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Achintya Mukhopadhyay
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Advances in Thermo-Fluid Engineering

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Preface

Thermofluid science is an important area of mechanical science and plays a key role in many natural phenomena and technological applications. Apart from the underlying rich and unique physics, this branch of science finds applications in a large number of applications, ranging from energy to thermal management of high-power electronic components and supercomputers, from biomedical engineering to materials processing. The wide diversity in the scales of phenomena where thermofluids play a major role ranging from atmospheric dynamics to micro- and nanoscale phenomena add to the richness of the subject. Consequently, this field has been the subject of extensive research worldwide for the last 100 years and continues to do so. The complexities and nonlinearities inherent in the subject have led to extensive use of sophisticated experimental and numerical techniques in addition to the classical analytical methods. The strong influence of other fields of physics like magnetic and electrical fields and surface chemistry have led to the development of modern thermofluids research as a multiscale Multiphysics discipline. The demands of increasingly stiff competition for commercial viability of engineering systems and stringent environmental regulations have pushed research in this field beyond its traditional boundaries and have led to collaboration of this field with emerging areas of data science like machine learning.

The International Conference on Mechanical Engineering (INCOM) originated at Jadavpur University's Department of Mechanical Engineering to create a global platform for researchers, academics, engineers, and industry professionals to showcase their work and discuss emerging concepts. After a successful inaugural conference in January 2018, plans for subsequent events were disrupted by the pandemic. However, the second edition, INCOM 2024, was finally held on January 5 and 6, 2024, at Jadavpur University, Kolkata. The inaugural ceremony of the Conference was held on the morning of January 5, 2024, at Dr. M. L. Sircar Hall, Indian Association for Cultivation of Science (IACS). Mr. Gautam Ray [Ex-Director (HR and Admin.)—CESC Ltd., President (HR)—Power Group, RPSG and President of BCC&I], Mr. Rambabu Ch. [CEO, AI Airport Services Ltd.] attended the session as guests of honor, while, Pro-Vice Chancellor, Dean, Faculty of Engineering and Technology and Head of the Department, Mechanical Engineering, Jadavpur University, were also present. Shri.

Sanjay Ghosh, ED (Operations) was also present there as special guest on behalf of the Chief Guest Mr. Raghu Ram, Member (Technical), DVC who could not attend the program due to a last-minute emergency call from the Power Ministry. The 2-day event was designed to have plenary and keynote lectures (both online and offline) by eminent personalities of important domains of mechanical engineering. A panel discussion, as a part of the valedictory program, deliberated on current trends of Mechanical Engineering Education in the context of academia and industry needs. The conference also included a session for industry presentations and, of course, parallel technical sessions for contributory papers. There were four plenary lectures distributed over two sessions, while six keynote lectures spread over three sessions.

The editors would like to express their sincere gratitude to a large number of authors from India and abroad for submitting their high-quality work on time and revising it appropriately at short notice. We want to express our special gratitude to our prolific reviewers who reviewed chapters of this monograph and provided their valuable suggestions to improve them. Financial support from various organizations, including the Science and Engineering Research Board (SERB) of India, Indian Oil, Damodar Valley Corporation, CESC, RSB Global, BTL Shrachi, and others was instrumental in making INCOM 2024 a reality.

This book includes selected contributed technical papers presented at the INCOM 24 Conference. Selected papers are purely based on quality and relevance to the theme of thermofluids. However, extended versions (with significant new knowledge to the same topic of the presented paper) of those selected conference papers were rigorously peer-reviewed by experts of that domain knowledge. Only those chapters which could qualify through the review process have been finally accepted. The content of this book is multidisciplinary and very much relevant for understanding the recent trends in thermofluids research.

Contributions to this book cover some of the frontier areas of thermofluids research and its interface with other areas like electromagnetics, control, and machine intelligence. The contributions have been grouped into several parts, based on topical proximity. We would like present a caveat here that some of the papers could indeed fit into more than one of the topical areas. In such cases, we have placed the chapter in the part where it appeared most relevant in our assessment.

We hope that this book will be of great interest and utility to the both beginners including undergraduate and graduate students and doctoral and postdoctoral researchers and experienced professionals in the field of thermofluids.

Jadavpur, India

Achintya Mukhopadhyay
Koushik Ghosh

Introduction

Thermofluids has emerged as a major interdisciplinary subject with relevance to many of the important areas like climate change, energy sustainability, thermal management of high-power devices, and materials processing and manufacturing.

