Center for Energy Efficiency and Renewable Energy

C E E R E

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A Comparison of Turbulence Natural Convection Modeling Prediction to Experimental Data for an Air Filled Square Cavity

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We conducted a numerical study of low turbulence natural convection in square cavity to assess the ability of a low-Reynolds-number (LRN) k-ε turbulence model to predict heat transfer and fluid flow within a two-dimensional enclosure with more complicated boundary conditions than usually used in numerical and experimental works with adiabatic horizontal walls. Numerical calculations have been performed for air filled square cavity and are compared with experimental measurements taken by and Tian and Karyiannis [1] for square cavity with highly conductive horizontal walls.

1. Numerical model and method

In our study we used LRN k-ε turbulence model with variable coefficients described in details in [2] as VC LRN k-ε turbulence model. Therefore we do not give here the model equations that are available in ref. [2] and our report [3]. Our second LRN k-ε model is the same model in which we included two additional source terms in equation of dissipation of turbulent kinetic energy. This model was described in [3] and designated here as LRN k-ε model++.

A computer code named FLU2TURB has been developed to solve the two-dimensional steady turbulent problem. The numerical discrete method is based on the upwind and fully implicit transient differencing control volume scheme used respectively for the convective, diffusive and time-dependent terms in the governing equations where the velocity control volumes are staggered with respect to the main control volumes. The resulting algebraic equations are solved iteratively using a line-by-line TDMA solution procedure and the SIMPLE algorithm formulated by Patankar [4]. Steady-state solutions are obtained using under-relaxation techniques.

To verify the numerical accuracy of the predicted results we used two mesh (1360 and 1800 points). For these grids we obtained less than 0.5 % difference in average Nusselt number and maximum velocities.

2. The geometry and boundary conditions

To compare results of numerical modeling with experimental data [1] we defined the geometric dimensions, temperature conditions and material properties close to the unit used in the experiment. The cavity geometry and boundary conditions are shown at Figure 1. The heat insulation of horizontal walls is modeled by film coefficient h = 1.0 W/(m^{2o}C). The conductivity of mild steel is 48.0 W/(m^{o}C).

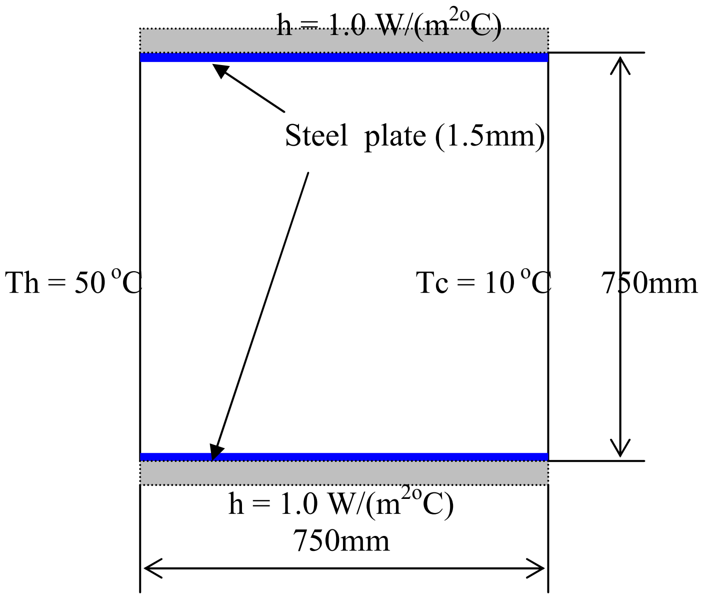

Figure 1. Geometry and boundary conditions of the modeled cavity.

As result we obtained temperature distribution along horizontal walls very close (Figure 2) to measured in experiment [1]. Our calculation of Rayleigh number based on average cavity temperature (30°C) and air properties from [5] gave us value Ra = $1.65x10^9$. In experimental work [1] was reported Rayleigh number of $1.58x10^9$.

