 1.0$. Right: $Ri = 10.0$

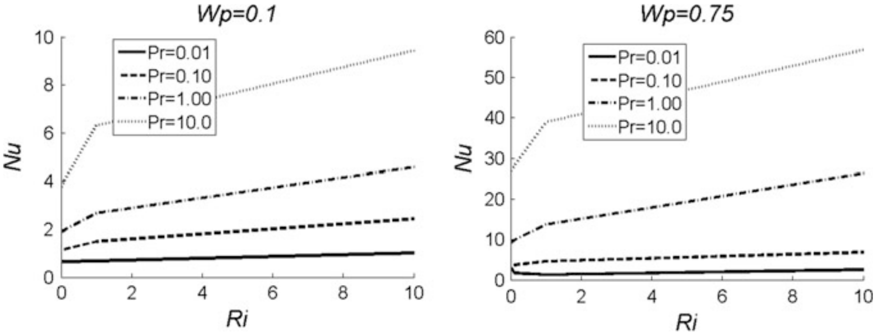

Fig. 6 Average Nusselt number as a function of the Richardson number for two different lengths of the heater with different Prandtl numbers

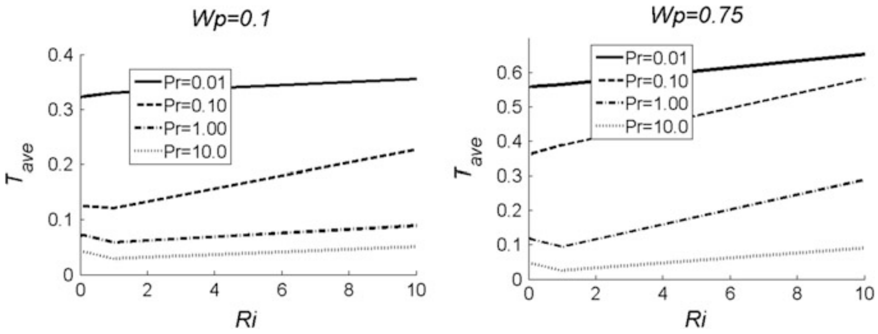

Fig. 7 Average temperature as a function of the Richardson number for two different lengths of the heater with different Prandtl numbers

plays a major role in the heat transfer process. The maximum value of the average temperature is *0.65* for $Ri = 10$, $Pr = 0.01$ and $W_p = 0.75$.

Figure 8 shows the outlet temperature of the fluid at the exit of the cavity is a function of the Richardson number for $W_p = 0.10$ (left) and $W_p = 0.75$ (right) with different Prandtl numbers. For $W_p = 0.10$ the outlet temperature of the fluid is lower than the corresponding values for $W_p = 0.75$. This variation is increased as the Prandtl number increases. Moreover, for a given Prandtl number the outlet temperature of the fluid is increased as the Richardson number is increased, this variation is intensified as Prandtl number increases, this implies that the buoyancy effect enhances the heat transfer rate inside the cavity. On the other hand, for a given Richardson number the outlet temperature of the fluid increases as the Prandtl number decreases, this behavior is observed for both lengths of the heater. This implies that the cooling of the cavity is enhanced when the viscous diffusion rate is augmented.

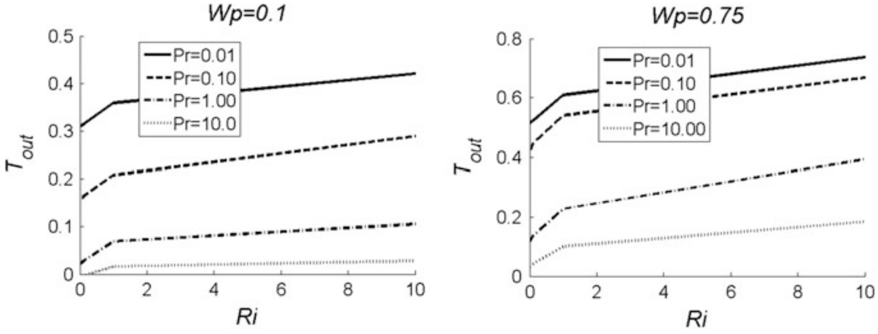

Fig. 8 Outlet temperature as a function of the Richardson number for two different lengths of the heater with different Prandtl numbers