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CONVECTIVE HEAT TRANSFER ENHANCEMENT IN NANOFLUIDS: REAL ANOMALY OR ANALYSIS ARTIFACT?

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ABSTRACT

The nanofluid literature contains many claims of anomalous convective heat transfer enhancement in both turbulent and laminar flow. To put such claims to the test, we have performed a critical detailed analysis of the database reported in 12 nanofluid papers (8 on laminar flow and 4 on turbulent flow). The methodology accounted for both modeling and experimental uncertainties in the following way. The heat transfer coefficient for any given data set was calculated according to the established correlations (Dittus-Boelter's for turbulent flow and Shah's for laminar flow). The uncertainty in the correlation input parameters (i.e. nanofluid thermo-physical properties and flow rate) was propagated to get the uncertainty on the predicted heat transfer coefficient. The predicted and measured heat transfer coefficient values were then compared to each other. If they differed by more than their respective uncertainties, we judged the deviation anomalous. According to this methodology, it was found that in nanofluid laminar flow in fact there seems to be anomalous heat transfer enhancement in the entrance region, while the data are in agreement (within uncertainties) with the Shah's correlation in the fully developed region. On the other hand, the turbulent flow data could be reconciled (within uncertainties) with the Dittus-Boelter's correlation, once the temperature dependence of viscosity was included in the prediction of the Reynolds number. While this finding is plausible, it could not be conclusively confirmed, because most papers do not report information about the temperature dependence of the viscosity for their nanofluids.

Keywords:

Nanoparticles, turbulent flow, laminar flow, uncertainty

NOMENCLATURE

c	Specific heat, J/kg·K
D	Diameter, m
h_m	Average heat transfer coefficient, J/kg
k	Thermal conductivity, W/m·K
L	Length, m
Nu_m	Nusselt number
Pe	Peclet number
Pr	Prandtl number
q"	Heat flux, W/m^2
Re	Reynolds number
s^2	Variance
T	Temperature, ^oC
V	Velocity, m/s
x	Distance from channel inlet, m

Greek Symbols

ϕ	Nanoparticle volumetric fraction
μ	Viscosity, Pa·s
ρ	Density, kg/m^3

Subscripts

f	Fluid
p	Nanoparticle

1. INTRODUCTION

A literature search was conducted for publications on nanofluids convective heat transfer; the search yielded 46 journal papers [1-46]. Most of these papers report that addition of nanoparticles to base fluids "enhances the convective heat transfer capabilities". However, what constitutes enhancement is subject to interpretation. According to the established correlations for turbulent and laminar convective heat transfer, the heat transfer coefficient (htc) depends on the thermophysical properties and flow parameters as follows:

Dittus-Boelter's correlation [47], fully developed turbulent flow

$$Nu_m = 0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.4} \Rightarrow$$

$$h_m = 0.023\,\mathrm{Re}^{0.8}\,\frac{c^{0.4}k^{0.6}\mu^{0.4}}{D} = 0.023\frac{c^{0.4}k^{0.6}\rho^{0.8}V^{0.8}}{\mu^{0.4}D^{0.2}} \qquad (1)$$

Eq.1 is valid for 0.7<Pr<120, Re>10000, L/D>10.

Shah's correlation [48], developing laminar flow (fixed wall heat flux)

$$Nu_m = \begin{cases} 1.953x^{*-1/3} - 1 & x^* \le 0.03 \\ 4.364 + 0.0722x^{*-1} & x^* > 0.03 \end{cases} \qquad (2)$$

where $x^* \equiv \dfrac{x/D}{\rho c V D/k}$. Eq. 2 is valid for Re < 2300 and any value of Pr.

