Comparison of Surface Area and Pumping Power Requirements in Heat Exchangers Using Nanofluids and Base Fluids Suitable for NASA Applications

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Thermal & Fluids Analysis Workshop
TFAWS 2011
August 15-19, 2011
NASA Langley Research Center
Newport News, VA

Topics of Discussion

- What are Nanofluids
- Advantages of Nanofluids
- Thermophysical Properties of Nanofluids
- Effect on the Prandtl Number
- Heat Transfer and Fluid Dynamic Characteristics of nanofluids Via Nusselt Number and Friction Factor
- Pumping Power and Surface Area Comparisons of Nanofluids in Heat Exchangers
- Acknowledgements

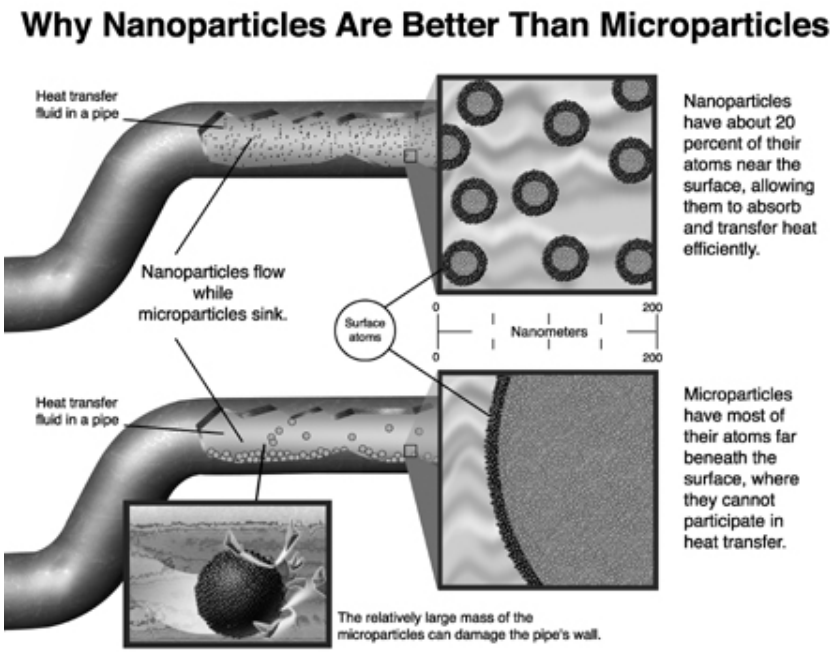
What are Nanofluids?

- The concept was proposed by Choi (1999), Argonne National Lab
- Dispersion of metallic nanometer sized particles (<100nm) in liquid

Significance of Nanoparticles

•Microparticles settle at the bottom due to gravity, leading to clogging and wear

•Nanoparticles are permanently suspended by Brownian motion and when there is no flow they are distributed in balance between buoyant weight and thermal agitation.

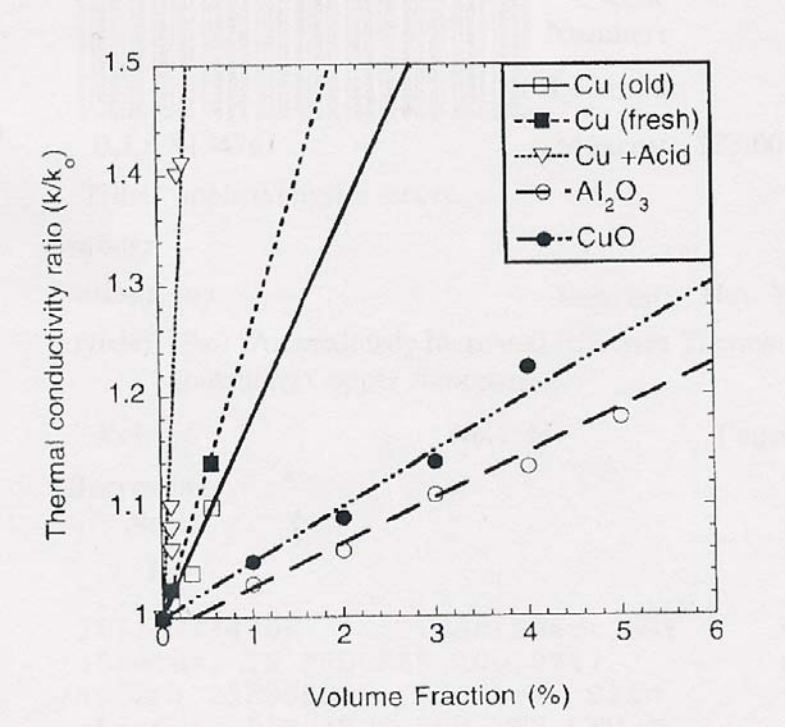


Source: Boutin, C., 2001

Advantages of Nanofluid

Dramatic Increase in thermal conductivity of base liquid

Material	Thermal conductivity (W/mK)	Material	Thermal Conductivity (W/mK)
Nonmetallic Liquid		Metallic Solids	
Water	0.613	Silver	429
Engine Oil	0.145	Copper	401
Ethylene Glycol	0.253	Aluminum	237



