Performance of Nanofluids in Micro Plate Heat Exchangers

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Presented By

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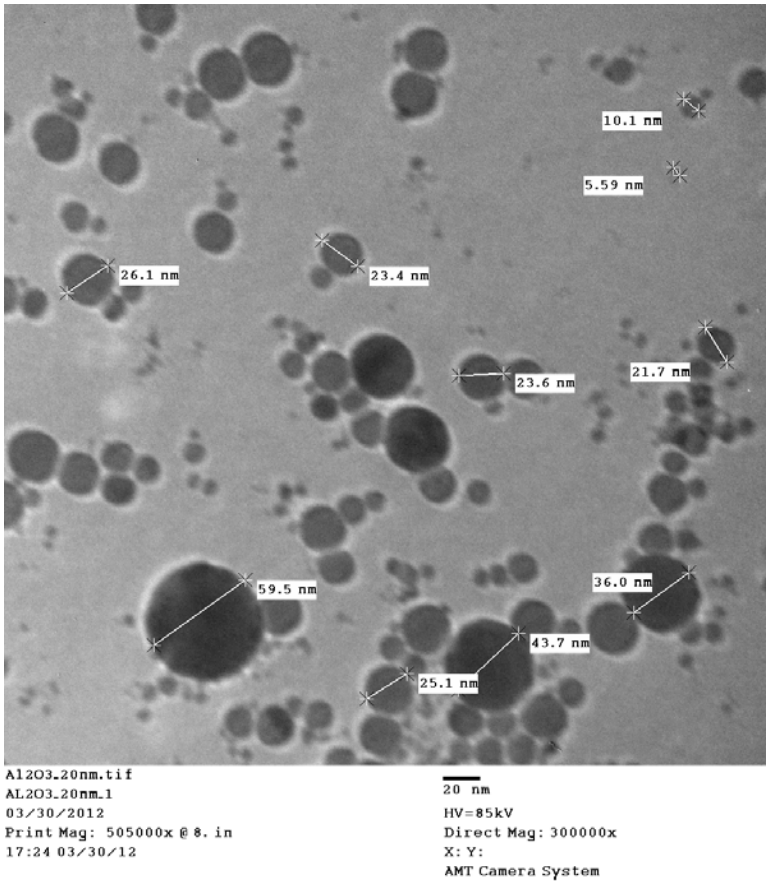
Topics of Discussion

- Introduction to nanofluids
- Advantages of nanofluids
- Theory of nanofluids
- Thermophysical properties of nanofluids
- Micro plate heat exchanger analysis
- Conclusions
- References
- Acknowledgements

Nanofluids

•The concept was proposed by Choi (1999), Argonne National Lab.

•Dispersion of metallic nanometer sized particles (<100nm) in liquid.



TEM image of Aluminum oxide, 20nm

Advantages

- They are permanently suspended by the Brownian motion.
- Nanoparticles posses much higher surface area. The surface/volume ratio of nanoparticles is 1000 times higher than that of microparticles.
- Nanoparticles are so small that they may erosion and clogging of microparticles may be avoided.
- Significant increase in the thermal conductivity of base fluids.

Thermal conductivity of various materials

	Material	Thermal Conductivity (W/m · K)[a]
Metallic solids	Silver	429
	Copper	401
	Aluminum	237
Nonmetallic solids	Diamond	3300
	Carbon nanotubes	3000
	Silicon	148
	Alumina (Al_2O_3)	40
Metallic liquids	Sodium at 644 K	72.3
Nonmetallic liquids	Water	0.613
	Ethylene glycol	0.253
	Engine oil	0.145

[a] At 300 K unless otherwise noted.

Source: Das et al. 2007

Theory of Nanofluids

Nusselt Number

$$Nu_{nf} = c_1(1.0 + c_2\phi^{m_1} Pe_d^{m_2})\,\mathrm{Re}_{nf}^{m_3}\,\mathrm{Pr}_{nf}^{0.4}$$

Particle Peclet Number

$$Pe_d = \frac{u_m d_p}{\alpha_{nf}}$$

Laminar Flow

$$Nu_{nf} = 0.4328(1.0 + 11.285\phi^{0.754} Pe_d^{0.218})\,\mathrm{Re}_{nf}^{0.333}\,\mathrm{Pr}_{nf}^{0.4}$$

Turbulent Flow

$$\begin{cases} Nu_{nf} = 0.0059(1.0 + 7.6286\phi^{0.6886} Pe_d^{0.001})\,\mathrm{Re}_{nf}^{0.9238}\,\mathrm{Pr}_{nf}^{0.4} \\ Nu_{nf} = 0.065(\mathrm{Re}^{0.65} - 60.22)(1 + 0.0169\phi^{0.15})\,\mathrm{Pr}^{0.542} \end{cases}$$

Heat Transfer Coefficient

$$h_{nf} = (Nu_{nf} k_{nf}) / d$$

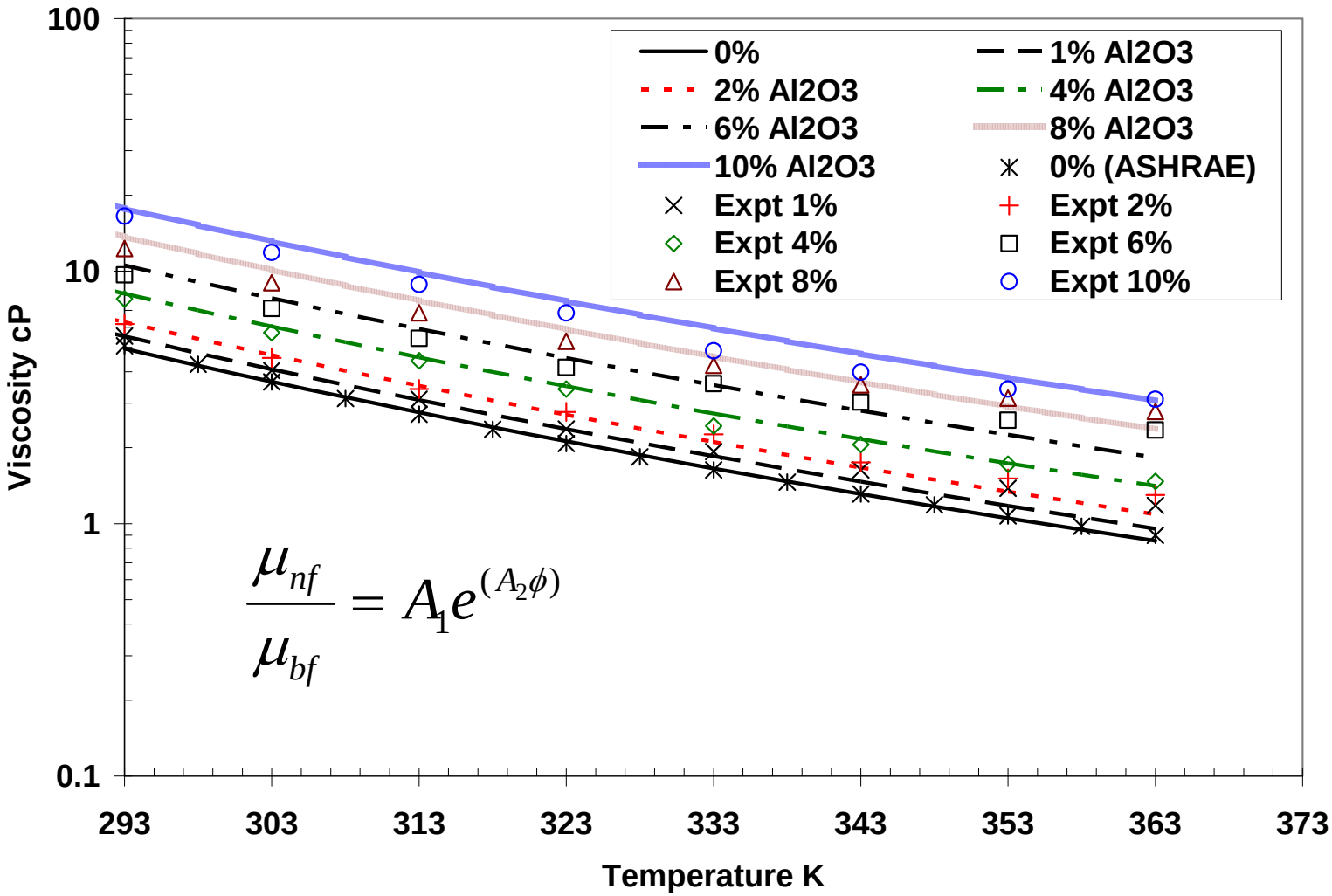
Friction factor

$$f_{nf} = 0.3164\,\mathrm{Re}^{-0.25}\left(\frac{\rho_{nf}}{\rho_{bf}}\right)^{0.797}\left(\frac{\mu_{nf}}{\mu_{bf}}\right)^{0.108}$$

