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Assessment of turbulence models in natural convection from two- and three-dimensional rectangular enclosures

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ABSTRACT

In this study, unsteady turbulent natural convection heat transfer in two- and three-dimensional rectangular enclosures is investigated numerically. The enclosures are heated and cooled from the vertical opposing isothermal walls. All other side walls are assumed to be smooth and adiabatic. The working fluid is air ($Pr = 0.71$), and the flow is turbulent. Two- and three-dimensional unsteady-state continuity, Reynolds-Averaged Navier-Stokes (RANS), along with the averaged-energy equation, are solved using the commercial software – FLUENT 6.3.26®. Standard $k-\varepsilon$ (SKE), Re-Normalization Group $k-\varepsilon$ (RNGKE), Realizable $k-\varepsilon$ (RKE), Reynolds Stress Model (RSM), Standard k-ω (SKW) and Shear Stress Transport $k-\omega$ (SSTKW) RANS models are used in conjunction with the two-layer (or Enhanced Wall Treatment, EWT) wall model for Rayleigh numbers ranging from 10^8 to 10^{13}. The performance of the turbulence models on the heat transfer rate predictions is comparatively investigated for 2D square enclosure, as well as 3D rectangular enclosures having the slenderness ratio of $H/W = 1$ and $H/W = 10$. The heat transfer rate predictions are assessed for each case via surface-averaged mean Nusselt numbers over the hot wall, and empirical power-law correlations are derived for 2D and 3D enclosures for each turbulence model. The study reveals that 3D laminar and RANS models yield almost identical mean Nusselt number predictions up to $Ra = 10^{10}$, and these predictions are compatible with those of obtained from 2D simulations. For larger Rayleigh numbers, the mean Nusselt numbers the flow becomes three-dimensional and 2D RANS models do not yield accurate predictions. The study reveals that 3D RANS models yield more accurate mean Nusselt numbers, and a mean Nusselt number correlation is proposed.

1. Introduction

Natural convection heat transfer is a fundamental problem due to a wide range of applications in fields concerning thermal processes involved in various engineering systems such as thermal insulation in buildings, fire hazards, solar energy collectors, electronic cooling components or equipment, etc.

In the last four decades, numerous theoretical and experimental studies on natural convection in enclosures have been carried out. As a result the heat and fluid flow due to natural convection has received considerable attention from many researchers. An extensive bibliography on natural convection in cavities up to 1988 may be found in the review article by Ostrach [1].

Leong et al. [2,3] experimentally studied natural convection Nusselt numbers for a cubical, air-filled cavity which is heated and cooled from opposing isothermal faces. Betts and Bokhari [4] experimentally investigated the natural convection of air in a tall differentially heated rectangular cavity for $Ra = 0.86 \times 10^6$ and 1.43×10^6. An extension to a previously published work was carried out by Mamun et al. [5] in which mean Nusselt number for $10^4 \le Ra \le 3 \times 10^8$ were measured. The results are considered to be suitable for the testing of computational codes. Low-level turbulent natural convection in an air-filled square-cavity were experimentally studied by Tian and Karayiannis [6], Ampofo and Karayiannis ($Ra = 1.58 \times 10^9$) [7], Ampofo [8,9] and Penot and N'Dame [10]. For $Ra = 1.5 \times 10^9$, Salat et al. [11] investigated the turbulent natural convection experimentally and numerically in a differentially heated cavity ($W/H = 1$, $L/H = 0.32$). Natural convection in air-filled 2D tilted-square cavities was also studied experimentally and numerically by Baïri [12]. Measurements and simulations of various geometrical and thermal configurations were performed for $10 \le Ra \le 10^{10}$ and tilt angles $0 \le \alpha \le 360$. The experimental results

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Nomenclature

g_i	gravitational acceleration components [m/s^2]
h	heat transfer coefficient [W/m^2 K]
H	height and/or width of the enclosure [m]
Nu	mean Nusselt number [−]
P	pressure [N/m^2]
Pr	Prandtl number [−]
Ra	Rayleigh number [−]
t	time [s]
T	temperature [K]
u_i	velocity components [m/s]
x_i	coordinate system components [m]
W	depth of the enclosure [m]
Greek symbol	
α	thermal diffusivity [m^2/s]
β	thermal expansion coefficient [K^{-1}]
υ	kinematic viscosity [m^2/s]
ρ	density [kg/m^3]
Subscripts	
c	cold
h	hot
r	reference

of this work complements relatively small amount of data available in the literature since most of the studies are numerical. Hsieh and Yang [13] experimentally studied transient buoyancy-induced natural convection in the Rayleigh number range of 6.9×10^7–4.12×10^8 for aspect ratios of $A_H = 3$ and $A_W = 1.2$ and silicon oil ($300 < Pr < 500$). Giel and Schmidt [14] experimentally studied high Rayleigh number ($Ra = 8 \times 10^{10}$) natural convection in an enclosure with aspect ratio of 10. Saury et al. [15] experimentally studied natural convection heat transfer, including wall radiation effects on the flow for a rectangular tall box for $4 \times 10^{10} \leq Ra \leq 1.2 \times 10^{11}$. ElSherbiny et al. [16,17] reported on the experimental measurements of the heat transfer by natural convection across vertical and inclined air layers for six aspect ratios between 5 and 110. The Ra numbers were in the range 10^2 to 2×10^7, and correlations were presented.