Source: Eastman, 2001

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 $$Nu_{nf} = 0.0059(1.0 + 7.6286\phi^{0.6886} Pe_d^{0.001})\,\mathrm{Re}_{nf}^{0.9238}\,\mathrm{Pr}_{nf}^{0.4}$$

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

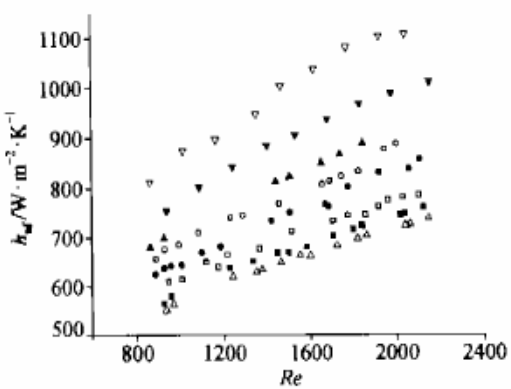


Fig. 3. The convective heat transfer coefficient of nanofluids for the laminar flow. △, Water (experimental values); ■, 0.3 vol%; □, 0.5 vol%; ●, 0.8 vol%; ○, 1.0 vol%; ▲, 1.2 vol%; ▼, 1.5 vol%; ▽, 2.0 vol%.

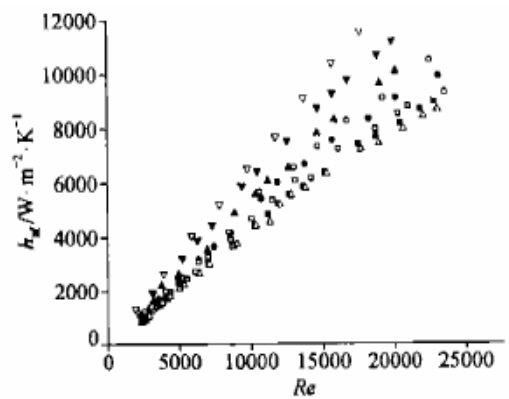


Fig. 4. The convective heat transfer coefficient of nanofluids for the turbulent flow. △, Water (experimental values); ■, 0.3 vol%; □, 0.5 vol%; ●, 0.8 vol%; ○, 1.0 vol%;, 1.2 vol%; ▼, 1.5 vol%; ▽, 2.0 vol%.

Source: Xuan & Li, 2003

Base Fluid (60:40 EG/W) Properties Correlations

Density: $\rho_{bf} = -0.0024T^2 + 0.963T + 1009.8$

Viscosity: $\mu_{bf} = A_4 e^{(\frac{B_4}{T})}$ where; $A_4 = 0.555 \times 10^{-3}$ and $B_4 = 2664$

