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CFD Simulations of Natural Convection Heat Transfer in Enclosures with Varying Aspect Ratios

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Buoyancy driven natural convection in enclosures has wide range of engineering applications in heat transfer processes. The study of fluid flow and heat transfer characteristics in enclosures has significant importance towards thermal management and optimal design of the systems. Limited studies are available on the numerical simulation of 3-dimensional enclosures with varying aspect ratios (AR). Heat transfer characteristics are investigated in 3D rectangular enclosures with hot and cold surface by computational fluid dynamics simulations at low (0.125) to high (150) aspect ratios (Height/Length). CFD simulations are performed with different fluids at a temperature range of 20 K $\leqslant \Delta T \leqslant$ 100 K and Prandtl number range of 0.01 $\leqslant$ Pr $\leqslant$ 4,500. The velocity and temperatures profiles in the enclosures are presented. Heat transfer coefficients are estimated for all cases. Correlations for Nusselt number (Nu) based on predicted findings have been developed to represent heat transfer characteristics.

1. Introduction

Natural convection heat transfer process takes place with the fluid movement induced by buoyancy force due to density difference of the fluid by temperature gradient. Natural convection heat transfer and fluid flow in enclosures is getting more attention in the recent years due to wide range of engineering applications involving energy conservation, cooling system for electronic devices, non-Newtonian chemical processes, solar energy collector and double pane windows (Ganguli et al., 2007). Fluid flow and heat transfer characteristics of the fluid during natural convection is relatively lower than forced convection process. However, natural convection process does not require any external energy and is highly dependent on geometry of enclosures.

Natural convection heat transfer has been studied experimentally and numerically extensively in previous studies using different geometries such as infinite vertical plates (Tippa et al., 2014), recessed windows (Oosthuizen and Oghbaie, 2012), vertical plates with thermal radiation (Narahari et al., 2012), micro-channels (Narahari and Pendyala, 2015), vertical enclosures (Ganguli et al., 2009), etc. However, limited simulation studies are available on natural convection heat transfer in 3-dimentional rectangular enclosures. 3D models of enclosures can predict heat transfer behaviour more accurately than 2D models due to edge effects of enclosure. The predicted results using 3D simulations are considered to be more reliable and close to experimental results. Ganguli et al. (2009) studied the temperature distribution across vertical enclosures with hot and cold wall at various aspect ratios for air. It was found that temperature distribution and flow pattern in enclosures are highly influenced by aspect ratios. In another study by Warren et al. (1998), the natural convection heat transfer characteristics were analysed in horizontal and vertical geometries. Convective heat transfer was enhanced with decrease in aspect ratio. Correlation was developed for Nusselt number and it was concluded that squared cavities showed higher Nusselt number than cavities with high aspect ratio. Kamotani et al. (1983) investigated heat transfer behaviour experimentally with varying aspect ratios. Enclosures with low aspect ratios (< 1) showed that Nusselt number is highly dependent on Prandtl number and for squared enclosures Nusselt number is independent of Prandtl number. Another numerical study on laminar natural convection in square cavity by

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Pesso and Piva (2009) demonstrated that higher values of Prandtl number increases the average Nusselt number and Rayleigh number (Ra).
Heat transfer and fluid flow characteristics during natural convection in varying aspect ratios of enclosures are studied using different fluids. Heat transfer coefficients for different fluids are estimated at varying Rayleigh number. Correlations are developed for Nusselt number as a function of Rayleigh number and aspect ratio for different fluids.

