World Academy of Science, Engineering and Technology
International Journal of Civil and Environmental Engineering
Vol:9, No:12, 2015

CFD Investigation of Turbulent Mixed Convection Heat Transfer in a Closed Lid-Driven Cavity

A. Khaleel, S. Gao

***Abstract*—**Both steady and unsteady turbulent mixed convection heat transfer in a 3D lid-driven enclosure, which has constant heat flux on the middle of bottom wall and with isothermal moving sidewalls, is reported in this paper for working fluid with Prandtl number Pr = 0.71. The other walls are adiabatic and stationary. The dimensionless parameters used in this research are Reynolds number, *Re* = 5000, 10000 and 15000, and Richardson number, *Ri* = 1 and 10. The simulations have been done by using different turbulent methods such as RANS, URANS, and LES. The effects of using different k-ε models such as standard, RNG and Realizable k-ε model are investigated. Interesting behaviours of the thermal and flow fields with changing the Re or Ri numbers are observed. Isotherm and turbulent kinetic energy distributions and variation of local Nusselt number at the hot bottom wall are studied as well. The local Nusselt number is found increasing with increasing either Re or Ri number. In addition, the turbulent kinetic energy is discernibly affected by increasing Re number. Moreover, the LES results have shown good ability of this method in predicting more detailed flow structures in the cavity.

***Keywords*—**Mixed convection, Lid-driven cavity, Turbulent flow, RANS model, URANS model, Large eddy simulation.

I. Introduction

In recent decades, the field of computational fluid dynamic of heat convection in cavities has been addressed in many research projects, due to their wide applications in engineering and industrial fields such as oil extraction, air conditioning, electronic devices cooling, lubrication technologies, high-performance buildings insulation and solar power collectors [1]-[6]. Researchers have conducted extensive studies on the natural or free convection in closed cavities with different geometry shapes. Cianfrini et al. [7] carried out numerically a 2D natural convection of Al_2O_3-water within a square enclosure which was cooled at one side and other opposite side was heated partially, while the rest walls were insulated. The main finding of this study was that by decreasing the nanoparticles size leads to reduced heat transfer performance. However, the position and the length of the heater had significant effect on the heat transfer ratio.

A 2D Newtonian fluid filled with porous cavity to study free convection for both laminar and turbulent flow was investigated numerically by [8]. The one and two temperature energy models were studied. The outcome of this computational experiment illustrated that both models give the same output when the ratio of thermal conductivity of solid to thermal conductivity of fluid is equal to unity. A number of other computational researches in this area include a 2D periodic free convection in square cavity with a thin heat source by [9], a 2D laminar natural convection in shallow wavy closed cavity by [10], a 2D natural convection of unsteady buoyancy driven flow and heat transfer in a partitioned triangular cavity by [11], natural convection of CuO-water nanofluid within a 2D rectangular enclosure at different low aspect ratios by [12], a 2D steady free convection of a non-Newtonian power-law fluid within trapezoidal cavity by [13], a 2D natural convection of comparison complex annular configuration enclosures which was filled by cold water by [14], and a 2D half-moon configuration closed cavity with diversity of thermal boundary condition for three types of nanofluids by [15].

Numerous investigations have been done on mixed convection by moving one wall or more of enclosure by changing either boundary conditions or fluid types. This kind of research has been continually developed and published in the literature. A mixed and an natural convections of stationary and rotating centred cylinder in a 2D square cavity with different rotating speeds was carried out by [16]. The aim was to find out the relation between Nu_{mean} and Ri as well as to study the effects of the aspect ratio between the inner cylinder and outer cavity on the heat transfer. It was found that the relation was not affected by changing the aspect ratio, but it was proved that reducing Nu_{mean} comes with decreasing value of Ri.