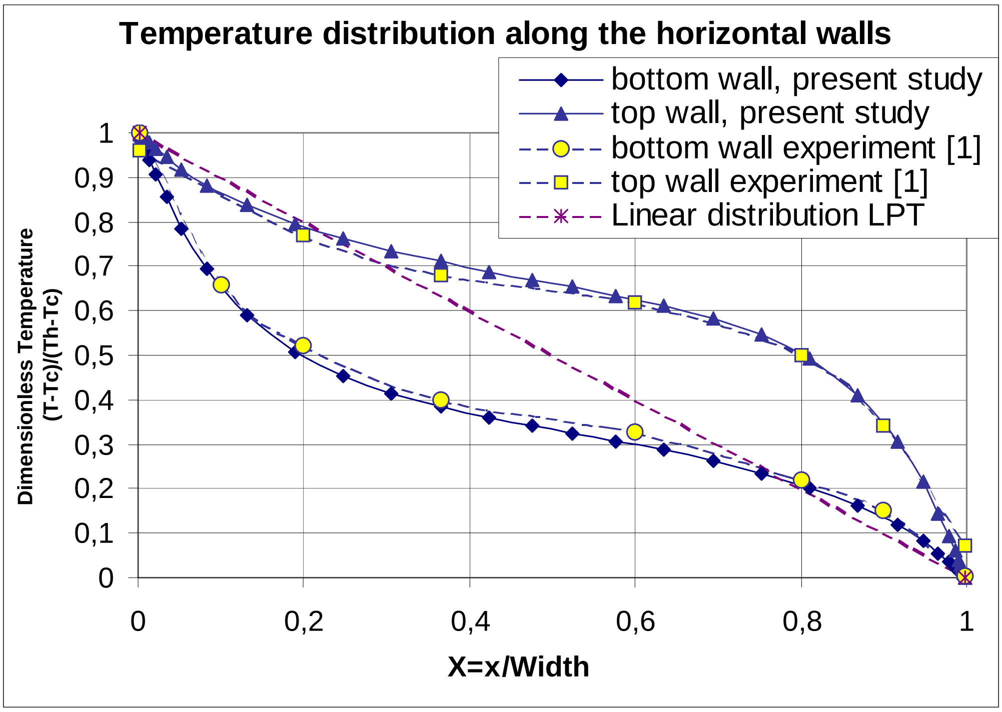

Figure 2. Comparison of experimental temperature distribution along horizontal walls with present study.

3. Comparison of experimental and numerical modeling results and discussion

Before we discuss and compare the present results with experimental study it is necessary to point that only LRN k-ε model++ gave us results close to experiments ones and below only references to this model were used if otherwise do not pointed directly.

3.1. The temperature distribution.

A contour plot of the thermal field is shown in Figure 3. The dimensionless temperature at the cavity center is 0.504 (0.514 in experiment [1]). From X = 0.13 to 0.87 (X = 0.1 to 0.9 in experiment [1]), the temperature decreased very slightly, indicating that the fluid in the core area is nearly stationary. Predicted temperature distribution at mid-height of cavity is shown at Figure 4. The temperature profiles near the hot wall at mid-height obtained in present study and in experiment [1] are shown at Figure 5. The agreement between profiles is very good. The temperature distribution at the cavity mid-width is compared with experimental results [1] in Figure 6. The stratification parameter was 0.5 in the experiment and 0.44 in numerical study.

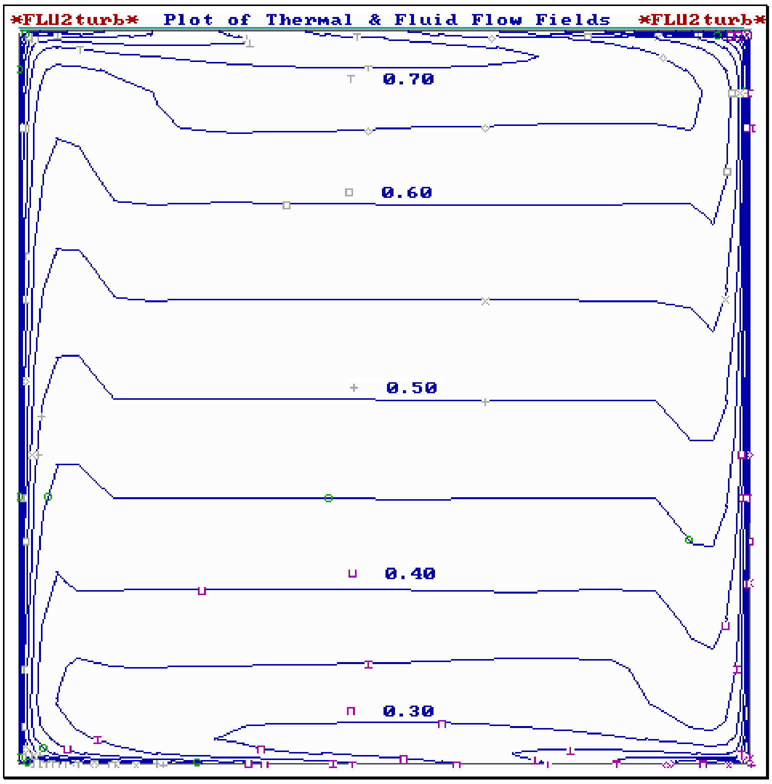

Figure 3. Contour plot of temperature distribution, (T-Tc)/(Th-Tc), in the cavity.