The present volume contains expanded versions of papers in the area of thermofluids, presented at INCOM 2024 held at the Mechanical Engineering Department of Jadavpur University, Kolkata, India, from January 5 to 6, 2024. Based on topical proximity, the chapters have been grouped into nine parts, namely, Magnetic Effects on Thermofluids Phenomena, Soft Computing and Control Applications, Thermofluid Devices, Transport Phenomena in Porous Media, Fluid–Structure Interactions and Thermofluid Phenomena in Presence of Bluff Bodies and Sudden Expansions, Thermofluid Phenomena in Complex Geometries, Electroosmotic Flows and Nanofluids, Transport Phenomena in materials Processing and Manufacturing, and Heat Transfer Augmentation. The contributors to the chapters range from very senior professionals and academics to graduate and undergraduate students.

Achintya Mukhopadhyay
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Dr. Koushik Ghosh is a Professor of Department of Mechanical Engineering at Jadavpur University, Kolkata, India. He received his Master's degree from Jadavpur University, and worked in Bhabha Atomic Research Centre (BARC), Mumbai, India. Dr. Ghosh did his Ph.D. at Jadavpur University. He worked as Post-Doctoral Researcher in Institut de Radioprotection et de SûretéNucléaire (IRSN), France. His teaching and research interests include thermodynamics, heat transfer, boiling and condensation, multiphase flow, transport in porous media and nuclear thermal hydraulics. Dr. Ghosh has published 60 research papers in various international journals in the area of heat and mass transfer and thermal engineering. He has also published 10 book chapters and more than 70 conference papers. He is a life member of Indian Society of Heat and Mass Transfer.

Impact of Conducting Block and System Inclination on Magneto-Hydrodynamic Heat Transport

Anurag Kabiraj, Aditya Raj, Nirmal K. Manna, Nirmalendu Biswas, and Dipak Kumar Mandal

Abstract This study investigates the influence of a central conducting block embedded in fluid flow systems, mimicking thermal systems with obstructions. Numerical solutions of energy, momentum, and continuity equations are employed to analyze pure water-based magneto-thermal systems under classical differential heating. The impact of cavity inclination (φ) and solid-to-fluid conductivity ratios (K_r) is examined at different Rayleigh numbers (Ra) and Hartmann numbers (Ha), keeping block size fixed. Findings reveal higher φ and Ra increase heat transfer rates (average Nusselt number, Nu), irrespective of K_r and Ha values, while Nu decreases with rising Ha. The study establishes the need for both lower and higher thermal conductivities to achieve higher heat transfer rates across all system inclinations, crucial for practical applications. These insights facilitate material selection and inclination angle considerations, holding practical implications for designing and optimizing thermal systems.

Keywords Conjugate heating · Inclined cavity · Natural convection · Nusselt number · Magneto-hydrodynamics (MHD)

1 Introduction

Magneto-hydrodynamic (MHD) heat transport encompasses the intricate interplay of fluid motion, thermal diffusion, and electromagnetic forces, influencing various applications such as stellar plasmas, electronic devices, microchip cooling, and

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medical sciences. The foundational work by De Vahl Davis and Jones [1] in 1983 provided a comparative understanding of natural convection in a square cavity, laying the groundwork for subsequent investigations. Researchers, including Bhave et al. [2], Mahapatra et al. [3], Datta et al. [4], and Biswas et al. [5], explored heat transfer enhancement using adiabatic and isothermal blocks, investigating optimal block sizes and Prandtl number effects. Experimental studies by Sivasubramanian et al. [6] focused on heat transfer enhancement in a channel with staggered blocks, primarily utilizing pure fluids.

The advent of nanofluids introduced new possibilities, with studies by Abbassi et al. [7] and Hussain et al. [8] incorporating nanofluids to analyze thermal convection around a rotating cylinder. Rashad et al. [9] explored MHD nanofluidic convection in a square porous cavity with elliptical blocks, while Sen et al. [10] investigated embedded porous obstacles' impact on fluid flow and thermodynamic irreversibility. Sarkar et al. [11] contributed insights by studying embedded obstacles' effect on convective heat transport, considering flow past semicircular and circular cylinders. Acharya [12] explored the effects of different thermal modes of obstacles in the natural convective transport of Al_2O_3-water nanofluid inside a triangular cavity. Kumar and Mahapatra [13] conducted a comprehensive investigation on thermal convection within a partially open cuboid enclosure featuring a cylindrical obstacle.