A 2D viscous, unsteady and incompressible nanofluid flow within heated lid-driven with pulsating flow was investigated numerically by [17]. The influence of the amplitude, oscillation frequency, and wave number of the sinusoidal velocity waves at the lid on the convection was the research aims. Using the Network Simulation method (NSM) it was found that Richardson number was increased in excited pulsating flow. Goodarzi et al. [18] studied numerically both laminar and turbulent mixed convection heat transfer of nanofluid inside a 2D shallow enclosure. The upper wall of the cavity was studied as a cooled moving wall and the bottom wall was heated, while the side walls were kept adiabatic. Two different values of $Gr=10^5$ (laminar flow) and 10^{10} (turbulent flow) with different values of Ri and different nanoparticles concentration were studied. It was observed that by increasing nanoparticles fraction leads to enhanced heat transfer ratio and Nu. In addition, turbulent kinetic energy, turbulence intensity, wall shear stress, and skin friction were affected by nanoparticles concentration.

A numerical investigation of mixed convection of 2D

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inclined shallow lid-driven enclosure filled with Cu-water nanofluid was carried out by [19]. The top wall had higher temperature than the bottom wall, and the side walls were kept insulated. It was found that at Ri = 0.1 the movement of the moving wall dominated the nanofluid, which means that forced convection dominated the heat transfer. However, at Ri = 10, the free convection has more control on the heat transfer. Moreover, increasing the concentration of the nanoparticles leads to enhanced heat transfer.

II. METHODOLOGY

The Computational Fluid Dynamic (CFD) method was used in this project to predict the flow and heat transfer characteristics in a cubic lid-driven cavity, by using the finite volume method of FLUENT solver.

A. Physical Models

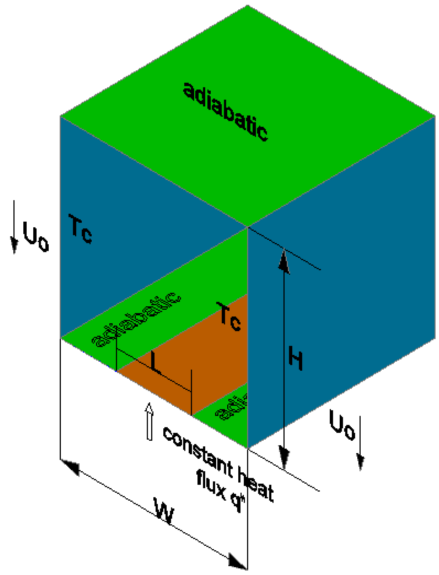


Fig. 1 Schematic diagram of the cubic lid-driven cavity

Fig. 1 illustrated the main geometry parameters of this research. Uniform velocity and cooled temperature are the features of the moving downward sidewalls of the cubic. Constant heat flux is feeding the middle part (L) of the bottom wall, while the rest domain parts are adiabatic walls. This type of geometry can refer to air cooling system of the electronic devices.

The boundary conditions for the present problem are specified as:

Top wall: $\partial\theta/\partial Y = 0,\ U = V = W = 0$

Bottom wall: $$\frac{\partial\theta}{\partial Y} = \begin{Bmatrix} 0, for\ 0 < X < (1-\varepsilon)/2 \\ 1, for\ (1-\varepsilon)/2 \le X \le (1+\varepsilon)/2 \\ 0, for (1+\varepsilon)/2 < X < 1 \end{Bmatrix}$$

Right and left wall: $\theta = 0,\ U = 0,\ W = 0,\ V = -1$

The condition $\partial\theta/\partial Y = -1$ for $(1-\varepsilon)/2 \le X \le (1+\varepsilon)/2$ at the bottom wall arises as a consequence of constant heat flux.

B. Grid Independence Tests

In order to obtain the best mesh type and number for the particular geometries, structured and non-uniform mesh is used in this work with refined mesh close to the walls of the domain. The grid independence tests were done for RANS and URANS separately by using the standard *k-ε* model at constant values of *Re* = 5000 and *A* = 1 with convergence criterion less than 10^{-6}.