Source: Xuan & Li, 2003 & Vajjha et al. 2010

Thermophysical properties

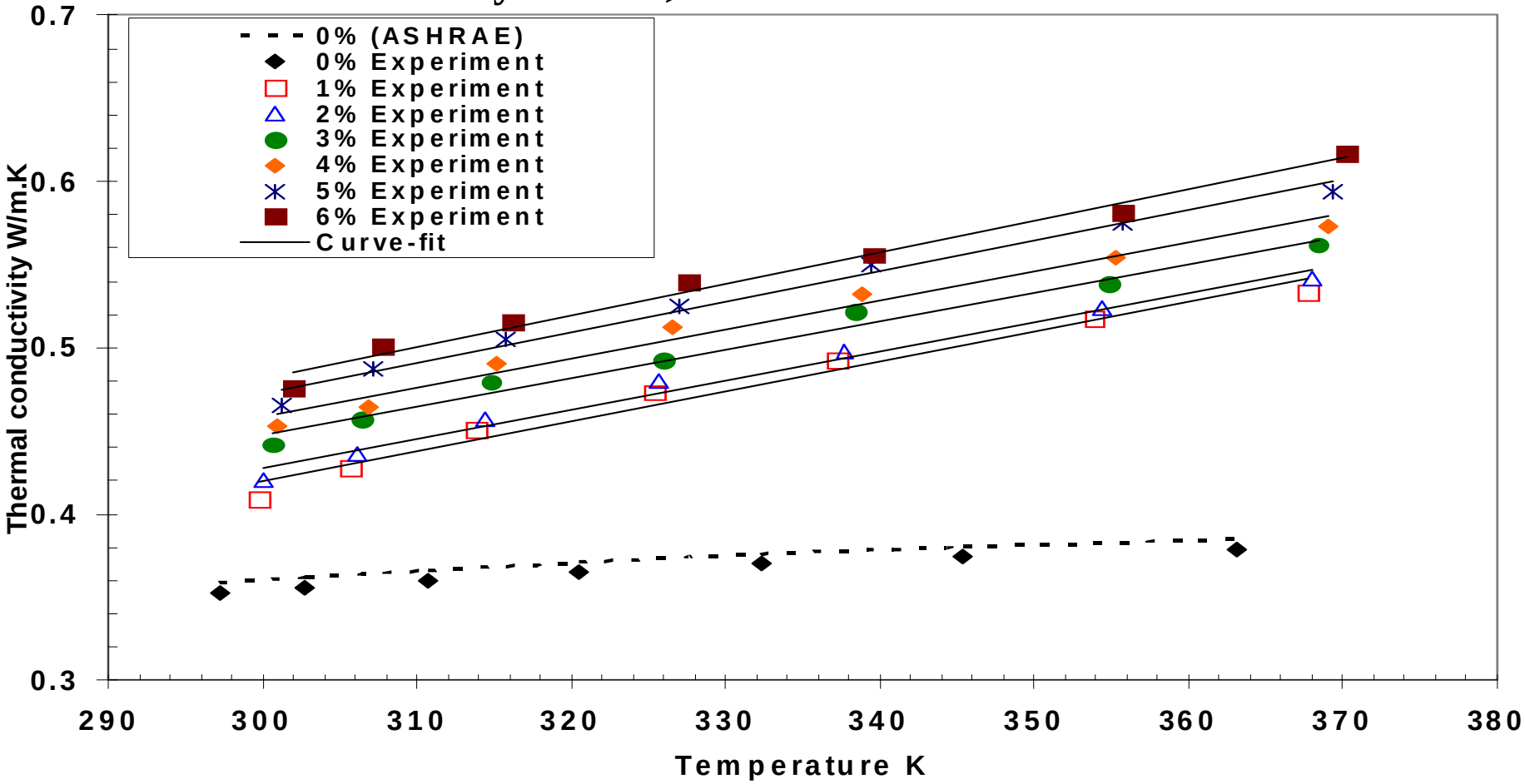
Viscosity versus temperature for Al_2O_3 nanofluids



Source: Vajjha et al. 2010

Thermophysical properties

Thermal conductivity of CuO, 30nm nanofluid.



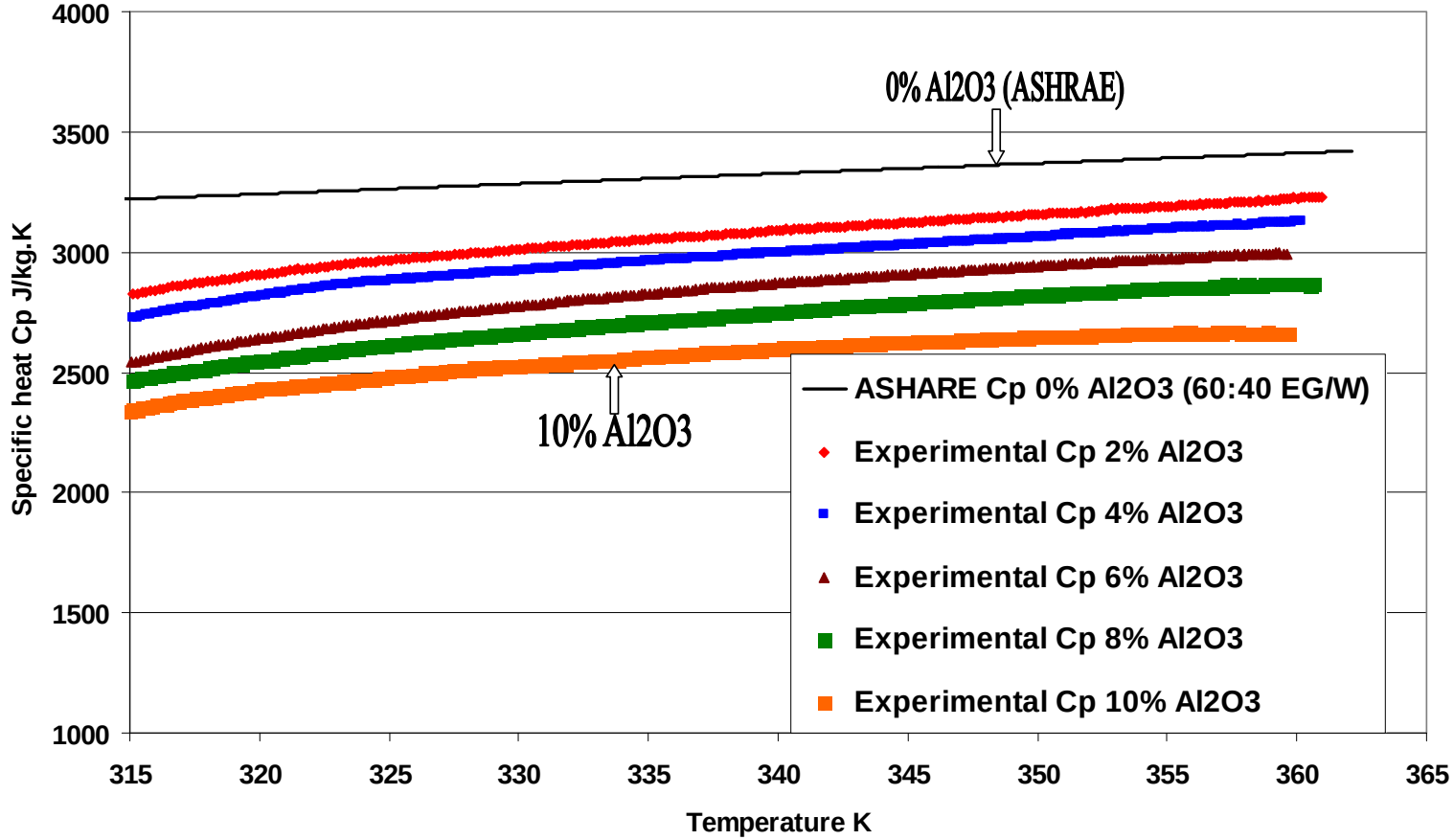
$$k_{nf} = \frac{k_p + 2k_{bf} - 2(k_{bf} - k_p)\phi}{k_p + 2k_{bf} + (k_{bf} - k_p)\phi} k_{bf} + 5\times10^4 \beta\phi\rho_{bf} C_{pbf} \sqrt{\frac{\kappa T}{\rho_p d_p}} f(T,\phi) \quad ; \quad \beta = 8.4407(100\phi)^{-1.07304}$$

