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Test of turbulence models for natural convection in an open cubic tilted cavity☆

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ABSTRACT

A comparison was made between six turbulence models and experimental temperature profiles for the turbulent natural convection in a tilted open cubic cavity. The experimental setup consists of a cubic cavity of 1 m by side with one vertical wall receiving a constant and uniform heat flux, whereas the remaining walls are thermally insulated. The thermal fluid is air and the aperture is facing the heated wall. The temperature profiles were obtained at different heights and depths and each one consists of 10 positions inside the cavity. A commercial computational fluid dynamic software was used for the simulation and different turbulence models of k-ε_t and k-ω families were evaluated against experimental data. The lowest absolute average percentage difference for the experimental and numerical temperature profiles was for the rk-ε_t model and the highest was for the sk-ω model.

1. Introduction

The heat transfer study in open cavities has been widely investigated due its relevance in some thermal engineering applications such as solar thermal receivers [15] and electronic cooling devices [13]. In several thermal systems formed by an open cavity, a turbulent flow exists because the characteristics of the system: size, thermal gradient or inclination angle; therefore the accuracy of the turbulence models has to be established.

On the other hand, the open cavities used as thermal receivers in solar concentration systems (such as Dish Stirling or solar tower) operate with different inclination angles to allow the income of the concentrated solar light. In literature there are several reported studies pertaining to the heat transfer in open cavities [1–44], some of those that take into consideration the effect of the open cavity inclination are briefly described next.

1.1. Numerical studies

Hinojosa et al. [30] reported numeric results of Nusselt numbers for a tilted open square cavity, considering laminar natural convection and surface thermal radiation applying the Boussinesq approach. The results were obtained for a Rayleigh range from 10^4 to 10^7 and for an inclination angle range of the cavity from 0° to 180°. Hinojosa et al. [33] realized a numerical work of the heat transfer by laminar natural convection in a tilted open cubic cavity considering laminar flow and considering the Boussinesq approximation using the finite volume method and the SIMPLEC algorithm. The results were obtained for steady state, Rayleigh number ranging from 10^4 to 10^7 and inclination angles ranging from 0° to 180°. It was observed that for high Rayleigh numbers the Nusselt number changes substantially with the inclination angle of the cavity.

Prakash et al. [44] investigated the natural convection from open cavities of three different shapes (cubical, spherical and hemispherical) having equal heat transfer area using commercial CFD software Fluent. The study was performed using wall temperatures of 100 °C, 200 °C and 300 °C. The effect of the opening ratios and the inclination was studied. The convective loss is found to increase with an increase of opening ratio. The increase in natural convection loss for different inclinations is found to vary between 30% and 80% when the opening ratio is increased.

1.2. Experimental studies

Hess and Henze [3] reported experimental results for natural convection in fully/partially open cavities. Laser Doppler velocimetry was used to obtain velocity profiles for Rayleigh numbers between 3×10^{10} and 2×10^{11}. The characteristics of two-dimensional and three-dimensional flows were observed with dye flow visualization, including boundary layer transition to turbulence, flow patterns in the cavity, and flow outside of the cavity. The local Nusselt number is correlated with local Rayleigh number. Chakroun et al. [21] carried out an experimental investigation to determine the heat transfer coefficient from a rectangular tilted cavity to the ambient due to the buoyancy driven flow in the cavity. The cavity is partially or fully open from one side. All the walls of the cavity are adiabatic except the wall facing the cavity opening which is heated at a constant heat flux. The results presented in terms

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Nomenclature

A	electric current, (A)
Cp	specific heat at constant pressure, (J/kg K)
g	gravitational acceleration, (m/s^2)
k	turbulent kinetic energy, (J/kg)
L	cavity wall length, (m)
Nu	local convective Nusselt number, nondimensional
$\overline{Nu}$	total average Nusselt number, nondimensional
q	heat flux, (W/m^2)
Ra	Rayleigh number $= g\beta q L_y^4/\alpha\nu\lambda$, nondimensional
$\overline{T}_h$	average temperature of the hot wall, (K)
T_∞	ambient temperature, (K)
V	voltage, (V)
x, *y*, *z*	coordinate system, (m)

Greek symbols

α	thermal diffusivity, (m^2/s)
β	thermal expansion coefficient, (1/K)
ε_t	turbulent kinetic energy dissipation, (J/kg)
λ	thermal conductivity, (W/m K)
ε	emissivity, nondimensional
μ_t	turbulent viscosity, (kg/m s)
ν	kinematic viscosity, (m^2/s)
ρ	density, (kg/m^3)
ω	turbulent specific dissipation rate, nondimensional

of the average Nusselt number for different values of the above experimental parameters. Conclusions are derived for the effect of changing the tilt angle, the aspect ratio, the opening ratio of the cavity on the average heat transfer coefficient between the cavity and the ambient air. Chakroun and Elsayed [23] studied the free convection from a square tilted partially open cavity. The tilt angles comprise 0° to 180° and the modified Grashof number for a constant heat flux was 5.5×10^8. All the surfaces were considered as adiabatic except for the opposite wall to the aperture which a constant heat flux was applied. Large differences in the heat transfer coefficient were observed between the high and the low wall slits where the high wall slit is found to transfer more heat to the surroundings than the low wall slit.

