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Laminar natural convection in right-angled triangular enclosures heated and cooled on adjacent walls

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ABSTRACT

This present investigation deals with experimental and numerical analysis of natural convection in a right-angled triangular cavity heated from below and cooled on sidewall while its other wall, the hypotenuse, is kept adiabatic. The enclosure is filled with water and heat transfer surfaces are maintained at constant temperature. Experimental study covers flow visualization studies involving the use of the particle tracing method. Numerical solutions are obtained using a commercial CFD package, FLUENT, using the finite volume method. Contradictory results existing in the open literature for the Nusselt number resulting from the singularity at the corners of heated surfaces and from the definition of the Nusselt number are discussed in detail. A new approach is used to overcome the singularity at the corner joining the differentially heated isothermal walls when determining Nu. Effects of Rayleigh number, Ra on the Nusselt number, Nu as well as velocity and temperature fields are investigated for the range of Ra from 10^3 to 10^7. It is shown that the experimental and numerical results agree fairly well. Finally, a correlation for Nu is developed.

1. Introduction

In the open literature, many studies have appeared on natural convection in triangular enclosures due to its wide applications in many industrial and domestic systems. Akinsete and Coleman [1] examined free convection in a horizontal right-triangular enclosure numerically. Their work aimed at studying the heat transfer problem associated with air-conditioning load calculations for pitched roofs with horizontal suspended ceiling. Ridouane et al. [2] investigated laminar natural convection in a right-angled triangular cavity filled with air. They reported that their study might find application in the miniaturization of electronic packaging severely constrained by space and weight. Lei et al. [3] concerned with transient natural convection in an isosceles triangular enclosure subject to cooling at the inclined surfaces and heating at the base, attracted with the application area of attics of buildings. The unsteady flows were visualized by shadowgraph technique. Poulikakaos and Bejan [4] reported the results of experimental study of steady natural convection heat transfer in an attic-shaped space. Xu et al. [5] numerically investigated natural convection around a horizontal cylinder to its concentric triangular enclosure. Holtzman et al. [6] performed a numerical and experimental study in an isosceles triangular enclosure with a heated base and cooled upper walls. They presented asymmetric boundary condition results and found pitchfork bifurcation. Ridouane and Campo [7] examined transient convection of air confined to an isosceles triangular cavity heated from the base and symmetrically cooled from the upper inclined walls. Papanicolaou et al. [8] studied convection inside an asymmetric, greenhouse-type solar still. Salmun [9] re-examined a triangular geometry over the parameters of aspect ratio, Rayleigh and Prandtl numbers. Flack et al. [10] studied heat transfer rates and flow patterns in triangular geometries representing attic spaces with solar collectors on one side. Ridouane et al. [11] studied turbulent natural convection of air confined in an isosceles triangular enclosure representing conventional attic spaces of houses and buildings with pitched roofs and horizontally suspended ceilings. Saha [12] investigated the fluid flow and heat transfer inside a triangular enclosure due to instantaneous heating on the inclined walls. Kent and his co-workers [13,14] numerically investigated effects of various heating conditions and the base angle on the natural convective heat transfer in triangular enclosures. Basak et al. [15] and Roy et al. [16] numerically studied the effect of non-uniform heating on natural convection in a triangular enclosure using the finite element method. Varol et al. [17] numerically studied natural convection in triangular enclosures with protruding isothermal heaters.

However, in the current literature, existing results are contradictory, confusing and misleading in terms of Nusselt number values. This mainly originates from its definition and the singularity. Many studies reported very high Nusselt numbers than expected values. For example, for the conduction regime, it is observed for

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Nomenclature

Ra	Rayleigh number, $g\beta(T_h - T_c)L^3/(\upsilon\alpha)$
Nu	Nusselt number
T	temperature
Pr	Prandtl number
L	enclosure height
e	emissivity
p	pressure
P	non-dimensional pressure
k	thermal conductivity
h	convective heat transfer coefficient
q	heat flux
c_p	specific heat
u	velocity component in x direction
v	velocity component in v direction
U	non-dimensional velocity component in x-direction
V	non-dimensional velocity component in y-direction
x,y	cartesian coordinate system
X,Y	nondimensional coordinates

Greek symbols

Ψ	non-dimensional stream function (=ψ/α)
ψ	stream function
ρ	density
β	coefficient of thermal expansion
ν	kinematic viscosity
α	thermal diffusivity
μ	dynamic viscosity
θ	dimensionless temperature

Subscripts

h	hot wall
c	cold wall
max	maximum
min	minimum

Nu to have values roughly a hundred times higher than its well-known conduction value that equals to unity. These results could mislead designers and practitioners.