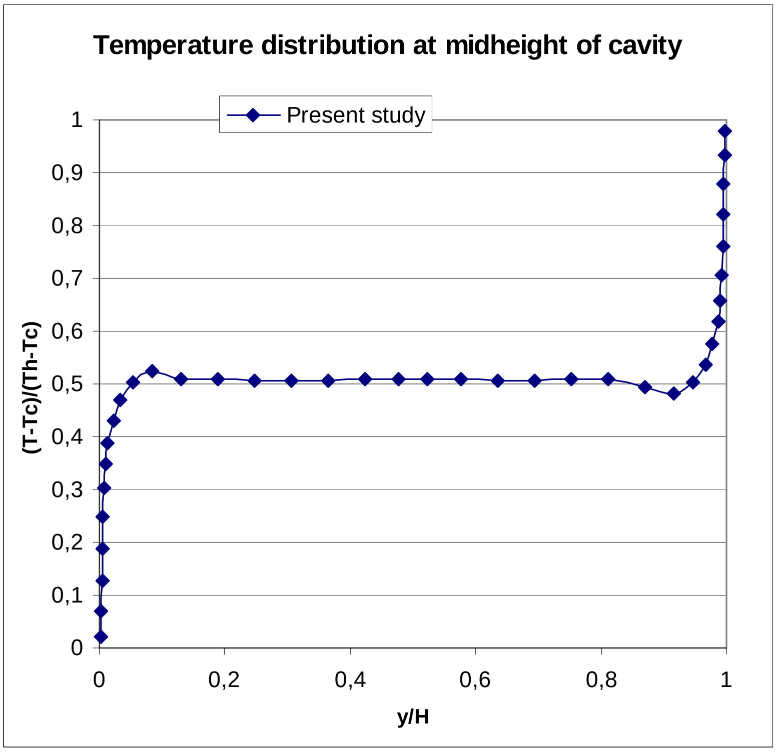

Figure 4. Predicted temperature distribution at mid-height of cavity.