1.3. Experimental–numerical studies

Showole and Tarasuk [14] presented a numerical and experimental steady two-dimensional laminar natural convection heat transfer from isothermal horizontal and inclined open cavities of rectangular cross section, using a Mach–Zehnder interferometer and numerically by a finite difference technique. The results show a flow recirculation with two counter rotating convective rolls developed in the cavity at $Ra \geq 10^5$. The inclination of the cavity induced flow entrainment, causing flow separation at the lower corner and flow reattachment at the upper corner of the aperture opening except in shallow cavities. For all Ra numbers, the first inclination of the cavity from the horizontal caused a significant increase in the average heat transfer rate, but further increase in the inclination caused very small increase in heat transfer rate.

The literature review shows the absence of studies of turbulent natural convection in tilted open cavities. Nevertheless the turbulent natural convection in tilted open cavities is relevant for the design of thermal receivers for thermosolar concentration systems. Considering the above, an experimental tilted open cavity was built to test several turbulence models. Six different turbulence models were compared against experimental temperature data and percentage differences were computed.

2. Physical and mathematical model

2.1. Physical model

The study of turbulent natural convection was performed on a cubic cavity with an edge (L) dimension of 1 m as is shown in Fig. 1. The left wall receives a constant and uniform heat flux, while the facing wall is open to the milieu. The remaining walls were assumed as adiabatic. Every wall of the cavity was covered with a film of polished aluminum ($\varepsilon = 0.05$), in order to minimize the thermal radiation exchange. The thermal fluid is air. The axis of rotation for inclining the cavity was the *z* axis and the inclination angle was measured from positive *x* axis.

2.2. Mathematical model

The considerations for the mathematical model are: steady state, Newtonian and compressible fluid, turbulent flow regime, variable

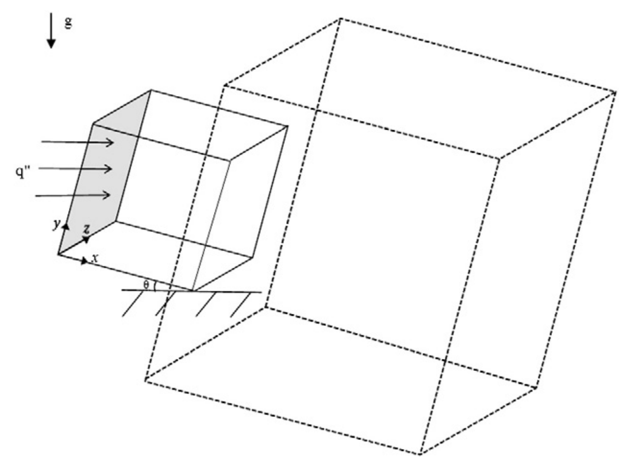

Fig. 1. Physical domain of the studied cavity (+15°).

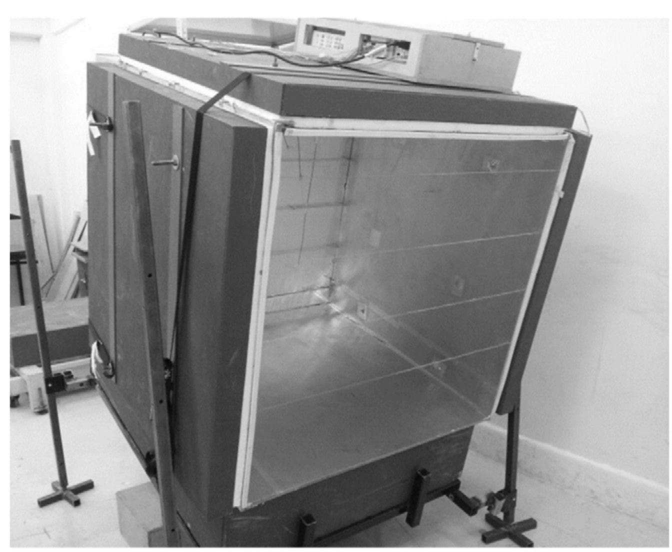

Fig. 2. Experimental cavity (+15°).