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On numerical modelling of conjugate turbulent natural convection and radiation in a differentially heated cavity

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ABSTRACT

Turbulent natural convection with and without radiation transfer in two-dimensional (2D) and three-dimensional (3D) air-filled differentially heated cavities is numerically investigated using various RANS (Reynolds Averaged Navier–Stokes) turbulence models and the Discrete Ordinates radiation model. Five different two-equation eddy-viscosity models including the standard k–ε model, the renormalization group (RNG) k–ε model, the realisable k–ε model, the standard k–ω model and the shear-stress transport (SST) k–ω model are selected for comparison. Qualitative and quantitative data are presented to demonstrate the effects of three-dimensionality, radiation transfer and the thermal boundary conditions on the horizontal surfaces on the numerical solution of the convective flow in the cavity. The present numerical results are compared against published experimental and direct numerical simulation data. It is found that the predicted thermal stratification in the interior of the cavity is improved when the simulation is extended from 2D to 3D and when the effect of radiation transfer is accounted for. The discrepancy with regard to the interior stratification between the experiment and numerical simulation is mainly caused by the negligence of radiation transfer. The thermal boundary conditions on the horizontal surfaces also have a significant impact on the numerical solution, especially when the radiation transfer is not accounted for. Further, the present results show that all the RANS models are capable of capturing the main features of the flow and the overall performance of these turbulence models in terms of predicting time-averaged quantities is acceptable. It is found that the variation of the numerical results obtained with the three k–ε models is very small, whereas the discrepancy between the two k–ω models is significant. The SST k–ω model has the best overall performance and the standard k–ω model has the worst overall performance.

1. Introduction

Conjugate natural convection with radiation transfer in a differentially heated cavity has many applications such as in building HVAC (heating, ventilation and air-conditioning) systems, solar collectors and water walls, etc. Therefore, extensive theoretical, experimental and numerical studies on this topic have been reported over the past several decades (see e.g. [1–3]). In most practical applications, the convective flow is turbulent, which contains eddies over a wide range of length and time scales. In general, three types of numerical approaches have been developed for dealing with turbulent flows: Direct Numerical Simulation (DNS), Large Eddy Simulation (LES) and Reynolds Averaged Navier–Stokes (RANS) equation method.

The most accurate numerical approach for resolving turbulent flows is DNS, which is capable of resolving all motions in the flow. Coupled turbulent natural convection, conduction and surface radiation in an air-filled three-dimensional (3D) differentially heated cavity was investigated by Xin et al. [4] using the DNS approach. The purpose of their study was to understand a discrepancy regarding interior stratification observed between numerical [5] and experimental [2] results. They concluded that surface radiation was an important factor that affected natural convection in air-filled cavities and thus should not be neglected. Using the DNS method, Soucasse et al. [6] explored surface and gas radiation effects in weakly turbulent regimes of natural convection in a differentially heated 3D cubic cavity. Air with small amounts of water vapour and carbon dioxide was considered with molar fractions fixed at $X_{H_2O} = 0.02$ and $X_{CO_2} = 0.001$ respectively. The results showed that both the surface and gas radiation significantly intensified turbulent fluctuations, reduced the thermal stratification in the core of the cavity, and enhanced the global circulation.