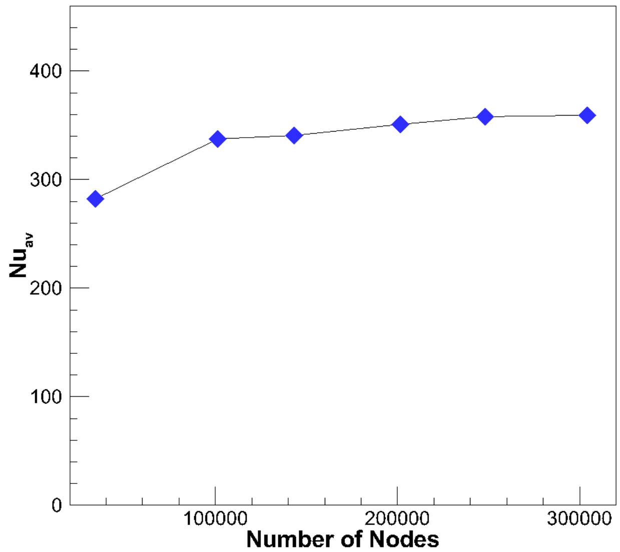


Fig. 2 Grid independence test of 3D cubic lid-driven cavity at *Re* = 5000 and *Ri* = 10

Firstly, six different nodes number (34200, 101250, 143312, 201840, 248400 and 304200) were generated for three dimensional RANS model, at *Ri* = 10. As shown in Fig. that the last three cases of nodes number are suitable because they showed very similar Nu_{av} of the bottom wall of the geometry. The nodes number used in this model is 248400.

Secondly, five different nodes number (120000, 410625, 980000, 1699200 and 1921875) were examined in three dimensional URANS at *Ri* = 1, with non-dimensional time step equal to 0.001. Although, the five cases did not show big difference in term of Nu_{av} results, the number of grid points used with this model is chosen as 1699200 to maintain good accuracy.

Finally, using LES method needs to have some specific modifications compared to the above URANS models such as fine grids and small time steps [20]. However, the nodes number using LES model is about 6 million with y^+ around 1 and low aspect ratio of the mesh elements. The non-dimensional time step used is 0.0006 based on the CFL conditions.

C. Code Validations

Code validation is a main beginning step of computational fluid dynamic in order to run new simulations. In this study two previous journal papers were validated: a 2D mixed convection heat transfer in trapezoidal lid-driven cavity that has constant heat flux at the stationary bottom wall and with adiabatic side walls [21], and a 2D mixed convection heat transfer in rectangular lid-driven cavity that partially heated at constant heat flux at the bottom wall [22]. Fig. 2 illustrates good agreement with the previous investigations.

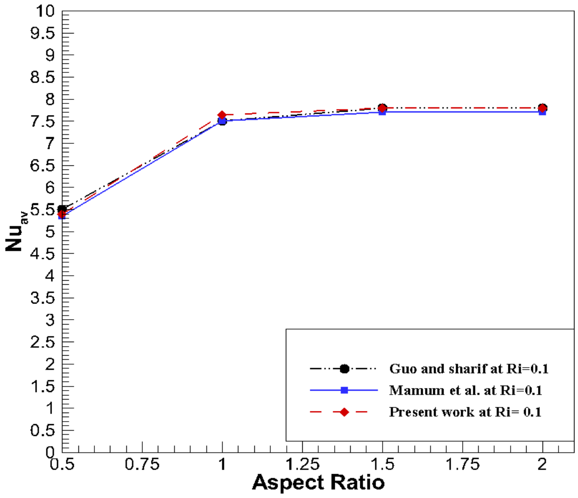


Fig. 2 Average Nusselt number comparison of the present simulations with previous results [21], [22]

III. Results and Discussion

A. RANS Model

The variation of local *Nu* along the heated centre bottom is shown in Fig. 4 to illustrate the effects of using different k-ε predictions in the turbulent flow case at Re = 5000 and Ri = 1 and 10. Overall, it can be seen that using different models shows only slight difference in the value of local Nusselt number. However, changing Richardson number shows significant effects on the values of local Nusselt number for all k-ε models. The effects of using various values of Reynolds number are presented in Fig. 5 in term of local Nusselt number, which are clearly discernible. In addition, for both Figs. 4 and 5, the highest *Nu* occurs at the edges of the bottom surface, while the minimum *Nu* occurs at the middle of the heat source. This is because the edges of the heat source have a direct attachment to the other unheated parts as well as the symmetrical boundary conditions. However, the lowest local Nusselt number is shown at the heat source centre that attains the maximum temperature and the minimum heat transfer rate.