By examining Eq. 1, we can readily see that, for a given Reynolds number, nanofluids tend to have a higher turbulent htc than their base fluids, because of their higher viscosity and thermal conductivity, in spite of a somewhat lower specific heat. On the other hand, for fixed velocity, the turbulent htc can be enhanced or decreased, depending on the relative magnitude of the viscosity, thermal conductivity and density increase. From Eq. 2, we see that for fully-developed laminar flow (x^*>>1), the htc is directly proportional to the thermal conductivity while no other thermophysical property matters. Thus, in fully-developed laminar flow, nanofluids are expected to have higher htc than their base fluids. In the entrance region (x^*<<1), the htc depends on thermal conductivity and also specific heat and density (but not on viscosity), so nanofluids can either have higher or lower htc depending on the relative magnitude of the changes in these properties. All these trends are expected and can be captured if accurate values of the thermo-physical properties are available for the nanofluids of interest. Of the 46 papers examined, only

12 papers (summarized in Tables I and II) claimed significant deviations from the above correlations[1]. However, often in these studies the nanofluid properties were not measured, but rather calculated from models (sometimes questionable models); moreover, the uncertainties in the calculated htc values were not quantified. These shortcomings make it difficult to assess if in fact a *significant* deviation from Eqs. 1-2 is present or not. Therefore, we decided to conduct a critical analysis of the claims of anomalous heat transfer enhancement in these papers. The question of anomalous enhancement is important, because a significant deviation of the data from Eqs. 1-2 would signal the presence of some nanoparticle-specific heat transfer mechanisms that make nanofluids behave in a fundamentally different way from homogenous fluids.

The methodology adopted in our analysis is described in Section 2, while the results are discussed in Section 3. Conclusions are offered in Section 4.

2. METHODOLOGY

The evaluation methodology comprised the following steps:

- *Collection of htc experimental data.* Measured htc data were extracted from the figures in the original papers. The data were sometimes plotted as htc vs Reynolds number, sometimes as htc vs x/D (especially in laminar flow). Uncertainties in the measured htc values were typically reported in the papers and ranged from 3 to 5%. If not reported, a 5% experimental uncertainty was assumed in our analysis.

- *Prediction of htc.* The htc was predicted according to Eqs. 1-2 using the measured values of velocity (or volumetric flow rate), channel diameter, and thermo-physical properties reported in the papers. If the thermo-physical properties had not been measured, we used the following models:

$$\rho = \phi\rho_p + (1-\phi)\rho_f \tag{3}$$

$$c = \frac{\phi\rho_p c_p + (1-\phi)\rho_f c_f}{\rho} \tag{4}$$

$$\frac{k}{k_f} = \frac{k_p + 2k_f + 2\phi(k_p - k_f)}{k_p + 2k_f - \phi(k_p - k_f)} \tag{5}$$

[1] All these papers present some form of 'validation' of the experimental apparatus by comparing pure fluid data to the Dittus-Boelter's and Shah's or equivalent correlations.

$$\frac{\mu}{\mu_f} = 1 + 2.5\phi \qquad (6)$$

Eqs 3 and 4 are the definitions of mixture density and specific heat for a two-component medium. Eq. 5 is Maxwell's model for thermal conductivity of a dispersion of particles in a homogenous medium; Maxwell's model (in its updated version due to Nan et al. [51]) was shown to correctly reproduce the thermal conductivity of nanofluids [52]. Eq 6 is Einstein's model for the viscosity of a dilute dispersion of non-interacting spherical particles in a homogenous medium. Unfortunately, Einstein's model does not reproduce the nanofluid viscosity data accurately [53]. Specifically, it has been found to greatly underestimate the nanofluid viscosity data [53]. Therefore, we have used Einstein's model as a lower bound for viscosity and Williams et al.'s data [42] as an upper bound. While this approach is hardly satisfactory, the reader should note that viscosity does not affect the htc in laminar flow, so this issue is of concern only for turbulent flow. Moreover, all turbulent flow studies have reported their viscosity except Duangthongsuk and Wongwises [12]. In summary, the Einstein's model was used solely in the analysis of Duangthongsuk and Wongwises's data.

- *Uncertainty on the predicted htc.* The uncertainty on the value of the predicted htc was calculated by propagating the uncertainties on the individual input parameters in Eqs. 1-2, i.e. velocity, diameter, and the thermo-physical properties. The thermo-physical property uncertainties were either picked directly from the original paper (when reported) or were in turn estimated by propagating the uncertainty of the input parameters in the models of Eqs. 3-6. For propagation of uncertainties, we used the standard methodology applicable to normal distributions; that is, for any generic function $y=f(x_1,x_2\ldots x_n)$, the variance of y, s_y^2, was calculated as follows:

$$s_y^2 = \sum_i \left(\frac{\partial f}{\partial x_i} \right)^2 s_{xi}^2 \qquad (7)$$

- *Definition of anomalous enhancement.* The measured and predicted htc were plotted in the same figure. If they differed by more than their respective uncertainties (error bars), we judged the deviation to be anomalous.

