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Control volume finite element method for a benchmark validation of a natural convection in a square cavity

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Abstract

The formulation written in terms of the primitive variables a co-located equal-order Control-Volume based Finite Element Method (CVFEM), for a benchmark validation of natural convection in a square cavity. The computer code Fortran that have been developed in the context of this work using all forms of dimensionless equations to allow a quick and easy comparison of results with the benchmark solution, the numerical of De Vahl Davis and other works. The problem considered, is for a two-dimensional flow, for a Prantl number of 0.71 using Boussinesq approximation. The results taken into account are the stream function, velocities and heat transfer, which are obtained at Rayleigh numbers of 10^3, 10^4,$10^5$and 10^6.

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Keywords: CVFEM; Equal-order Control-Volume-based; Benchmark validation; Rayleigh number; Natural convection

1. Introduction

Natural convection heat transfer in a square cavity is important in many engineering applications, such as nuclear reactor insulation, ventilation of rooms, solar energy collection and crystal growth in liquids. Therefore, many investigations have been carried out to study the interaction between the hydrodynamic and thermal effects theoretically used a method for the numerical solution, for a great variety of parameters.

Many papers on this problem have been published with numerical results obtained mainly by finite differences and the Reynolds number has been slowly pushed upwards [1,2,3,4,5].A complete analysis of the solutions by numerical computations were given by Vahl Davis [6] for laminar natural convection in an enclosed rectangular

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cavity. Later Vahl Davis [7] presented a solution second-order, central difference approximations were used mesh refinement and extrapolation led to solutions for $10^3 \leq Ra \leq 10^6$.Vahl Davis and Jones [8] have presented a number of contributed solutions to the problem of laminar natural convection in a square cavity have been compared with what is regarded as a solution of high accuracy. Reading of Stevens [9] work, is based on the solution of the derivation of vorticity and power lines, for the formulation of primitive equation of the equations of motion, of energy and continuity for an incompressible fluid. Use of boundary vorticity formula or iterative fulfillment of the no-slip boundary condition is avoided by application of the finite element discretization and a displacement of the appropriate discrete equations. Solution is obtained by Newton-Raphson iteration of all equations simultaneously. A similar study was documented by T. Fusegi and al [10] a high-resolution, finite-difference numerical study is reported on natural convection in a square cavity. The internal Rayleigh number varies in the range $10^9 \leq Ra_L \leq 10^{10}$, while the external Rayleigh number is set at $Ra_E = 5.10^7$ for most computations. C. Wan and al [11] has proposed the problem of a new benchmark quality solution for the buoyancy-driven cavity by discrete singular convolution (DSC) for the numerical simulation of coupled convective heat transfer problems. The problem is solved by two completely independent numerical procedures. One is a quasi-wavelet-based DSC approach, while the other is a standard form of the Galerk in finite-element method. The objective of Guo.Y and Bathe.K.-J.[12]is to present the results obtained using the 9-node quadrilateral element in ADINA, and it was used with various meshes. A. Dalal and al.[13]states that natural convection occur in the vicinity of inclined square cylinder in the range of $(0^0 \leq \theta \leq 45^0)$ inside an enclosure having horizontal adiabatic wall and cold vertical wall figure out by cell-centered finite volume method, which is used to calculate two dimension Navier-strokes equation for incompressible laminar flow. Basak et al.[14]have reported the effect of temperature boundary conditions (Constant temperature and sinusoidally varying) on the bottom wall for Ra varying from 10^3 to 10^5 for both the Prandtl numbers of 0.7 and 10.

This paper presents a solution of a natural convection in a square cavity problem based on extending the co-located equal-order Control-Volume-based Finite Element Method (CVFEM) by Lamoureux and Baliga [15].As an advantage of the present method is the use of primitive variables which facilitates the application of the boundary conditions. To validate the present method of solution, the results are analyzed and compared with Vahl Davis.[7]bench mark solution and Ismail and Scalon [16].

Nomenclature

b	Length (m)	U,V	Non-dimensional velocity (ub/α), (vb/α)
p	Pressure (Pa=N/m^2)	X,Y	Non-dimensional cartesian (=x/b),(=y/b)
T	Temperature absolute (K)	θ	Non-dimensional temperature (= $(T-T_0)/(T_p-T_o)$)
ρ	Density of fluid (Kg/m^3)	P_m	Non-dimensional Pressure($= Pb^2/\rho\alpha^2$)
α	Diffusivity, Thermal (m^2/s)	∇	Spatial gradient operator
β	Coefficient of volume expansion (K^{-1})	n	Outward unit normal vector at X=0
ψ	Streamline function	Ra	Rayleigh number ($= g\beta\Delta T b^3/\alpha\upsilon$)
υ	Kinematic viscosity	Pr	Prandtl number ($= \upsilon/\alpha$)

2. Governing equations

The non-dimensional governing equations for the natural convection in a square cavity are given by two-dimensional incompressible Navier-Stokes and energy equation in primitive variable form as:

Continuity equation:

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

X-momentum equation:

$$U\frac{\partial U}{\partial X} + V\frac{\partial U}{\partial Y} = -\frac{\partial P_m}{\partial X} + \Pr\left[\frac{\partial^2 U}{\partial^2 X} + \frac{\partial^2 U}{\partial^2 Y}\right] \tag{2}$$

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