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Numerical simulation of a conjugate turbulent natural convection combined with surface thermal radiation in an enclosure with a heat source

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A detailed numerical analysis of complex heat transfer (turbulent natural convection, conduction and surface thermal radiation) in a rectangular enclosure with a heat source has been carried out. The finite difference method for the solution of the governing equations using the dimensionless stream function, vorticity and temperature variables has been utilized. The effects of Rayleigh number in a range from 10^8 to 10^{11}, thermal conductivity ratio in a wide range from 10 to 1000, as well as internal surface emissivity $0 \le \tilde{\varepsilon} < 1$ on the fluid flow and heat transfer have been extensively explored. Detailed results including temperature fields, flow profiles, and average Nusselt numbers have been presented. In this investigation we have tried to study the main regularities of heat and mass transfer in the considered domain.

1. Introduction

Turbulent natural convection inside enclosures has been widely investigated experimentally and theoretically [1–6]. These heat and mass transfer processes are of practical interest in many applications, such as solar energy collectors, building engineering, cooling of electronic equipment and aerospace systems. Natural convection in enclosures is often coupled with thermal surface radiation. Surface radiation modifies the temperature and velocity fields which, in turn, affect the heat transfer. The interest in this problem has led to numerous experimental and numerical studies [5–13]. For example, Sharma et al. [9] studied the interaction of turbulent natural convection and surface thermal radiation in inclined square enclosures. They found that the orientation of the enclosure plays an important effect on the heat transfer characteristics in a cavity. Moreover, the intensity of circulation in the enclosure increases with angle of inclination rising up. Influence of convection and radiation on the thermal environment in an industrial building has been investigated (using a commercial computational fluid dynamics package FLUENT) by Wang et al. [10]. It has been found that radiation modified the temperature distribution and airflow through secondary convection near the sidewalls of the industrial building. Also, accurately predicting the total Nusselt number is very important to provide a comfortable thermal environment in buildings. Martyushev and Sheremet [11,12] have analyzed numerically natural convection combined with surface thermal radiation in a square [11] and cubical [12] enclosures bounded by solid walls of finite thickness and conductivity with a heat source. It has been found that regardless of the considered solid-fluid interface the average convective Nusselt number is an increasing function of the Rayleigh number and thermal conductivity ratio, and a decreasing function of the surface emissivity and ratio of solid wall thickness to cavity spacing. While the average radiative Nusselt number increases with the Rayleigh number, surface emissivity and thermal conductivity ratio and decreases with ratio of solid wall thickness to cavity spacing. Vivek et al. [13] studied the interaction effects between laminar natural convection and surface radiation in shallow enclosures. They found that these interaction effects are very strong in shallow enclosures compared to square enclosures. Furthermore, the radiative Nusselt number is a weak function of the tilt angle. Ridouane et al. [14] analyzed the radiation effect of gray surfaces on hydrodynamics and heat transfer in a square cavity heated from below. They found that total