Table III reports many of the assumptions made in the analysis of the various datasets. However, because of space limitations, it is impossible to report all details here. The interested reader is strongly encouraged to consult N. Prabhat's M.S. Thesis [54].

3. RESULTS

3.1 Laminar Flow

The analysis of the laminar flow data produced the following results:

- Anomalous htc enhancement (as defined in Section 2) was observed in the data by Anoop et al. [2], Wen and Ding [40] and Ding et al. [9], Heris et al. [16], Kurowska et al. [23] and Li and Xuan [28], but not in the data by Hwang et al. [17] and Lai et al. [25]. Representative htc plots from these two groups are shown in Figs 1 through 5.
- The deviations from the Shah's correlation were generally more pronounced at higher Reynolds number (still within the laminar flow range) and higher nanoparticle concentrations. Investigation of the physical mechanisms responsible for these trends is an interesting area for future contributions.

3.2 Turbulent Flow

Anomalous enhancement was observed for all 4 turbulent flow datasets. Representative htc plots are shown in Fig 6 (solid lines). However, we noted that in all 4 turbulent studies the Reynolds number was defined in terms of the nanofluid viscosity at room temperature. Interestingly, if the nanofluid viscosity dependence on temperature is assumed to be as strong as that of water (an assumption justified by Williams et al.'s viscosity data [42]) and taken into account in the definition of the Re number, the experimental htc-vs-Re curves shift to the right and overlap with the predicted curves, as shown in Fig 6 (broken lines). In other words, the anomalous enhancement in turbulent flow might simply be a case of 'mistaken viscosity', although this suspicion cannot be confirmed conclusively, since none of the 4 turbulent flow studies reported the nanofluid viscosity as a function of temperature. This is also an area for future contributions.

4. CONCLUSIONS AND FUTURE WORK

A detailed analysis of 12 nanofluid convective heat transfer datasets (both in the laminar and turbulent flow regimes) was conducted. The data were compared to the predictions of the Dittus-Boelter (turbulent) and Shah's (laminar) correlations, using the properties of the nanofluids, measured (when available) or calculated. Experimental as well as model uncertainties were accounted for in the analysis. It was shown that significant deviations (i.e. beyond uncertainties) between the data and the predictions of the heat transfer correlations can occur in the laminar flow regime, particularly in the entrance region; the enhancement becomes more pronounced at higher (but still laminar) Reynolds number and higher particle concentration. This finding was surprising to us, since our own nanofluids experimental data for

laminar flow [36] had showed no deviation from the Shah's correlation; in fact we were initially rather skeptical of the claims of anomalous enhancement found in the literature.

On the other hand, we suspect that the anomalous enhancement observed in the turbulent flow regime could be an analysis artifact, due to the use of the room-temperature viscosity in the definition of the Reynolds number.

The following items are recommended for future work:

- Mixed forced/free convection effects in the laminar flow data sets (especially those in the low Reynolds number range) should be assessed and possibly ruled out, to strengthen the conclusion of anomalous enhancement.
- Investigation of the physical mechanisms responsible for anomalous enhancement in the laminar flow regime is needed.
- Viscosity-vs-temperature data for nanofluids are needed to clarify the apparent discrepancy in turbulent flow.