The predicted turbulent kinetic energy contours for three representative values of Reynolds number (*Re* = 5000, 10000 and 15000) are shown in Fig. 6 for mixed convection parameter, *Ri* = 1, and at dimensionless source length, $\varepsilon = 0.6$. In general, the contours are symmetric about the vertical midline of the moving sidewalls enclosure, because of using symmetric lid-driven domain and boundary conditions. Obviously, at constant Richardson number, the Reynolds number has a discernible effect on the turbulent kinetic energy values, especially with the high speed regime that is close to the moving sidewalls of the lid-driven cavity.

B. URANS Model

The predicted isotherm and turbulent kinetic energy contours are shown in Fig. 7 to investigate the enhancement of changing Reynolds number, Re = 5000, 10000 and 15000. This investigation is carried out by using standard k-ε model. At constant Ri, the contours indicate that increasing value of *Re* leads to increasing the temperature, due to the increase of the value of *Gr* number. In addition, the turbulent kinetic energy increases gradually by increasing *Re*, especially at the regions of lid-driven walls. That is due to the higher turbulent velocity in these areas.

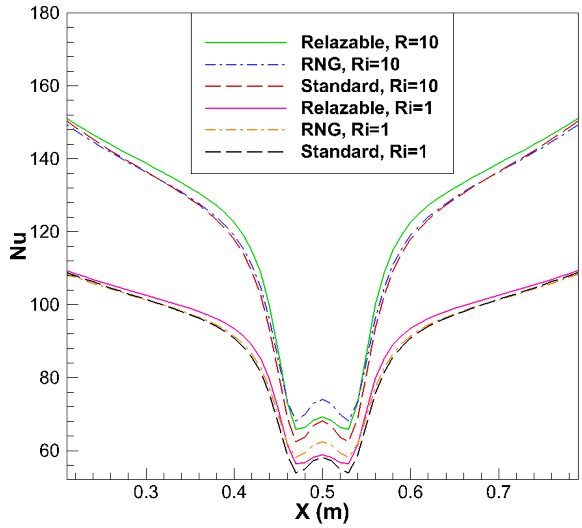


Fig. 4 Local Nusselt number along the heated centre bottom part for different k-ε models and Ri

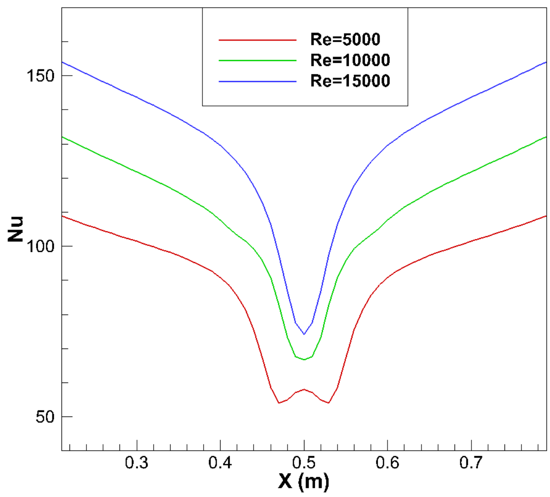
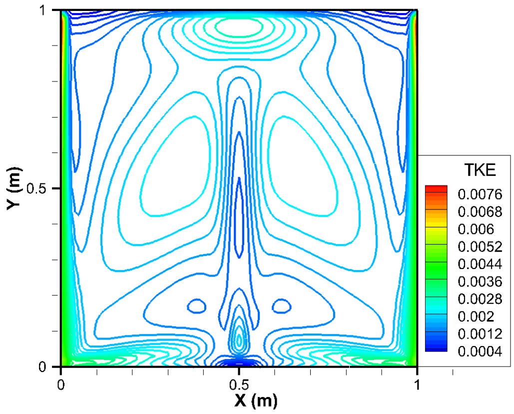


