



# A continuum mechanical modeling of fully-developed forced convection of nanofluids in a coaxial cylinder



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## ABSTRACT

Nanofluid is a suspension of nanoparticles with high thermal conductivity. Many investigations have been performed to find out the mechanism of enhanced heat transfer in the nanofluids. In the present work, we model the  $Al_2O_3/H_2O$  nanofluid employing the pseudo-single-phase continuum model and investigate the fully-developed forced convection in a coaxial cylinder under a fixed pressure drop. It is found that the heat transfer coefficients of both the cold inner wall and hot outer wall increase with respect to the inlet mass fraction of nanoparticles. The enhancement of convective heat transfer coefficient is found to be slightly higher than that of thermal conductivity of nanofluid itself due to the drift of nanoparticles. On the other hand, the Nusselt number of cold inner wall increases but that of hot outer wall decreases as the inlet mass fraction of nanoparticles increases. It is revealed that this peculiar behavior of Nusselt number on the hot outer wall is caused by the drift of nanoparticles from the cold inner wall to the hot outer wall due to the thermophoresis. As the inlet mass fraction of nanoparticles increases under the condition of fixed pressure drop, the mixture viscosity increases and the volumetric flow rate is retarded, since the viscous dissipation must balance the input rate of mechanical energy at the steady state.

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## 1. Introduction

Nanofluids are colloidal dispersion of nano-sized particles in traditional heat transfer fluids such as water, oil and ethylene glycol. By adding nanoparticles, the thermal conductivity increases. Therefore, in the well-mixed state, the enhanced thermal conductivity is expected to promote heat transfer rate as the particle mass fraction of nanofluids increases. Several investigators performed experimental works on the effects of nanoparticles in the heat transfer characteristics of nanofluids. Xuan and Li [1] investigated turbulent convective heat transfer of copper-oxide in water nanofluids. Yang et al. [2] measured laminar convective heat transfer performance of graphite nanofluids in a circular tube. Wen and Ding [3] investigated laminar forced convection of nanofluids in the entrance region. Heris et al. [4] also studied experimentally the laminar forced convection of nanofluids in a circular tube under constant wall temperature. Williams et al. [5] considered turbulent forced convection of nanofluids in horizontal tubes. Most

of these studies concluded that the presence of nanoparticles enhances heat transfer rate in the nanofluids as compared to their respective base fluids. However, the cause of heat transfer enhancement is still controversial. Is it simply due to the changes in the thermophysical properties of the nanofluids or due to other dynamic effects of nanoparticles?

In the present investigation, we adopt a rigorous continuum model of nanofluids to resolve these controversies. In most models of nanofluids [6], it has been assumed that nanoparticles do not affect the dynamics of nanofluids and adopted the momentum and energy balance equations of the base fluid as those for nanofluids, only with the modification of thermophysical properties induced by nanoparticles [7,8]. However, the effects of particle mass loading on the dynamics of nanofluids are significant, especially in the nonisothermal systems where the thermophoretic drift of particles cannot be neglected [9,10]. In Park [9], a pseudo-single-phase continuum model of nanofluids have been developed from a two-phase model when the particle mass loading is not negligible. In the present investigation the pseudo-single-phase continuum model is implemented for a steady-state, fully-developed forced convection in a coaxial cylinder. It shall be investigated how the nanoparticles effect the heat transfer characteristics in the forced convection in the coaxial cylinder.

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**Nomenclature**

$C_p^l$	liquid phase heat capacity	$\beta$	thermal conductivity ratio defined in Eq. (20)
$C_p^p$	particle phase heat capacity	$\mu$	mixture viscosity
$D^p$	particle Brownian diffusivity	$\mu_l$	liquid phase viscosity
$\mathbf{F}^p$	momentum interaction defined in Eq. (4)	$\boldsymbol{\pi}$	mixture stress tensor
$\mathbf{g}$	gravity vector	$\boldsymbol{\pi}^{diff}$	diffusive stress tensor defined in Eq. (16)
$\mathbf{j}^p$	diffusion flux of particle defined in Eq. (15)	$\rho$	mixture density
$k$	mixture thermal conductivity	$\rho^l$	bulk density of liquid phase
$k^l$	liquid phase thermal conductivity	$\rho^p$	bulk density of particle phase
$k^p$	particle thermal conductivity	$\hat{\rho}_l$	intrinsic density of liquid
$L$	length of the coaxial cylinder	$\hat{\rho}_p$	intrinsic density of particle
$P$	mixture pressure	$\phi$	volume fraction of particle phase
$Q^p$	energy interaction (Eq. (5))	$\omega^p$	mass fraction of particle phase
$T$	mixture temperature		
$T^l$	liquid phase temperature	<i>Superscript</i>	
$T^p$	particle phase temperature	$l$	liquid phase
$\mathbf{v}$	mixture velocity vector	$p$	particle phase
$v^r, v^z$	components of mixture velocity vector	<i>Subscript</i>	
$\mathbf{v}^l$	liquid phase velocity vector	$in$	inlet condition
$\mathbf{v}^p$	particle phase velocity vector	$out$	outlet condition
<i>Greek symbols</i>			
$\alpha^T$	thermal diffusion coefficient		