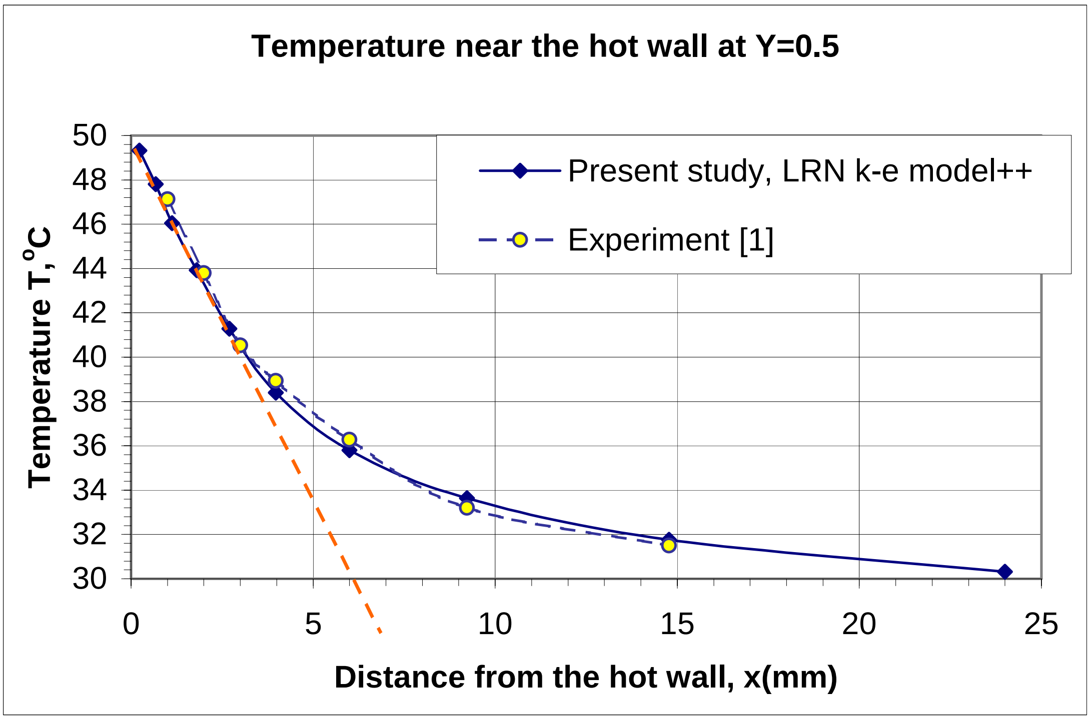

Figure 5. Comparison of temperature profiles near the hot wall.

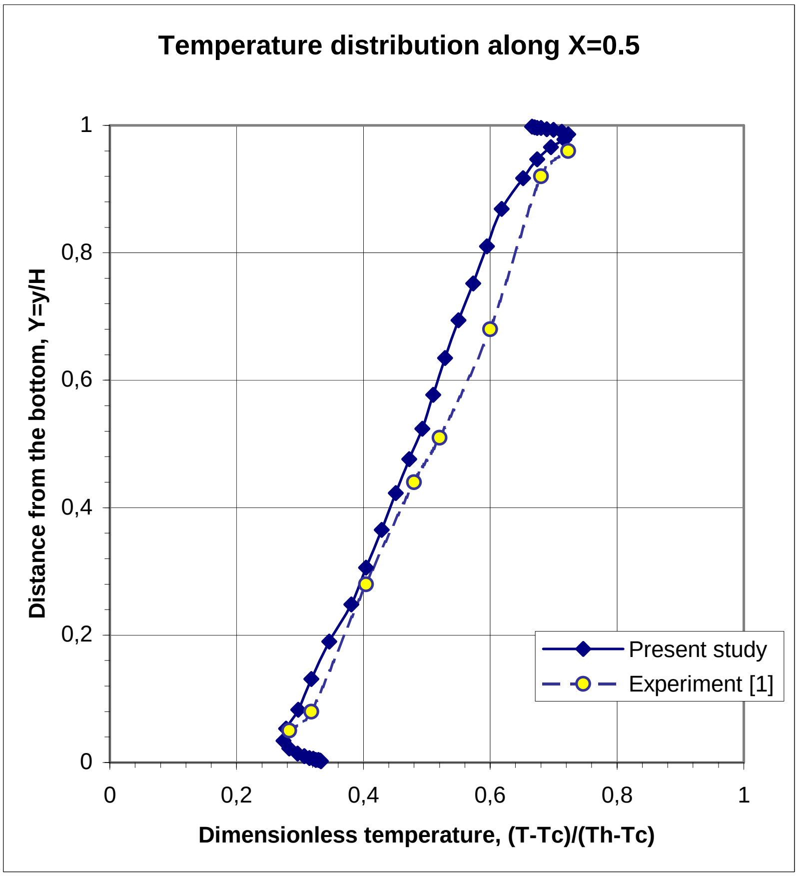

Figure 6. Comparison temperature distribution at the cavity mid-width.

3.2. The velocity distribution.

The whole fluid flow vector plot in the cavity is given in Figure 7.