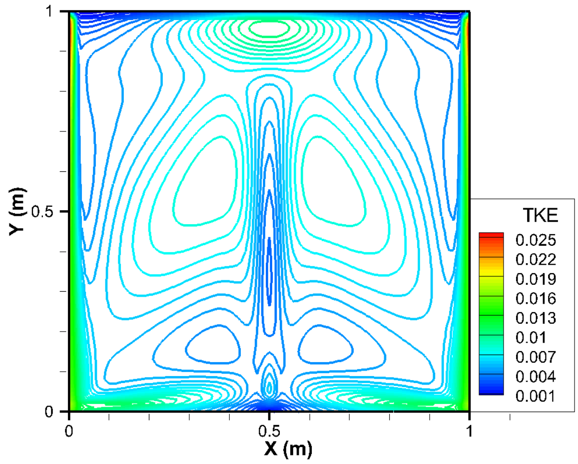
Fig. 5 Local Nusselt number along the heated centre bottom part for different Re

C. Instantaneous Temperature Fields of URANS vs LES

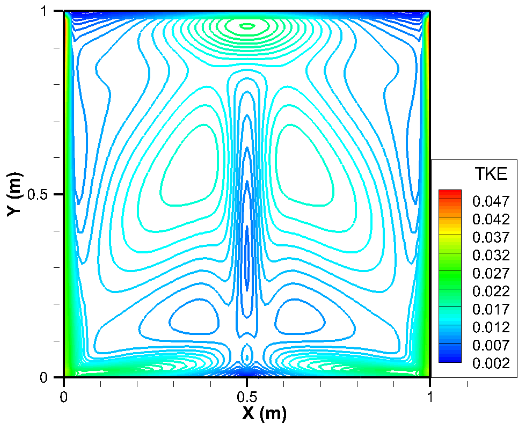
By using URANS and LES models, Fig. 8 illustrates the snapshots of temperature distribution patterns with time at z=0 for the x-y plane in the domain. Obviously, LES model can predict more detailed eddy structures while URANS produced only the big eddy scales.