Thermal Conductivity: $K_{bf} = -3 \times 10^{-6} T^2 + 0.0025T - 0.1057$

Specific Heat: $C_{pbf} = 4.2483T + 1882.4$

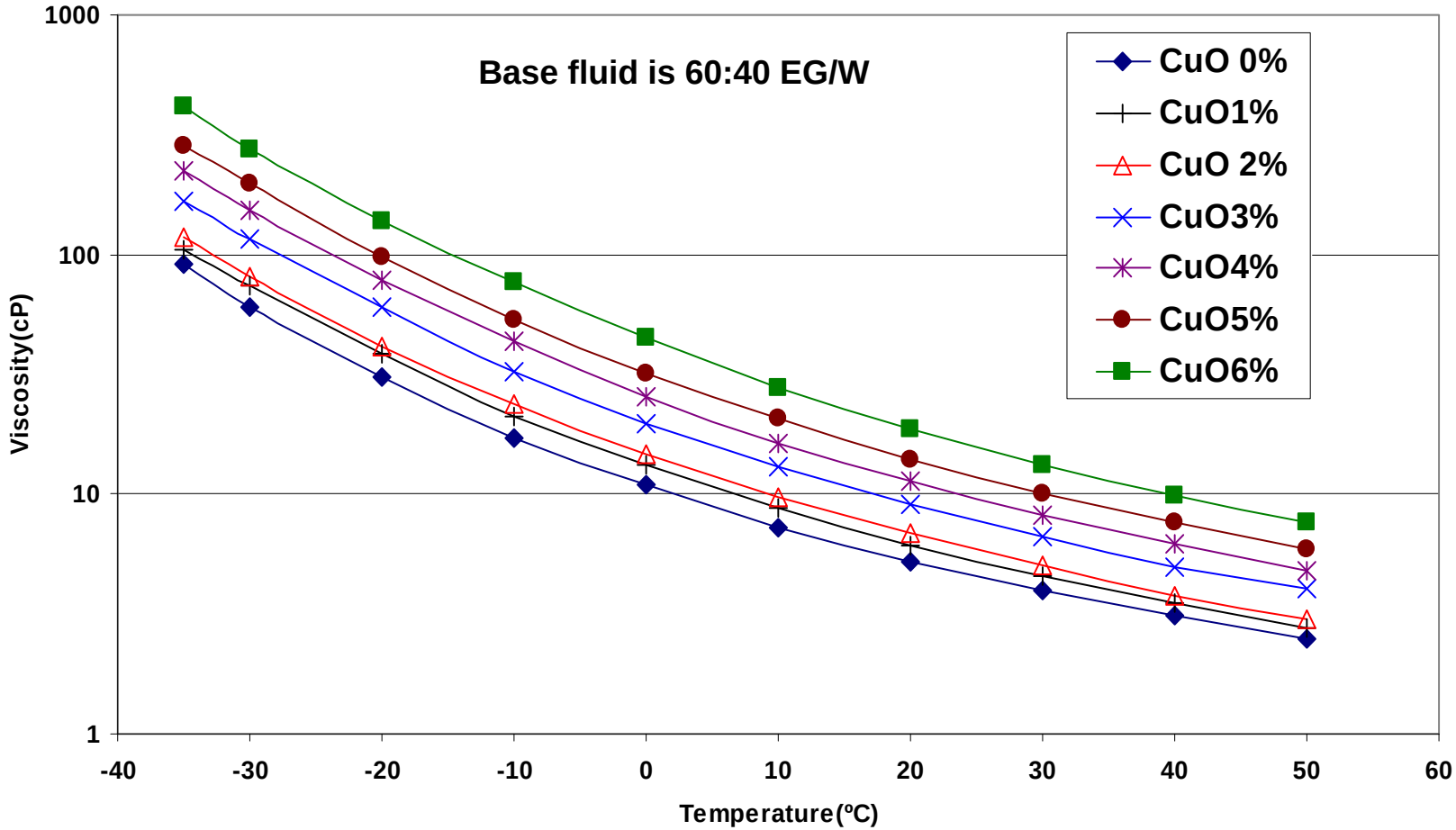
Source: Vajjha et al., 2010 from ASHRAE data

Nusselt Number : $Nu = 0.012(\mathrm{Re}^{0.87} - 280)\,\mathrm{Pr}^{0.4}$ where; $1.5 \le \mathrm{Pr} \le 500$,

$3000 \le \mathrm{Re} \le 10^6$ Gnielinski equation

Friction Factor : $f = 0.3164\,\mathrm{Re}^{-0.25}$ $4000 < \mathrm{Re} < 10^5$ Blasius equation

