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Conjugate heat transfer in rarefied gas in enclosed cavities

Ammar Alkhalidi [a,*], Suhil Kiwan [b], Wael Al-Kouz [c], Aiman Alshare [d]

[a] Energy Engineering Department, German Jordanian University, Amman, Jordan
[b] Mechanical Engineering Department, Jordan University of Science and Technology, Irbid, Jordan
[c] Mechatronics Engineering Department, German Jordanian University, Amman, Jordan
[d] Mechanical and Maintenance Engineering Department, German Jordanian University, Amman, Jordan

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ABSTRACT

The heat transfer in buoyancy driven rarefied gas in a conjugate cavity has been investigated in this paper. The governing equations along with the slip flow and temperature jump boundary conditions are solved using finite-volume technique. The simulations are carried by varying cavity aspect ratios, conductivity ratios and cavity tilt angles. The Nusselt number values are calculated for different Knudsen, Rayleigh and Prandtl numbers. It was found that Kn number is the most influential parameter on the heat transfer; as it increases the heat transfer in the cavity decreases. The effect of all other investigated factors was found and documented; however, it is found that, in general, at high Kn Numbers their effect on the heat transfer is marginal. It is also found that cavity walls with good conducting materials will have minor effect on heat transfer while insulation material will have moderate effect on heat transfer. Two correlations for average Nusselt number are proposed: one for horizontal cavities; $Nu = 0.149k_r^{0.0101}Ra^{0.135}Kn^{-0.393}\mathrm{Pr}^{0.178}$ and the second correlation equation introduces the effect of the cavity tilt angle along with Ra and Kn; $Nu = 0.158Ra^{0.130}, Kn^{-0.396}, \cos(\theta)^{0.216}$.

1. Introduction

Design and fabrication of micro-electro mechanical systems (MEMS) have increased the need for understanding fluid flow and heat transfer in micro-fluidic devices such as micro heat exchangers. Furthermore, the use of evacuated or low-pressure spaces and cavities in various engineering applications gave additional motivation and momentum to such problems. Especially, in applications where the convection heat transfer takes place in gases below atmospheric pressures. Of particular interest are solar collectors and receivers where evacuation or working under low pressure becomes a major characteristic of these components in order to minimize the convection losses. In addition, the use of solar tracking systems introduces the need for studying the effect of tilting of cavities on the convection heat transfer process. The majority of these systems require studying the conjugate heat transfer problem. The authors noticed that there is a lack of studies in this area and there is a need for correlations that can be used as design tool for engineers.

Rarefied, micro and Nanoscale flows are characterized using the dimensionless Knudsen number (Kn). This number is the ratio of the mean free path (λ) to the characteristic length (L) of the geometry of interest. It measures the degree of rarefaction of the flow. Based on the Knudsen number, the respective flow regimes are classified into four types [1,2]. For $Kn < 0.01$ the flow is in the continuum regime in which the Navier-Stokes equations are used to describe the flow. If $0.01 < Kn < 0.1$ the flow is in the slip regime. In this regime the Navier-Stokes equations are used to describe the flow but with velocity slip and temperature jump boundary conditions. In the range of $0.1 < Kn < 10$, the flow is in the transitional regime and for $10 < Kn$, the collision between particles is very rare and the flow is in the free molecular regime.

In this section, previous work will be presented. It is divided into two categories: (1) problems related to cases that are studied under micro-fluidic or rarefied gas assumptions [3–14] and (2) problems in cavities under normal pressures where conventional no-slip condition is valid [15–23].

Moghadam et al. [3] investigated the characteristics of thermal cavities in the rarefied flow regime using the Direct Simulation Monte Carlo (DSMC). They presented their results for constant heat flux conditions. Shakhov and Titarev [4] carried out a numerical analysis of the time-dependent rarefied gasflow into vacuum from a circular pipe closed at one end. Their results demonstrated the

* Corresponding author.
E-mail address: Ammar.alkhalidi@gju.edu.jo (A. Alkhalidi).

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Nomenclature

c_p	specific heat capacity at constant pressure, (kJ/kg K)
d	molecular diameter
Fr	Froude number
g_x	gravitation acceleration component in x direction
g_y	gravitation acceleration component in y direction
H	computational domain width, (m)
h	convection heat transfer coefficient, (W/m^2 K)
k_B	Boltzmann constant, (J/K)
k_f	thermal conductivity of the fluid, (W/m K)
k_r	solid to fluid thermal conductivity ratio, $k_r = k_s/k_f$
k_s	thermal conductivity of solid wall, (W/m K)
Kn	Knudsen number
L	computational domain height, (m)
n	normal coordinate, (m)
NSF	Navier–Stokes–Fourier equation
Nu	average Nusselt number
P	pressure, (Pa)
Pr	Prandtl number, $Pr = \nu/\alpha$
Ra	Rayleigh number, $Ra = \frac{g\beta\Delta TL_c^3}{\nu\alpha}$
T_c	temperature of the cold wall of the cavity, (K)
T_f	temperature in fluid, (K)
T_h	temperature of the hot wall of the cavity, (K)
T_s	temperature in solid, (K)
T_w	cavity outer surface temperature, (K)
u	axial velocity, (m/s)
u_g	axial velocity of the gas adjacent to solid wall, (m/s)
u_w	axial velocity of the wall, (m/s)
v	longitudinal velocity, (m/s)
x	axial coordinate, (m)
y	vertical coordinate, (m)
Q	total heat transfer, (W)

