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Numerical simulations of the effect of an isotropic heat field on the entropy generation due to natural convection in a square cavity

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ABSTRACT

Entropy generation associated with laminar natural convection in an infinite square cavity, subjected to an isotropic heat field with different intensities; was numerically investigated for different values of Rayleigh number. The numerical work was carried out using, an in-house CFD code written in FORTRAN, which discretizes non-dimensional forms of the governing equations using the finite volume method and solves the resulting system of equations using Gauss-Seidal method utilizing a TDMA algorithm. Proper code validation was undertaken in order to establish the entropy generation calculations. It was found that the increase in the isotropic heat field intensity resulted in a corresponding exponential increase of the entropy augmentation number, and promoted high values of Bejan number within the flow. The entropy generation due to heat transfer was approximately one order of magnitude higher than the entropy generation due to fluid friction. The spatial uniformity of the Bejan number was more sensitive to the change in Rayleigh number than to the heat field intensity. The thermodynamic penalty of the isotropic heat field is shown by means of global integrals of the entropy source terms over the entire flow domain.

1. Introduction

Natural convection at high Rayleigh number values is characterized by gravitational–buoyancy interaction, which overruns the viscous effects. The applications of natural convection in different engineering systems are indeed uncountable. The present study is focused on natural convection in an infinite square cavity, which can be reduced to a two-dimensional problem. This problem has several applications, which have been addressed by the authors in a number of recent studies [1–3]. The cooling systems of nuclear reactors are of the most important applications as reported by Jasmin Sudha and Velusamy [4]. The cooling system of Egypt Test and Research Reactor Number 2 (ETRR-2) is an example for such systems studied by El-Messiry [5]. Such system contains components that cool miniaturized parts of the reactor core assembly, which generate high-intensity isotropic heat fields within the cooling domain (i.e. cavity). The application of waste-heat recovery systems, such as thermoelectric systems [6] to these components requires an estimation of the thermodynamic behavior of the heat transfer process, which is radically affected by the presence of the isotropic heat field. Motivated by the entropy generation minimization concept of Bejan [7], the present work aims at investigating the effects of an isotropic heat field on entropy generation in enclosed natural convection flows induced by differential heating. First, we present a brief literature survey to highlight the problem significance and demonstrate the originality of results. Second, the mathematical model and numerical code, which adopts the finite volume method, are presented. The results are given in section three, followed by a discussion and conclusions section.

1.1. Literature review

This section presents a brief discussion of some important studies of entropy generation in cavities under natural convection conditions. Entropy generation in the presence of heat fields and sources was studied in a far less number of papers. Famouri and Hooman [8] showed that the heat transfer irreversibilities resulting from natural convection in a partitioned cavity increases monotonically with Nusselt number. Ilis et al. [9] studied the effect of geometry on the entropy generation in rectangular cavities. They demonstrated that the geometrical aspect ratio has a critical value, below which the local entropy generation increases with the increase of aspect ratio. When such critical aspect ratio is

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Nomenclature

Be	local Bejan number, $S_{hL}/(S_{hL}+S_{fL})$
Be_{av}	average Bejan number
C_P	specific heat, J/kg K
g	acceleration of gravity, m/s^2
h	heat transfer coefficient, W/m^2 K
k	fluid thermal conductivity, W/m K
L	cavity width, m
Nu	average Nusselt number, Nu = hL/k
Nu_L	local Nusselt number
p	pressure, N/m^2
P	dimensionless pressure, $P = pL^2/\rho\alpha^2$
Pr	Prandtl number, Pr = ν/α
Q_o	volumetric intensity of the isotropic heat field, W/m^3 K
Ra	Rayleigh number, $Ra = g\beta L^3 \Delta T/\nu\alpha$
S_f	dimensionless average entropy generation due to fluid friction
S_h	dimensionless average entropy generation due to heat transfer
S_{fo}	average entropy generation due to fluid friction, W/m^3
S_{ho}	average entropy generation due to heat transfer, W/m^3
S_t	dimensionless average total entropy generation
T	local temperature, K
T_c	cold wall temperature, K
T_h	hot wall temperature, K
ΔT	temperature difference, $T_h - T_c$, K
u	velocity components in x direction
v	velocity components in y direction
U	dimensionless velocity component in X direction
V	dimensionless velocity component in Y direction
x, y	dimensional coordinates
X, Y	dimensionless coordinates