Re=5000

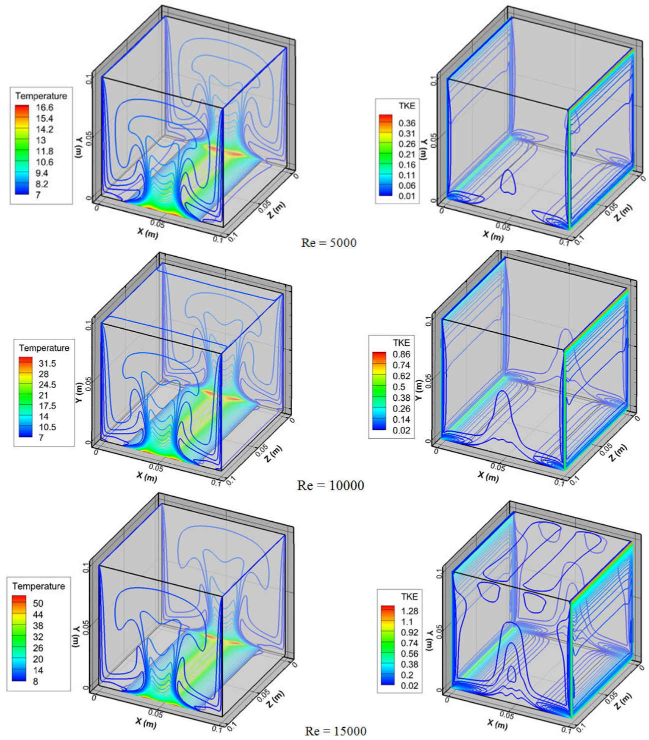


Re=10000



Re=15000

Fig. 6 Turbulent kinetic energy contours at Ri = 10 and ε = 0.6



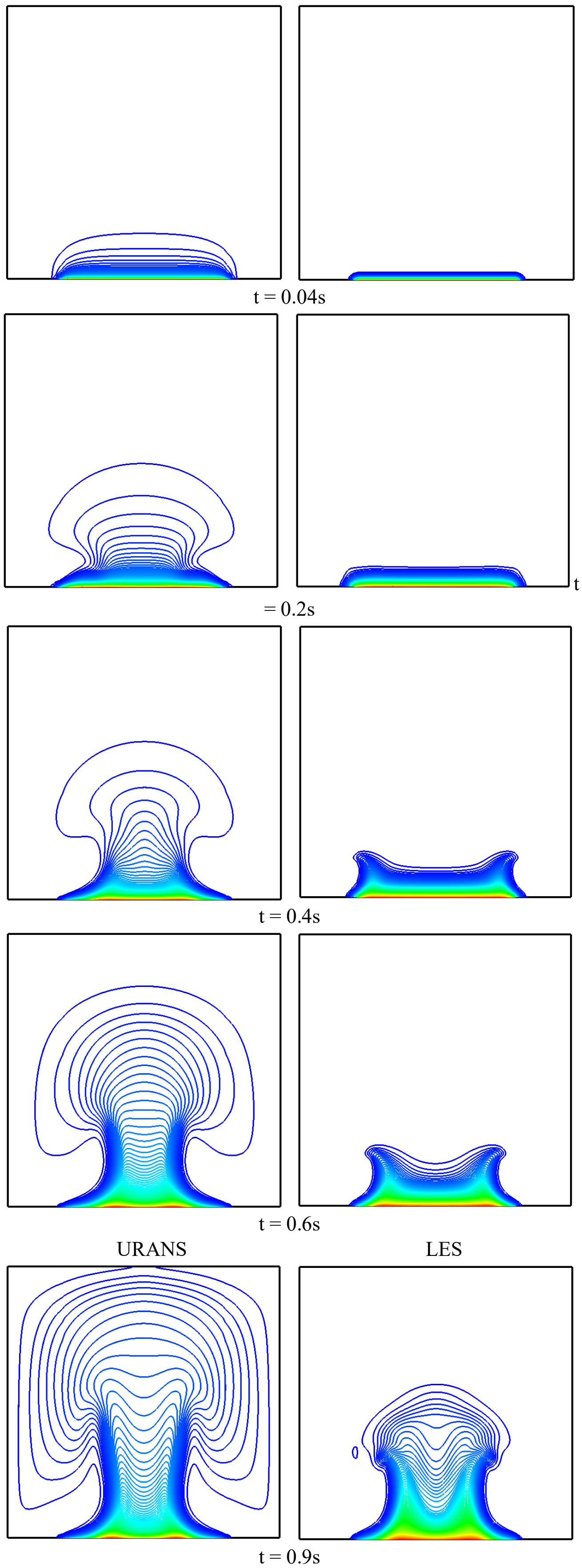
(a) (b)

Fig. 7 Isotherm (a) and turbulent kinetic energy (b) contours at Ri = 1 and ε = 0.6 by using URANS model

IV. Conclusion

This paper presented the numerical results of mixed convection heat transfer of air (*Pr* = 0.71) in a lid-driven cubic enclosure that is heated at the centre of the bottom wall and has moving sidewalls. In particular, the effects of varying both Reynolds and Richardson numbers on the convection are studied. The obtained new results proved the following points:

- Using different models of k-ε shows only slight difference in term of local Nusselt number.
- The highest Nusselt occurs at the edges of the bottom surface, while the minimum Nusselt occurs at the middle of the heat source. The lowest local Nusselt number is shown at the centre of the heat source.
- Increasing either Richardson or Reynolds number leads to increasing the Nusselt number and velocity of the fluid in the cavity.
- Reynolds number has a discernible effect on the turbulent kinetic energy values, especially in the high speed region.
- The highest turbulent velocity occurs in the region near the moving walls and it increases as Reynolds number increases.
- LES model shows good ability to capture the finer eddy structures in the cavity in comparison to the URANS prediction.



