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Unsteady natural convection flow of multi-phase nanofluid past a vertical plate with constant heat flux

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HIGHLIGHTS

- Transient nanofluid flow past a vertical plate with constant heat flux is investigated.
- Governing partial differential equations are solved using Crank-Nicolson method.
- Numerical solution is validated with the correlation results for the limiting case.
- Local and average skin-friction increases with increasing thermophoresis.
- Local and average skin-friction decreases with increasing Brownian motion.

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ABSTRACT

The objective of the present study is to investigate the two-dimensional transient natural convective boundary-layer flow of multi-phase nanofluid past a vertical plate with constant heat flux. The effects of Brownian motion and thermophoresis are incorporated in this nanofluid model. It is further considered that the nanoparticle volume fraction on the boundary is passively rather than actively controlled. An effective implicit finite difference technique of Crank-Nicolson method has been used to solve the governing non-linear coupled partial differential equations. The effects of time, Brownian motion parameter, thermophoresis parameter, buoyancy ratio parameter, Prandtl number and Lewis number on the dimensionless velocity, temperature and nanoparticle volume fraction have been illustrated graphically and analyzed in detail. The results for local as well as average skin-friction and Nusselt number are also presented graphically and discussed thoroughly. It is found that the velocity, temperature and nanoparticle volume fraction evolves with time and reached steady state as time progressed. The local Nusselt number is found to be slightly increased with increasing Brownian motion parameter and it decreased with increasing thermophoresis parameter, but the influence of buoyancy ratio parameter does not show any impact on the local Nusselt number. To validate the present numerical results, a comparison study has been carried out between the present steady state local Nusselt number results for a limiting case of regular fluid with the well-established experimental correlation results and an excellent agreement is found between the results.

1. Introduction

Natural convective heat transfer phenomena involved widely in science and engineering applications such as solar energy collectors, geothermal systems, cooling of electronic equipment, cooling of nuclear reactors, lubricants and space technology, etc. The term "nanofluid" was first proposed by Choi (1995) to indicate engineered colloids composed of nanoparticles of size 1–100 nm dispersed in a base fluid. The main characteristic feature of nanofluids is thermal conductivity enhancement. This property of nanofluids plays a remarkable role in convective heat transfer processes. The literature on thermal conductivity enhancement of nanofluids was reviewed by Masuda et al. (1993), Das et al. (2003), and Chon et al. (2005), among several others. These studies made an important observation that even with a small volumetric fraction of nanoparticles in the base fluids the thermal conductivity was enhanced significantly. As a result of such enhanced thermal conductivity properties, nanofluids can be considered as the next

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Nomenclature

D_B	Brownian diffusion coefficient
D_T	thermophoretic diffusion coefficient
g	acceleration due to gravity
Gr	thermal Grashof number
k'	thermal conductivity
L	characteristic length of the plate
Le	Lewis number
Nb	Brownian motion parameter
Nr	buoyancy ratio parameter
Nt	thermophoresis parameter
$Nu_{x'}$	local Nusselt number
Nu_X	non-dimensional local Nusselt number
Nu_L	average Nusselt number
Nu	non-dimensional average Nusselt number
Pr	Prandtl number
q	heat flux
t'	time
t	non-dimensional time
T'	temperature
T	non-dimensional temperature
T'_w	wall temperature of the vertical plate
T'_∞	temperature of the fluid far away from the plate
u'	velocity of the fluid along the plate
U	non-dimensional velocity along the plate
v'	velocity of the fluid normal to the plate
V	non-dimensional velocity normal to the plate
x'	spatial coordinate along the plate
X	non-dimensional spatial coordinate along the plate
y'	spatial coordinate normal to the plate
Y	non-dimensional spatial coordinate normal to the plate