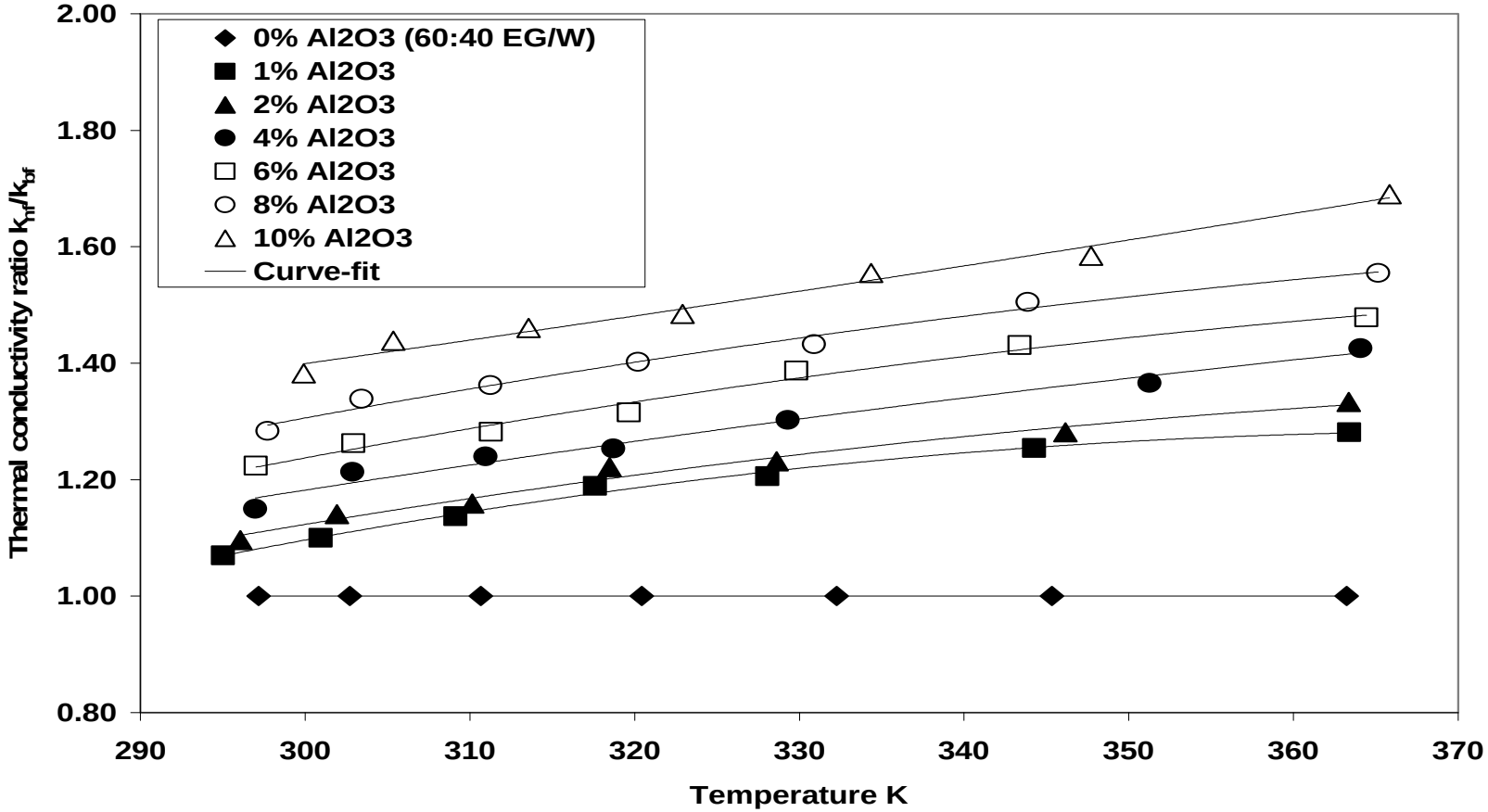
Viscosity Vs Temperature



$$\frac{\mu_{nf}}{\mu_{bf}} = A_1 e^{(A_2 \phi)}$$

Figure Source: Namburu et al., 2007
Eqn. Source: Vajjha et al., 2010

Thermal Conductivity Vs Temperature