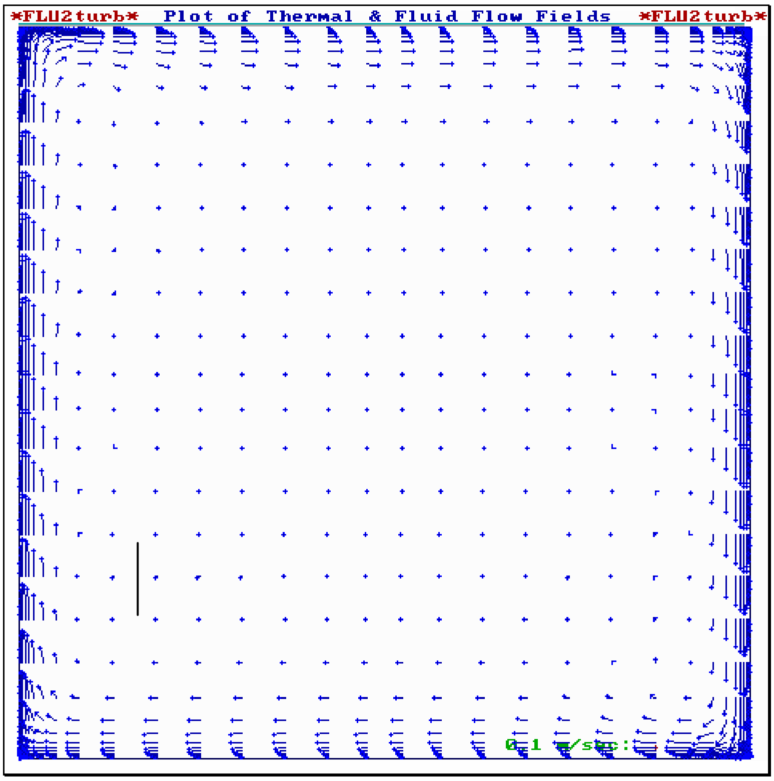

Figure 7. The fluid flow vector plot in the cavity.

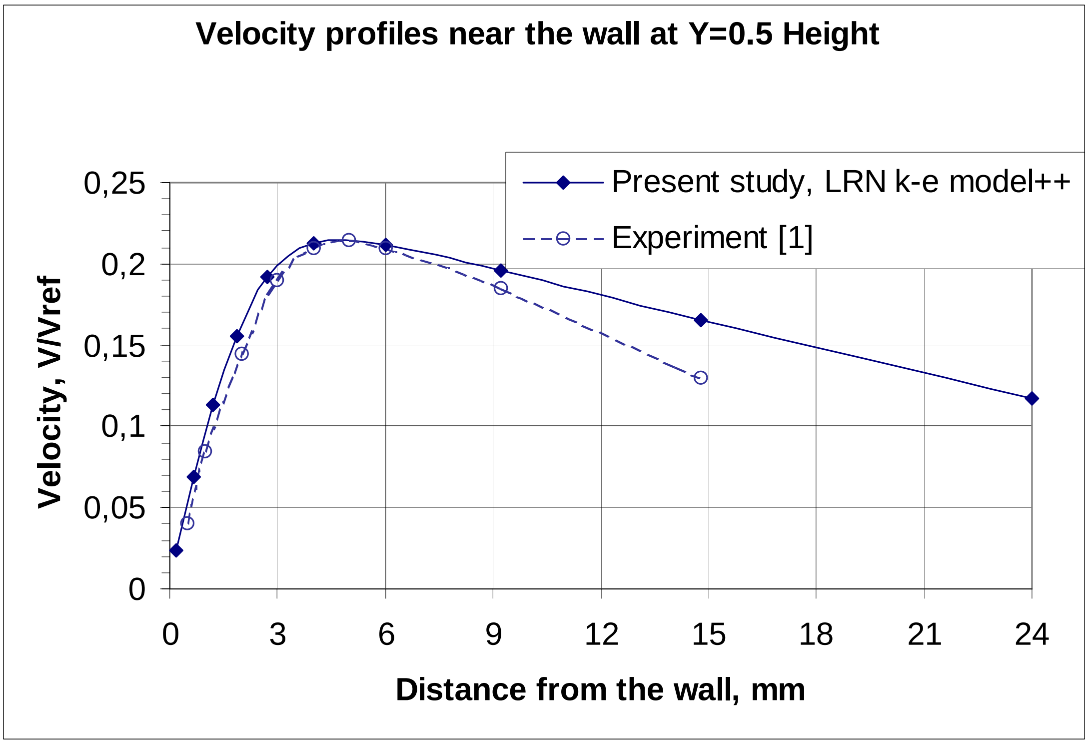

Figure 8. Comparison of velocities profiles near the hot wall.

At Figure 8 we give comparison of predicted velocities profile near the hot wall with profile obtained in experimental work [1]. Vref is buoyancy velocity defined as $Vref = (g\beta H\Delta T)^{1/2}$ and in our case is equal to 1 m/s. LRN k-ε model++ predicted the same velocity change as in experiment and the same peak velocity position to wall so the wall shear stress was estimated by numerical model adequate to the experiment. But predicted thickness of boundary layer is larger than the one obtained in the experiment.