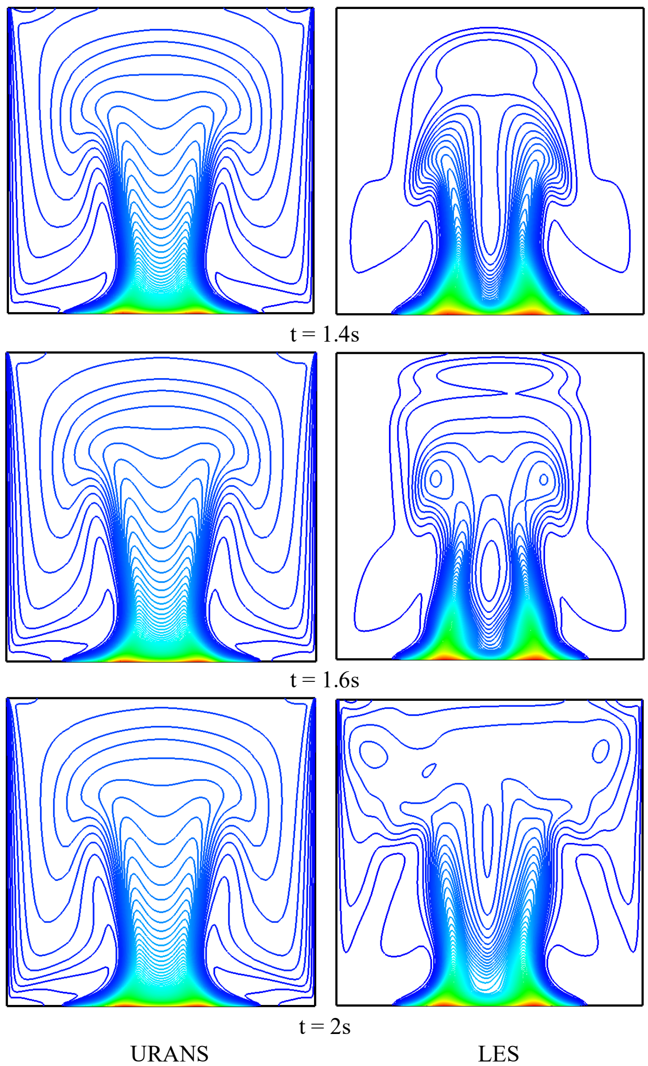


Fig. 8 Instantaneous isotherm comparison between URANS and LES at Ri = 10, Re = 5000 and ε = 0.6, located at z=0 for the x-y plane

ACKNOWLEDGMENT

The authors would like to thank the sponsor and financial support that came from ministry of higher education of Iraq. This research used the ALICE High Performance Computing Facility at the University of Leicester.

REFERENCES

[1] Selimefendigil F., Öztop H.F., Numerical study of MHD mixed convection in a nanofluid filled lid driven square enclosure with a rotating cylinder, International Journal of Heat and Mass Transfer, 78 (2014) 741-754.
[2] Elshehabey H.M., Hady F., Ahmed S.E., Mohamed R., Numerical investigation for natural convection of a nanofluid in an inclined L-shaped cavity in the presence of an inclined magnetic field, International Communications in Heat and Mass Transfer, 57 (2014) 228-238.
[3] Pekmen B., Tezer-Sezgin M., MHD flow and heat transfer in a lid-driven porous enclosure, Computers & Fluids, 89 (2014) 191-199.
[4] Chatterjee D., Gupta S.K., Mondal B., Mixed convective transport in a lid-driven cavity containing a nanofluid and a rotating circular cylinder at the center, International Communications in Heat and Mass Transfer, 56 (2014) 71-78.

