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Numerical study of laminar natural convection inside square enclosure with single horizontal fin

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ABSTRACT

A numerical study for laminar natural convection inside a square enclosure with a single horizontal fin attached to its hot wall has been carried out. The enclosure horizontal surfaces are adiabatic, the left wall is hot while the right one is cold. The Prandtl number for the flow inside the enclosure is 0.71. A parametric study has been carried out to investigate the effect of Rayleigh number, fin length, conductivity ratio, thickness and position on heat transfer. The fin thickness showed negligible effect on the average Nusselt number for all values of fin conductivity ratios. The fin efficiency and temperature distribution were examined. The fin effectiveness was also studied and it was found that the fin effectiveness enhanced in general with the increase of fin length. Also, the maximum fin effectiveness was found at the lowest Rayleigh number for a given fin conductivity ratio. A correlation has been proposed for the relation between Nusselt number and the parameters of study.

1. Introduction

Natural convection inside a cavity with different boundary conditions has been studied extensively with and without fin/partition in the last few decades due to its importance and the several applications that can be simplified into such a model. This type of research can be applied in different applications such as double glass windows, cooling of nuclear reactors, solar collectors and electronic equipment to name a few.

Natural convection inside cavities has been examined extensively for different boundary conditions, aspect ratios and Rayleigh numbers [1–8]. It was also examined inside cavities with the employment of heating elements [9–12]. Adding a fin inside the enclosure has a significant effect on both flow field and heat transfer and many studies have investigated heat transfer behavior under such condition. Frederick [13] studied numerically natural convection in a differentially heated inclined square enclosure with a fin attached to the cold vertical wall. Bilgen [14] studied numerically natural convection heat transfer inside a differentially heated cavity (left heated wall and cooled right wall) with a horizontal fin attached to the hot wall. It was found that the fin position has a major role in heat transfer inside the cavity. It was also found that the heat transfer rate was minimum with the fin attached to the center or near the center of the wall. Shi and Khodadadi [15] studied numerically steady laminar natural convection within a differentially heated square cavity with a thin fin attached to the hot wall. They found that for high Rayleigh numbers, heat transfer was enhanced regardless of the position or the length of the fin. Frederick and Valencia [16] studied numerically heat transfer in a square cavity with conducting horizontal surfaces. A conducting horizontal partition was attached to the center of the hot wall. It was found that increasing thermal conductivity ratio enhanced heat transfer.

Nag et al. [17] studied numerically natural convection in a differentially heated square enclosure with a horizontal fin attached to the hot wall. The study was done for two cases: a highly conductive fin and an adiabatic fin. For the case of highly conductive fin, it was found that the Nusselt number on the cold wall increased compared to the case with no fin. For the case with the adiabatic fin, heat transfer was reduced compared to the case without a fin. Tasnim and Collins [18] investigated numerically natural convection of air inside a square enclosure with left heated wall, right cold wall and two horizontal adiabatic walls. A highly conductive fin was attached to the hot wall. The study

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Nomenclatures

b	fin thickness
B	dimensionless fin thickness, b/W
g	gravitational acceleration,
Gr	Grashof number, W^3 g β (T_h − T_c)/$ν^2$
h^*	heat transfer coefficient
h	fin position
H	dimensionless fin position, h/W
k	thermal conductivity
l	fin length
L	dimensionless fin length, (l/W)
n	distance normal to S coordinate
N	dimensionless distance normal to S coordinates (n/W)
Nu_{av}	average Nusselt number
Nu_L	local Nusselt number
p	pressure
P	dimensionless pressure, (p W^2/ρ α^2)
Pr	Prandtl number, (ν/α).
Ra	Rayleigh number, (Gr * Pr)
R_k	conductivity ratio, (k_f/k_a)
S	dimensionless special coordinate along enclosure surface
T	temperature
u, v	velocity components in X and Y direction respectively,
U, V	dimensionless velocity in X and Y direction respectively, (U = u W/α) and (V = v W/α)
W	enclosure width and height
x	horizontal coordinate
X	dimensionless horizontal coordinate (x/W)
y	vertical coordinate
Y	dimensionless vertical coordinate (y/W)