Greek symbols

α	heat diffusivity, (m^2/s)
β	coefficient of volumetric expansion, (K^{-1})
θ	cavity tilt angle, (degree)
λ	molecular mean free path (m)
ν	kinematic viscosity, (m^2/s)
ρ	density, (kg/m^3)
σ	Lennard-Jones characteristic length, (Å)
σ_T	thermal accommodation coefficient
σ_v	momentum accommodation coefficient

dependence of flow pattern and evacuation time on the Knudsen number. Sazhin [5] used computation techniques to investigate gas flow rate and flow field through a slit and channel of finite length. The case has been carried out for large pressure differences in a wide range of gas rarefaction. They used direct simulation Monte Carlo method.

Kiwan and Al-Nimr [6] investigated convection heat transfer over linearly stretched, isothermal microsurface via similarity solution of the boundary layer equations. They presented correlations for skin friction coefficient and Nusselt number in terms of velocity slip and temperature jump parameters. Kiwan and Al-Nimr [7] also showed that complete similarity solution is possible for boundary layer flows only for a stagnation flow over isothermal microsurface. Numerical solutions based on the stream-function-vorticity formulation were obtained for two-dimensional flow of air in a differentially heated, slender cavity with conducting fins on the cold wall [8]. They obtained the results for Rayleigh numbers of 10^3–10^5, angles of inclination of 45° and 90°, overall aspect ratios of 20 and ∞, and microcavity aspect ratios of 20–0.25.

Several Authors had investigated the Be'nard problem for a rarefied gas. For example, Sone et al. [9] studied numerically the instability of a stationary stratified gas in two-dimensional rectangular domain based on the kinetic theory using a finite-difference analysis of the Boltzmann–Krook–Welander equation (the so-called BGK model). Stefanov et al. [10] investigated the long time behavior (final state) of the Rayleigh–Benard (RB) flow of a rarefied monatomic gas for a set of the non-dimensional Knudsen and Froude numbers in the intervals $Kn \in [1.0 \times 10^{-3}, 4 \times 10^{-2}]$ and $Fr \in [1.0 \times 10^{-1}, 1.5 \times 10^{3}]$. The Rayleigh–Bénard flow problem was investigated in three-dimensional geometry by Stefanov et al. [11] for a set of different Knudsen and Froude numbers at a fixed temperature ratio, as well as for different aspect ratios.

Heat transfer through micro cavity was investigated by Rana et al. [12] where flow and heat transfer in a bottom-heated square micro cavity in a moderately rarefied gas is investigated using Monte Carlo (DSMC), the R13 equations and the Navier–-Stokes–Fourier (NSF) equations. They used the same flow regimes classification in Refs. [1,2]. Their results will be used to validate the results in this work. Vargas et al. [13] investigated the flow of a rarefied gas in a rectangular enclosure for the case of non-isothermal walls. The rarefied driven cavity flow was investigated by Naris et al. [14] for the entire range of the Knudsen number. The formulation is based on the two–dimensional linearized Bhatnagar-Gross-Krook (BGK) kinetic equation with Maxwell diffuse-specular boundary conditions.

Natural convection in inclined rectangular enclosures under no-slip conditions with conducting fins on the heated wall was studied by Lakhal et al. [15]. The conjugate heat transfer in an inclined open shallow cavities with a thick wall facing the opening has been numerically studied [16]. The effect of inclination was studied and documented. Natural convection in cavities with fins attached to one surface is studied by Refs. [17,18].

The steady-state conjugate natural convection-conduction heat transfer in a square domain composed of a cavity heated by a triangular solid wall is studied by Chamkha and Ismael [19]. Naffouti and Djebali [20] reported numerical results of natural convection flow evolving inside square enclosure containing isothermal heat source placed asymmetrically at bottom wall. They applied the lattice Boltzmann method to solve the dimensionless governing equations with the associated boundary conditions.

One area of research of solar thermal applications aims at combining the benefits of evacuation in flat plate collectors [21]. In the present work, the steady two-dimensional analysis of buoyancy driven rarefied flow in cavity with uniform wall temperature is investigated. The flow is assumed to be laminar and incompressible. The continuum governing equations along with Maxwell slip [22] and Smoluchowski [23] temperature boundary conditions are solved numerically. The effect of different geometric and flow parameters on Nusselt number is investigated for ranges of Ra and Kn numbers. The ratio of the thermal conductivity of the solid wall material and the gas in the cavity is investigated for wide range of material. The range of conductivity ratio covers good conducting walls all the way to insulating walls.

2. Statement of the problem

Fig. 1 shows the schematic diagram of the problem under consideration. The cavity consists of four walls; two adiabatic