[5] Kalteh M., Javaherdeh K., Azarbarzin T., Numerical solution of nanofluid mixed convection heat transfer in a lid-driven square cavity with a triangular heat source, Powder Technology, 253 (2014) 780-788.
[6] Ismael M.A., Pop I., Chamkha A.J., Mixed convection in a lid-driven square cavity with partial slip, International Journal of Thermal Sciences, 82 (2014) 47-61.
[7] Cianfrini C., Corcione M., Habib E., Quintino A., Buoyancy-induced convection in Al2O3/water nanofluids from an enclosed heater, European Journal of Mechanics - B/Fluids, 48 (2014) 123-134.
[8] Carvalho P.H., de Lemos M.J., Turbulent free convection in a porous cavity using the two-temperature model and the high Reynolds closure, International Journal of Heat and Mass Transfer, 79 (2014) 105-115.
[9] Sourtiji E., Ganji D., Gorji-Bandpy M., Seyyedi S., Numerical study of periodic natural convection in a nanofluid-filled enclosure due to transitional temperature of heat source, Powder Technology, 259 (2014) 65-73.
[10] Varol Y., Oztop H.F., Free convection in a shallow wavy enclosure, International communications in heat and mass transfer, 33 (2006) 764-771.
[11] Saha S.C., Khan M., Gu Y., Unsteady buoyancy driven flows and heat transfer through coupled thermal boundary layers in a partitioned triangular enclosure, International Journal of Heat and Mass Transfer, 68 (2014) 375-382.
[12] Bouhalleb M., Abbassi H., Natural convection of nanofluids in enclosures with low aspect ratios, International Journal of Hydrogen Energy, (2014).
[13] Sojoudi A., Saha S.C., Gu Y., Hossain M., Steady Natural Convection of Non-Newtonian Power-Law Fluid in a Trapezoidal Enclosure, Advances in Mechanical Engineering, 2013 (2013).
[14] Hu Y.-P., Li Y.-R., Wu C.-M., Comparison investigation on natural convection of cold water near its density maximum in annular enclosures with complex configurations, International Journal of Heat and Mass Transfer, 72 (2014) 572-584.
[15] Rahman M., Saha S., Mojumder S., Mekhilef S., Saidur R., Numerical Simulation of Unsteady Heat Transfer in a Half-Moon Shape Enclosure with Variable Thermal Boundary Condition for Different Nanofluids, Numerical Heat Transfer, Part B: Fundamentals, 65 (2014) 282-301.
[16] Liao C.-C., Lin C.-A., Mixed convection of a heated rotating cylinder in a square enclosure, International Journal of Heat and Mass Transfer, 72 (2014) 9-22.
[17] Serna J., Velasco F., Soto Meca A., Application of network simulation method to viscous flows: The nanofluid heated lid cavity under pulsating flow, Computers & Fluids, 91 (2014) 10-20.
[18] Goodarzi M., Safaei M., Vafai K., Ahmadi G., Dahari M., Kazi S., Jomhari N., Investigation of nanofluid mixed convection in a shallow cavity using a two-phase mixture model, International Journal of Thermal Sciences, 75 (2014) 204-220.
[19] Karimipour A., Hemmat Esfe M., Safaei M.R., Toghraie Semiromi D., Jafari S., Kazi S., Mixed convection of copper–water nanofluid in a shallow inclined lid driven cavity using the lattice Boltzmann method, Physica A: Statistical Mechanics and its Applications, 402 (2014) 150-168.
[20] FLUENT A., 15.0 Theory Guide, Ansys Inc, 5 (2013).
[21] Mamun M., Tanim T., Rahman M., Saidur R., Nagata S., Mixed convection analysis in trapezoidal cavity with a moving lid, International Journal of Mechanical and Materials Engineering, 5 (2010) 18-28.
[22] Guo G., Sharif M.A., Mixed convection in rectangular cavities at various aspect ratios with moving isothermal sidewalls and constant flux heat source on the bottom wall, International journal of thermal sciences, 43 (2004) 465-475.