$$f(T,\phi) = (2.8217\times10^{-2}\phi + 3.917\times10^{-3})\left(\frac{T}{T_0}\right) + (-3.0669\times10^{-2}\phi - 3.91123\times10^{-3})$$

Source: Vajjha & Das, 2009

Thermophysical properties

Specific heat of Al_2O_3, 45nm nanofluid.

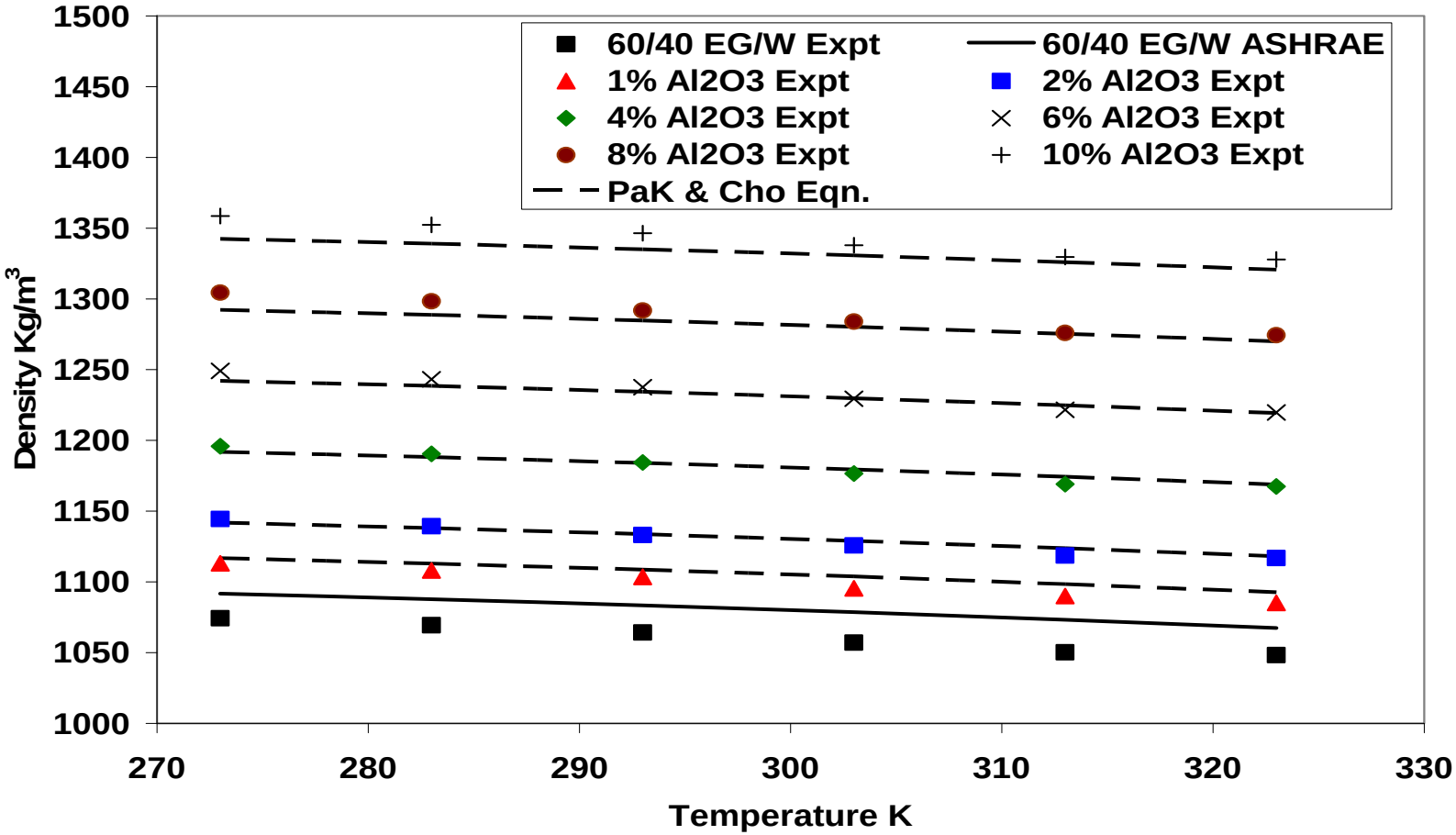


$$\frac{C_{pnf}}{C_{pbf}} = \frac{\left(\left(A*\left(\frac{T}{T_0}\right)\right) + B*\left(\frac{C_{pp}}{C_{pbf}}\right)\right)}{(C+\phi)}$$

Source: Vajjha & Das, 2009

Thermophysical properties

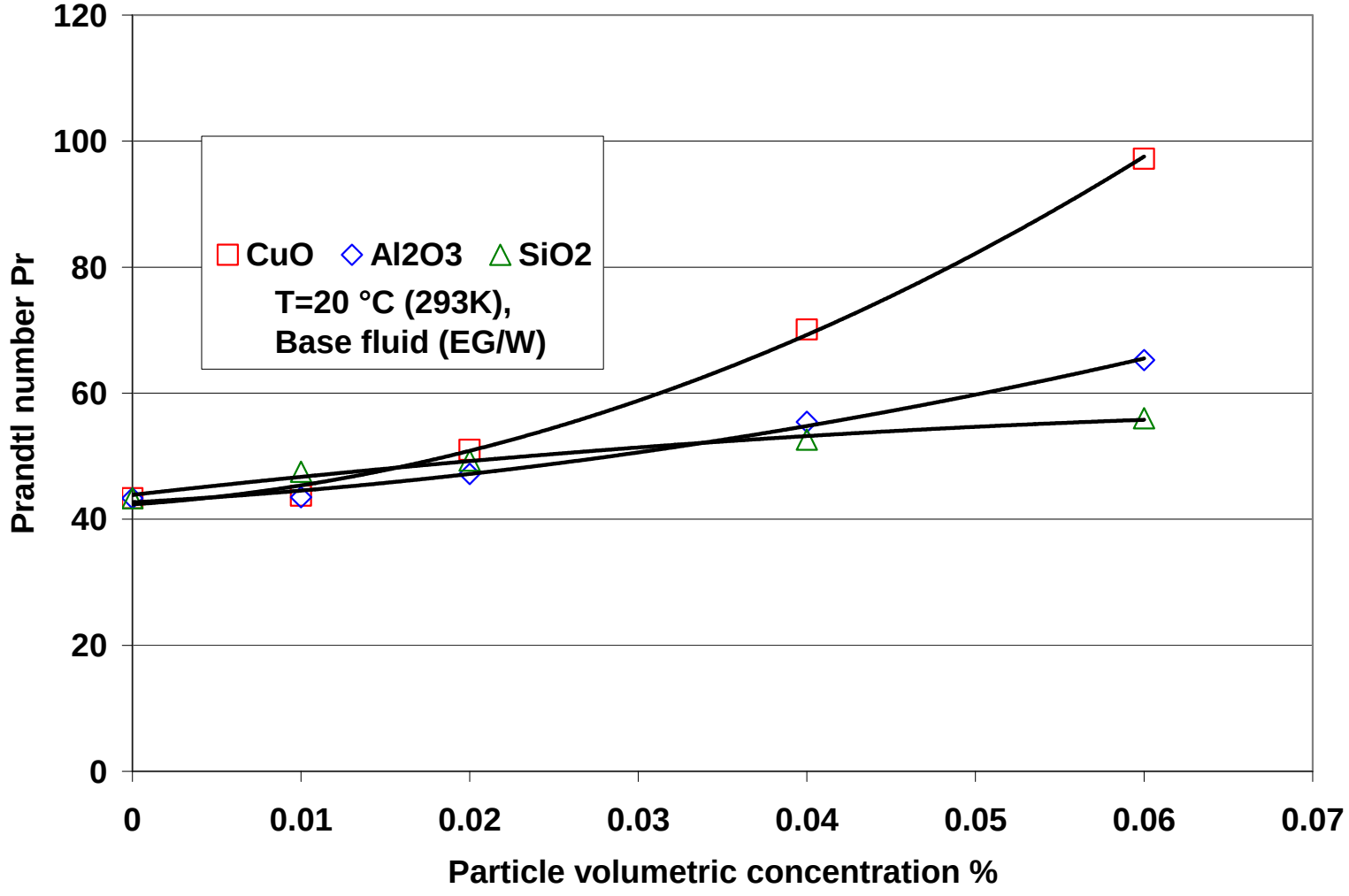
- **Density of Al_2O_3, 45nm nanofluid**