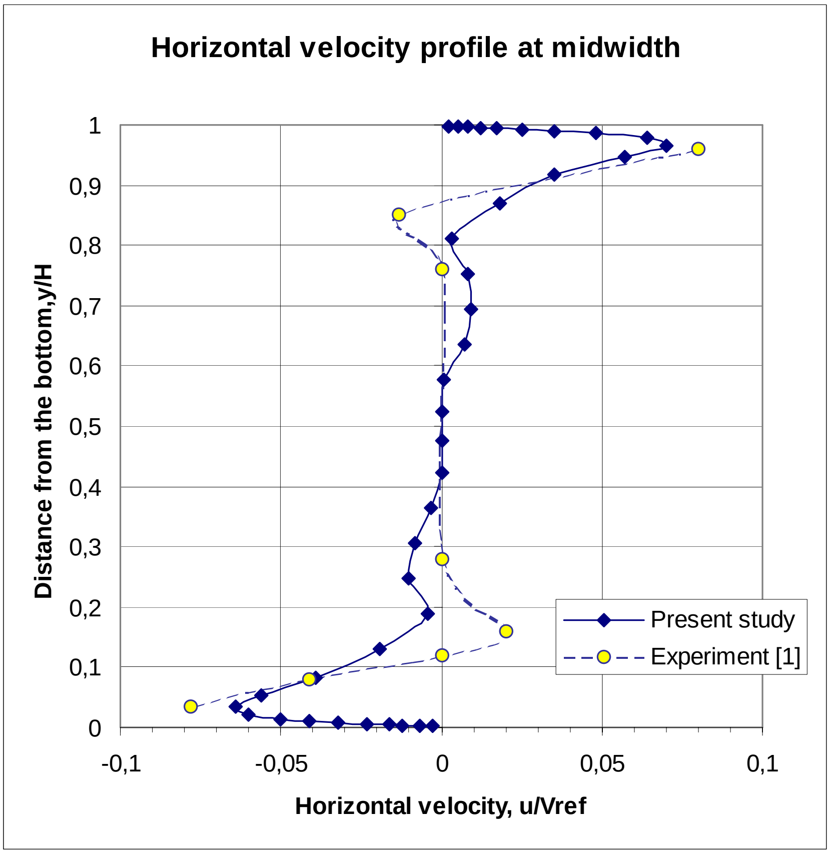

Figure 9. Comparison of the horizontal velocity at mid-width.

Comparison of the horizontal velocity profiles at cavity mid-width is shown at Figure 9. Experimental measurements give flow reversal along the outer edge of the horizontal boundary layer that is not indicated by numerical model. The maximal velocity in the horizontal boundary layer obtained in the experiment exceeds the predicted one at 15%.

3.3. The heat flux.

A comparison of predicted local Nusselt numbers along the hot wall for experimental conditions [1] is shown in Figure 10. The local Nusselt number is defined by a ratio of local heat flux (q) and reference heat flux

$$Nu = q / [k_g (Th - Tc)/H] \quad (1)$$

where k_g is gas conductivity for average temperature of cavity.
LRN k-ε turbulence model predicted higher level of heat transfer than LRN k-ε model++ and than values obtained in the experiment [1] but maxim Nu value more close to experimental value (135) than LRN k-ε model++ (115). We give also comparison of predicted local Nusselt number along bottom cavity wall and obtained in the experiment at Figure 11.