The synergies of MHD and buoyancy-induced flow, explored by Manna et al. [14, 15], revealed the unique effects of a magnetic field with multiple bands on a convective heat transport system filled with a porous medium and hybrid nanofluid. Biswas et al. [16] extended this exploration, presenting a narrative on a hybrid nanofluid-filled wavy-walled tilted porous enclosure with a partially active magnetic field. In a subsequent study, Manna et al. [17] investigated the impact of magnetic forces in association with the heating–cooling position on quadrantal thermal systems filled with hybrid nanofluid, providing deeper insights into the interplay of magnetic forces and thermal influences. Chatterjee et al. [18] examined the intricate interplay between natural convection and magnetic fields in a triangular enclosure embedded with inverted triangular thermal obstacles.

Studies, such as Sivaraj and Sheremet [19], highlighted the importance of cavity inclination in MHD natural convection within an inclined square porous cavity with a heat-conducting solid block. Tayebi and Chamkha [20] focused on entropy generation during MHD natural convection with a corrugated conducting block, revealing insights into the thermodynamic aspects of MHD heat transfer. Kardgar [21] contributed by numerically investigating conjugate heat transfer and entropy generation in an inclined enclosure with MHD natural convection, offering valuable insights into the interplay of magnetic fields with inclined geometries. Geridonmez and Oztop [22] explored the effects of a conducting wavy wall, magnetic field, and hybrid nanofluid on entropy generation, enhancing the understanding of the impact of complex boundary conditions on heat transfer.

Limited studies exist under conjugate natural convection embracing magnetohydrodynamic effects and system inclination. Das and Reddy [23] investigated conjugate natural convection heat transfer in the absence of a magnetic field in an inclined square cavity containing a conducting block, providing insights into the interaction of solid conducting surfaces with natural convection flows. Aminossadati and Ghasemi [24] studied conjugate natural convection in an inclined nanofluid-filled enclosure, contributing valuable insights into the understanding of coupled heat transfer phenomena. Further detailed study could be found in refs. [25–31].

Despite significant strides in understanding MHD natural convection and heat transfer enhancements, a notable gap exists in comprehensively studying the combined influence of conducting blocks and system inclination on heat transport. Our investigation aims to address the influence of block conductivity ratio, magnetic field strength, and system inclination on heat transport phenomena from fundamental viewpoints. This study unravels the complex interplay between conducting blocks and system inclination utilizing a common base fluid and explores the need for both low and high thermal conductivities of the solid obstacle to obtain higher heat transfer rates over all ranges of the system inclinations.

2 Mathematical Modeling

The study focuses on a classical differentially heated square enclosure containing a central conducting block, aiming to explore the interaction between heat transfer and magnetic fields. Illustrated in Fig. 1, the enclosure has a heated left side (at T_{h} temperature—Dirichlet Condition) and a cooled right side (at T_{c} temperature—Dirichlet Condition), with a constant perpendicular magnetic field (B) on the sidewalls [32–34]. The other two sides are adiabatic ($\partial T/\partial y = 0$—Neumann Condition). The cavity which is inclined at an angle φ to the horizontal, features a central conducting block with a height equal to half of the cavity's height (H). Water (Prandtl number, $\mathrm{Pr} = 5.83$), commonly used in mono and hybrid nanofluids, is the chosen working fluid.

The derived governing equations encompass the Lorentz and buoyancy forces within the Navier–Stokes equations. The Boussinesq approximation is valid. The fluid's electric conductivity (σ) induces the generation of the Lorentz force upon interaction with the magnetic field. Neglecting minor influences such as viscous dissipation and Joule heating, the dimensionless form of the governing equations, associated variables, and parameters [18, 35] are expressed in Eqs. (1–8), utilizing standard symbols. Specifically, Eqs. (5) and (8) depict the conduction equation for the solid block with a solid-to-fluid conductivity ratio (K_{r}) and the average Nusselt number (Nu), respectively. The equality of fluid–solid interface heat-fluxes is assumed [36–38], and the wall velocity is set to zero.