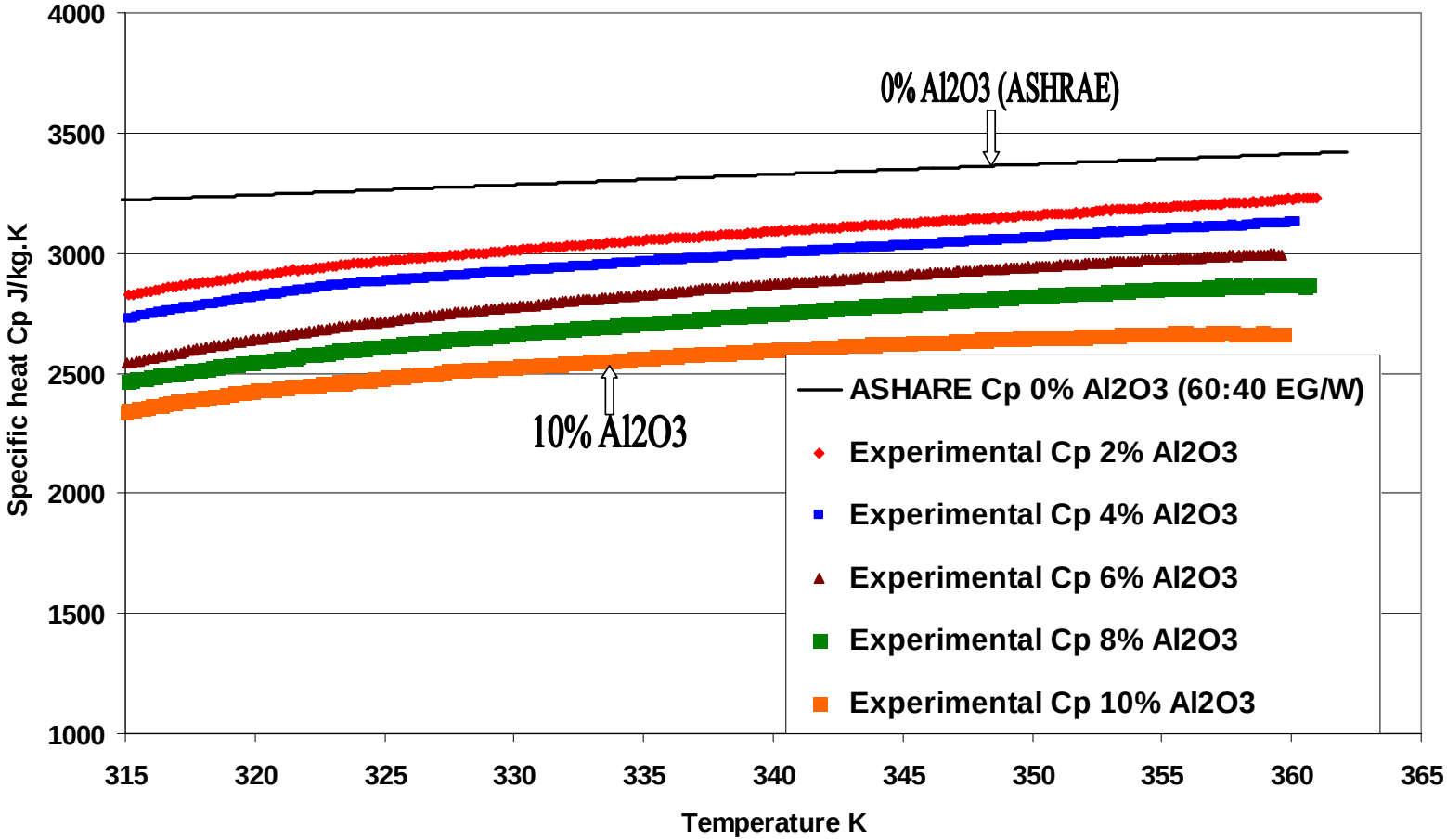


$$k_{nf} = \frac{k_p + 2k_{bf} - 2(k_{bf} - k_p)\phi}{k_p + 2k_{bf} + (k_{bf} - k_p)\phi} k_{bf} + 5\times10^4 \beta\phi\rho_{bf} C_{pbf} \sqrt{\frac{\kappa T}{\rho_p d_p}} f(T,\phi) \;;\; \beta = 8.4407(100\phi)^{-1.07304}$$