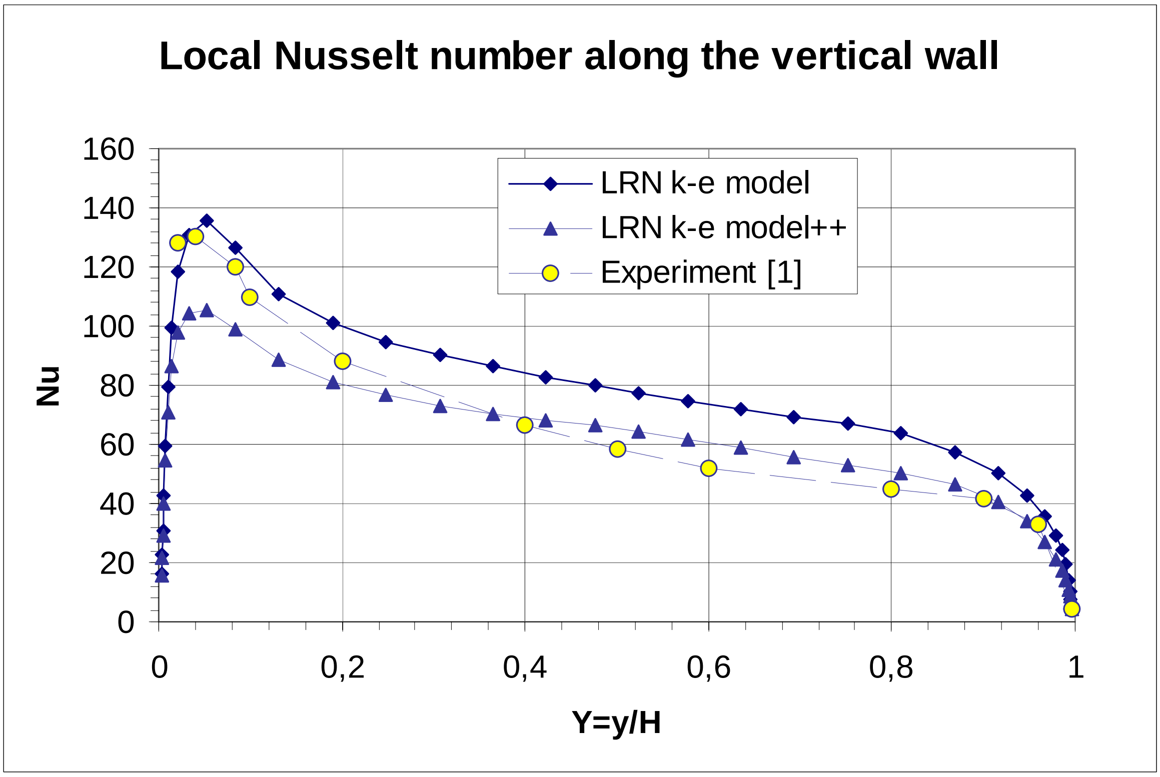

Figure 10. Comparison of local Nusselt number along the hot wall.

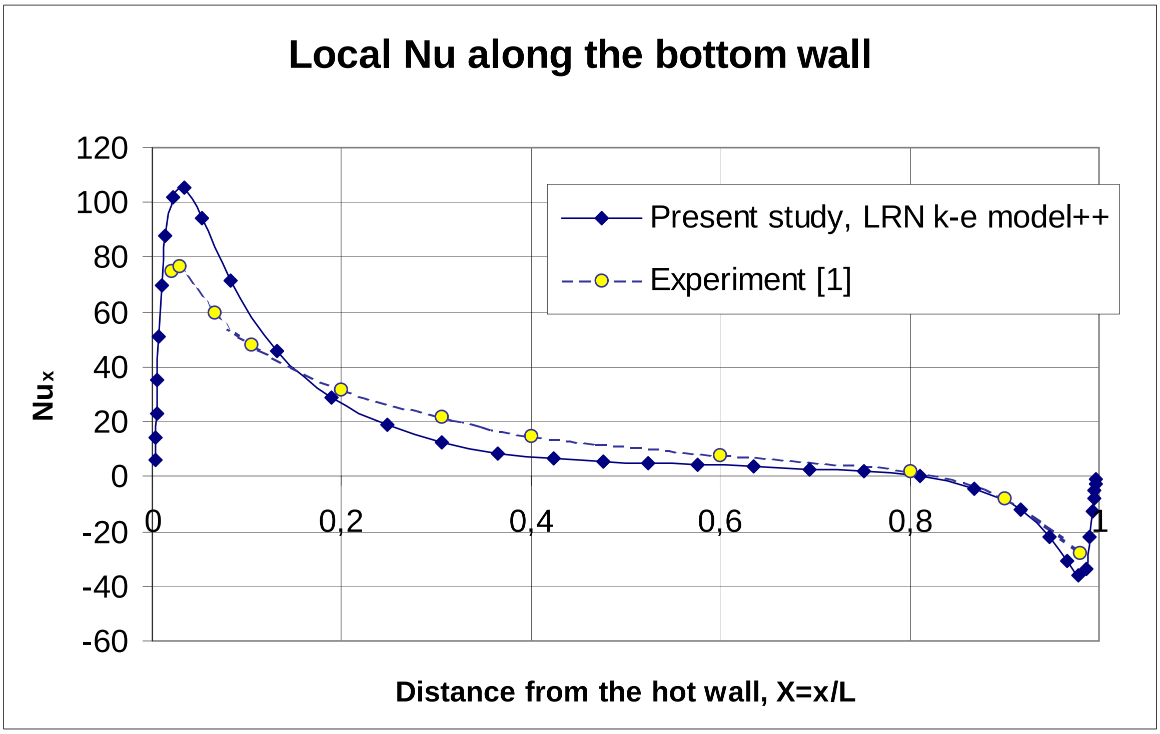

Figure 11. Comparison of local Nusselt number along the bottom wall.