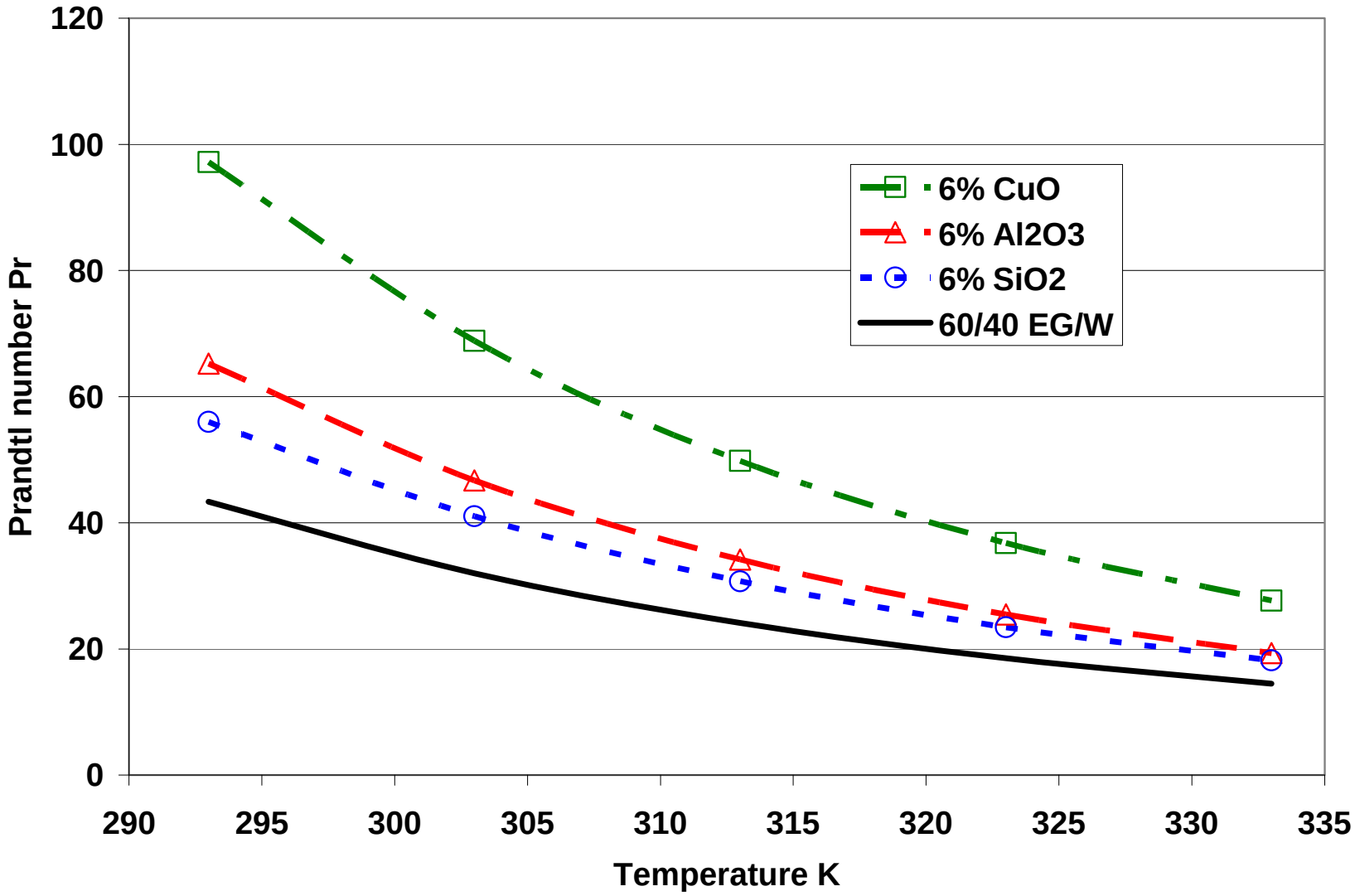
$$\rho_{nf} = \rho_p \phi + \rho_{bf}(1-\phi)$$

Source: Vajjha et al., 2009

Prandtl Number Vs Particle Concentration



Prandtl Number Vs Temperature



Micro Plate Heat Exchanger

Plate width, w (m)	0.073
Plate length, $L_{p\ (m)}$	0.278
Channel spacing, b (m)	0.0012
Thickness of plate, t (m)	0.0006
No. of channels for each fluid, $N_c + N_h$	10
Cheveron angle, β (degrees)	45
Corrugation pitch or wavelength, λ (m)	0.0006
Equivalent diameter, D_e =2b (m)	0.0024
Projected area per plate, A_p (m^2)	0.020294
Flow area on one fluid side of PHE, A_f (m^2)	0.000438
Surface area on one fluid side of PHE, A_h (m^2)	0.20294

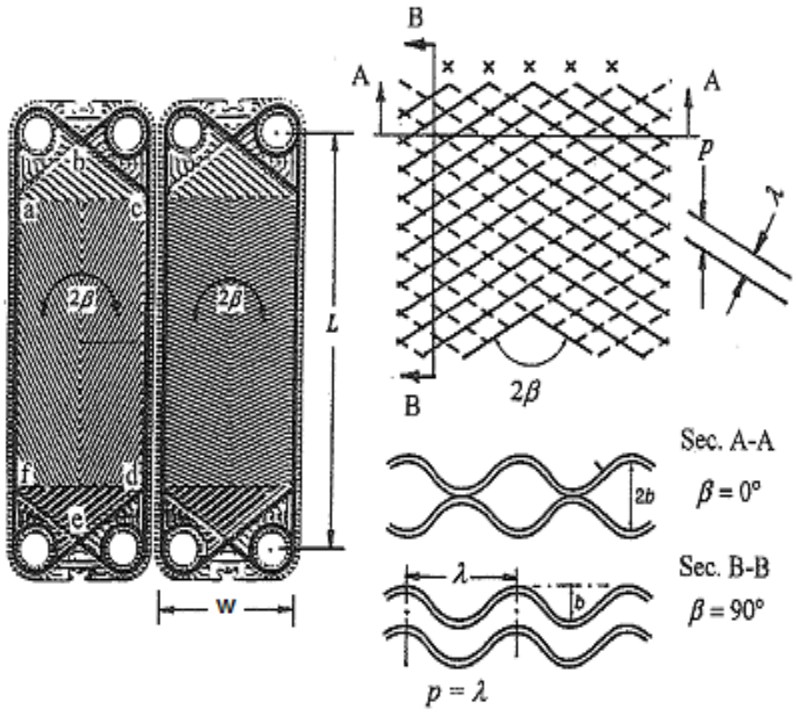


Figure Source: Wang et al., 2007

Equations for Plate Heat Exchangers

Nusselt number

$$Nu = C_1(\beta)\,\mathrm{Re}^{P_1(\beta)}\,\mathrm{Pr}^{1/3} \qquad \mathrm{Re} \geq 1000, 30\,\mathrm{deg} \leq \beta \leq 60\,\mathrm{deg}$$