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

Source: Vajjha & Das, 2009

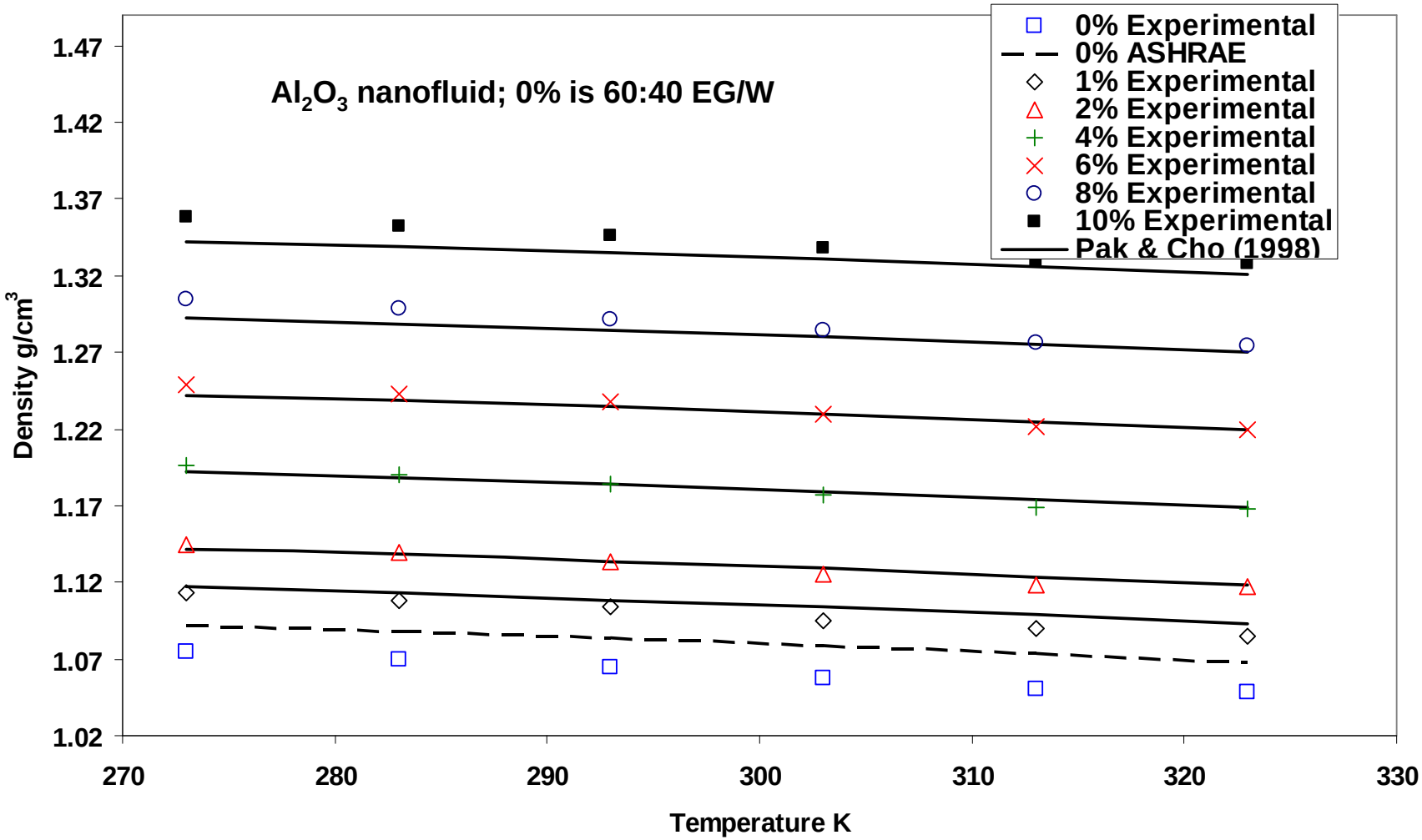
Specific Heat Vs Temperature



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