Greek symbols

α	thermal diffusivity,
ρ	local density,
β	coefficient of thermal expansion
μ	dynamic viscosity
ν	kinematic viscosity, (μ/ρ)
θ	dimensionless temperature (T − T_c)/(T_h − T_c)
ε	fin effectiveness, (Q_{fin}/Q_{nofin})
η	fin efficiency, (Q_{real}/$Q_{isothermal}$)

Subscripts

av	average
a	air
f	fin

showed that the presence of a fin always increases heat transfer. They found that the effect of fin position on the heat transfer rate was strongly affected by Rayleigh number and the fin length. Ben-Nakhi and Chamkha [19] studied numerically steady laminar natural convection inside an enclosure with a highly conductive inclined fin attached to its hot wall and adiabatic horizontal walls. It was found that the effect of fin inclination angle was dependent on the fin length. Ben-Nakhi and Chamkha [20] also studied numerically conjugate natural convection inside an enclosure with three thick cold walls and a hot thin vertical left wall. They found that increasing the thermal conductivity and decreasing the fin length enhanced the average Nusselt number on the hot wall, while increasing the fin length enhanced the average Nusselt number on cold surfaces. Shi and Khodadadi [21] studied heat transfer inside a led-driven cavity with a fin attached perpendicular to any of the three stationary surfaces. They concluded that the fin slowed the flow near the anchoring wall and reduces the temperature gradient, thus the heat transfer capacity was degraded. Oztop and Bilgen [22] studied numerically heat transfer in a differentially heated square cavity with adiabatic horizontal walls and internal heat generation. An isothermal partition was vertically attached on the bottom wall. The study has shown that increasing both thickness and length of the cold partition reduce heat transfer rate. Bilgen [23] studied a differentially heated enclosure with partial partitions attached vertically to the top and bottom adiabatic walls. It was concluded that up to $Ra = 10^8$, laminar flow regime was found while turbulent flow regime starts to be formed for higher values of Rayleigh number.

Three-dimensional study of natural convection for air inside a cubic enclosure with a thick fin attached to the hot left wall was conducted by Frederick and Moraga [24]. The right wall was kept cold and the two horizontal walls were adiabatic. The study showed that by increasing thermal conductivity ratio between the fin material and the air inside the enclosure, the cell was displaced away from the hot wall and the blockage effect was reduced. They also found that for a high conductivity ratio, 20% enhancement of heat transfer was obtained compared to the cube without a fin.

As seen from the literature, natural convection inside enclosure has been studied for different boundary conditions with or without fins attached. However, no significant work has been conducted to investigate the effect of the fin thermal conductivity and fin thickness inside a differentially heated square enclosure. In addition, the fin efficiency and effectiveness are two important parameters under such circumstances; however, there was not a detailed investigation of these parameters under different fin design conditions. The aim of this study is to investigate steady two-dimensional laminar natural convection inside an enclosure with a horizontal fin attached to the hot wall. A parametric study will be conducted to investigate the effect of fin thickness, fin thermal conductivity, length and position on heat transfer inside the enclosure at different values of Rayleigh number. In addition, the fin performance in terms of efficiency and effectiveness will be investigated.

2. Mathematical model

The physical model and coordinate system under consideration are schematically shown in Fig. 1 which represents a two-dimensional square enclosure. The left wall is maintained at a high temperature T_h, the right wall is kept at a low temperature T_c ($T_h > T_c$) and the two horizontal surfaces are insulated. The side length of the enclosure is (W). A horizontal fin is attached to the hot left wall with a length (l) at a position (h) from the bottom surface and thickness (b). The fin is assumed to exchange heat by convection with the surrounding fluid (radiation, if it exists, is lumped with convection). The fluid inside the space is assumed to be Newtonian and incompressible (constant property fluid) except for the density in the buoyancy force components existing in the momentum equations. The Boussinesq approximation is applied, which relates the density to the local temperature of the fluid. Consequently, the momentum equations will be coupled with the energy equation.