$$C_1(\beta) = 0.2668 - 0.006967\beta + 7.244\times10^{-5}\beta^2$$

$$P_1(\beta) = 0.728 + 0.0543 Sin\left[\left(\pi\beta/45\right) + 3.7\right]$$

Friction factor

$$f = C_2(\beta)\,\mathrm{Re}^{-P_2(\beta)} \qquad \mathrm{Re} \geq 1000, 30\,\mathrm{deg} \leq \beta \leq 60\,\mathrm{deg}$$

$$C_2(\beta) = 2.917 - 0.1277\beta + 2.016\times10^{-3}\beta^2$$

$$P_2(\beta) = 0.2 + 0.0577 Sin\left[\left(\pi\beta/45\right) + 2.1\right]$$

Pressure loss

$$\Delta p = \frac{4fLG^2}{2\rho D_e}$$

Pumping power

$$\dot{W} = \Delta p \times \dot{V}$$

Source: Wang et al., 2007

Equations for Plate Heat Exchangers

Overall heat transfer coefficient

$$\frac{1}{U} = \frac{1}{h_c} + \frac{1}{h_h} + \frac{t}{k_p}$$

Effectiveness

$$\varepsilon = \frac{C_c\left(T_{c,o} - T_{c,i}\right)}{C_{\min}\left(T_{h,i} - T_{c,i}\right)} \quad ; \quad \varepsilon = \frac{1 - EXP\left[-\left(1 - C^*\right)NTU\right]}{1 - C^* EXP\left[-\left(1 - C^*\right)NTU\right]}$$

No. of transfer units

$$NTU = \frac{1}{\left(1 - C^*\right)} LN\left(\frac{1 - \varepsilon C^*}{1 - \varepsilon}\right) \quad ; \quad NTU = \frac{UA}{C_{\min}}$$

$$C^* = \frac{C_{\min}}{C_{\max}}$$

Heat transfer rate

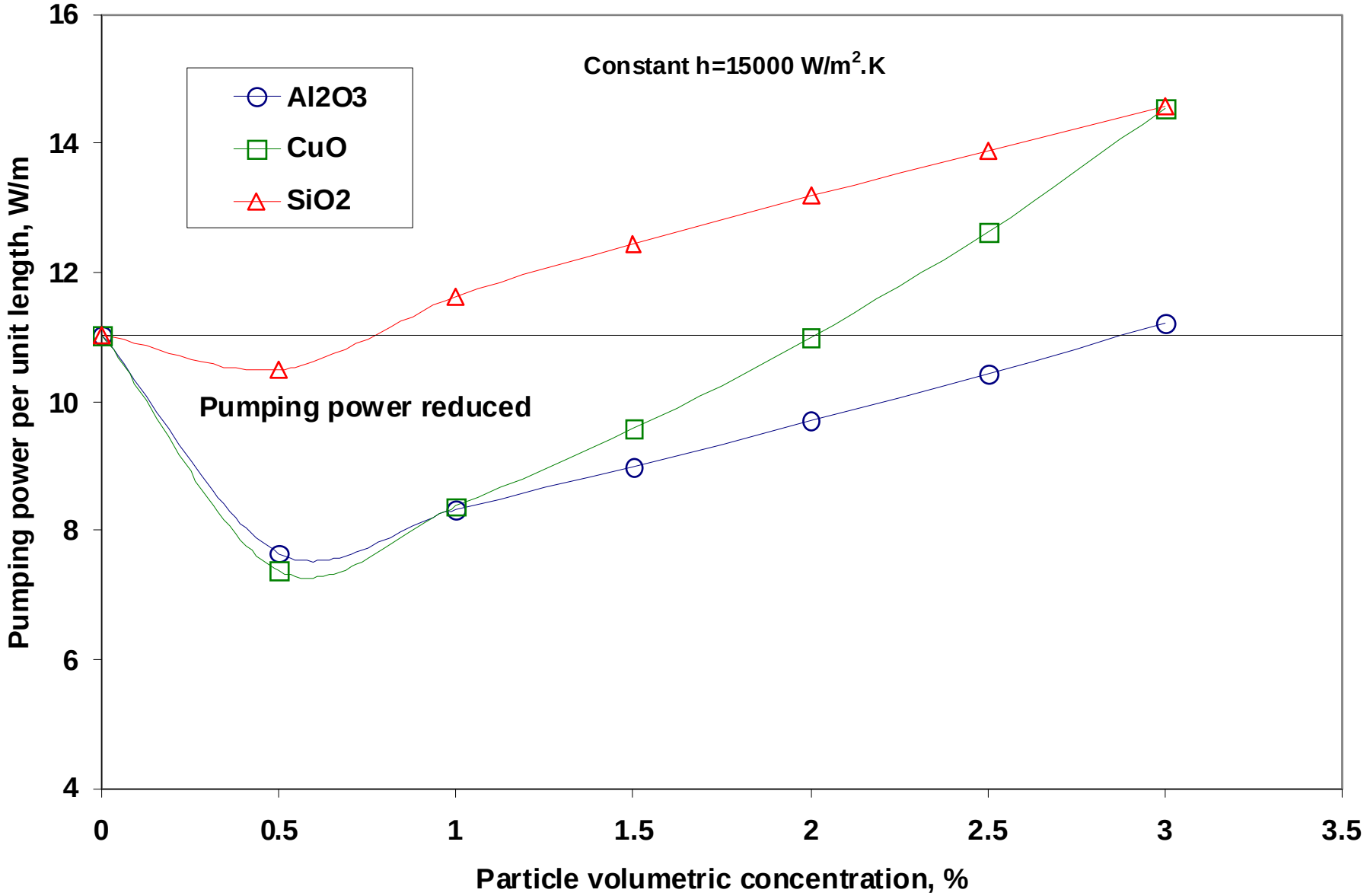
$$Q = \varepsilon C_{\min}\left(T_{h,i} - T_{c,i}\right)$$

Source: Wang et al., 2007

For Constant Heat Transfer Coefficient

Type of Fluid Parameters	0% Water	0.5% Aluminum Oxide	0.5% Copper Oxide	0.5% Silicon Dioxide
Heat Transfer Coefficient ($W/m^2.K$)	15000	15000	15000	15000
Density (kg/m3)	971.873	985.014	999.514	978.114
Specific Heat (J/kgK)	4231.541	4168.194	4111.280	4191.974
Viscosity (mPa.s)	0.000364	0.000381	0.000375	0.000409
Thermal conductivity (W/m K)	0.66715	0.79545	0.79407	0.73838
Prandtl number (Pr)	2.306	1.998	1.941	2.322
Nusselt number (Nu)	53.961	45.258	45.336	48.756
Reynolds Number (Re)	2810	2372	2408	2450
Velocity (m/s)	0.438	0.383	0.376	0.427
Mass Flow Rate (kg/s)	0.186	0.165	0.165	0.183
Reduction in Mass Flow Rate (%)	……	**11.454**	**11.629**	**1.914**
Volumetric Flow Rate (m^3/s)	0.00019	0.00017	0.00016	0.00019
Reduction in Volumetric Flow Rate (%)	……	**12.635**	**14.072**	**2.540**
Mass velocity ($kg/m^2.s$)	425.675	376.919	376.175	417.527
friction factor, f	0.37030	0.37984	0.37897	0.37800
Pressure Loss per Unit Length(kPa/m)	57.533	45.653	44.712	56.143
Pumping Power per Unit Length(W/m)	**11.037**	**7.652**	**7.370**	**10.497**
Reduction in Pumping Power (%)	…….	**30.675**	**33.222**	**4.895**