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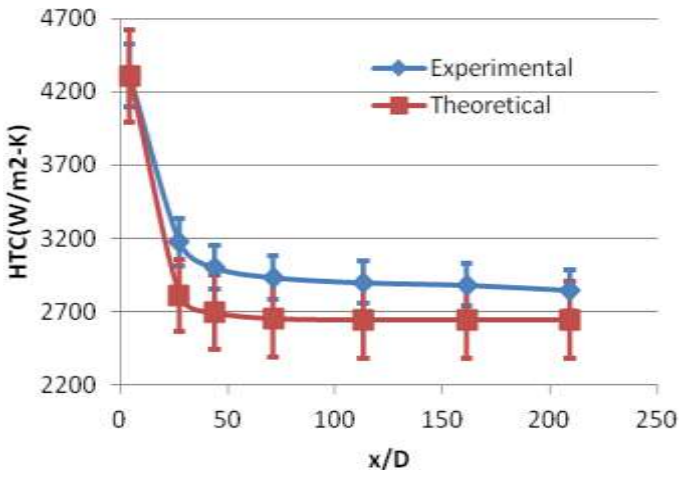


Fig 1. Local htc [W/m^{2}K] for Lai et al.'s data (1.0 vol% alumina, 5 ml/min), showing no significant deviation between the measured and predicted htc.

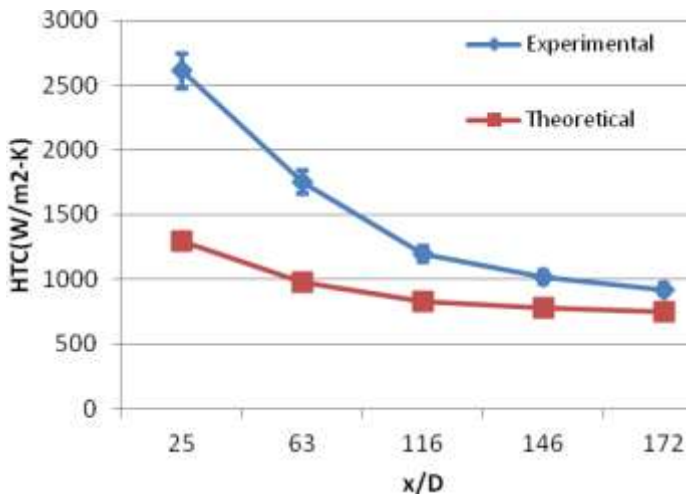


Fig 2. Local htc [W/m^{2}K] for Wen and Ding's data (1 vol% alumina, Re=1600), showing a very large anomalous enhancement in the entrance region, a lot smaller at high x/D. The uncertainty bars for the predicted curve are present, but small in this case.

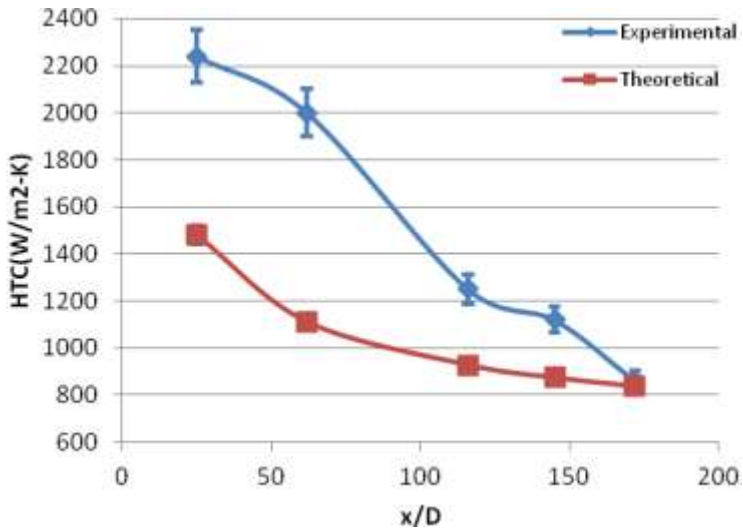


Fig 3. Local htc [W/m^{2}K] for Ding et al.'s data (0.1 wt% Carbon Nano-Tubes, Re=800), showing a very large anomalous enhancement in the entrance region, but no deviation at high x/D. The uncertainty bars for the predicted curve are shown, but small in this case.

