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Mixed convection of nanofluids in a three dimensional cavity with two adiabatic inner rotating cylinders

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ABSTRACT

In this study, mixed convection of nanofluids in a three dimensional cavity with two inner adiabatic rotating circular cylinders were analyzed by using finite element method. Vertical surfaces are kept at constant temperature while other walls and rotating cylinder surfaces were taken as adiabatic. The three dimensional cavity was filled with water and various types of nanoparticles (Cu, Al_2O_3 and TiO_2). The water-Cu nanofluid provided the highest heat transfer rate and at the highest value of Rayleigh number, 4% higher average heat transfer rate is obtained when compared to other particles. When cylinders rotate, depending on the rotational direction either enhancement or deterioration of average Nusselt number is observed. For the highest value of rotational speed of the cylinders, 8.5% discrepancy between the average Nusselt number is observed for the nanofluid with Cu and Al_2O_3 nanoparticles. For Cu-water nanofluid at the highest volume fraction as compared to base fluid, 38.10% of enhancement in the average heat transfer is obtained. A correlation for the average Nusselt number in polynomial form was developed which is a function of Rayleigh number and angular rotational speed of the cylinders.

1. Introduction

The complicated interaction between the natural convection and shear driven flow due to a moving surface may be encountered in some practical engineering applications such as in food processing, MEMs, cooling of electronic devices and many others. Convection in a cavity is a simplified model for various thermal engineering applications such as thermal storage, electronic equipments cooling and solar collectors. Some industrial applications that use a rotating cylinders immersed in a fluid confined in a cavity are: rotating heat exchangers, nuclear reactor fuel rods and drilling of oil wells. Heat and mass transfer within enclosures can be controlled by using obstacles [1–4]. A numerical study with an active inner rotating cylinder in a square enclosure was performed by Roslan et al. [5]. Size, rotational speed and thermal conductivity of the cylinder was investigated and it was noted that slowly rotating cylinder with moderate size was effective for heat transfer enhancement. In the numerical study by Panda and Chhabra [6], it was observed that heat transfer from a heated cylinder with power-law fluids can be reduced by 60–70% when compared to a stationary cylinder depending on various parameters such as power law-index, Reynolds number. Paramane and Sharma [7] showed that the rotation of a cylinder can be used as a control parameter for heat transfer suppression and drag reduction. In a series of papers, Selimefendigil and his colleagues used rotating cylinders in combination with other active/passive heat transfer enhancement techniques [8–12].

In thermal engineering applications, nano-sized additives are used in the base fluid which has a relatively lower thermal conductivity. Higher thermal conductivity of nano-particles results in better thermal transport properties of base fluid even at very small amount of addition of particles which are metallic or nonmetallic such as Cu, Ag, Au, CuO, Al_2O_3, TiO_2, SiO_2 with an average particle size less than 100 nm. Among other factors, size, shape and type of particles are most influential on the thermal conductivity enhancement of base fluids such as water or ethylene glycol. In the heat transfer applications, a vast amount of literature study with nanofluids can be found by various researcher [13–32]. In the analytical study of Cimpean and Pop [33], even very small amount of nanoparticles results in significant heat transfer enhancement for the mixed convection in an inclined porous channel. Abu-Nada and Chamkha [34] performed mixed convection of nanofluids in a lid-driven inclined square cavity. At moderate and large Richardson numbers, heat transfer was found to increase with nanoparticle addition and with cavity inclination. Effects of various viscosity models on the mixed-convection of lid-driven

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Nomenclature

Gr	Grashof number
h	local heat transfer coefficient
k	thermal conductivity
H	length of the enclosure
n	unit normal vector
Nu_x	local Nusselt number
Nu_m	averaged Nusselt number
p	pressure, (Pa)
Pr	Prandtl number
Re	Reynolds number
Ri	Richardson number
T	temperature, (K)
u, v	x-y velocity components, (m/s)
x, y	Cartesian coordinates, (m)

Greek Characters

α	thermal diffusivity
β	expansion coefficient
ϕ	solid volume fraction
ν	kinematic viscosity
θ	non-dimensional temperature
ρ	density of the fluid

Subscripts

c	cold
h	hot
m	average
nf	nanofluid
p	solid particle
st	static

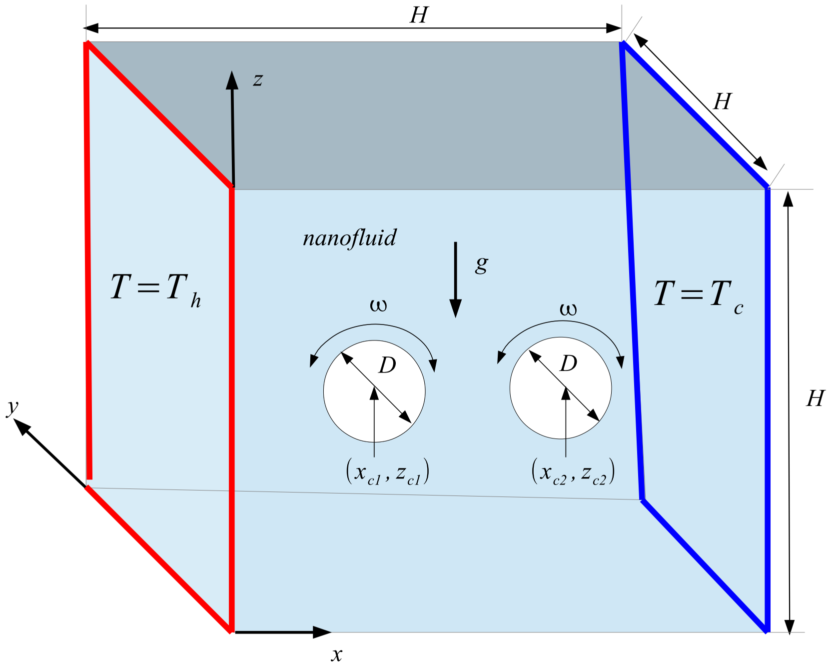

Fig. 1. Physical model and boundary conditions.

Table 1
Thermophysical properties of base fluid and nanoparticles.

Property	Water	Al_2O_3	TiO_2	Cu
ρ (kg/m^3)	997.1	3970	4250	8933
c_p (J/kg K)	4179	765	686.2	385
k (W/m K)	0.6	40	8.95	401
$\beta \times 10^5$ (1/K)	21	0.85	0.90	1.67

Table 2
Grid independence test results ($Ra = 10^6, \Omega = 1000, \phi = 0.04$, Cu nanoparticles).

Grid name	of elements	Nu_m
G1	7973	7.7813
G2	19382	7.4714
G3	35540	7.2524
G4	75350	7.2260
G5	109048	7.1990

Table 3
Comparison results of averaged Nusselt number at the top wall of the lid driven cavity.

Re = 400	Ref. [43]	Present
Gr = 100	3.84	3.81
$Gr = 10^4$	3.62	3.63
$Gr = 10^6$	1.22	1.26