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Numerical investigation of buoyancy-driven compressible laminar flow using new method preconditioned all-speed roe scheme

Deboprasad Talukdar[a,*], Chung-Gang Li[b], Makoto Tsubokura[c]

[a] Graduate School of System Informatics, Kobe University, Kobe 657 8501, Japan
[b] Graduate School of System Informatics, Kobe University, Kobe 657 8501, Japan
[c] Faculty of Graduate School of System Informatics, Kobe University, Kobe 657 8501, Japan

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ABSTRACT

In this study, numerical simulation is performed with a focus on the application of new modified preconditioned all-speed Roe scheme to simulate natural convection flows. The new modified preconditioned all-speed Roe Scheme primarily utilizes the local flow parameters for calculation of the coefficients of numerator in dissipation term of the scheme instead of using the global cut-off Mach number strategy (which is advantageous for natural convection flows) and has been shown to have better accuracy than preconditioned Roe Scheme for Low Mach number flows. For the present simulation, the compressible governing equation in conservation form, new modified preconditioned all-speed Roe scheme and dual time stepping are employed. The validation of numerical algorithm is divided into two investigations a) natural convection flow within differentially heated enclosed square cavity and b) open-ended vertical channel asymmetrically heated for a wide range of Rayleigh number with air (*Pr* 0.72) as working fluid. Visualization of fluid flow dynamics conducted for both classes of geometries for all range of Rayleigh number show similar phenomena in accordance with previous literatures and compared data also show very good agreement with previous literatures. All results indicate that the new modified preconditioned all-speed Roe scheme is very much competent and accurate for simulation of buoyancy-induced compressible convection flows without relying on the correct prediction of global cut-off Mach number.

1. Introduction

Buoyancy-driven convective flows are one of the fundamental problems in fluid dynamics playing decisive roles in many natural and industrial applications. Many applications in diverse areas of geophysics, nuclear reactor systems, energy management systems, chemical and metallurgical industries encounter naturally convective flows induced under high-temperature difference ($> 30K$). For such applications, Gray and Giorgini [1] suggested taking into consideration the compressibility of the fluid and governing equations without Boussinesq approximation. Investigations in [2–4] showed that preconditioned Roe scheme under low Mach number limit as proposed by Weiss and Smith [5] is quite suitable for simulation of compressible viscous natural convection flow.

It is to be noted that the preconditioned Roe scheme utilizes the global cut-off Mach number to calculate the coefficients in both the numerator and denominator of the dissipation term. Usually, the value of inlet Mach number or average Mach number of flow or maximum Mach number of flow is used to set the global cut-off Mach number. But for compressible natural convection flow without having any prior knowledge of the flow, it is very difficult to predict the global cut-off Mach number which dictates the numerical dissipation and accuracy of the scheme.

Taking into consideration the drawback presented by the preconditioned Roe scheme, X.S.Li et.al. [6] based on asymptotic analysis for Roe type schemes concluded that the coefficient of the pressure derivative dissipation term has to be in order of $O(c^0)$ to suppress checkerboard or $O(c^{-1})$ to have weak checkerboard and the coefficient of the velocity-derivative dissipation term has to be in order of $O(c^0)$ for accuracy. For accuracy, it is just sufficient to multiply the sound speed term in the numerator by considering the function of Mach number related to local flow velocity. Based on this finding, a new modified preconditioned all-speed Roe scheme was proposed in [6]. This scheme calculates the numerator utilizing the local Mach number based on local velocity and still utilizing the global cut-off strategy for calculation of denominator in the dissipation term. For the case of the preconditioned Roe scheme, it treats the sound speed terms in both numerator and denominator equally. As concluded and reported through

* 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).

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numerical experiments in the [6], this difference of treating the dissipation terms differently leads to new modified preconditioned all-speed Roe scheme having higher accuracy and less numerical dissipation (if global cut-off Mach number predicted higher) than the preconditioned Roe scheme. In [6] numerical experiments on lid-driven cavity problem with a typical very low Mach number of 0.005 was conducted and the solution from new modified preconditioned all-speed Roe scheme agreed well with the compared benchmark solution and also had better accuracy than the preconditioned Roe scheme.

It is noteworthy that this new modified preconditioned all-speed Roe scheme is yet to be tested for compressible natural convection flows and can be a good alternative to preconditioned Roe scheme for simulation of compressible natural convection flows. This provides the motivation to adopt the new scheme and perform the present numerical investigation.

