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# Comparative study of Euler and mixture models for turbulent flow of $Al_2O_3$ nanofluid inside a horizontal tube☆

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ABSTRACT

In this paper, turbulent forced convective flow of water $Al_2O_3$ nanofluid, with particle diameter equal to 40 nm in a horizontal circular tube, exposed to convection with saturated steam at the wall, is numerically analyzed. Two different approaches are taken into consideration: Euler and mixture models. It is comprehended that convective heat transfer coefficient enhances with increasing the particle volume concentration and Reynolds number. The two models almost showed the same results. However, mixture model was in a better agreement with experimental results for the estimation of average Nusselt number.



## 1. Introduction

Convective heat transfer performs a significant character in many industrial heating or cooling equipment. The heat of convection can be increased by changing various factors like flow geometry and boundary conditions or enhancing fluid thermophysical properties.

One way is by adding small solid particles into the fluid. Because solid materials have higher thermal conductivities than fluids, suspending small solid particles in the fluid can cause an improvement on the thermal conductivity of the fluid [1]. This idea was first suggested by Maxwell [2] more than one century ago. He showed the possibility of increasing thermal conductivity of a fluid–solid mixture by more volume fraction of solid particles. Choi [3] was the first to employ the nanometer-sized particles in conventional fluids and showed considerable increase in the nanofluid thermal conductivity. The term 'nanofluid' refers to a two-phase mixture usually composed of a continuous liquid phase and dispersed nanoparticles in suspension [1]. A number of studies have been performed to investigate the transport properties of nanofluids. Lee et al. [4] observed that oxide ceramic nanofluids including CuO or $Al_2O_3$ nanoparticles in water or ethylene glycol intensify thermal conductivity [5,6]. Wen and Ding [7] focused on the entry region under laminar flow condition using nanofluids containing γ-$Al_2O_3$ nanoparticles of various concentrations. It is shown that the enhancement increases with the Reynolds number as well as the volume concentration of nanoparticle. In a comparison between particle sizes it was observed that nanofluid with smaller particles shows higher heat transfer coefficient than that with larger particles [8]. Heris et al. [9–11] studied the laminar flow convective heat transfer of $Al_2O_3$/water and CuO/water nanofluids through circular tube and found that the $Al_2O_3$/water nanofluids showed greater enhancement compared with CuO/water nanofluids [1]. Mansour et al. [12] experimentally studied the mixed convection of water–$Al_2O_3$ mixture inside an inclined tube. Their results indicated that a higher particle volume concentration clearly induced a decrease of the Nusselt number for the horizontal inclination. On the other hand, they showed that for the vertical one, the Nusselt number remains nearly constant with an increase of particle volume concentration from 0% to 4% [13].Commonly, homogenous (single-phase) and two-phase models are used for numerical modeling of nanofluid flow. In single-phase modeling, the particles and the base fluid are considered to have the same temperature and velocity. Thus, the single-phase equations are valid applying proper effective thermophysical properties (thermal conductivity, viscosity, specific heat and density). In this method, the accuracy of the models is very dependent on effective thermophysical properties [14]. Moraveji et al. [15] numerically investigated the developing region of $Al_2O_3$/water nanofluid in a horizontal tube. They realized that heat transfer coefficient magnifies with adjusting of nanoparticle concentration and Reynolds number. Also, the heat transfer coefficient declines with increasing the axial location and particle diameter. On the other hand, several factors such as gravity, friction between the fluid and solid particles and Brownian forces, the phenomena of Brownian diffusion, sedimentation, and dispersion may affect a nanofluid flow [16]. This fact enticed the researchers to use two-phase methods in their numerical studied. Haghshenas Fard et al. [17] made a comparison of the single-phase with the two-phase model for the laminar convective flow of Cu/Water nanofluid. They studied the effects of some important parameters such as Peclet number, particle volume fraction and nanofluid type on heat transfer rate. They concluded that the two-phase model is more accurate than the single-phase model. Mirmasoumi

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**Nomenclature**

| | |
|---|---|
| $C$ | specific heat, j/kg k |
| $D$ | inner diameter of the tube, m |
| $f$ | friction factor |
| $\overline{h}$ | average convective heat transfer coefficient, W/m$^2$ K |
| $I$ | turbulent intensity |
| $K$ | thermal conductivity, W/m K |
| $k$ | turbulent kinetic energy (m$^2$ s$^{-2}$) |
| $L$ | length of the tube, m |
| $\overline{Nu}$ | average Nusselt number |
| $\Delta P$ | pressure drop, Pa |
| $Pr$ | Prandtl number |
| $q''$ | heat flux, W/m$^2$ |
| $Re$ | Reynolds number |
| $T$ | temperature, °C |
| $V$ | fluid velocity, m/s |

*Greek letters*

| | |
|---|---|
| $\mu$ | viscosity of the fluid, kg/m s |
| $\rho$ | density, kg/m$^3$ |
| $\phi$ | volume concentration of nanoparticles, % |

*Subscripts*

| | |
|---|---|
| 0 | initial |
| b | bulk |
| corr | correlation |
| nf | nanofluid |

and Behzadmehr [5] used a two-phase mixture model to study the laminar mixed convection of water/$Al_2O_3$ nanofluid in a horizontal tube. They could present that adjustment of the nanoparticles volume fraction increases the secondary flow strength and makes the mean temperature more uniform.