$$\frac{\partial U}{\partial X} + \frac{\partial V}{\partial Y} = 0 \tag{1}$$

$$\left(U\frac{\partial U}{\partial X} + V\frac{\partial U}{\partial Y}\right) = \mathrm{Pr}\left(\frac{\partial^2 U}{\partial X^2} + \frac{\partial^2 U}{\partial Y^2}\right) - \frac{\partial P}{\partial X} - \theta\,\mathrm{Ra}\,\mathrm{Pr}\cos\varphi \tag{2}$$

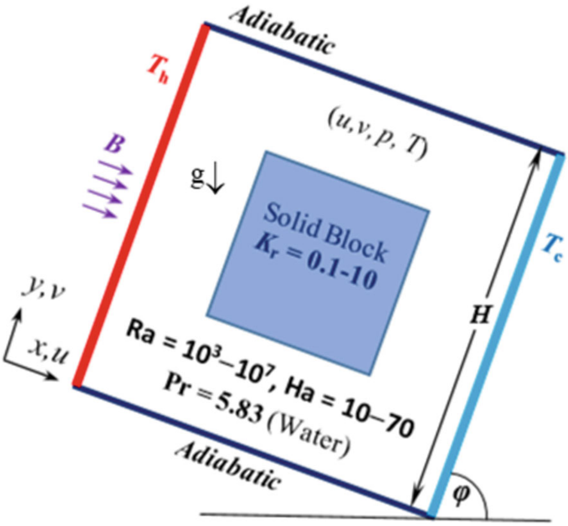

Fig. 1 Problem mimicking real thermal system with a central solid block

$$\left(U\frac{\partial V}{\partial X}+V\frac{\partial V}{\partial Y}\right)=\Pr\left(\frac{\partial^2 V}{\partial X^2}+\frac{\partial^2 V}{\partial Y^2}\right)-\frac{\partial P}{\partial Y}+\theta\,\mathrm{Ra}\,\Pr\sin\varphi-\Pr\mathrm{Ha}^2 V \quad (3)$$

$$\left(U\frac{\partial V}{\partial X}+\frac{\partial V}{\partial Y}\right)=\left(\frac{\partial^2\theta}{\partial X^2}+\frac{\partial^2\theta}{\partial Y^2}\right) \quad (4)$$

$$K_r\left(\frac{\partial^2\theta}{\partial X^2}+\frac{\partial^2\theta}{\partial Y^2}\right)=0 \quad (5)$$

$$[X, Y, U, V, P, \theta]=[(x,y)/H, (u,v)/(\alpha/H), p/(\rho\alpha/H)^2, (T-T_c)/(T_h-T_c)] \quad (6)$$

$$\Pr=\nu/\alpha,\ \mathrm{Ra}=g\beta(T_h-T_c)H^3/\nu\alpha,\ K_r=k_s/k_f,\ \mathrm{Ha}=BH\sqrt{\sigma/\rho\nu} \quad (7)$$

$$\mathrm{Nu}=\int_0^1\left(-\frac{\partial\theta}{\partial X}\right)\bigg|_{\substack{hot\\wall}} dY \quad (8)$$

3 Computational Aspects

The governing equations are solved using the finite element method (FEM) with a direct solver employing Newton's method [18]. A second-order scheme is adopted for the discretization of all the used equations, and convergence is set with a tolerance value below 10^{-6} [39–41]. To ensure the adequacy of the present computation, a competent validation of a similar problem is conducted. Das and Reddy's work [23], involving an embedded central square conducting block in a side-heated and side-cooled square enclosure filled with air (Pr = 0.71), is used for this purpose. The study explores inclination variations of this conjugate heating system from 15° to 90°, along with the thermal conductivity ratio and Rayleigh number. The published results are compared with the present predictions in Table 1, where errors indicated along the rows establish the accuracy of the present computational methodology and the chosen mesh distribution as acceptable.

The details of the grid independence test are illustrated in Table 2, considering $K_r = 3$, $\varphi = 75°$, and Ra = 10^6. The mesh arrangement of the chosen mesh size (Grid-III) is illustrated in Fig. 2, featuring sufficiently finer meshes. [The total element count is 11060, comprising three layers of the finest quad elements near the walls and the rest as triangular shapes with relatively larger sizes away from the walls. The smallest and largest element sizes are 5×10^{-5} and 0.03, respectively, with a smaller growth rate of 1.08. Extra care is taken at the corners of the inner block. Finer meshes are deployed to effectively capture evolving sidewall vortices, particularly at higher Rayleigh numbers.