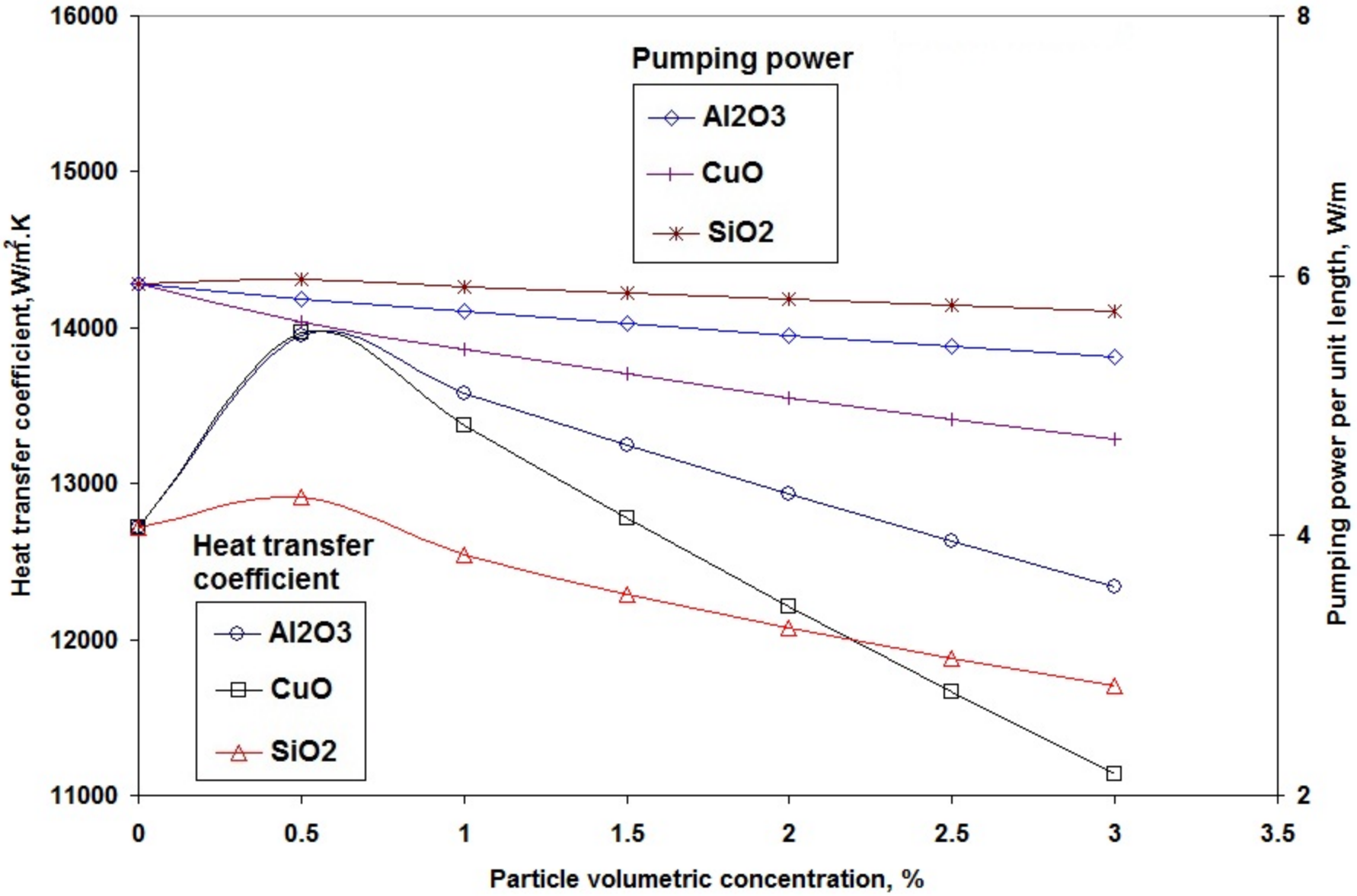
For Constant Heat Transfer Coefficient



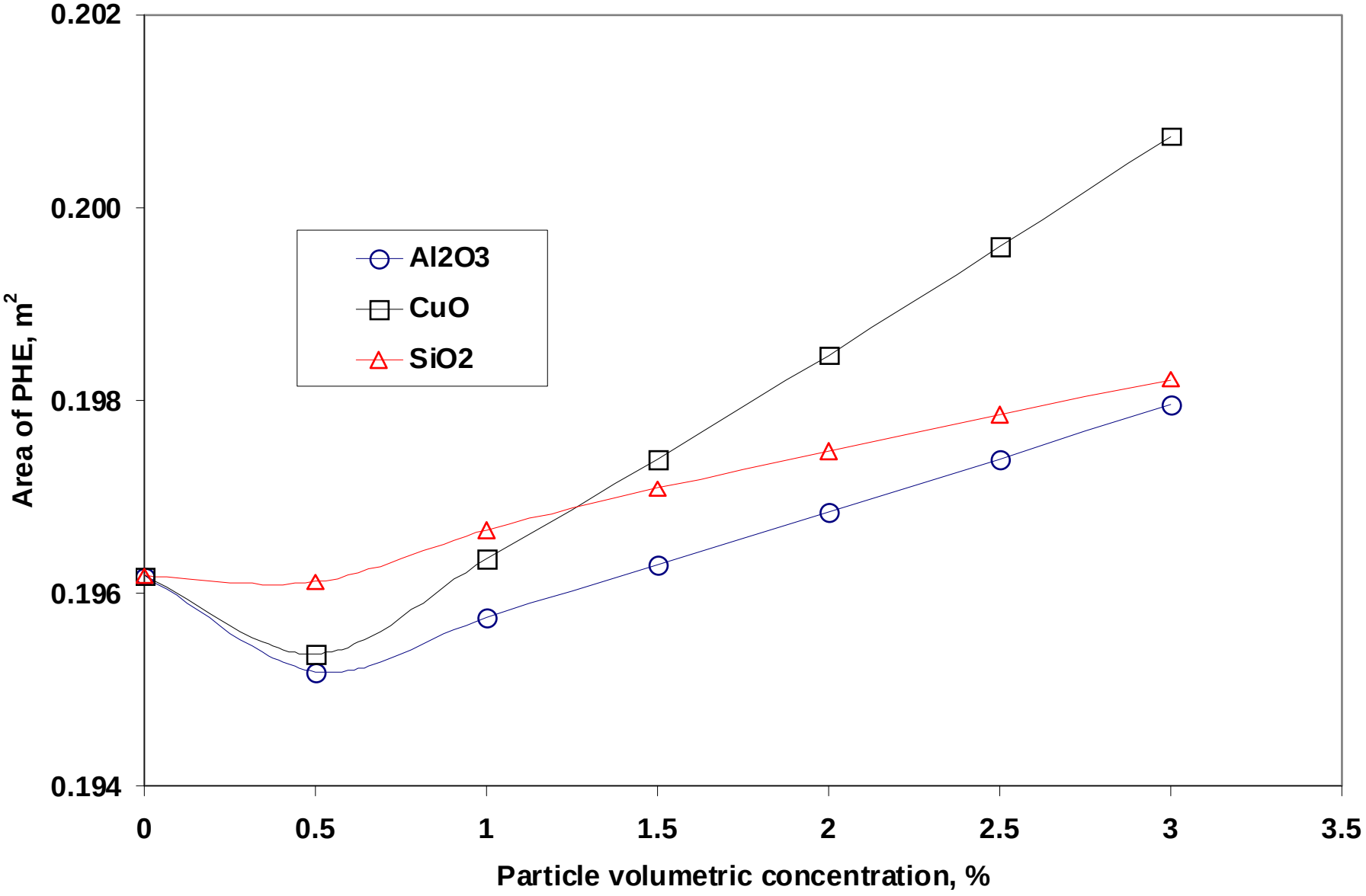
For Constant Mass Flow Rate

Type of Fluid Parameters	0% Water	0.5% Aluminum Oxide	0.5% Copper Oxide	0.5% Silicon Dioxide
Mass Flow Rate (kg/s)	**0.15**	**0.15**	**0.15**	**0.15**
Density (kg/m3)	971.873	985.014	999.514	978.114
Specific Heat (J/kgK)	4231.541	4168.194	4111.280	4191.974
Viscosity (mPa.s)	0.000364	0.000381	0.000375	0.000409
Thermal conductivity (W/m K)	0.66715	0.79545	0.79407	0.73838
Prandtl number (Pr)	2.306	1.998	1.941	2.322
Mass velocity (kg/m^2.s)	342.466	342.466	342.466	342.466
Reynolds number	2261	2155	2193	2009
Velocity (m/s)	0.352	0.348	0.343	0.350
Nusselt number (Nu)	45.772	42.091	42.227	41.965
Heat transfer coefficient (W/m2.K)	**12723.487**	**13950.390**	**13971.270**	**12910.941**
Increase in Heat transfer coefficient (%)	……	**9.643**	**9.807**	**1.473**
Volumetric Flow Rate (m^3/s)	0.00015	0.00015	0.00015	0.00015
Reduction in Volumetric Flow Rate (%)	……	**1.334**	**2.765**	**0.638**
friction factor, f	0.38260	0.38534	0.38436	0.38942
Pressure Loss per Unit Length(kPa/m)	38.475	38.235	37.584	38.912
Pumping Power per Unit Length(W/m)	5.938	5.822	5.640	5.967
Reduction in Pumping Power (%)	…….	**1.951**	**5.019**	**-0.490**
Overall heat transfer coefficient (W/m2.K)	894.278	899.841	899.928	895.192
C* (Cmin/Cmax)	0.108	0.109	0.111	0.109
Effectiveness	0.908	0.908	0.908	0.908
NTU	2.564	2.567	2.570	2.566