The present investigation focusses on the validation of new modified preconditioned all-speed Roe scheme in the whole range of steady laminar flow. Two class of geometries are considered for the investigation - a) differentially heated enclosed square cavity with isothermal vertical walls and adiabatic horizontal walls for range of Rayleigh number 10^3 to 10^7 under low-temperature difference ($< 30K$) which represents a typical physical model for validation of numerical algorithm and b) open-ended vertical channel heated asymmetrically and isothermally under high temperature difference ($> 30K$) for range of Rayleigh number 10^4 to 10^7 which represents a practical engineering applications. Additionally, the governing equations without Boussinesq approximation along with temperature dependent fluid viscosity and thermal conductivity is considered for simulation. Similar to [7], the numerical results obtained from simulation of the differentially heated square cavity with compressible governing equations without Boussinesq approximation and under low-temperature difference is compared with well-established benchmark numerical solution of De Vahl Davis [8] and P.L.Quere [9]. The flow dynamics observed inside the square cavity is found to show similar phenomena as also described in [10,11]. In case of simulation in vertical channel geometry, the development of flow with time for Ra 10^4 and flow dynamics at steady state condition for Ra 10^4 to 10^7 as observed is qualitatively compared with previous literature [2,12]. The average Nusselt number obtained is compared with the correlation given in [2]. All compared data show very good agreement with previous literatures. This investigation validates that the new modified preconditioned all-speed Roe scheme can be successfully implemented for numerical simulation of compressible natural convection flow induced under high-temperature difference with an advantage of not to depend on the correct prediction of global cut-off Mach number for maintaining the accuracy of the solution.

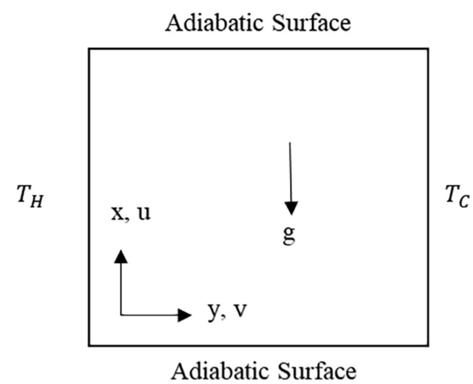

Fig. 1. Square cavity geometry.

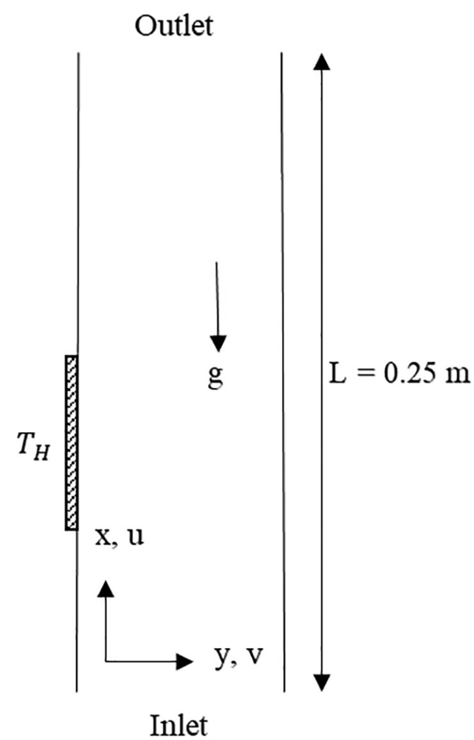

Fig. 2. Open-ended vertical channel.

2. Mathematical formulation and numerical method

The physical model considered herein for the investigation is a) two-dimensional differentially heated cavity with isothermal temperature imposed on the vertical walls and adiabatic horizontal walls as shown in Fig. 1, b) two-dimensional open-ended vertical channel heated asymmetrically and isothermally as shown in Fig. 2. For both geometries, air (Pr 0.72) is considered as the working fluid. For square cavity, a temperature difference of $20K$ is imposed across the vertical walls and for the case of vertical channel, an overall temperature difference of $110K$ between T_w and T_0 is imposed. Air inside the channel is drawn at T_0 due to the pressure difference induced by buoyancy force generated. Gravity is considered downward and ambient temprature and pressure are 298.0592 K and 101,300 Pa respectively For both investigations, compressible governing equations without Boussinesq approximation is considered.

Such considerations lead to the following compressible governing equations in conservation form for a calorically and thermally perfect gas:

$$\frac{\partial U}{\partial t} + \frac{\partial F}{\partial x} + \frac{\partial G}{\partial y} = S \tag{1}$$

Where,

$$U = \begin{bmatrix} \rho \\ \rho u \\ \rho v \\ \rho E \end{bmatrix} \tag{2}$$

$$F = \begin{bmatrix} \rho u \\ \rho u^2 + p - \tau_{xx} \\ \rho uv - \tau_{xy} \\ \rho Eu + pu - k\dfrac{\partial T}{\partial x} - u\tau_{xx} - v\tau_{xy} \end{bmatrix} \tag{3}$$

$$G = \begin{bmatrix} \rho v \\ \rho uv - \tau_{yx} \\ \rho v^2 + p - \tau_{yy} \\ \rho Ev + pv - k\dfrac{\partial T}{\partial y} - u\tau_{yx} - v\tau_{yy} \end{bmatrix} \tag{4}$$

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