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Nomenclature

a	absorption coefficient
C_p	specific heat capacity, J/kg K
C_μ	constant in the k–ε models
D	cavity depth, m
g	acceleration due to gravity, m/s^2
H	cavity height, m
I	radiation intensity, W/m^2
k	turbulent kinetic energy, m^2/s^2
n	refractive index
Nu^C	convective Nusselt number
Nu^R	radiative Nusselt number
P	pressure, Pa
q^C	convective heat flux, W/m^2
q^R	radiative heat flux, W/m^2
$\vec{r}$	position vector
Ra	Rayleigh number, $g\beta\Delta TH^3/\nu\kappa$
$\vec{s}$	direction vector
$\vec{s}'$	scattering direction vector
S	modulus of the mean rate-of-strain tensor
S_{ij}	mean rate of strain tensor
t	time, s
T, T_0	temperature and initial (reference) temperature, K
u, v	horizontal and vertical velocity components, m/s
U_0	characteristic velocity, m/s
W	cavity width, m
x, y, z	horizontal, vertical and spanwise coordinates, m
Greek letters	
α_1	constant in the SST k–ω model
α^*	coefficient in the standard k–ω model
β	coefficient of thermal expansion, 1/K
δ_{ij}	Kronecker delta
ΔT	temperature difference, K
Δ_T	thicknesses of the thermal boundary layer
Δ_v	thicknesses of the velocity boundary layer
Δ_{vi}	thicknesses of the viscous boundary layer
ε^*	emissivity
ε	dissipation rate of k, m^2/s^3
θ	dimensionless temperature
κ	thermal diffusivity, m^2/s
λ	thermal conductivity, W/m K
μ	dynamic viscosity, kg/m s
μ_t	turbulent eddy viscosity, kg/m s
ν	kinematic viscosity, m^2/s
ρ	density, kg/m^3
σ	Stefan–Boltzmann constant, 5.669×10^{-8} W/m^2 K^4
σ_s	scattering coefficient
σ_T	turbulent Prandtl number
Φ	phase function
ω	specific dissipation rate, 1/s
Ω'	solid angle
Subscripts	
1D	one-dimensional
2D	two-dimensional
c	cold
h	hot
i, j	elemental directions (i, j = 1, 2 and 3 corresponding to the x, y, and z directions)
max	maximum value
min	minimum value

Another commonly adopted numerical approach for turbulent convection is LES, which resolves large-scale flow structures and models small-scale motions. Capdevila et al. [7] analysed the effect of surface and gas radiation on turbulent natural convection in a 3D differentially heated tall cavity with an aspect ratio of 5 and a Rayleigh number of 4.5×10^{10} based on the height of the cavity by means of LES. The same authors also investigated the effects of a grey participating gas [8] and a semi-grey participating mixture of air and water vapour [9] in the 3D tall cavity model. The LES results were compared with the experimental data available in the literature and the DNS results. It was found that radiation broke the symmetry of the flow, increased the flow intensity and reduced the level of stratification in the cavity. Ibrahim et al. [10] also used LES to study natural convection coupled with surface and gas radiation in a two-dimensional (2D) differentially heated square cavity. They concluded that the surface radiation increased the turbulence intensity while the gas radiation had little influence on the flow structure.

Whilst DNS is very powerful in resolving turbulent flows, the computational cost associated with DNS is extremely high and thus DNS is not feasible for practical applications. The LES approach requires significantly less computational resources than DNS. However, it is still computationally too expensive for modelling turbulent flows of practical interests. Both the DNS and LES approaches remain to be research tools that can only deal with turbulent flows with relatively low turbulent Reynolds numbers. In contrast, the RANS models, which have been developed by decomposing flow properties into mean and fluctuation components, are the most computationally economical among the three types of numerical approaches. Since for many engineering applications the mean flows are of more interest than the instantaneous fluctuations, the RANS models have been widely adopted to solve engineering problems.

Among the various RANS models, the standard k–ε model has been adopted by many authors. Using this model, Fusegi and Farouk [1] investigated the interactions of turbulent natural convection and radiation in a 2D differentially heated square cavity filled with carbon dioxide gas. Mesyngier and Farouk [11] further studied the same problem with either a single participating gas (H_2O or CO_2) or a homogeneous mixture of two participating gases along with a non-participating gas (N_2). Velusamy et al. [12] analysed the interaction of surface radiation with turbulent natural convection of a transparent medium in 2D square and tall enclosures with differentially heated vertical walls and adiabatic horizontal walls, covering the Rayleigh numbers of 10^9–10^{12} and the aspect ratios of 1–200. Sharma et al. [13] investigated the same problem in a rectangular enclosure heated from below and cooled from the other three walls with the Rayleigh number varying from 10^8 to 10^{12} and the aspect ratio changing from 0.5 to 2.0. The same problem in an inclined differentially heated square cavity with the inclination angle varying from 0° to 90° was also studied by Sharma et al. [14]. Serrano-Arellano and Gijón-Rivera [15] reported conjugated heat (by turbulent natural convection–thermal radiation) and mass transfer in a 2D differentially heated square cavity filled with a mixture of Air–CO_2. The hot wall was kept at a constant temperature of 75 °C with a CO_2 concentration of 3000 ppm, whereas the cold wall is considered to be an isothermal wall at 25 °C with a CO_2 concentration of 500 ppm. They found that the radiative heat transfer depressed the heat transfer by natural convection but enhanced the total heat transfer inside the cavity.