2. Methodology

Natural convection heat transfer process is numerically studied in rectangular enclosures with varying aspect ratios, Prandtl number and temperature difference between hot and cold surfaces. The typical rectangular enclosure is shown in Figure 1. Heat transfer and fluid flow properties have been studied in 3-dimensional enclosures with varying aspect ratios ($0.125 \leqslant AR \leqslant 150$). The numerical simulations are carried out in ANSYS 15.0 (Fluent). Vertical enclosure consists of hot and cold wall, the other four surfaces are assumed to be insulated. Heat transfer characteristics in eighteen enclosures are studied using three different fluids i.e. fluid 1, 2 and 3 which have equivalent thermophysical properties with air, water and engine oil at varying Prandtl number range ($0.5 \leqslant Pr \leqslant 4500$) and temperature differences ($20\ K \leqslant \Delta T \leqslant 100\ K$). The aspect ratios of considered enclosures are shown in Table 1. Fluids are assumed to exist in single phase for all simulations during natural convection. Fine meshing along with bias meshing technique is selected near the edges of the enclosure for better accuracy. Boussinesq approximation is employed in all models in which density of fluid is assumed to be constant and flow of fluid is mainly due to buoyancy force. Thermophysical data used in current simulation are taken from fundamental equations (Incorpera and Dewitt, 2002) and previous literature (Bejan, 2004).
Pressure-based solver with absolute velocity formulation has been used to perform steady state simulation with gravitational accelerations in negative y-direction. Laminar model, energy and surface-to-surface radiation equations are considered (Ganguli et al., 2009). Scaled residuals for continuity, velocity and energy are set to be the convergence criteria. Body force weighted method is selected for pressure solutions to solve buoyancy calculations. First-order upwind and Third-order Monotone Upstream centred Schemes for Conservation Laws (MUSCL) is employed for discretisation of momentum and energy.

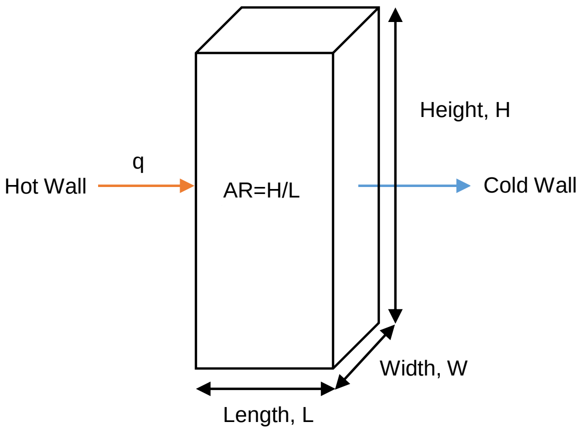

Figure 1: Rectangular vertical enclosure under consideration

Table 1: Aspect ratio (AR) of enclosures

Height (cm)	Length (cm)	AR	Height (cm)	Length (cm)	AR
5	40	0.125	170	2.35	72.25
10	20	0.5	180	2.22	81
20	10	2	190	2.11	90.25
40	5	8	200	2	100
60	3.33	18	260	2.31	112.67
80	2.5	32	270	2.22	121.5
100	2	50	280	2.14	130.67
150	2.86	56.25	290	2.07	140.17
160	2.67	64	300	2	150

3. Results and discussion

3.1 Effect of aspect ratio on flow patterns for different fluid

Simulations are performed at different aspect ratios for various fluids to study the fluid flow characteristics. Velocity contours of fluid 1, fluid 2 and fluid 3 in an iso-surface for AR = 0.125 to AR = 50 with temperature difference of 100 K are shown in Figure 2. It is found that average velocity of fluids increases with the increase in aspect ratio of rectangular enclosures. It is observed that fluid 1 has the highest average velocity in enclosures followed by fluid 2 and fluid 3 due to low viscosity. Heat transfer coefficients of fluids during natural convection are mainly governed by flow regime in the enclosures. Multicellular flow formation is seen in few conditions for the enclosures with low aspect ratios, shown in Figure 2(a), Figure 2(d) and Figure 2(g). Formation of unequally distributed multiple cells indicates that heat transfer in the fluid region of enclosures are dominated by convective heat transfer. Multicellular flow patterns are observed to disappear with increase in aspect ratio and only unicellular flow is observed.

Convective heat transfer performance in enclosures with unicellular flow is less (Ganguli et al., 2009). Variation in heat transfer coefficient at different aspect ratios for fluid 1, fluid 2 and fluid 3 with temperature gradient from 20 K to 100 K is shown in Figure 3. Enclosures with high aspect ratios demonstrate higher values of heat transfer coefficient. However, due to conductive dominated heat transfer performance, high aspect ratio enclosures show lower values of Nusselt number. It is evident from previous studies by Ganguli et al. (2009) that enclosures with low aspect ratios gives better convective heat transfer performance due to formation of multicellular flow pattern in enclosures.