Area of PHE (m2)	**0.196**	**0.195**	**0.195**	**0.196**

For Constant Mass Flow Rate



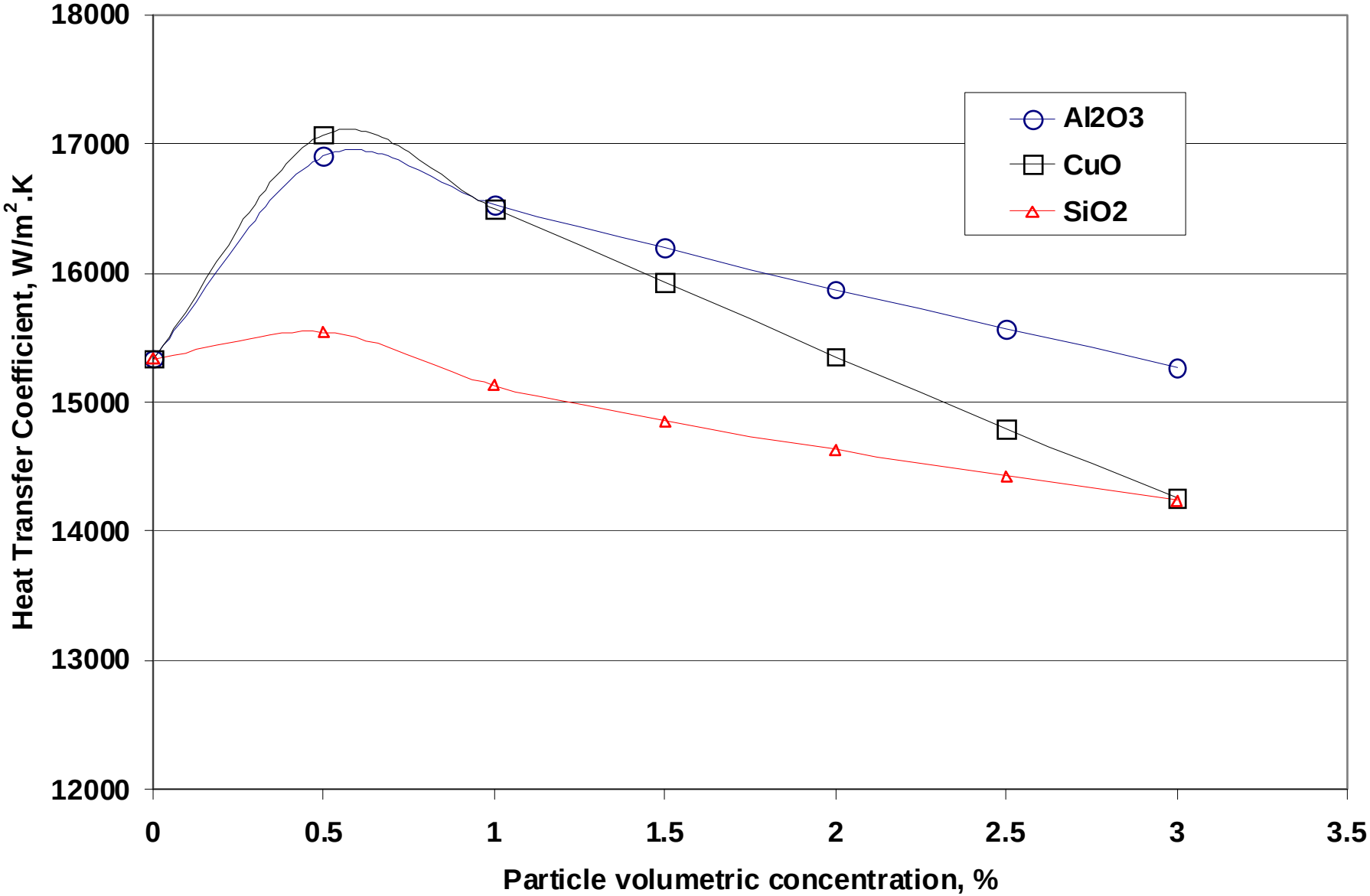
For Constant Mass Flow Rate



For Constant Pumping Power

Type of Fluid Parameters	0% Water	0.5% Aluminum Oxide	0.5% Copper Oxide	0.5% Silicon Dioxide
Pumping Power per Unit Length(W/m)	12	12	12	12
Density (kg/m3)	971.873	985.014	999.514	978.114
Specific Heat (J/kgK)	4231.541	4168.194	4111.280	4191.974
Viscosity (Pa.s)	0.000364	0.000381	0.000375	0.000409
Thermal conductivity (W/m K)	0.66715	0.79545	0.79407	0.73838
Prandtl number (Pr)	2.306	1.998	1.941	2.322
Mass velocity (kg/m2.s)	438.352	441.393	446.345	437.601
Mass Flow Rate (kg/s)	0.192	0.193	0.195	0.192
Volumetric Flow Rate (m^3/s)	0.00020	0.00020	0.00020	0.00020
Reynolds Number (Re)	2893	2778	2858	2568
Velocity (m/s)	0.451	0.448	0.447	0.447
Nusselt number (Nu)	55.173	51.002	51.601	50.519
Heat transfer coefficient (W/m2.K)	**15336.853**	**16903.976**	**17072.811**	**15542.620**
Increase in Heat transfer coefficient (%)		**10.218**	**11.319**	**1.342**
friction factor, f	0.36867	0.37093	0.36936	0.37535
Overall heat transfer coefficient (W/m2.k)	1069.420	1076.378	1077.056	1070.408
C_h (J/s.K)	812.448	805.838	803.752	803.472
C_c (J/s.K)	87.578	87.578	87.578	87.578
C* (Cmin/Cmax)	0.108	0.109	0.109	0.109
Effectiveness	0.908	0.908	0.908	0.908
NTU	2.564	2.566	2.566	2.566
Area of PHE (m2)	**0.210**	**0.209**	**0.209**	**0.210**
Q (kW)	4.448	4.479	4.529	4.440