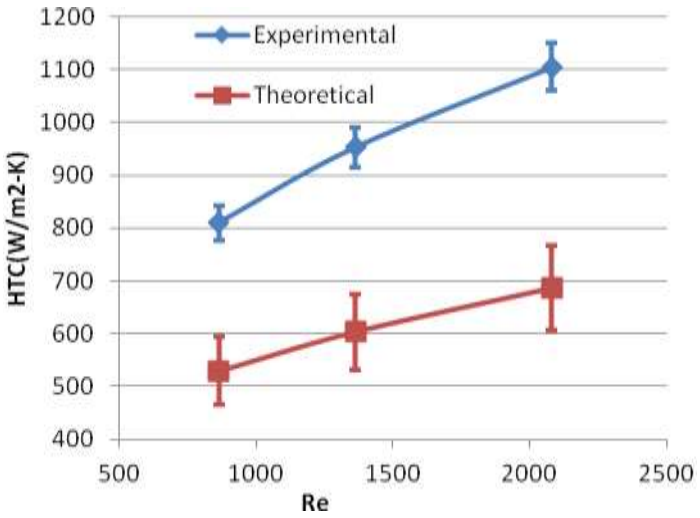


Fig 4. Average htc [W/m^{2}K] for Li and Xuan's data (2.0 vol% Cu), showing large anomalous enhancement, whose magnitude increases with increasing Re number.

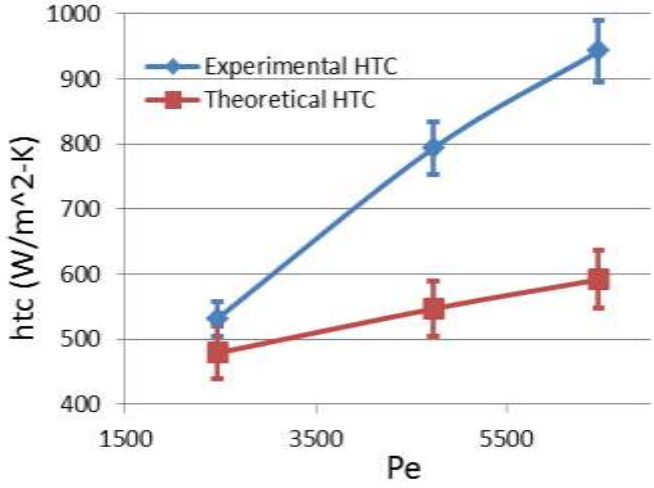
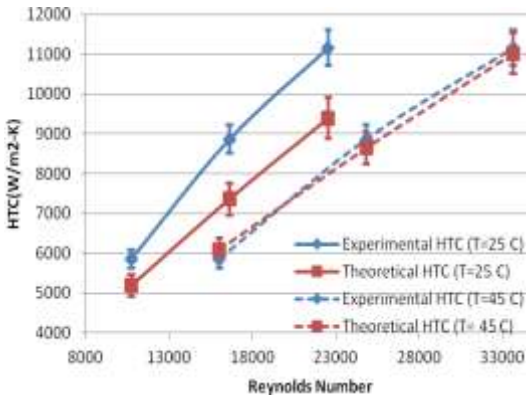
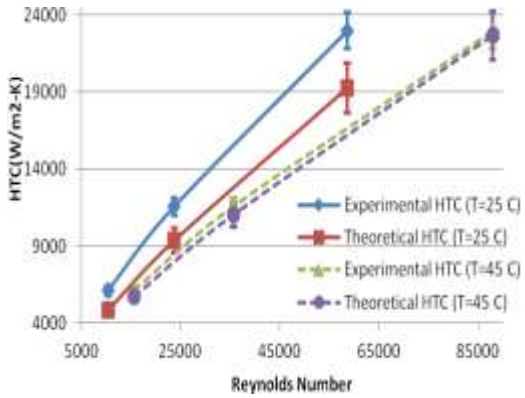


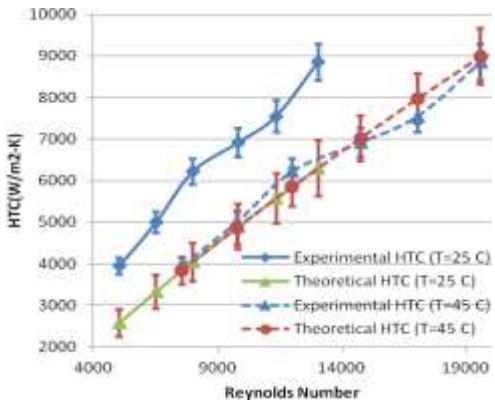
Fig 5. Average htc [W/m^{2}K] for Heris et al.'s data (3.0 vol% alumina), showing anomalous enhancement, whose magnitude increases with increasing Pe number.