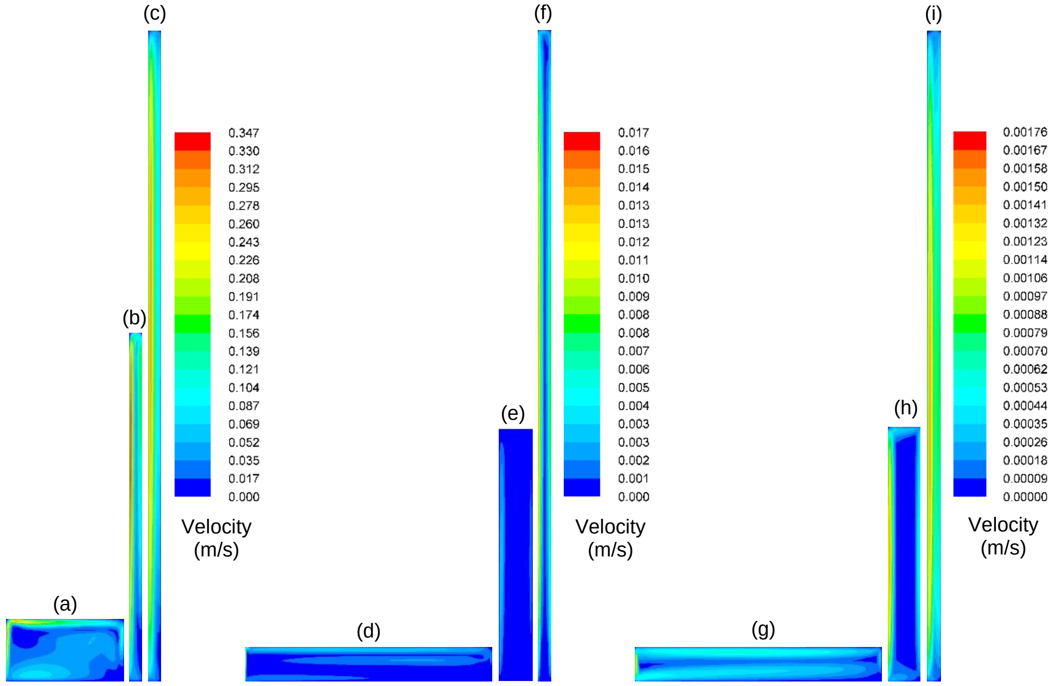

Figure 2: Velocity distribution in enclosure for ∆T = 100 K in fluid 1 ((a) AR = 0.5, (b) AR = 18, (c) AR = 50), fluid 2((d) AR = 0.125, (e) AR = 8, (f) AR = 50) and fluid 3 ((g) AR = 0.125, (h) AR = 8, (i) AR = 50)

3.2 Effect of temperature difference and aspect ratio on Nusselt number

Heat transfer performance in enclosures are analysed by creating an iso-surface in the middle of enclosures with z-coordinate equals to 0.025m. Nusselt number is analyzed extensively to understand the effect of aspect ratio on heat transfer performance in rectangular enclosures using different fluids. The variation of Nusselt number with aspect ratios for fluid 1, fluid 2 and fluid 3 at different temperature gradient is shown in Figure 4. From the results it is found that Nusselt number is highly dependent on aspect ratio, type of fluids and temperature difference between hot and cold wall. It is observed that for a constant aspect ratio, Nusselt number increases as temperature gradient increase. Heat transfer coefficient is mainly governed by flow regime in the enclosures. Flow regime of fluids in enclosures can be divided into three categories: conduction flow regime, transition flow regime and boundary layer flow regime (Ganguli et al., 2009).

