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Short Communication

# The effect of nanoparticles on laminar heat transfer in a horizontal tube

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ABSTRACT

Heat transfer coefficient in laminar flow of water-based alumina, titania and carbon nanotube nanofluids in a straight pipe with constant heat flux at the wall have been investigated independently by two universities. The nanoparticles affect the thermo-physical properties of the suspensions, however, nanoparticles presence and movement due to Brownian diffusion and thermophoresis seemed to have insignificant effect on heat transfer coefficient. The Nusselt number of all investigated nanofluids followed standard heat transfer correlations developed for liquids within ±10% suggesting that all investigated nanofluids can be treated as homogenous fluids. Different methods of comparison between heat transfer coefficient in nanofluids and base fluid are also critically discussed.



## 1. Introduction

The use of nanoparticles to increase the effectiveness of conventional coolants, such as water, has been proposed by Choi et al. [1] who subsequently patented a single step method to produce these nanoparticle dispersions [2]. They called these nanoparticle dispersions *nanofluids* and claimed that they showed very high thermal conductivity enhancements compared to their base fluids well beyond the prediction of the classical effective medium theory but with negligible viscosity increases. These reports have attracted the interest of many researchers because of the high demand for good coolants in high power electronics, computer servers, microelectronic systems (MEMS), etc. Besides that, new coolants with enhanced thermal conductivity but negligible increase in viscosity are definitely attractive from industrial point of view. Both experimental and theoretical investigations of nanofluids have been carried out and a majority of them focused on thermal conductivity and heat transfer coefficient. However, during almost twenty years of intensive research, inconsistencies regarding thermal conductivity and heat transfer coefficient enhancements of nanofluids have been frequently reported in the literature [3–5]. Recently, some researchers appear to accept that the heat transfer in nanofluids do not show unusual behaviour and is well described by models developed for liquids as long as the effective thermo-physical properties of nanofluids were used [6–8].

High thermal conductivity enhancements of nanofluids have been reported by several researchers. Masuda et al. [9], Eastman et al. [10] and Choi et al. [11] reported that the thermal conductivities of 5 vol.% alumina in water, 0.3 vol.% copper in ethylene glycol (EG) and 1 vol.% carbon nanotube (CNT) in engine oil were 30%, 40% and 150%, respectively, higher than their base fluids. They claimed that the introduction of nanoparticles into base fluids increased the effective thermal conductivity of nanofluids beyond the prediction of the effective medium theory commonly used for composite materials. However, more recent experimental data showed that the effective thermal conductivity of nanofluids could also be lower than that predicted by using the effective medium theory [12–14].

Several mechanisms have been proposed to explain the anomalously high thermal conductivity enhancements of nanofluids, such as micro-convection induced by the Brownian motion of nanoparticles [15,16], the formation of nano-layer of solvent molecules around nanoparticles [17,18], the formation of nanoparticle aggregates [19–21] and combinations of those mechanisms [22,23]. Unfortunately, those models agreed only with experimental data selected by the authors but were contradictory to data by others.

The thermal conductivity of nanofluids is mainly affected by the thermal conductivity of the base fluid and by the volume fraction and thermal conductivity of solid particles. However, it has also been claimed that shape and size, manufacturing method

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**Nomenclature**

| | |
|---|---|
| $c_p$ | specific heat capacity, J/kgK |
| $d$ | diameter of primary particle or aggregate, m |
| $D$ | pipe diameter, m |
| $D_B$ | diffusion coefficient, $m^2/s$ |
| $f$ | friction factor, – |
| $h$ | heat transfer coefficient, $W/m^2K$ |
| $k$ | thermal conductivity, W/mK |
| $L$ | tube length, m |
| $L^*$ | dimensionless length, $(L/D_{in})/(RePr)$ |
| $l$ | mean-free path, m |
| $\dot{m}$ | mass flow rate, kg/s |
| $Nu$ | Nusselt number, $hD_i/k$ |
| $Pr$ | Prandtl number, $c_p\mu/k$ |
| $Re$ | Reynolds number, $DV\rho/\mu$ |
| $\Delta p$ | Pressure drop, Pa |
| $q$ | heat, W |
| $q''$ | heat flux, $W/m^2$ |
| $r$ | radius of primary particle or aggregate |
| $S$ | heat source, $W/m^3$ |
| $T$ | temperature, °C |
| $V$ | velocity, m/s |
| $W_p$ | pumping power, W |
| $x$ | axial distance, m |
| $x_p$ | mass fraction, – |
| $x^*$ | dimensionless axial distance, $(x/D_{in})/(RePr)$ |

*Greek letters*

| | |
|---|---|
| $\phi$ | volume fraction, – |
| $\mu$ | viscosity, kg/ms |
| $\rho$ | density, $kg/m^3$ |