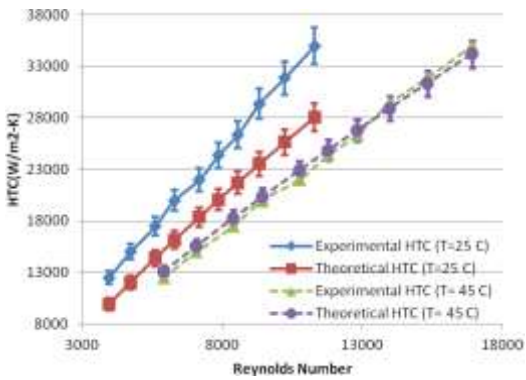
(a)



(b)



(c)



(d)

Fig 6. Average htc [W/m^{2}K] for (a) Xuan and Li's data (1.5 vol% Cu), (b) Pak and Cho's data (3.16 vol% titania), (c) Duangthongsuk and Wongwises's data (0.2 vol% Ti), and (d) Yu et al.'s data (3.2 vol% silicon carbide). The solid lines are for a Reynolds number based on room-temperature viscosity, while the broken lines are for a Reynolds number based on viscosity at 45°C. Note that the when the effect of temperature on viscosity is taken into account, the measured htc no longer displays anomalous deviations from the predicted htc.

Table I. Nanofluids convective heat transfer studies analyzed in this paper (laminar flow).

Ref.	Nanofluid Characteristics		Nanoparticle Concentration	Reynolds Number or Flowrate	Boundary Condition	Properties			
	Composition	Particle Size and Shape				k (W/m-K)	μ (Pa-s)	ρ (kg/m^3)	c (J/kg-K)
Anoop et al [2]	Al_2O_3/water Nanofluid	45 nm and 150 nm, Spherical	0.26-2 18 vol %	750-2200	Constant heat flux	Transient Hot Wire	Ubbelohde viscometer	Mixture formula	Mixture formula
Ding et al [9]	CNT/water Nanofluid	Aspect ratio >100	0.10-0.50 wt%	800-1200	Constant heat flux	KD-2	Bohlin CVO Rheometer	Mixture formula	Mixture formula
Heris et al [16]	Al_2O_3/water Nanofluid	20 nm, Spherical	0.1-3.0 vol%	N/A	Constant Wall Temp.	Maxwell's equation	Einstein's formula	Mixture formula	Mixture formula
Hwang et al [17]	Al_2O_3/water Nanofluid	30±5 nm, Spherical	0.01-0.3 vol%	400-750	Constant Heat flux	Transient Hot Wire	VM 10-A Viscometer	BX 300	DSC 204 F1
Kurowska et al [23]	151 nm (0.15 vol %), 350 nm (0.25 vol %), Cu/Ethylene Glycol Nanofluid	Spherical	0.15 vol%, 0.25 vol%	30-60	Constant heat flux	N/A	Brookfield DV II+ Viscometer	Mixture Formula	Mixture formula
Lai et al [25]	20 nm (SEM), Aggregate size (100-300 nm), Al_2O_3/water Nanofluid	Spherical	0.5-1.00 vol%	1-9 (ml/min)	Constant heat flux	N/A	N/A	Mixture formula	Mixture formula
Li and Xuan [28]	<100 nm, Cu/water nanofluid	Spherical	0.3-2.0 vol%	850-2200	Constant heat flux	Transient Hot Wire	NXE-1 viscometer	Mixture formula	Mixture formula
Wen and Ding [40]	27-56 nm, Al_2O_3/water Nanofluid	Spherical	0.6-1.60 vol%	1050, 1600	Constant heat flux	KD-2	Einstein Equation	Mixture formula	Mixture formula

N/A = not available

Table II. Nanofluids convective heat transfer studies analyzed in this paper (turbulent flow).