Greek symbols

α	thermal diffusivity, m^2/s
β	coefficient of thermal expansion, K^{-1}
ζ	irreversibility distribution ratio
ϕ	dimensionless heat generation
θ	dimensionless temperature
μ	dynamic viscosity, kg/m s
ν	kinematics viscosity, m^2/s
ρ	local density, kg/m^3
ψ	dimensionless stream function

exceeded, the entropy generation decreases with higher values of aspect ratio. A significant number of the studies available on the topic were focused on natural convection in nanofluids. Erbay et al. [10] investigated the entropy generation in square enclosures at low Ra values using a numerical approach comparable to the approach used in the present work. They investigated the flow structure due to differentially heated walls and its effect on the entropy generation pattern for Prandtl numbers ranging from 0.01 to 1.0. They found that the flow configuration had a small effect on changing the active locations of entropy generation in the enclosure. In a recent study, Bouabid et al. [11] investigated the transient entropy generation due to natural convection in an inclined rectangular cavity using numerical analysis. They concluded that entropy generation increases with the increase of thermal Grashof number, irreversibility distribution ratio and aspect ratio of the cavity.

The use of entropy generation minimization method has become popular in heat transfer enhancement techniques. Entropy generation associated with forced convection in an elliptical tube enhanced with longitudinal fins was experimentally investigated by Ibrahim and Moawed [12]. Such research focused on the effects of fin location and geometrical parameters on entropy generation patterns. A similar research aimed at investigated in the effect of baffles on the entropy generation in a circular tube was reported by Tandiroglu [13]. The latter work proposed nine correlations to predict the time averaged entropy generation as a function of the Reynolds number and other flow variables. In addition, the concept of entropy generation minimization has been used to evaluate the performance of nanofluids in a number of studies reviewed by Mahian et al. [14]. Shahi et al. [15] analyzed the entropy generation due to free cooling in a square cavity filled with water–Cu nanofluid. There parametric investigation focused on analyzing the effect of metal concentration and Ra number on the local entropy generation. In addition, they analyzed the location effect of a discrete heat source and concluded that the minimum entropy generation occurs when the heat sources is mounted on the lower wall of the cavity. Recently, an optimization methodology based on entropy generation minimization was proposed for nanofluid flow [16]. Such method involves the nano-particle concentration and size, in order to determine criteria of nano-particle characteristics to be used with each flow regime.

The literature survey shows that although a reasonable number of studies have been devoted to analyze entropy generation in natural convection heat transfer; there is no available information on the effect of isotropic heat sources on such entropy generation. In addition, the ranges of Ra number studied in previous works are significantly small, which cannot be considered in intensive natural convection existing in nuclear reactor cooling applications. In previous works, there are no correlations of any kind relating Ra number to the entropy generation rates; hence, there is a lack of theoretical understanding of such relation which is strongly manifested in all previous literature. Such outcome of the literature review has motivated the objectives of the present study, as shown in the following section.

1.2. Scope, objectives and methodology

The scope of the present study is focused on finding the effects of an isotropic heat field, resulting from intense heat sources, on the entropy generation associated with natural convection in a relatively small confinement region. The limitations of the scope of work are drawn from the heat transfer characteristics in ETRR-2, which are dominated by natural convection [5,17]. The numerical work was conducted after rigorous verification and validation procedures, which proved that the code solves the governing equations with negligible numerical and modeling errors, respectively.

The main objective of the present work was to establish correlations between the isotropic heat field intensity and local and global entropy generation rates. A secondary objective was to investigate the effect of the isotropic heat field on the sources of entropy generation as represented by Bejan number. These objective are very important for future research on waste heat recovery in relevant configurations, especially if an emphasis on the heat and mass transfer enhancement is required. The methodology followed to achieve these objectives, via numerical analysis, were greatly built on a comprehensive practical understanding of the verification and validation procedures required for CFD analysis as stipulated in [18].