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Nomenclature

$Bi = \tilde{h}L/k_1$ Biot number
F_{k-i} view factor from k-th element to the i-th element of an enclosure
g acceleration of gravity
G_k dimensionless generation/destruction of buoyancy turbulent kinetic energy
h thickness of walls
$\tilde{h}$ heat transfer coefficient
k dimensional turbulent kinetic energy
K dimensionless turbulent kinetic energy
$k_{1,2} = k_1/k_2$ thermal conductivity ratio
k_1 thermal conductivity of the solid wall material
k_2 air thermal conductivity
L size of an air cavity
$N_{rad} = \sigma T_{hs}^4 L/[k_2(T_{hs} - T^e)]$ radiation number
$Nu_{con} = \int_{h/L}^{1+h/L} \left|\frac{\partial\Theta}{\partial Y}\right|_{Y=Y_{hs}} dX$ average convective Nusselt number
$Nu_{rad} = N_{rad}\int_{h/L}^{1+h/L} Q_{rad}|_{Y=Y_{hs}} dX$ average radiative Nusselt number
p pressure
P_k dimensionless shearing production
$Pr=\nu/\alpha_2$ Prandtl number
$Pr=\nu_t/\alpha_t$ turbulent Prandtl number
Q_{rad} dimensionless net radiative heat flux
R_k dimensionless radiosity of the k-th element of an enclosure
$Ra = g\beta(T_{hs} - T^e)L^3/(\nu\alpha_2)$ Rayleigh number
t time
T temperature
T^e environmental temperature
T_{hs} heat source temperature
u, v dimensional velocity components in x and y directions
U, V dimensionless velocity components in X and Y directions
x, y dimensional Cartesian coordinates
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
α_2 air thermal diffusivity
α_t turbulent thermal diffusivity
β coefficient of volumetric thermal expansion
ε dimensional dissipation rate of turbulent kinetic energy
$\tilde{\varepsilon}$ surface emissivity
Θ dimensionless temperature
ν kinematic viscosity
ν_t turbulent viscosity
$\zeta=T^e/T_{hs}$ temperature parameter
ρ density
κ compaction parameter
σ Stefan-Boltzmann constant
τ dimensionless time
ψ dimensional stream function
Ψ dimensionless stream function
ω dimensional vorticity
Ω dimensionless vorticity
ξ, η new dimensionless independent variables

Nusselt numbers increase monotonically and the critical Rayleigh number (characterizing the transition toward the oscillatory convection) decreases considerably with increasing surface emissivity. Xaman et al. [15] carried out two-dimensional numerical simulations of laminar and turbulent natural convection combined with surface thermal radiation in an enclosure with a glass wall. Detailed computational investigations have been conducted to study the effect of transparent wall on temperature distribution and flow pattern in the cavity. It was shown that flow patterns are not symmetric due to the combined effect of temperature variation over the glass wall and the radiative interchange inside the enclosure. The influence of radiation on natural convection airflows in confined areas was reported by Ibrahim et al. [16]. They have shown that radiation modifies the airflow structure especially at the top hot corner and the bottom cold corner. At the same time gas radiation has little influence on the flow structure.

From the above literature survey, it is clear that comprehensive numerical computations of complex heat transfer can be very valuable. The aim of the present study is mathematical simulation of conjugate turbulent convective-radiative heat transfer in an enclosure having heat-conducting walls in the presence of a heat source of constant temperature. Thereby, the present paper is directed towards a comprehensive investigation of all the parameters that affect hydrodynamics and heat transfer inside the cavity.

It is worth noting that for the first time in the present paper turbulent natural convection combined with surface thermal radiation inside the cavity and heat conduction in all solid walls of finite thickness and conductivity is analyzed under the time effect. It should be noted that surface thermal radiation is an essential heat transfer mechanism for the natural convection and the role of this mechanism increases for conjugate heat transfer. The latter can be explained by the nature of surface thermal radiation inside the cavities filled with a nonparticipating medium [17]. In the case of solid walls of infinite thickness only adiabatic walls participate in surface thermal radiation [13] but in the case of solid walls of finite thickness all walls participate in this heat transfer process. Moreover for unsteady natural convection it is possible to analyze evolution of the considered process. Also in the present paper for the first time we used the dimensionless variables “stream function – vorticity” with corresponding algebraic transformation for the difference mesh. Such approach allows to decrease the computational time taking into account the governing equations (1)–(7) and (8)–(13).

2. Physical and mathematical model

The problem under consideration is shown in Fig. 1. It consists of a square enclosure with sides of length L and solid walls with a finite thickness h. The heat source of constant temperature T_{hs} is located at the bottom of the enclosure. The medium inside the cavity is air, which is radiatively transparent and incompressible. Buoyancy effects are taken into account through the Boussinesq approximation, under turbulent flow regime [18,19]. The external surface of the bottom wall ($y = 0$) is assumed to be adiabatic. Convective heat exchange with an environment is modeled on other borders of solid walls, where the outside temperature T^e is a constant temperature. It is considered that the thermal properties of the solid wall material and air are the temperature independent.