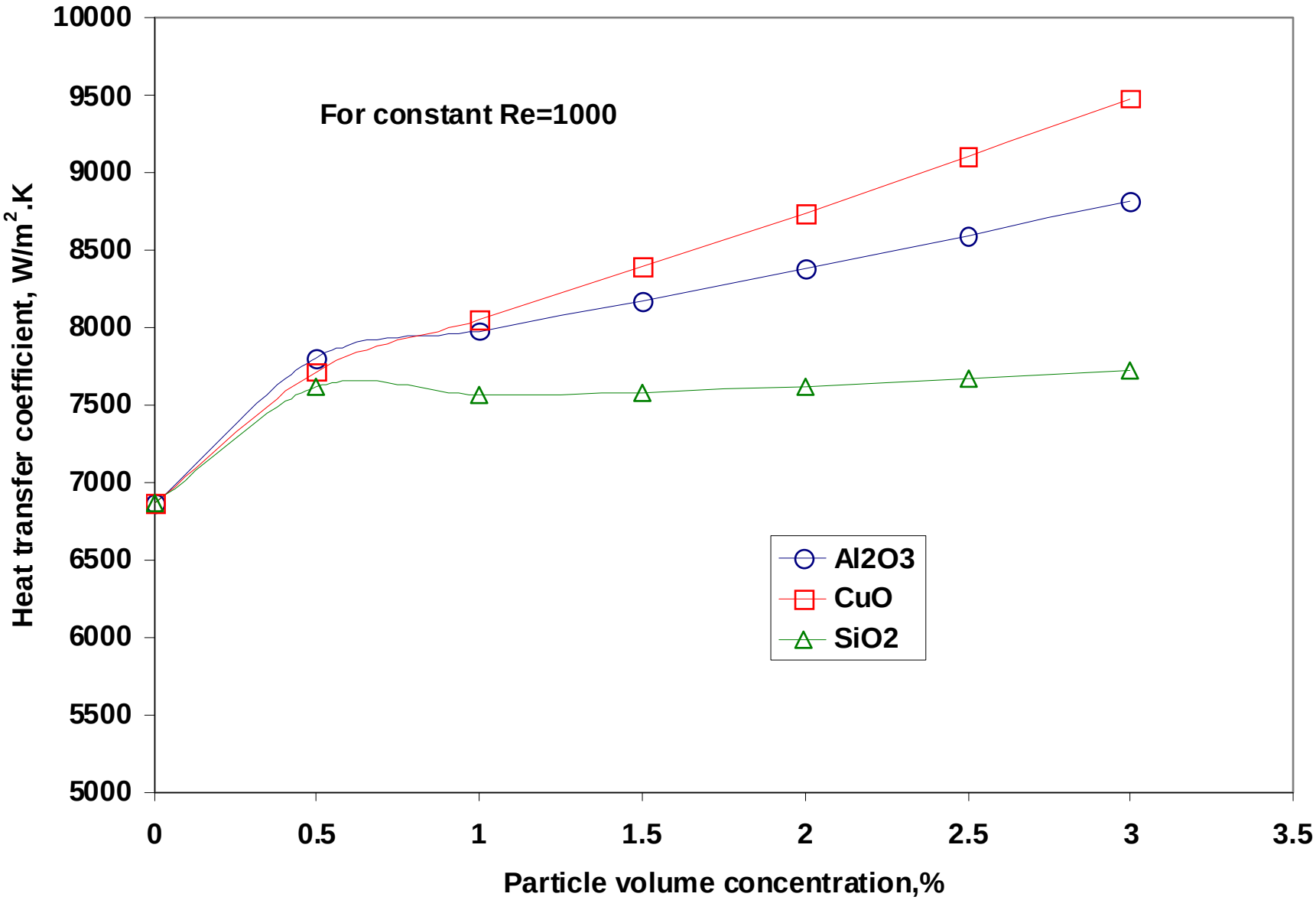
For Constant Pumping Power



For Constant Reynolds Number

Type of Fluid Parameters	0% Water	2.0% Aluminum Oxide	2.0% Copper Oxide	2.0% Silicon Dioxide
Reynolds Number (Re)	1000	1000	1000	1000
Density (kg/m3)	971.873	1024.436	1082.436	996.836
Specific Heat (J/kgK)	4231.541	3987.904	3787.348	4076.247
Viscosity (mPa.s)	0.000364	0.000463	0.000528	0.000447
Thermal conductivity (W/m K)	0.66715	0.82103	0.84035	0.71668
Prandtl number (Pr)	2.306	2.250	2.380	2.544
Nusselt number (Nu)	24.691	24.487	24.953	25.511
Heat transfer coefficient (W/m2.K)	**6863.495**	**8377.056**	**8737.130**	**7618.123**
Increase in Heat transfer coefficient (%)	…..	**22.052**	**27.299**	**10.995**
Mass velocity (kg/m^2.s)	151.496	192.981	220.066	186.354
Mass Flow Rate (kg/s)	0.438	0.438	0.438	0.438
Volumetric Flow Rate (m^3/s)	0.00045	0.00043	0.00040	0.00044
Reduction in Volumetric Flow Rate (%)	……	**5.131**	**10.214**	**2.504**
Overall heat transfer coefficient (W/m2.K)	1582.521	1651.314	1664.839	1619.510
C_h (J/s.K)	1853.415	1746.702	1658.858	1785.396
C_c (J/s.K)	199.790	199.790	199.790	199.790
C* (Cmin/Cmax)	0.108	0.114	0.120	0.112
NTU	1.607	1.677	1.691	1.645
Effectiveness	0.782	0.794	0.796	0.788
Q_{PHE} (kW)	**8.804**	**8.944**	**8.961**	**8.880**

For Constant Reynolds Number



For Constant Velocity

Type of Fluid Parameters	0% Water	0.5% Aluminum Oxide	0.5% Copper Oxide	0.5% Silicon Dioxide
Velocity (m/s)	**0.2**	**0.2**	**0.2**	**0.2**
Density (kg/m3)	971.873	985.014	999.514	978.114
Specific Heat (J/kgK)	4231.541	4168.194	4111.280	4191.974
Viscosity (mPa.s)	0.000364	0.000381	0.000375	0.000409
Thermal conductivity (W/m K)	0.66715	0.79545	0.79407	0.73838
Prandtl number (Pr)	2.306	1.998	1.941	2.322
Mass velocity ($kg/m^2.s$)	194.375	197.003	199.903	195.623
Mass flow rate (kg/s)	0.085	0.086	0.088	0.086
Reynolds number	1283	1240	1280	1148
Nusselt number (Nu)	29.816	27.698	28.097	27.469
Heat transfer coefficient (W/m2.K)	**8288.153**	**9180.197**	**9296.177**	**8451.099**
Increase in Heat transfer coefficient (%)	……	**10.763**	**12.162**	**1.966**
Volumetric Flow Rate (m^3/s)	0.00009	0.00009	0.00009	0.00009
friction factor, f	0.41657	0.41871	0.41672	0.42359
Pressure Loss per Unit Length(kPa/m)	13.495	13.748	13.884	13.811
Pumping Power per Unit Length(W/m)	**1.182**	**1.204**	**1.216**	**1.210**
Overall heat transfer coefficient (W/m2.K)	1035.848	1048.583	1050.079	1038.350
C_h (J/s.K)	846.308	833.639	822.256	838.395
C_c (J/s.K)	91.228	91.228	91.228	91.228
C* (Cmin/Cmax)	0.108	0.109	0.111	0.109
Effectiveness	0.908	0.908	0.908	0.908
NTU	2.564	2.567	2.570	2.566
Area of PHE (m2)	**0.226**	**0.223**	**0.223**	**0.225**
Reduction in area of PHE (%)	….	**1.104**	**1.143**	**0.172**
Q (kW)	**1.972**	**1.999**	**2.028**	**1.985**

Conclusions

- The CuO nanofluid showed the highest heat transfer coefficient and highest pressure loss followed by the Al_2O_3 nanofluid.

- For constant h basis, both Al_2O_3 and CuO showed better performance. Recommend low volumetric concentration of less than 2%. Results in reduction in fluid volume flow rate up to 11%, mass flow rate up to 8% and pumping power up to 24% was observed for 1% concentration.

- For constant mass flow rate basis, both Al_2O_3 and CuO showed an increase in heat transfer coefficient of about 9% compared to base fluid at 0.5% concentration.

- For constant Reynolds number, heat transfer coefficient and volumetric flow rate increases with an increase in particle volume concentration.

- Since the thermophysical properties of nanofluids are functions of temperature and concentration, they must be determined accurately. The performance of nanofluids strongly depends on them.

- Use of nanofluids will reduce volume of fluid, size of heat exchanger, weight and pumping power in heat transfer systems and is therefore attractive for applications in space systems.

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