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Mixed convection analysis in heat transfer enhancement of a nanofluid filled porous enclosure with various wall speed ratios

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ABSTRACT

This study aims to investigate the mixed convection stimulated by a uniformly heated moving lid at the centre of the non-Darcian porous enclosure filled with nanofluid subjected to various wall speed ratios. A nonlinear heating resembling sinusoidal pattern is imposed on the vertical walls, while the horizontal walls are kept adiabatic. The transport equations for fluid and heat are solved using finite volume method with SIMPLE algorithm with a written code. Numerical simulations are carried out for a range of parameters: Richardson number ($0.01 \leq Ri \leq 1$), Darcy number ($10^{-3} \leq Da \leq 10^{-5}$), speed ratios ($0.5 \leq \lambda \leq 3$) and solid volume fraction ($0.0 \leq \varphi \leq 0.05$). The obtained results showed that the mid-moving lid produces an excellent enhancement in heat transfer rate (92.5%) and thereby yields the highest among the conventional moving boundary lids. Further, the heat transfer performance becomes efficient with high Darcy number, maximum speed ratio and increasing nanoparticle volume fraction.

1. Introduction

The influences of shear driven flow and natural convection are of comparable magnitude in heat transfer flows, generally referred as mixed convection and this kind of flow patterns are exposed in lid-driven enclosures. The lid-driven enclosure has simple geometry with regular boundary conditions and considerably easiness to apply in flow, temperature fields. Since past few decades mixed convection flow in enclosures has been analyzed in literatures due to this phenomenon influences the thermal performance in enormous mechanical applications [1–3]. The function of mixed convection can be established in nuclear reactor technology and some aspects of electronic cooling when the power of forced convection itself is not enough to dissolve all the necessary heat in very-high-power-output devices and some industrial processing like heat exchangers, float glass production and metal coating, etc.

Extensive parametric study has been done by Iwatsu et al. [4] by considering the top wall is moving with uniform velocity in a square enclosure, which provides the benchmark solutions for the lid-driven problems. They invented that the thermal cooling performance under mixed convection is faster than in the natural convection regime. Due to simplicity, easiness and high heat transfer rate under lid-driven problems, most of the researchers are attracted and further research was carried out with horizontal moving wall [5,6] or vertical moving wall [7,8] or by an oscillating lid [9,10] to understand the flow and heat transfer characteristics in enclosure. Former research works are done by single moving wall with various thermal boundary conditions and they obtained inadequate cooling performance in equipments. Hence, the researchers are designed the double lid-driven enclosure to improve the heat transfer performance and this phenomenon is conducted by Oztop and Dagtekin [11], Alleborn et al. [12]. Most recently, Roy et al. [13] examined the exhaustive study about the effects of various moving horizontal or vertical walls on fluid flow and heat transfer characteristics. The study encountered by six different cases of moving wall with upward and downward directions at different velocities. They highlighted that the configuration like bottom heating enclosure having upward moving sidewalls with uniform velocity produces the higher heat transfer rate than the remaining cases.

The lid-driven devices also need more efficient cooling systems with higher cooling abilities, thus augmenting heat transfer capacity is one of the new technique to enhance the equipment cooling performance. In general, solid particles have the higher thermal conductivity than the fluid, thus the idea of including solid nanoparticles in low thermal conductivity fluids will enhance the conductivity of nanoparticle-fluid mixture causes the higher heat

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Nomenclature

a	amplitude ratio
c_p	fluid specific heat (J/(kg K))
d_p	particle diameter (m)
Da	Darcy number
Gr	Grashof number
g	gravitational acceleration (m/s^2)
H	height of the enclosure (m)
k	thermal conductivity (W/m.K)
K	permeability of porous medium (m^2)
L	width of the enclosure (m)
Nu	local Nusselt number
$\overline{Nu}$	average Nusselt number
p	pressure (N/m^2)
P	dimensionless pressure
Pr	Prandtl number
Re	Reynolds number
Ri	Richardson number
t	time (s)
T	dimensionless temperature (K)
T_0	reference temperature (273 K)
U_0	lid velocity (m/s)
u, v	velocity components (m/s)
U, V	dimensionless velocity components
x, y	Cartesian coordinates (m)
X, Y	dimensionless Cartesian coordinates
α	thermal diffusivity (m^2/s)
β	thermal expansion coefficient (1/K)
ε	porosity of the porous medium
ϕ	phase deviation
φ	solid volume fraction
κ	Boltzmann constant (1.381×10^{23} J/K)
γ	inclination angle
λ	wall speed ratio
μ	dynamic viscosity (N s/m^2)
ν	kinematic viscosity (m^2/s)
θ	temperature
ρ	density of the working fluid (kg/m^3)
τ	dimensionless time

Subscripts

c	cold wall
h	hot wall
l	left wall
r	right wall
f	base fluid
p	solid particle

transfer rate. The reason behind this phenomenon is thermal conductivity of the fluid act as significant function on the heat transfer coefficient among the heat transfer medium and the heat transfer surface. Also, the mobility of the small sized particles may bring about micro-convection of fluid and therefore increases the heat transfer. The less weigh small nanoparticles control the sedimentation which makes the nanofluids more stable. Therefore, the idea of nanoparticle-fluid mixture promotes the heat transfer rate in a successive way and Choi [14] has introduced the word 'nanofluid' for this mixture. Numerical analysis of mixed convection flows in a square enclosure filled with copper-water nanofluid is studied by Talebi et al. [15]. Their results highlighted that the increases in solid volume fractions assures the enhancement in overall heat transfer rate. But the augmenting Reynolds number reduces the

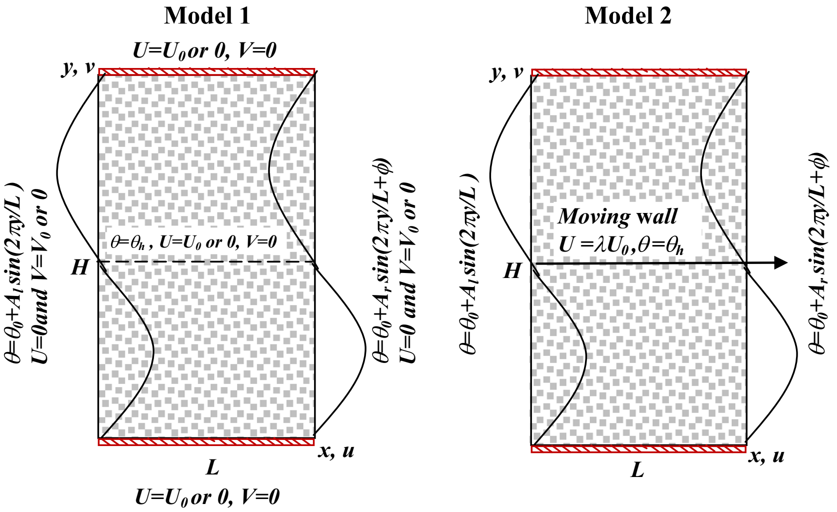

Fig. 1. Physical model of the computational domain with various boundary conditions.

Table 1
Thermo-physical properties of base fluid (water) and CuO.

	ρ (kg/m^3)	C_p (J/kg.K)	k (W/m.K)	β (1/K)	d_p
Base fluid	997.1	4179.0	0.613	2.1×10^{-4}	–
CuO	6500.0	540.0	18.0	0.85×10^{-5}	29