In this regard, the aim of this study is to experimentally and numerically analyze steady laminar natural convection inside a water-filled triangular enclosure heated from below and cooled from sidewall while the remaining other wall, the hypotenuse, is adiabatic. The main focus is to overcome the singularity using a proper mesh structure physically adapted to the physics of the problem and a new reasonable definition of the Nusselt number at the corner.

2. Numerical study

In the present study, buoyancy-induced flow in a right-angled triangular cavity isothermally heated from below and cooled by the vertical wall at uniform temperatures of T_h and T_c, respectively is investigated. The other hypotenuse wall is insulated. The schematic of the problem studied with the coordinates and the regarding boundary conditions is shown in Fig. 1.

All the walls are impermeable. The flow is assumed to be steady and laminar. Constant fluid properties are assumed, except for the density changes with temperature that induce buoyancy forces, so that the Boussinesq approximation is adopted.

2.1. Governing equations

The dimensionless form of the governing equations can be obtained via introducing dimensionless variables. These are defined as follows:

$$X = \frac{x}{H}, \quad Y = \frac{y}{H}, \quad U = \frac{u}{\alpha/H}, \quad V = \frac{v}{\alpha/H},$$
$$P = \frac{pH^2}{p\alpha^2}, \quad \theta = \frac{T - T_c}{T_h - T_c} \tag{1}$$

where u, v are the velocity components in the x, y direction and T is temperature. ρ and α are the density and thermal diffusivity of the fluid, respectively. Based on the dimensionless variables defined in Eq. (1), the non-dimensional equations for the conservation of mass, momentum and energy equations are

$$\frac{\partial U}{\partial X} + \frac{\partial V}{\partial Y} = 0 \tag{2}$$

$$U\frac{\partial U}{\partial X} + V\frac{\partial U}{\partial Y} = -\frac{\partial P}{\partial X} + \mathrm{Pr}\left(\frac{\partial^2 U}{\partial X^2} + \frac{\partial^2 U}{\partial Y^2}\right) \tag{3}$$

$$U\frac{\partial U}{\partial X} + V\frac{\partial U}{\partial Y} = -\frac{\partial P}{\partial Y} + \mathrm{Pr}\left(\frac{\partial^2 V}{\partial X^2} + \frac{\partial^2 V}{\partial Y^2}\right) + \mathrm{RaPr}\theta \tag{4}$$

$$U\frac{\partial \theta}{\partial X} + V\frac{\partial \theta}{\partial Y} = \frac{\partial^2 \theta}{\partial X^2} + \frac{\partial^2 \theta}{\partial Y^2} \tag{5}$$

Appearing in Eqs. (3) and (4), Pr and Ra are the Prandtl and Rayleigh numbers, respectively which are defined as

$$\mathrm{Pr} = \frac{\nu}{\alpha}, \qquad \mathrm{Ra} = \frac{g\beta L^3(T_hT_c)}{\nu\alpha}) \tag{6}$$

where β and ν are thermal expansion coefficient and the kinematic viscosity of the fluid, respectively. Through the introduction of the

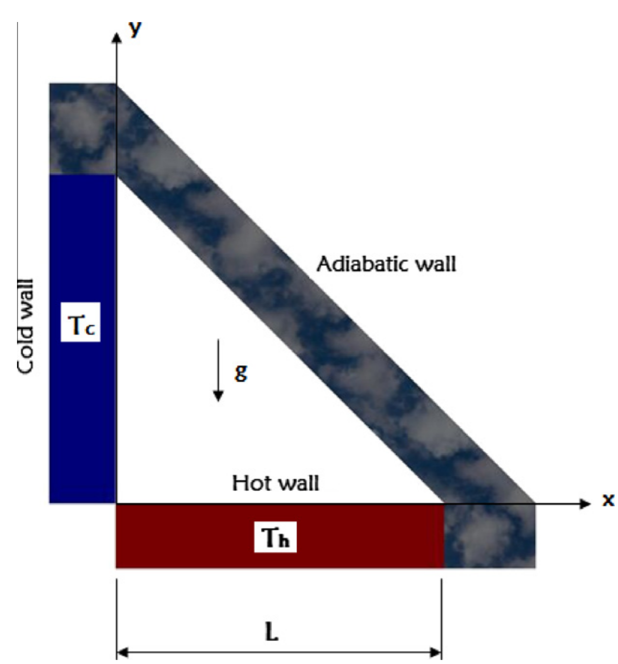

Fig. 1. The schematic of the problem.