Source: Vajjha & Das, 2009

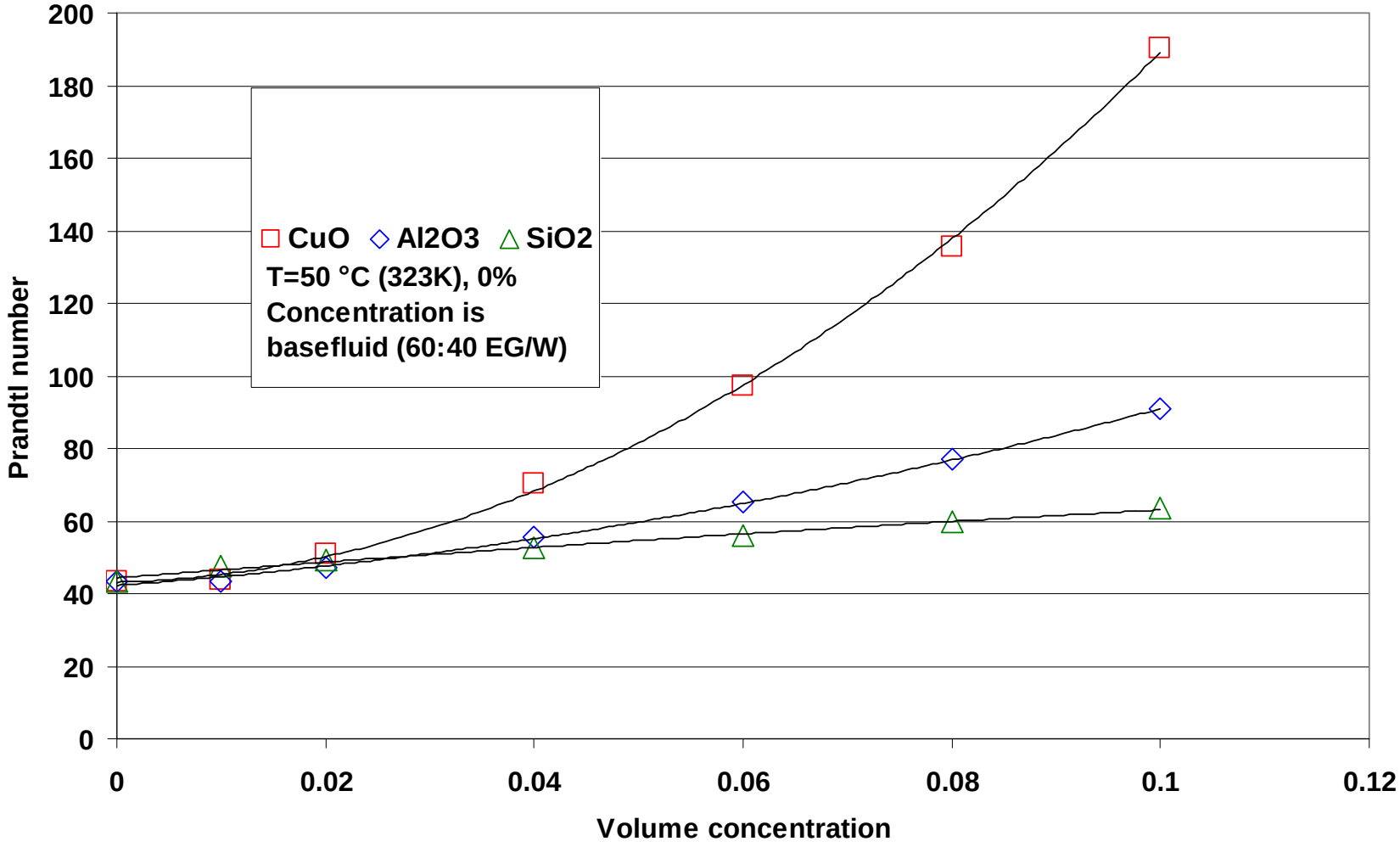
Density Vs Temperature



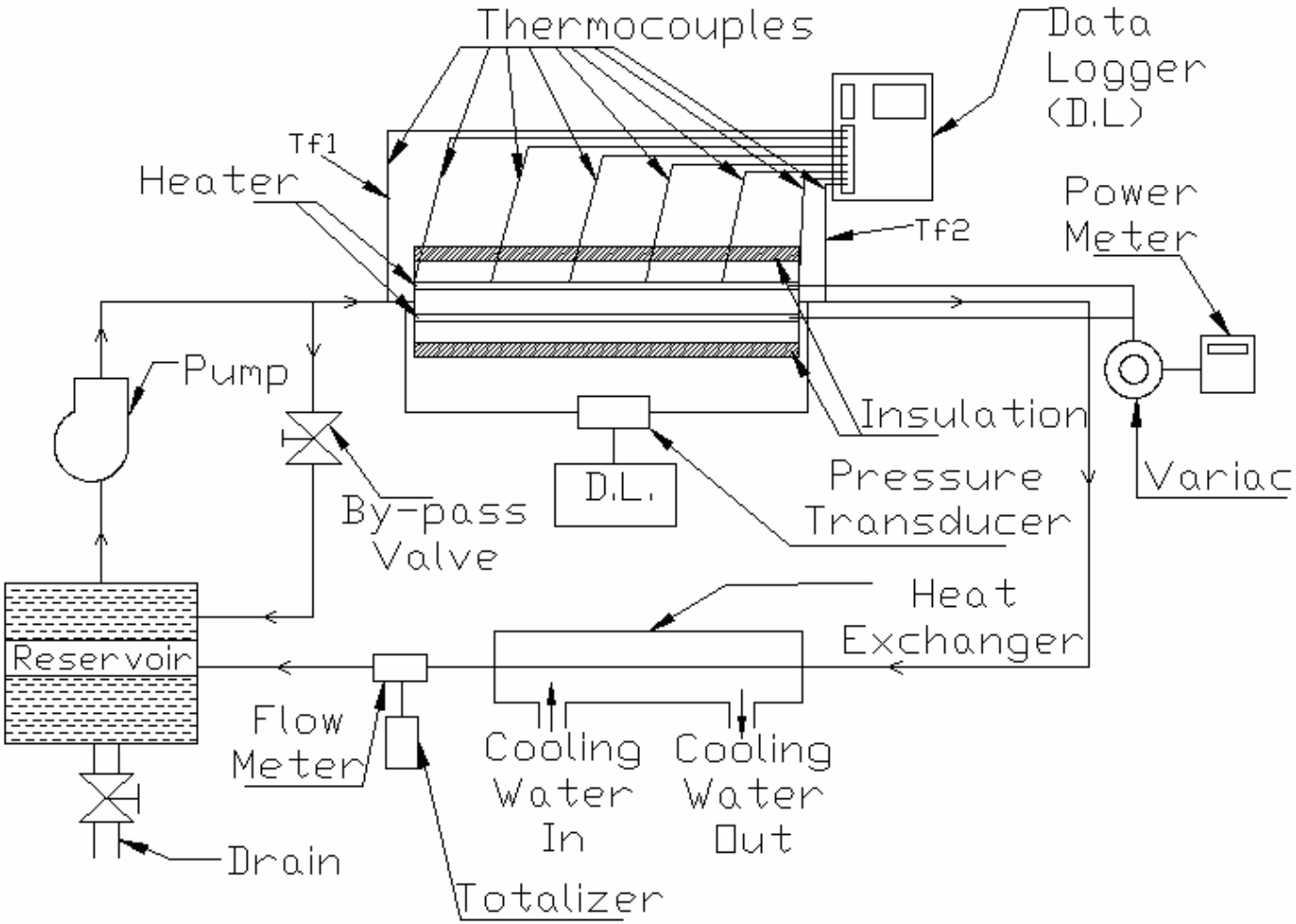
$$\rho_{nf} = \rho_p \phi + \rho_{bf}(1-\phi)$$

