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Two-dimensional analysis of low-pressure flows in an inclined square cavity with two fins attached to the hot wall

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ABSTRACT

The gaseous low-pressure flow of a steady-state two-dimensional laminar natural convection heat transfer in a cavity with an attached two solid fins to the hot wall is numerically investigated. Such flows can be found in many engineering applications such as the "evacuated" solar collectors and in the receivers of the solar Parabolic Trough Collectors (PTCs), nuclear reactor cooling and electronic equipment cooling. Buoyancy effect is modeled using Boussinesq approximation. Effects of Knudsen and Rayleigh numbers, location and length of the fins, conductivity ratio and fins porosity, and the tilt angle on the flow and heat transfer characteristics are investigated. Physical parameters ranges in this study are as follows; $0 \le Kn \le 0.1$, $10^3 \le Ra \le 10^6$, L_F takes the values of 0.25, 0.5 and 0.75 m, H_F takes the values of 0.25_0.5, 0.25_0.75 and 0.5_0.75, $1 \le K_r \le 8000$, $0 \le \varepsilon \le 1$ and $0° \le \theta \le 90°$. It is shown that Nusselt number depends directly on Rayleigh number and inversely on Knudsen number. In addition, it is found that attaching two solid fins to the hot wall will enhance the heat transfer for such flows. Moreover, it is found that the porous fins are superior to the solid fins as far as the heat transfer is concerned. In addition, it is shown that for the geometry where the lower fin height to cavity length ratio is 0.25 and the upper fin height to cavity length ratio is 0.75, the best heat transfer is achieved. In addition, for the fin lengths considered in the study, it is concluded that by increasing the length of the fin, a better heat transfer is achieved. Also, it is found that by increasing the tilt angle of the cavity, a better heat transfer is achieved up to a certain value which was found to be (30°) where beyond this value, Nusselt number will decrease. In addition, it is found that by increasing the conductivity ratio up to a certain value (10^3), better heat transfer is gained. Finally, a correlation among Nusselt number and the parameters investigated in this research proposed as $Nu = 0.02197\frac{\varepsilon^{0.00932}\,\sin(\theta)^{0.00373}K_r{}^{0.0273}(h_2/L_F)^{2.814}Ra^{0.13}}{((h_2-h_1)/L_F)^{1.373}(h_1/L_F)^{1.615}Kn^{0.37}}$.

1. Introduction

Rarefied and micro/nano flows have been studied extensively in the past two decades due to their wide applications that can be found in MEMS and NEMS devices as well as in the industry, such as aerospace, plasma and material processing [1,2]. In this study, we will focus on the natural convection of rarefied gaseous flow in enclosed cavities in which the hot wall is attached to two fins. We will address two cases for fin types: solid and porous fins. Natural convection in enclosed cavities can be found in many engineering applications such as energy transfer in rooms and buildings, nuclear reactor and electronic equipment cooling. In addition, such flows are very good vehicle for both experimental and theoretical studies due to their simplicity when it comes to constructing the geometry and applying the boundary conditions, this will allow researchers to focus on measurements and analysis of results [3]. This study aims to investigate the effect of attaching two solid/porous fins to the hot wall on the flow and heat characteristics of the low-pressure gaseous flow confined in a square cavity. Moreover, the effect of Knudsen number, Rayleigh number, conductivity ratios, positions of the fins and lengths of the fins and porosity of the fins on these characteristics will be addressed as well.

A low-pressure flow is classified based on Knudsen number (Kn). According to Schaaf and Chambre [4]; Cercignani and Lampis [5], four distinct flow regimes can be identified; (i) Continuum regime,

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Nomenclature

A_c	Cold wall area [m^2]
A_h	Hot wall area [m^2]
A_F	Fin area [m^2]
A_T	Area of the fin and the hot wall = A_{h+} A_F
C_p	Specific heat [J kg^{-1} K^{-1}]
C_F	Forchheimer coefficient [1/m]
Da	Darcy number [K/L^2]
g_x	Gravity acceleration in the x direction [m/s^2]
g_y	Gravity acceleration in the y direction [m/s^2]
H_F	Fins Position, $h_1\_h_2$
h_1	Fin 1 Position [m]
h_2	Fin 2 Position [m]
h	Convection heat transfer coefficient
K	Permeability [m^2]
k	Thermal conductivity [W m^{-1} K^{-1}]
k_{eff}	Effective thermal conductivity [W m^{-1} K^{-1}]
Kn	Knudsen number
K_r	Fin thermal conductivity ratio
k_f	Fluid thermal conductivity [W m^{-1} K^{-1}]
k_s	Solid thermal conductivity [W m^{-1} K^{-1}]
L	Length of the square cavity [m]
L_F	Fin length [m]
M_a	Mach Number
Nu	Nusselt Number
P	Pressure [Pa]
Q	Heat transfer [W]
q''_c	Local heat flux at the wall of the cold surface[W/m^2]
q''_h	Local heat flux at the wall of the hot surface[W/m^2]
q''_F	Local heat flux at the fin [W/m^2]
R	Universal gas constant [J/mol.K]
Ra	Rayleigh number ($g\beta(T_1\text{-}T_2)L^3/\alpha\nu$)
T	Temperature [°C]
T_c	Temperature of the first cell from the wall [°C]
T_i	Hot surface temperature [°C]
T_o	Cold surface temperature [°C]
t	Fin thickness [m]
u	Velocity in x-direction [m/s]
u_c	Tangential velocity of the first cell from the wall [m/s]
v	Velocity in y-direction [m/s]
x, y	Cartesian coordinates [m]