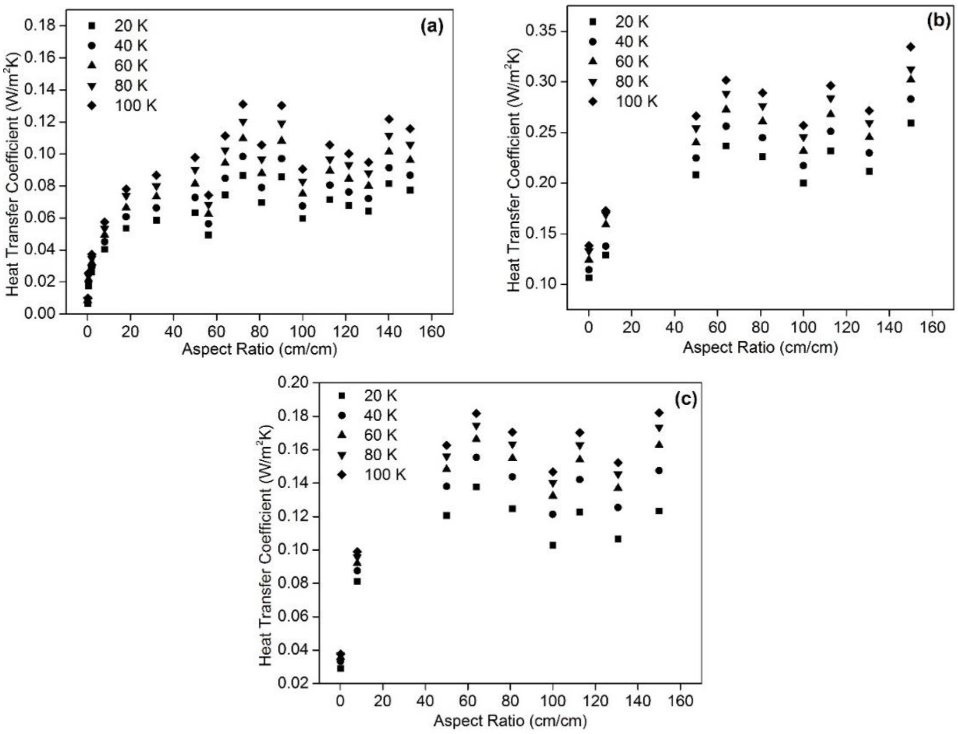

Figure 3: Variation of heat transfer coefficient with aspect ratio for (a) fluid 1, (b) fluid 2 and (c) fluid 3 at various temperature gradient

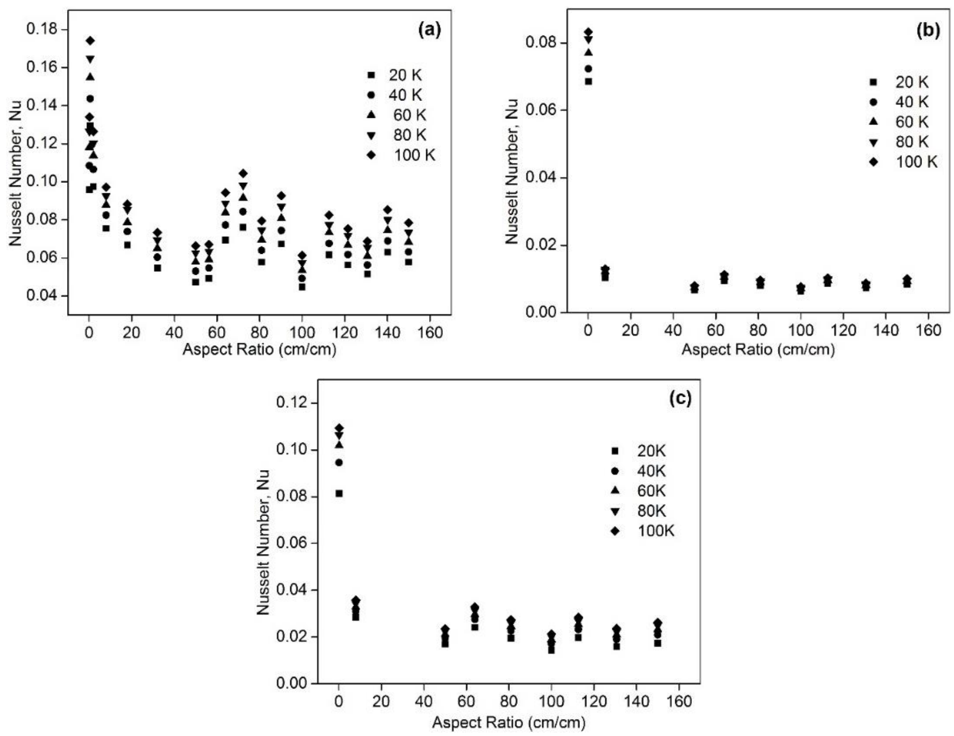

Figure 4: Variation of Nusselt number with aspect ratio for (a) fluid 1, (b) fluid 2 and (c) fluid 3 at various temperature differences