Greek symbols

α	thermal diffusivity
β	volumetric coefficient of thermal expansion
μ	coefficient of viscosity
ν	kinematic viscosity
ρ_p	density of the nanoparticles
$\rho_{f\infty}$	density of the base fluid
$(\rho c_p)_f$	heat capacity of the fluid
$(\rho c_p)_p$	effective heat capacity of the nanoparticle material
$\tau_{x'}$	local skin-friction
τ_L	average skin-friction
τ_X	non-dimensional local skin-friction
τ	non-dimensional average skin-friction
ϕ'	nanoparticle volume fraction
ϕ	non-dimensional nanoparticle volume fraction
ϕ'_∞	free stream nanoparticle volume fraction

Subscripts

i	grid points along X-direction
j	grid points along Y-direction
k	time step along the t-direction

generation heat transfer agents. Hence, a special attention to the fundamental analysis of convective boundary layer heat transfer in nanofluids is highly demanded. Buongiorno (2006) developed an exceptional analytical model for the convective transport phenomena in nanofluid by considering seven slip mechanisms. He concluded that, out of these seven mechanisms, only Brownian diffusion and thermophoresis were important slip mechanisms in nanofluid flows. Moreover, he elucidated that the abnormal heat transfer increase in nanofluid was due to decrease fluid viscosity caused by excessive temperature variations within the boundary layer. Using Buongiorno's (2006) analytical model, many authors analyzed the convective boundary layer flow of nanofluid by considering different physical conditions. For example, Kuznetsov and Nield (2010) developed a classic problem of natural convection in nanofluids past a vertical plate and proposed the governing transport equations for boundary layer flow of a nanofluid. The first study on boundary layer flow of a nanofluid past a stretching sheet was conducted by Khan and Pop (2010). These studies emphasized that the reduced local Nusselt number decreased with the increase of Brownian motion and thermophoresis parameters. This designates the effects of Brownian motion and thermophoresis parameters significantly influence the flow and heat transfer characteristics in nanofluids. Rashad et al. (2011) analyzed the natural convection boundary layer flow of a non-Newtonian nanofluid past a vertical cone in a porous medium. Uddin et al. (2012) studied the free convection flow of nanofluid past a heated horizontal plate embedded in a porous medium with convective boundary condition. An important observation made by the above two studies was that the heat transfer rate decreased with the increase of thermophoresis parameter. Tavakoli et al. (2013) studied the natural convection flow past a vertical wall through a non-Darcy porous medium filled with nanofluids. Their study revealed that the heat transfer rate increased in the case of injection and it was decreased in the case of suction. Narahari et al. (2013) investigated the effects of Brownian diffusion and thermophoresis on free convection flow of a nanofluid past an isothermal inclined plate. Turkyilmazoglu (2012) analytically studied the heat and mass transfer characteristics on magnetohydrodynamic (MHD) nanofluid flow over a permeable stretching/shrinking surface. Rashidi et al. (2014) studied the thermal radiation and buoyancy effects on MHD natural convection flow of nanofluid past a stretching sheet. They found that the increment of magnetic parameter tends to decrease the local Nusselt number profiles. Srinivasacharya and Surender (2014) analyzed the thermal and mass transfer effects on natural convection flow of a nanofluid past a vertical plate through a porous medium. They found that the nanoparticle volume fraction strongly influenced by Brownian motion and thermophoresis effects. Sheikholeslami and Ganji (2014) investigated the two-phase nanofluid flow and heat transfer in a rotating system numerically using fourth order Runge-Kutta scheme and shooting technique with the MAPLE software package. Sheikholeslami et al. (2016) studied the influence of magnetic field dependent viscosity on free convection nanofluid flow in an enclosure using control volume based finite element method. They found that Nusselt number increased with increased nanoparticle volume fraction, while it was decreased with increased viscosity parameter. Sheikholeslami (2017a,b) investigated the effect of a constant magnetic field on the natural convection flow of CuO-water nanofluid in a porous cavity by considering the Darcy law and found that the Nusselt number was diminished with increased nanoparticle volume fraction. Sheikholeslami and Rokni (2017) studied numerically the influence of magnetic field on the two-phase nanofluid flow between two vertical porous sheets with constant heat flux at one boundary. The effect of magnetic field on natural convection nanofluid flow in a porous curved cavity was investigated by Sheikholeslami (2017a,b) using control volume based finite element method