Greek symbols

α	Thermal diffusivity [m^2/s]
β	Thermal expansion coefficient [$1/K$]
γ	Specific Weight (N/m^3)
λ	Molecular mean free path (m)
μ	Dynamic viscosity [kg m^{-1} s^{-1}]
ν	Kinematic viscosity [m^2s^{-1}]
ρ	Density of air, given by ideal gas equation (P/RT), [Kg/m^3]
σ_T	Thermal accommodation coefficient
σ_v	Momentum accommodation coefficient

Subscripts

eff	Effective
f	Fluid
F	Fin
g	Gas flow
i	Hot wall
n	Normal
o	Cold wall
r	Ratio
w	wall

$Kn < 0.01$ (ii) Slip regime, $0.01 < Kn < 0.1$ (iii) Transitional regime, $1 < Kn < 10$ and (iv) for $10 < Kn$, free molecular regime. For slip flows, both slip velocity and temperature jump boundary conditions are applied at the surfaces, while for the transitional and free molecular regimes, particle simulation methods such as direct simulation Monte Carlo method can be used to analyze the flow characteristics. For example, Gatsonis et al. [6] investigated supersonic gaseous flows into nanochannels using the unstructured 3-D direct simulation Monte Carlo method. Effects of inlet Mach number (Ma), inlet pressure and the aspect ratio of the channel on the flow and heat transfer characteristics are studied. Similarity method is another technique that was utilized to solve the flow and heat characteristics for continuum and slip regimes. For instance, Kiwan and Al-Nimr [7] used the power law along with the similarity solution to solve for the flow and heat characteristics of a flow over a stretched microsurface. Also, Kiwan and Al-Nimr [8] used the same technique to investigate the flow and heat characteristics for boundary layer flows in microsystems. In addition, Al-Kouz et al. [9] investigated the flow and heat transfer for rarefied flows over stretched surfaces using the similarity solution as well.

Natural convection in cavities has been extensively studied experimentally and numerically in the past decades. Bilgen [10] studied numerically the natural convection heat transfer in differentially heated cavities, which are formed by horizontal adiabatic walls and vertical isothermal walls. Streamlines and isotherms are produced and a parametric study to analyze the effects of Rayleigh number and the relative conductivity ratio on the flow characteristics is carried out. It is found that Nusselt number increases as Rayleigh number increases and Nusselt number decreases as the relative conductivity ratio increases. Frederick and Moraga [11] investigated numerically a three dimensional natural convection in finned cubical enclosures. In their study, Rayleigh number was varied between 10^3-10^6 and the fin thickness is taken as 10% of the cavity characteristic dimension. In addition, conductivity ratio and the width of the fin are varied as well. They found that low values of the conductivity ratio cause heat transfer reductions and they concluded that for the range of $10^5 < Ra < 10^6$, a fin of partial width is more effective in promoting heat transfer than a fin with full width. Shi and Khodadi [12] investigated laminar natural convection heat transfer in differentially heated square cavity due to a thin film on the hot wall using a finite volume based computational study. The length of the fin was varied to take the values of 20, 35 and 50% of the side length. The

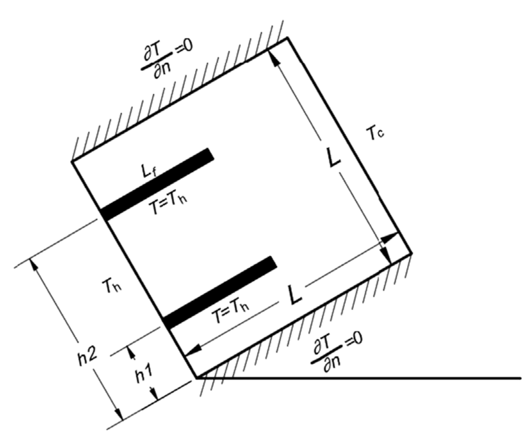

Fig. 1. The geometry used for the computational domain.