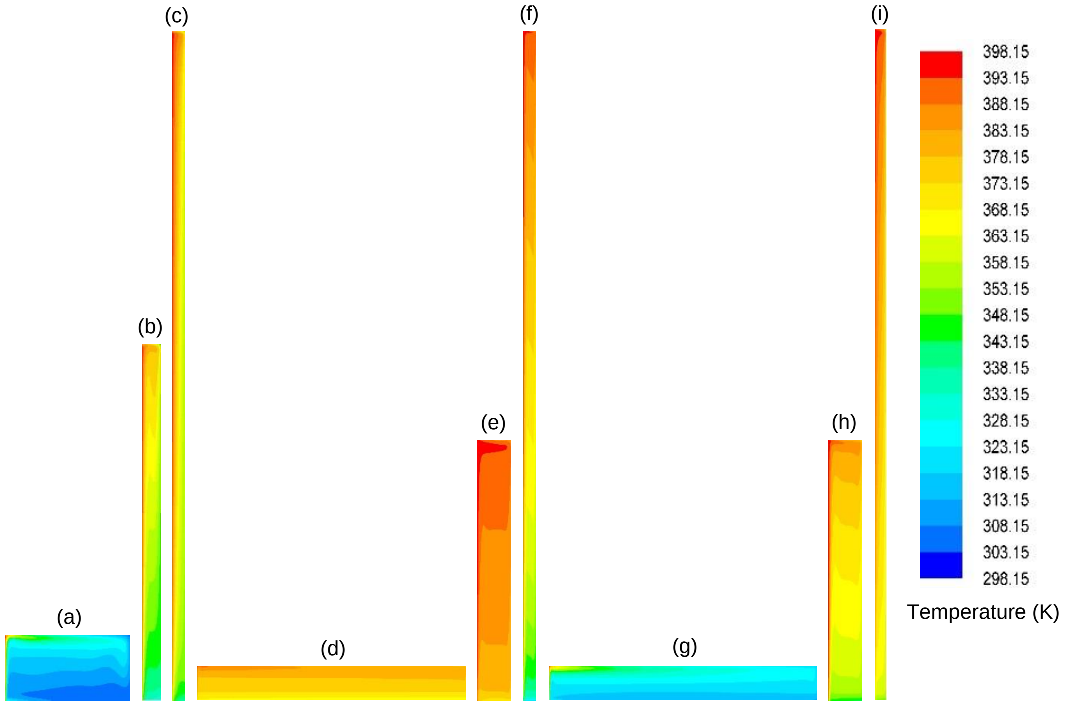

Figure 5: Temperature distribution in enclosure for ∆T = 100 K in fluid 1 ((a) AR = 0.5, (b) AR = 18, (c) AR = 50), fluid 2 ((d) AR = 0.125, (e) AR = 8, (f) AR = 50) and fluid 3 ((g) AR = 0.125, (h) AR = 8, (i) AR = 50)

Aspect ratio of 0.5 exhibits highest value of Nusselt number, shown in Figure 4 (a). This can be attributed to convective dominated heat transfer in this enclosure. Temperature distribution contours of AR = 0.5 at ∆T = 100 K for fluid 1 are shown in Figure 5 (a). It is found that heat transfer in this enclosure falls in boundary layer flow regimes in which conductive heat transfer is limited to thin boundary layer near the wall of enclosure and majority of the fluid region exhibits convective heat transfer. Similar trends are observed in natural convection of fluid 2 and fluid 3. Temperature distribution contours of AR = 18 at ∆T = 100 K for fluid 1 (Figure 5(b)) shows that the heat transfer performance in enclosure is considered to be in the transition regime. This may be because convective heat transfer in fluid region decreases while conductive heat transfer near the wall increases which causes decrease in Nusselt number. The results showed similar behavior with previous literature (Ganguli et al., 2009). Lower values of Nusselt number are seen in AR = 50 at ∆T = 100 K for fluid 1. The heat transfer in this enclosure is concluded to be governed by conduction because linear temperature distribution in the enclosure is observed, shown in Figure 5 (c). Similar heat transfer behavior is seen for fluid 2 and fluid 3, shown in Figure 5 (f) and Figure 5 (i). It can be concluded that heat transfer in enclosures with low aspect ratio is generally governed by convection while high aspect ratio is dominated by conduction (Warren et al., 1998). For higher Rayleigh number conditions, improved convective heat transfer is observed.