Since the two-phase models regard the movement between the solid and fluid molecular, they anticipate the nanofluid behavior with more preciseness. Many articles admitted the accuracy of two-phase approaches [6,8,18–24]. In the present work we focus on two-phase studies only. The scope of this study is to compare mixture and Eulerian two-phase models for prediction of turbulent heat transfer in a circular tube which its wall is exposed to saturated steam. For this purpose, a computer code was developed for each of the models. The effects of the Reynolds number and nanoparticle volume fraction on heat transfer rate are investigated. The results from the simulations are also compared with the experimental data reported by Heyhat et al. [25].

## 2. Mathematical modeling

Turbulent mixed convection of a nanofluid consisting of water and $Al_2O_3$nanoparticles with 40 nm diameter in a horizontal circular tube with wall exposed to saturated steam (convection boundary condition) is considered. The computation domain, as shown in Fig. 1, is composed of a straight copper tube with 5 mm diameter and 2 m length. The computational domain is effectively reduced by exploiting axisymmetric boundary along the centerline of the tube.

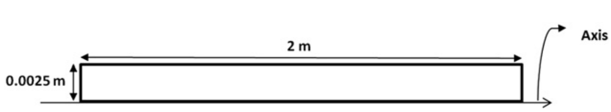

**Fig. 1.** Numerical domain of the horizontal tube (axial symmetry).

Mixture and Eulerian models are engaged in order to examine heat transfer and pressure drop of the mentioned nanofluid. Also, the realizable $\kappa$–$\varepsilon$ turbulent model was applied to model the turbulent flow inside the tube. The following formulations stand for the mathematical description of mixture and Eulerian models governing equations, and the $\kappa$–$\varepsilon$ turbulent model [16,18,26].

### 2.1. Mixture model

The mixture model, considers a combination of continuous and dispersed phases. The governing equations are written for the mixture analogously to the homogeneous model. The slip of a dispersed phase relative to the continuous phase is calculated by balancing the drag and body forces resulting from density differences. The underlying assumption is a local equilibrium, in which the dispersed particles always move with their terminal velocity relative to the continuous phase. The mixture model can be applied for a wide range of the velocity differences, particle size, and density ratios, as long as the force equilibrium is achieved. It is best suited for small particles or bubbles in liquids. The mixture model formulation is presented as follows [23]:

Continuity equation:

$$\nabla.(\rho_m V_m) = 0 \tag{1}$$

Momentum equation:

$$\nabla.(\rho_m V_m V_m) = -\nabla p + \nabla.(\mu_m \nabla V_m) + \nabla.\left(\sum_{k=1}^{n} \varphi_k \rho_k V_{dr,k} V_{dr,k}\right) - \rho_{m,i} \beta_m g (T - T_i) \tag{2}$$

$\rho_m$ is the mixture density,

$$\rho_m = (1-\varphi)\rho_f + \varphi\rho_p \tag{3}$$

where φ is volume fraction of the solid or liquid phases.

Fluid energy equation:

$$\nabla.\sum_{k=1}^{n} \left(\rho_k C_{pk} \varphi_k V_k T\right) = \nabla.(k_m \nabla T) \tag{4}$$

Volume fraction equation:

$$\nabla.\left(\varphi_p \rho_p V_m\right) = -\nabla.\left(\varphi_p \rho_p V_{dr,p}\right) \tag{5}$$

$V_m$ is mass average velocity,

$$V_m = \frac{\sum_{k=1}^{n} \varphi_k \rho_k V_k}{\rho_m} \tag{6}$$

In Eq. (2), $V_{dr,k}$ is the drift velocity for the secondary phase $k$, i.e. the nanoparticles in the present study, which is related to the relative velocity,

$$V_{dr,p} = V_{pf} - \sum_{k=1}^{n} \frac{\varphi_k \rho_k}{\rho_m} V_{fk} \tag{7}$$

The slip velocity (relative velocity) is defined as the velocity of a secondary phase (nanoparticles, $p$) relative to the velocity of the primary phase (water, $f$),

$$V_{pf} = V_p - V_f \tag{8}$$