In Table 1, predicted average Nusselt numbers are compared with value obtained from experimental study [1]. Table 1 shows that only LRN k-ε model++ predict average Nusselt numbers very close to value determined from experimental study.

Table 1. Comparison of predicted average Nusselt number with experimental data.

Source of data	Nu Hot wall	Nu cold wall	Nu average value	Percentage difference
Experiment [1]	64.0	65.3	64.5	-
LRN k-ε turbulence model++			62.44	3.4%
LRN k-ε turbulence model			78.2	20.6%
Laminar model			48.9	24.2%

3.4. The turbulence quantities.

The predicted turbulent kinetic energy distribution is shown at Figure 12. The maximum value of turbulent kinetic energy was estimated in the experiment [1] as $3.5x10^{-3}$ m^2/s^2 for cold wall and $4.5x10^{-3}$ m^2/s^2 for hot wall. LRN k-ε model++ predicted maximum turbulent kinetic energy to $3.6x10^{-3}$ m^2/s^2 and maximum no dimensional turbulent viscosity $\nu_t/\nu = 38$.

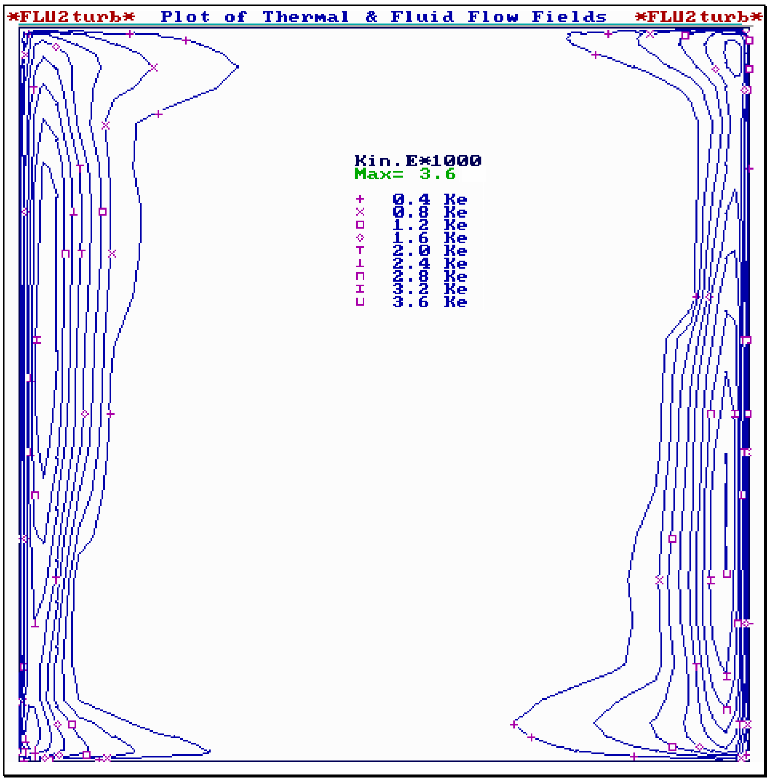

Figure 12. Distribution of the turbulent kinetic energy, $k_* 10^3$ m^2/s^2.

CONCLUSIONS

Two low-Reynolds-number k-ε turbulence models were used to predict turbulent natural convection within a differentially heated air filled square cavity with highly conductive horizontal walls at Rayleigh number $1.58x10^9$.

Both models predicted laminar and turbulent flow regimes, but only the LRN k-ε model++ predicted heat transfer rate, flow and turbulence quantities close to experimental data [1]. The difference between predicted average Nusselt number and reported in experimental work is 3.4%. The maximum turbulent kinetic energy predicted by LRN k-ε turbulence model++ is $3.6x10^{-3}$ m^2/s^2 and maximum no dimensional turbulent viscosity $\nu_t/\nu = 38$.

When compared to the experimental results of Tian and Karyiannis [1], this model predicted the velocity profiles and maximal velocity values in inner boundary layer very close to experimental data but thicker boundary layer than obtained in the experiment.

From the foregoing results, it is concluded that the LRN k-ε model++ does a satisfactory job of predicting natural convection flow and heat transfer within a differentially heated square cavity with highly conductive horizontal walls at Rayleigh number $1.58x10^9$.

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