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Impacts of nanofluid flow on skin friction factor and Nusselt number in curved tubes with constant mass flow

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Abstract

Three-dimensional elliptic governing equations were solved to investigate laminar mixed convection of a nanofluid consists of water and Al_2O_3, buoyancy-affected and heat transfer of a curved tube. Simultaneous effects of the buoyancy force, centrifugal force and nanoparticles concentration on the fluid flow developing and heat transfer along the pipe is investigated in this paper. The nanoparticles concentration does not have any significant effect on the secondary flow, while the axial velocity, Nusselt number, skin friction factor as well as fluid temperature have been affected considerably. In this paper, some important new results are obtained. Firstly, for a given flow rate; nanoparticles concentration have positive effects on the axial velocity and skin friction factor. Secondly, buoyancy force has negative effect on the Nusselt number and skin friction factor.

Keywords: Nanofluid; Curved pipe; Centrifugal force; Buoyancy force; Laminar mixed convection

1. Introduction

In order to cope with growing demand from different industries such as electronic, automotive and aerospace industries, heat exchanger devices have to be small in size, light in weight and of high performance. Low thermal conductivity of conventional heat transfer fluids such as water, oil, and ethylene glycol mixture is a serious limitation in improving the performance and compactness of these engineering equipments. To overcome those disadvantages, there is strong motivation to develop advanced heat transfer fluids with substantially higher conductivity. An innovative w ay of improving the thermal conductivities of fluids is to suspend small solid particles in the fluid. However, more than a century ago Maxwell (1873, 1904) showed the possibility of increasing thermal conductivity of a mixture by more volume fraction of solid particles.

Various types of powders such as metallic, non-metallic and polymeric particles can be added into fluids to form slurries. An industrial application test was carried out by Liu et al. (1988) and the effects of flow rates on the slurry pressure drop and heat transfer behavior was investigated. In conventional cases, the suspended particles are of μm or even mm in dimensions. However, such large particles may cause severe problems such as abrasion and clogging. Therefore, fluids with suspended large particles have little practical application in heat transfer enhancement.

Nanofluids are a new kind of heat transfer fluid containing a small quantity of nano-sized particles (usually less than 100 nm) that are uniformly and stably suspended in a liquid. The dispersion of a small amount of solid nanoparticles in conventional fluids changes their thermal conductivity remarkably. Compared to the existing techniques for enhancing heat transfer, the nanofluids show a superior potential for increasing heat transfer rates in a variety of cases. Choi (1995) quantitatively analyzed some potential benefits of nanofluids for augmenting heat transfer and reducing size, weight and cost of thermal apparatuses, while incurring little or no penalty in the pressure drop.

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Nomenclature

a	radius of curved pipe (m)
C_p	specific heat (J/kg K)
d	horizontal direction
D	diameter of curved tube (m)
De	Dean number ($=Re.\delta^{1/2}$)
f_θ	local skin friction coefficient
g	gravitational acceleration (m s^{-2})
Gr	Grashof number $\left(=\frac{g\beta_{\mathrm{eff}}q''D^4}{k_{\mathrm{eff}}\upsilon_{\mathrm{eff}}^2}\right)$
k	thermal conductivity (W/m K)
$\dot{m}$	flow rate ($=2\pi D\rho_{\mathrm{eff}}u_0$)
Nu_θ	local Nusselt number $\left(=\frac{q''D}{k_{\mathrm{eff}}(T_{\mathrm{w}}-T_{\mathrm{b}})}\right)$
P	pressure (Pa)
Pr	Prandtl number $\left(=\frac{\alpha_{\mathrm{eff}}}{\nu_{\mathrm{eff}}}\right)$
q''	uniform heat flux (W m^{-2})
R_c	curvature radius
Re	Reynolds number $\left(=\frac{\rho_{\mathrm{eff}}u_0D}{\mu_{\mathrm{eff}}}\right)$
T	temperature (K)
u, v	velocity (m s^{-1})
y	vertical direction

Greeks

α	thermal diffusivity
β	volumetric expansion coefficient (K^{-1})
δ	curvature ratio ($=a/R_c$)
θ	angular coordinate in axial direction
ϕ	volume fraction
μ	dynamic viscosity (N s m^{-2})
ν	kinematics viscosity (m^2 s^{-1})
ρ	density (kg m^{-3})

Subscripts

b	bulk
eff	effective
f	base fluid
m	average
0	inlet condition
r	radial direction
w	wall
z	axial direction
φ	tangential direction

Researchers have demonstrated that oxide ceramic nanofluids consisting of CuO or Al_2O_3 nanoparticles in water or ethylene glycol exhibit enhanced thermal conductivity (Lee et al., 1999). A maximum increase in thermal conductivity of approximately 20% was observed in that study, having 4 vol.% CuO nanoparticles with mean diameter 35 nm dispersed in ethylene glycol. A similar behavior has been observed in Al_2O_3/water nanofluid. For example, using Al_2O_3 particles having a mean diameter of 13 nm at 4.3% volume fraction increased the thermal conductivity of water under stationary conditions by 30% (Masuda et al., 1993). On the other hand, larger particles with an average diameter of 40 nm led to an increase of less than 10% (Lee et al., 1999). Furthermore, the effective thermal conductivity of metallic nanofluid increased by up to 40% for the nanofluid consisting of ethylene glycol containing approximately 0.3 vol.% Cu nanoparticles of mean diameter less than 10 nm (Choi, 1995).

Different concepts have been proposed to explain this enhancement in heat transfer. Xuan and Li (2000) and Xuan and Roetzel (2000) have identified two causes of improved heat transfer by nanofluids: the increased thermal dispersion due to the chaotic movement of nanoparticles that accelerates energy exchanges in the fluid and the enhanced thermal conductivity of nanofluids considered by Choi (1995). On the other hand Keblinski et al. (2002) have studied four possible mechanisms that contribute to the increase in nanofluid heat transfer: Brownian motion of the particles, molecular-level layering of the liquid/particle interface, heat transport in the nanoparticles and nanoparticles clustering. Similarly to Wang et al. (1999), they showed that the effects of the interface layering of liquid

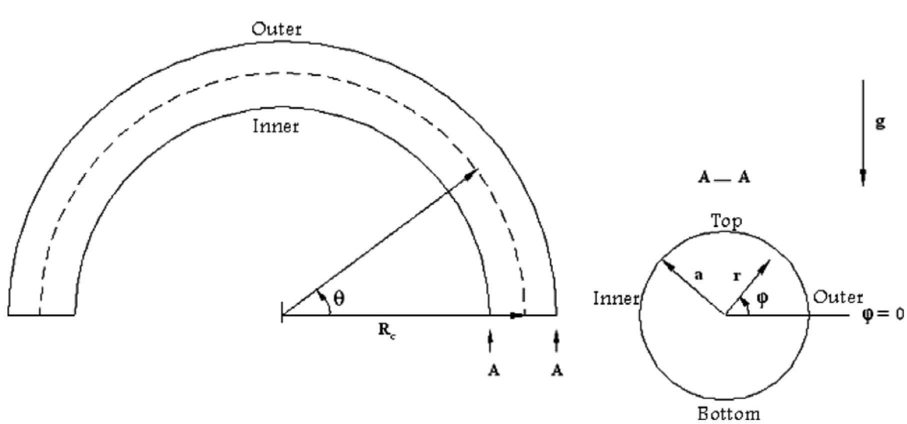

Fig. 1. Schematic of a horizontal curved tube.