3.3 Development of correlations for Nusselt number

Correlations are developed for Nusselt number as a function of aspect ratio and Rayleigh number. The correlations are proposed for fluid 1, fluid 2 and fluid 3 with varying aspect ratios (0.125 ⩽ AR ⩽ 150) and temperature gradients (20 K ⩽ ∆T ⩽ 100 K), given in Eq(1), Eq(2) and Eq(3). The presented correlation for fluid 1, fluid 2 and fluid 3 exhibits Average Absolute Deviation (AAD) of 11.33 %, 16.04 % and 13.29 %. The Sum of Squared Errors (SSE) for fluid 1, fluid 2 and fluid 3 is found to be 0.015, 0.001 and 0.0006. The performance of correlation for fluid 1, fluid 2 and fluid 3 is shown in Figure 6.

$$Fluid\,1: \quad Nu = 1.46\times10^{-5}(AR)^{0.19}(\ln Ra)^{3.228} \tag{1}$$

$$Fluid\,2: \quad Nu = 1.02\times10^{-6}(AR)^{-0.0907}(\ln Ra)^{3.337} \tag{2}$$

$$Fluid\,3: \quad Nu = 7.57\times10^{-6}(AR)^{0.0256}(\ln Ra)^{3.114} \tag{3}$$

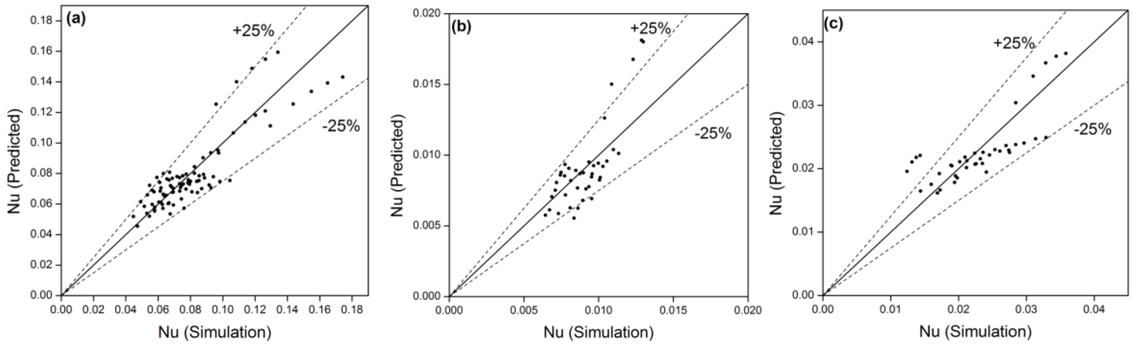

Figure 6: Parity plot for predicted Nusselt numbers by the correlation of (a) fluid 1, (b) fluid 2 and (c) fluid 3

4. Conclusion

Natural convection in 3-Dimentional rectangular enclosures is studied with varying aspect ratios and temperature gradients. Fluid flow and heat transfer characteristics are numerically studied for fluid 1, fluid 2 and fluid 3. It is found that aspect ratios of enclosures have significant importance in predicting optimum design for a desired product to improve heat transfer characteristics. Enclosures with low aspect ratios are observed multicellular fluid flow in some conditions in fluid 1 and they have better convective heat transfer performance. A high value of convective heat transfer performance is observed at increased Rayleigh number conditions. High aspect ratio enclosures are found to be conductive dominated. Further studies in natural convection heat transfer can be carried out by various fluids in different geometries with varying aspect ratios. Heat transfer coefficients and the flow patterns in different fluids have significant impact towards the optimum height and width of the system.

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