**2. The pseudo-single-phase continuum model of nanofluids**

Nanofluids are basically multiphase fluids. Our starting point is to describe the nanofluids as a two-phase mixture, with each phase having its own velocity, temperature and density. These two phases interact through the interfacial exchange of momentum and energy. Let the superscript  $\ell$  indicate the liquid phase and  $p$  the nanoparticle phase. Then  $\rho^i$  denotes the  $i$  phase bulk density,  $\mathbf{v}^i$  the  $i$  phase velocity field,  $\boldsymbol{\pi}^i$  the  $i$  phase stress tensor,  $T^i$  the  $i$  phase temperature,  $C_p^i$  the  $i$  phase heat capacity,  $k^i$  the  $i$  phase thermal conductivity,  $t_{mom}$  the momentum relaxation time,  $t_T$  the thermal relaxation time,  $D^p$  the particle Brownian diffusivity and  $\alpha^T$  is the thermal diffusion coefficient. Then the base liquid phase and the nanoparticle phase balance equations are given by;

(Base liquid phase)

$$\frac{\partial \rho^\ell}{\partial t} + \nabla \cdot (\rho^\ell \mathbf{v}^\ell) = 0 \tag{1}$$

$$\frac{\partial}{\partial t} (\rho^\ell \mathbf{v}^\ell) + \nabla \cdot (\rho^\ell \mathbf{v}^\ell \mathbf{v}^\ell) = \nabla \cdot \boldsymbol{\pi}^\ell + \rho^\ell \mathbf{g} + \mathbf{F}^p \tag{2}$$

$$\rho^\ell C_p^\ell \frac{\partial T^\ell}{\partial t} + \rho^\ell C_p^\ell \mathbf{v}^\ell \cdot \nabla T^\ell = \nabla \cdot k^\ell \nabla T^\ell + Q^p \tag{3}$$

where the momentum and energy source terms are:

$$\mathbf{F}^p = \rho^p \frac{\mathbf{v}^p - \mathbf{v}^\ell}{t_{mom}} + \rho^p \frac{\alpha^T D^p}{t_{mom}} \nabla \ln T^\ell + \rho^p \frac{D^p}{t_{mom}} \nabla \ln \omega^p \tag{4}$$

$$Q^p = \rho^p C_p^p \frac{T^p - T^\ell}{t_T} \tag{5}$$

(Nanoparticle phase)

$$\frac{\partial \rho^p}{\partial t} + \nabla \cdot (\rho^p \mathbf{v}^p) = 0 \tag{6}$$

$$\frac{\partial}{\partial t} (\rho^p \mathbf{v}^p) + \nabla \cdot (\rho^p \mathbf{v}^p \mathbf{v}^p) = \nabla \cdot \boldsymbol{\pi}^p + \rho^p \mathbf{g} - \mathbf{F}^p \tag{7}$$

$$\rho^p C_p^p \frac{\partial T^p}{\partial t} + \rho^p C_p^p \mathbf{v}^p \cdot \nabla T^p = \nabla \cdot k^p \nabla T^p - Q^p \tag{8}$$

The momentum and thermal interactions between the two co-existing phases are contained in  $\mathbf{F}^p$  and  $Q^p$  terms. Eq. (4) indicates that the nanoparticles drift under the mechanism of thermophoresis [10] and Brownian motion [11]. The last two terms of the right hand side of Eq. (4) shall take care of the effect of particle drifts on the enhancement of heat transfer coefficient. In [9], it is shown that the momentum relaxation time  $t_{mom}$  and thermal relaxation time  $t_T$  are very small. Then, we find from Eqs. (7) and (8) that

$$\mathbf{v}^p - \mathbf{v}^\ell = -\alpha^T D^p \nabla \ln T^\ell - D^p \nabla \ln \omega^p \tag{9}$$

$$T^p - T^\ell = 0 \tag{10}$$

Now, we introduce the following mixture variables [9,12]

$$\rho \equiv \rho^\ell + \rho^p;$$

$$\rho \mathbf{v} \equiv \rho^\ell \mathbf{v}^\ell + \rho^p \mathbf{v}^p;$$

$$\boldsymbol{\pi} - \rho \mathbf{v} \mathbf{v} \equiv (\boldsymbol{\pi}^\ell - \rho^\ell \mathbf{v}^\ell \mathbf{v}^\ell) + (\boldsymbol{\pi}^p - \rho^p \mathbf{v}^p \mathbf{v}^p);$$

$$\rho C_p T \equiv \rho^\ell C_p^\ell T^\ell + \rho^p C_p^p T^p \tag{11}$$

where  $\rho, \mathbf{v}, \boldsymbol{\pi}, T, C_p$  are the mixture density, velocity, stress tensor, temperature and heat capacity, respectively. Exploiting the definitions of mixture variables and Eq. (10), which implies  $T = T^p = T^\ell$ , the governing equations of the base liquid phase and the nanoparticle phase may be combined to yield the following set of mixture conservation equations.

(Mixture conservation equations)

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \tag{12}$$

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