*Subscripts*

| | |
|---|---|
| $a$ | aggregate |
| $ave$ | average |
| $B$ | Brownian |
| $b$ | bulk |
| $bf$ | base fluid |
| $i$ | inner |
| $in$ | bulk inlet |
| $j$ | thermocouple no. 1, 2, 3, etc. |
| $n$ | total number of thermocouples |
| $nf$ | nanofluid |
| $o$ | outer |
| $out$ | bulk outlet |
| $p$ | nanoparticle, primary particle |
| $r$ | relative |
| $w$ | wall |
| $w,i$ | wall inner surface |
| $w,o$ | wall outer surface |

(single-step method where the nanoparticles are synthesized and dispersed directly in the base fluid and two-step method where the nanoparticles were manufactured separately and dispersed in the base fluid [5]), temperature, pH, nanofluids stability, etc. influence the conductivity. To clarify the inconsistency of thermal conductivity enhancements of nanofluids, Buongiorno et al. [4] organized the International Nanofluids Property Benchmark Exercise (INPBE) where the thermal conductivity of identical samples of nanofluids was measured by over thirty institutions worldwide. Various parameters possibly influencing the results were investigated, e.g. measurement technique, manufacturing method (single-step and two-step methods), base fluid (water and oil), particle type (metals and metal oxides), particle size, shape and solid concentration. They found that most experimental data from various institutions agreed with the sample averages within +/−10% and that they were in a good agreement with the predictions of the effective medium theory (developed in the 19th century) confirming that nanofluids do not show anomalous enhancement of thermal conductivity.

Similarly, there are also a lot of contradictions regarding the heat transfer coefficients of nanofluids. Unlike thermal conductivity, the heat transfer coefficient is not a property of the fluid but depends on flow regime and geometry, thermal boundary condition (constant heat flux or constant surface temperature),

**Table 1**
Heat transfer coefficient enhancements of alumina, titania and CNT nanofluids relative to water reported in the literature.

| Author | Nanofluid | Dimension, $Re$ | Method of Comparison | Enhancement of $h_{nf}$ and comments |
|---|---|---|---|---|
| Wen and Ding [24] | Alumina 1.6 vol.% | $Di$ = 4.5 mm $L/D_i$ = 216 $Re$=500−2100 | Same $Re$ | 47 % near the inlet region, 14% near the discharge region. |
| Hwang et al. [25] | Alumina 0.3 vol.% | $Di$ = 1.8 mm $L/D_i$ = 1390 $Re$ = 400−700 | Same $Re$ | 8% in the developed region, $k$ increase by 1.44%, viscosity increase by 3% |
| Rea et al. [7] | Alumina 6 vol.% Zirconia 1.32 vol.% | $Di$ = 4.5 mm $L/D_i$ = 224 $Re$ = 140–1888 | Same velocity | 27% for alumina and 3% for zirconia. $Nu_{nf}$ followed single-phase correlation. |
| Anoop et al. [30] | Alumina 4 wt.% | $Di$ = 4.75 mm $L/D_i$ = 253 $Re$ = 700−2000 | Same $Re$ | 25% for 45 nm particle size and 11% for 150 nm particle size. |
| Liu and Yu [29] | Alumina 5 vol.% | $Di$ = 1.09 mm $L/D_i$ = 280 $Re$ = 600−4500 | Same $Re$ | 19% near the entrance region, 9% near the discharge region. $Nu_{nf}$ followed single-phase correlation |
| Vafaei and Wen [31] | Alumina 1−7 vol.% | $Di$ = 0.51 mm $L/D_i$ = 600 | Same velocity | 100% at high flow rate, but no enhancement at low flow rate |
| He et al. [32] | Titania 1.1 vol.% | $Di$ = 3.97 mm $L/D_i$ = 462 $Re$ = 900−5900 | Same $Re$ | 12% in laminar flow and 40% in turbulent flow |
| Ding et al. [26] | CNT 0.5 wt.% | $Di$ = 4.5 mm $L/D_i$ = 216 $Re$ = 800−1200 | Same $Re$ | 350% in the developed region |
| Garg et al. [27] | CNT 1 wt.% | $Di$ = 1.55 mm $L/D_i$ = 590 $Re$ = 600−1200 | Same $Re$ | 32% in the developed region |
| Lao and Liu [28] | CNT 0.5 – 2 wt.% | $Di$ = 1.02 mm $L/D_i$ = 217 $Re$ = 500−10000 | Same velocity | 18−25% at 29 °C for 2 wt.% nanofluid, 49−56% at 58 °C for 1 wt.% nanofluid at the same velocity. |