Ref.	**Nanofluid Characteristics**		**Nanoparticle Concentration**	**Reynolds Number**	**Boundary Condition**	**Properties**			
	Particle Size	**Particle Shape**				k (W/m-K)	μ (Pa-s)	ρ (kg/m^3)	c (J/kg-K)
Duangthongsuk and Wongwises [12]	21 nm, TiO_2/water nanofluid	N/A	0.2%	4000-18000	N/A	Yu and Choi's Model [49]	Einstein formula	Mixture formula	Mixture formula
Pak and Cho [33]	27 nm (TiO_2) 13 nm (Al_2O_3) in water	Aspect Ratio ~ 1, Grain like shape	Al_2O_3 (1.34%, 2.78%), TiO_2 (0.99%, 2.04%, 3.16%)	14000-60000	Constant heat flux	Masuda et al [50]	Brookfield cone and plate viscometer	Mixture formula	Mixture formula
Xuan and Li [44]	< 100 nm, Cu/water nanofluid	N/A	0.3-2.0%	10,000-25,000	Constant heat flux	Transient Hot Wire	NXE-1 viscometer	Mixture formula	Mixture formula
Yu et al [49]	~170 nm (DLS and Small angle X-ray scattering), SiC/water nanofluid	Disks or platelets, Aspect Ratio 4:1	3.7%	3,000-12,000	Constant heat flux	Transient Hot Wire	DV-II+Pro viscometer	Mixture formula	Mixture formula

N/A = not available

Table III. Uncertainties in input parameters for prediction of htc.

Ref.	k (W/m-K) uncertainty	μ (Pa.s) uncertainty	ρ (kg/m^3) uncertainty[c]	c (J/kg-K) uncertainty[c]	$\dot{m}$ (kg/s) uncertainty	Experimental htc uncertainty
Anoop et al [2]	THW (±2%)	a	Calculated from mixture formula	Calculated from mixture formula	±5% (assumed)	±5% (assumed)
Ding et al [9]	KD2 (±3%)	a	Calculated from mixture formula	Calculated from mixture formula	±4.6%(reported)	±5% (assumed)
Heris et al [16]	Maxwell's model (±10% assumed)	a	Calculated from mixture formula	Calculated from mixture formula	±5% (assumed)	±5% (assumed)
Hwang et al [17]	THW (±5%, assumed)	a	Calculated from mixture formula	Calculated from mixture formula	±5% (assumed)	±3%
Kurowska et al [23]	Maxwell's model (±10% assumed)	a	Calculated from mixture formula	Calculated from mixture formula	±5% (assumed)	±5% (assumed)
Lai et al [25]	Maxwell's model (±10% assumed)	a	Calculated from mixture formula	Calculated from mixture formula	±5% (assumed)	±5% (assumed)
Li and Xuan [28]	THW (±5%, assumed)	a	Calculated from mixture formula	Calculated from mixture formula	±1% (reported)	±4%
Wen and Ding [40]	KD2 (±3%)	a	Calculated from mixture formula	Calculated from mixture formula	±4.6%(reported)	±5% (assumed)
Duangthongsuk and Wongwises [12]	Maxwell's model (±10% assumed)	Mean of MIT data and Einstein's model [b]	Calculated from mixture formula	Calculated from mixture formula	±5% (assumed)	±5% (assumed)
Pak and Cho [33]	Maxwell's model (±10% assumed)	Brookfield viscometer (±2%)	Calculated from mixture formula	Calculated from mixture formula	±5% (assumed)	±5% (assumed)
Xuan and Li [44]	THW (±5%, assumed)	NXE-1 viscometer (±5%)	Calculated from mixture formula	Calculated from mixture formula	±1% (reported)	±4%
Yu et al [49]	THW (±5%, assumed)	DV II+ Viscometer (±5%)	Calculated from mixture formula	Calculated from mixture formula	±1% (reported)	±5%

[a] The laminar flow htc is independent of viscosity.
[b] Since this paper did not report nanofluid viscosity data, its value was bounded using Einstein's formula (lower bound) and the MIT data [42] (upper bound)
[c] Uncertainties in density and specific heat of nanofluid were calculated using uncertainty propagation through the mixture formula assuming 10% uncertainty in nanoparticle properties.