The majority of the theoretical and numerical studies carried out in this field deal with 2D rectangular enclosures. The limitations of computer technologies restricted the numerical studies to 2D models up until the last decades. Most of the limited number of numerical studies deal with 3D laminar natural convection. Three-dimensional laminar natural convection was studied by Mallinson et al. [18], Lee et al. [19] and Lankhorst and Hoogendoorn [20] for enclosures with $1 \leq A \leq 2$ and for $10^6 \leq Ra \leq 10^8$. Fusegi et al. [21] investigated 3D natural convection in a differentially heated cavity (DHC) for $10^3 \leq Ra \leq 10^6$. Tric et al. [22] studied laminar natural convection of air-filled cubical cavity for $10^3 \leq Ra \leq 10^7$. Wakashima and Sayitoh [23] studied the same problem for $10^4 \leq Ra \leq 10^6$. A numerical benchmark study for $10^5 \leq Ra \leq 10^8$ was conducted by Pepper and Hollands [24]. Ravnik et al. [25] examined 3D natural convection in an inclined enclosure by using the boundary element method for $10^3 \leq Ra \leq 10^5$. The results for an inclined enclosure with $A = 2$ are also presented. Lo et al. [26] investigated 3D natural convection for $10^3 \leq Ra \leq 10^6$ in an inclined cavity by DQ method. Janssen et al. [27] numerically investigated transition to time-periodicity of laminar natural-convection flow in a 3-D DHC.

Two- and three-dimensional numerical investigations of turbulent natural convection flows have attracted interest in the last two decades. Owing to the advances in computer memory and cpu-technologies, one now has the capability of dealing with larger grids as well as tackling additional differential equations of Reynolds Averaged Navies Stokes (RANS) models. One of the earliest numerical work on 2D turbulent natural convection has been carried out with k–ε model up to $Ra = 10^{16}$ by Markatos and Pericleous [28]. Hsieh and Lien [29] numerically studied buoyancy-driven turbulent flows in enclosures using an unsteady RANS approach in conjunction with the low-Re number k–ε model. Niu and Zhu [30] evaluated numerically 2D turbulent air flow patterns due to natural convection in a square enclosure with differentially heated side walls. Ozoe et al. [31] numerically studied for $10^6 \leq Ra \leq 10^9$ and $5.12 \leq Pr \leq 9.17$ laminar and for $10^{10} \leq Ra \leq 10^{11}$ and $Pr = 6.7$ turbulent natural convection in DHCs using k–ε turbulent model. It was reported that the mean Nusselt numbers agreed well with those of experimental data. Using k–ε model, Dol and Hanjalić [32] studied turbulent natural convection 2D and 3D differentially heated near-cubic cavities for $Ra = 4.9 \times 10^{10}$. Sharma et al. [33] studied 2D conjugate turbulent natural convection with surface radiation in air-filled rectangular enclosures using the standard k–ε turbulence model with physical boundary conditions for $10^8 \leq Ra \leq 10^{12}$ and $0.5 \leq A \leq 2$. Heindel et al. [34] used low-Re number k–ε turbulence models with variable and fixed coefficient models to predict 2D turbulent natural convection heat transfer in DHCs with $Ra = 9.1 \times 10^{10}$, $Pr = 3.1$, $A = 10$ and $Ra = 5 \times 10^{10}$, $Pr = 0.71$, $A = 5$. It was found that the mean Nu numbers are predicted more accurately by the variable coefficient model. Hanjalić and Vasić [35] numerically studied laminar ($10^4 \leq Ra \leq 10^6$) and turbulent ($10^7 \leq Ra \leq 10^{12}$) natural convection using low-Re number k–ε model in 2D rectangular enclosures with aspect ratios of 1 and 5. Ince and Launder [36] numerically studied 2D buoyancy-driven flows in air-filled rectangular enclosures with aspect ratios of 5 and 30. It was concluded that Jones-Launder's low-Re number k–ε model performed satisfactorily in these cases. Henkes et al. [37] also numerically studied laminar and turbulent natural convection (using three turbulence models) in a 2D DHCs up to $Ra = 10^{14}$ for air and up to $Ra = 10^{15}$ for water. Peng and Davidson [38] numerically investigated 2D turbulent buoyant convection flows induced by differentially heated side walls using low-Re number k–ω model for $10^{10} \leq Ra \leq 10^{12}$. It was found that the buoyancy source term for the turbulence kinetic energy exhibited strong grid sensitivity with standard gradient diffusion hypothesis. It was also reported that by introducing a damping function for this term, the grid-dependence problem was eliminated. Dixit and Babu [39] numerically simulated laminar ($10^3 \leq Ra \leq 10^6$) and turbulent ($10^7 \leq Ra \leq 10^{10}$) natural convection in a DHC using the lattice Boltzmann method. Barakos et al. [40] similarly investigated laminar and turbulent flows in 2D DHCs for Rayleigh numbers up to 10^{10}. The k–ε model solutions, with and without wall functions, was compared based on the Nu number with experimental data, and they demonstrated the limitations of the standard k–ε model with wall functions which over-predicted the Nu values.

With fast developing computer hardware and software, the numerical analysis of natural convection in 3D DHCs has also accelerated. Very limited 3D numerical investigations have used large-eddy simulation (LES) and/or direct numerical simulation (DNS). Tiras et al. [41] used 2D/3D DNS simulations for $Ra = 6.4 \times 10^8$, 2×10^9 and 10^{10} in air-filled cavity having an aspect ratio of $A = 4$. Using the DNS method, Trias et al. [42] also numerically investigated 3D turbulent natural convection flows in air filled DHCs for $Ra = 4.5 \times 10^{10}$ and $A = 5$. In follow up papers, Trias et al. [43,44] further investigated the DNS solutions of the