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Radiation effect on conjugate turbulent natural convection in a cavity with a discrete heater

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ABSTRACT

A numerical study of a conjugate turbulent natural convection with thermal surface radiation inside a square cavity with heat-conducting solid walls and a local heat source has been performed. Two-dimensional equations for conservation of mass, momentum and energy using k–ε turbulence model with a heat conduction equation inside the solid walls and corresponding boundary conditions have been solved using the finite difference method. The developed numerical method can be widely used in some engineering problems, such as the simulation of heat and mass transfer in heat-generating elements in power engineering. Discrete heater has been simulated by a heat source of constant temperature centrally located on the bottom wall. Numerical solutions have been obtained for $Ra = 10^9$ and different values of surface emissivity ($0 \le \tilde{\varepsilon} < 1$) and thermal conductivity ratio ($10 \le \lambda_{1,2} \le 1000$). It has been found that an increase in surface emissivity and thermal conductivity ratio leads to a growth of the average total Nusselt number, while a rise of surface emissivity only illustrates a reduction of the average convective Nusselt number. The obtained numerical results are useful for predicting the convective and radiative heat transfer in domain similar to the one under consideration.

1. Introduction

The problem of turbulent heat transfer in enclosures is one of fundamentals in thermal science and fluid mechanics. Accurate prediction of turbulent natural convection flows is very important for the study of various engineering applications such as cooling of electronic and power generating equipments, solar energy collectors, building insulation systems, and passive heat removal systems of nuclear reactor, etc. Due to its importance in various applications, a large number of experimental and numerical studies have been carried out in the last several decades [1–5]. Choi and Kim [6] presented a review of recent developments of turbulence models for natural convection in enclosures. The work of Peng and Davidson [7] deals with the computation of turbulent convection flows with thermal stratification using the low-Reynolds number k–ω model. The authors reported that the buoyancy source term for the turbulence kinetic energy exhibits strong grid sensitivity, as this term is modeled with the Standard Gradient Diffusion Hypothesis [8,9]. Numerical simulation of turbulent natural convection of compressible air in a tall cavity has been carried out by Mao and Zhang [10]. Their findings indicated that RANS-based models (standard k–ε and RNG k–ε) have impressive agreement with measured data at all sample

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Nomenclature

$Bi = hL/\lambda_1$	modified Biot number
E	dimensionless dissipation rate of turbulent kinetic energy
F_{k-i}	view factor from kth element to the ith element of an enclosure
g	acceleration of gravity (m/s^2)
G_k	dimensionless generation/destruction of buoyancy turbulent kinetic energy
h	heat-transfer coefficient (W/m^2 K)
k	dimensional turbulence kinetic energy (m^2/s^2)
K	dimensionless turbulent kinetic energy
l	thickness of walls (m)
L	air cavity size (m)
$N_{rad} = \sigma T_{hs}^4 L/[\lambda_2(T_{hs} - T^e)]$	radiation number (or Stark number)
Nu_{conv}	average convective Nusselt number
Nu_{rad}	average radiative Nusselt number
p	pressure (N/m^2)
P_k	dimensionless shearing production
$\mathrm{Pr} = \nu/\alpha_2$	Prandtl number
$\mathrm{Pr}_t = \nu_t/\alpha_t$	turbulent Prandtl number
Q_{rad}	dimensionless net radiative heat flux
R_k	dimensionless radiosity of the kth element of an enclosure
$Ra = g\beta(T_{hs} - T^e)L^3/\nu\alpha_2$	Rayleigh number
t	dimensional time (s)
T^e	environmental temperature (K)
T	dimensional temperature (K)
T_{hs}	dimensional heater temperature (K)
U, V	dimensionless velocity components along X and Y axis
X, Y	dimensionless Cartesian coordinates

Greek symbols

$\alpha_{1,2} = \alpha_1/\alpha_2$	thermal diffusivity ratio
α_1	thermal diffusivity of the wall material (m^2/s)
α_2	air thermal diffusivity (m^2/s)
β	coefficient of volumetric thermal expansion (1/K)
ε	dimensional dissipation rate of turbulent kinetic energy (m^2/s^3)
$\tilde{\varepsilon}$	surface emissivity
$\zeta = T^e/T_{hs}$	temperature parameter
Θ	dimensionless temperature
$\lambda_{1,2} = \lambda_1/\lambda_2$	thermal conductivity ratio
λ_1	thermal conductivity of the wall material (W/m K)
λ_2	air thermal conductivity (W/m K)
ν	kinematic viscosity (m^2/s)
ν_t	turbulent viscosity (m^2/s)
ξ, η	new dimensionless independent variables
σ	Stefan–Boltzmann constant (W/m^2 K^4)
τ	dimensionless time
ψ	dimensional stream function (m^2/s)
Ψ	dimensionless stream function
ω	dimensional vorticity (s^{-1})
Ω	dimensionless vorticity

lines, while LES models (Smagorinsky SGS and dynamic Smagorinsky SGS) can predict temperature better than RANS-based models.

Sharma et al. [11] studied the main regularities of turbulent natural convection in a square enclosure with localized heating from below and symmetrical cooling from the vertical side walls. They used the finite volume method as a method of solution. Turbulence is modeled using the standard k–ε model. In this work, the source length is varied from 20 to 80% of the total width of the bottom wall. They showed that the flow intensity is found to increase linearly with the heated width. Numerical simulation of turbulent natural convection in rectangular cavity with localized heating was performed by Brito et al. [12] using the finite element method with a Galerkin scheme with LES technique. Niu and Zhu [13] investigated weakly turbulent natural convection of air in a rectangular enclosure with differentially heated side walls and adiabatic horizontal