Table 1 Validation of conjugate heating simulation using Das and Reddy's [23], comparing with published results

Ra	K_r		Average Nusselt number (Nu) at varying inclinations (φ)					
			15°	30°	45°	60°	75°	90°
10^3	0.2	Ref. [23]	0.703	0.709	0.722	0.739	0.730	0.730
		Present	0.709	0.714	0.721	0.729	0.737	0.742
		Error %	−0.801	−0.630	0.070	1.302	−0.968	−1.621
10^4	0.2	Ref. [23]	0.743	0.856	1.043	1.300	1.611	1.906
		Present	0.740	0.840	1.015	1.260	1.549	1.833
		Error %	0.460	1.785	2.739	3.088	3.833	3.871
10^6	5	Ref. [23]	1.628	2.242	3.454	5.411	7.727	8.624
		Present	1.614	2.198	3.403	5.378	7.386	8.593
		Error %	0.850	1.956	1.472	0.613	4.416	0.357

Table 2 Grid study results with Pr = 5.83, $K_r = 3$, $\varphi = 75°$, and Ra = 10^6

Details	Grid-I	Grid-II	Grid-III	Grid-IV
Total elements	2564	5864	11,060	18,588
Element size: min.–max.	5×10^{-3}–0.18	5×10^{-4}–0.13	5×10^{-5}–0.03	5×10^{-5}–0.02
Max. growth rate	1.2	1.2	1.08	1.05
Avg. Nu	7.77	7.75	7.74	7.74

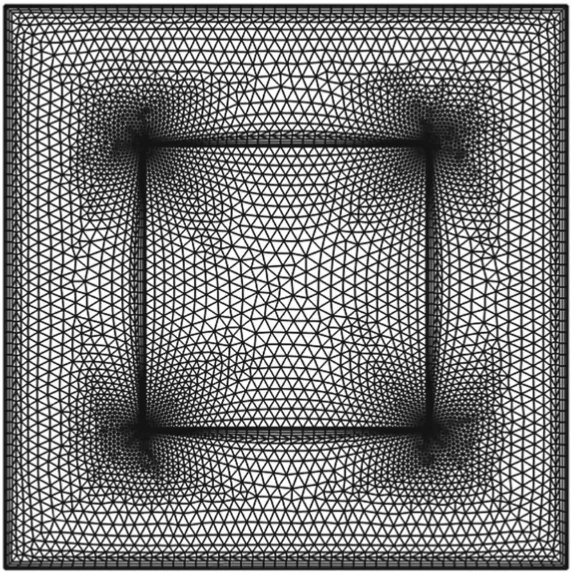

Fig. 2 Mesh arrangement with 11,060 elements, showing very refined meshes (Grid-III)

4 Results and Discussion

This study aims to offer fundamental insights into the interplay of cavity inclination and magnetic fields on heat transport in a conjugate heating configuration. The investigation explores the effects of varying Rayleigh number (Ra), thermal conductivity ratio (K_r), and Hartmann number (Ha). Results are presented in Figs. 3, 4, 5, 6, 7 and 8, where each figure corresponds to different cavity inclinations ranging from $\varphi = 15°$ to $90°$ at $15°$ intervals, subfigures marked by (a–f).

4.1 Buoyancy Effect at Various Inclinations

Figures 3 and 4 illustrate heat and fluid flow characteristics at Ra $= 10^4$ and Ra $= 10^6$, while keeping $K_r = 1$ and Ha $= 10$ constant. In Fig. 3, a substantial increase in Nusselt number (Nu), mentioned below the isotherm plots, is observed as φ and Ra increase, evidenced by densely packed isotherm contours over the active walls. The results show that thermal conduction dominates with thicker boundary layers at Ra $= 10^4$ (Fig. 3A), while thermal convection governs thinner boundary layers at Ra $= 10^6$ (Fig. 3B). This coupling of heat and fluid flow is evident from the governing equations. At very weak flow velocities (Ra $\leq 10^4$), as indicated by streamlines in Fig. 4A, isotherm contours become almost parallel to the heating and cooling walls (Fig. 3A(a–c)). However, they incline strongly rightward with increased convective velocity, ultimately orienting horizontally at Ra $= 10^6$ and $\varphi = 90°$ (Fig. 3B(f)).