Fig. Source: Vajjha et al., 2009

Prandtl Number Vs Particle Concentration

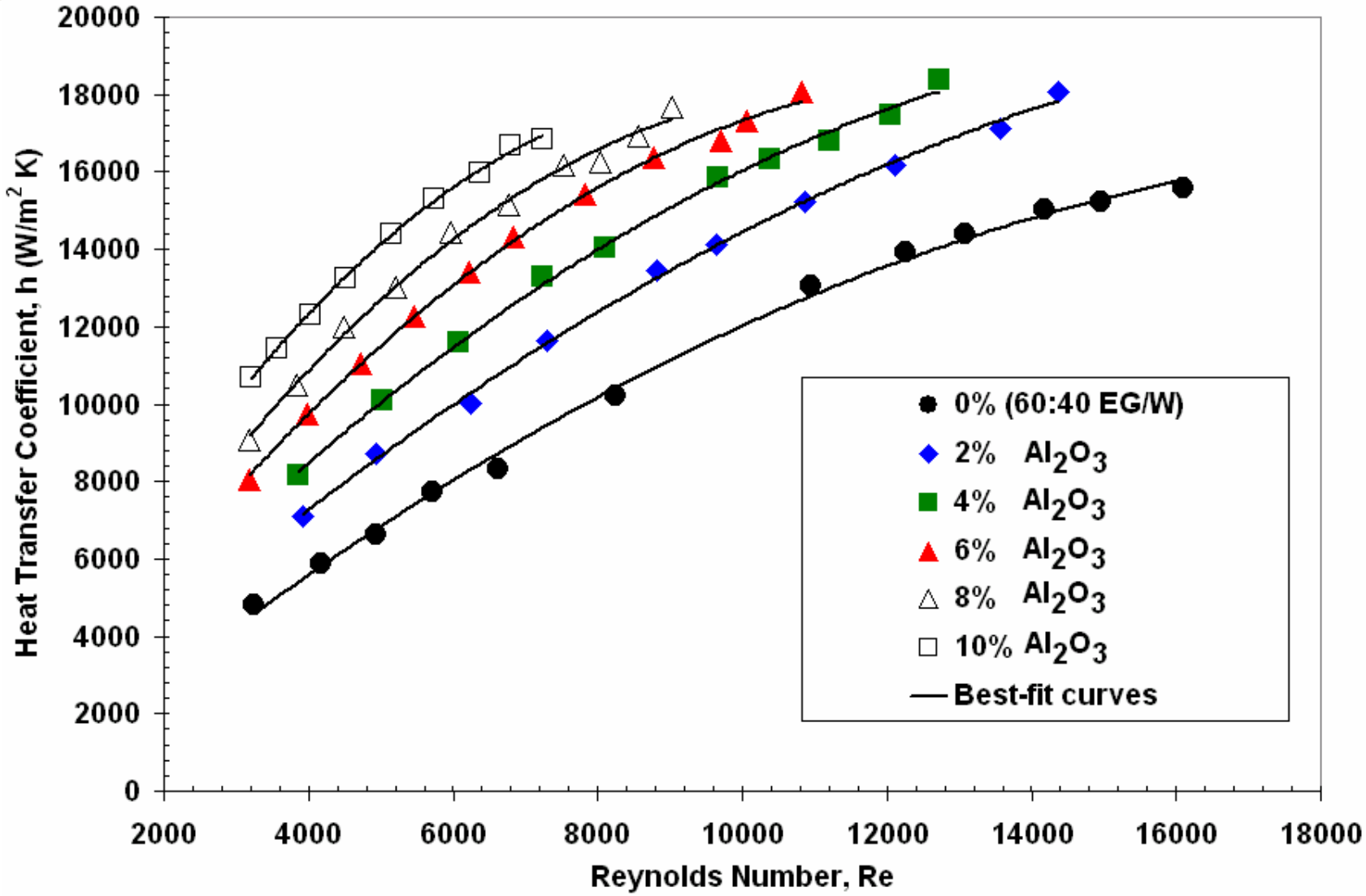


Experimental Setup



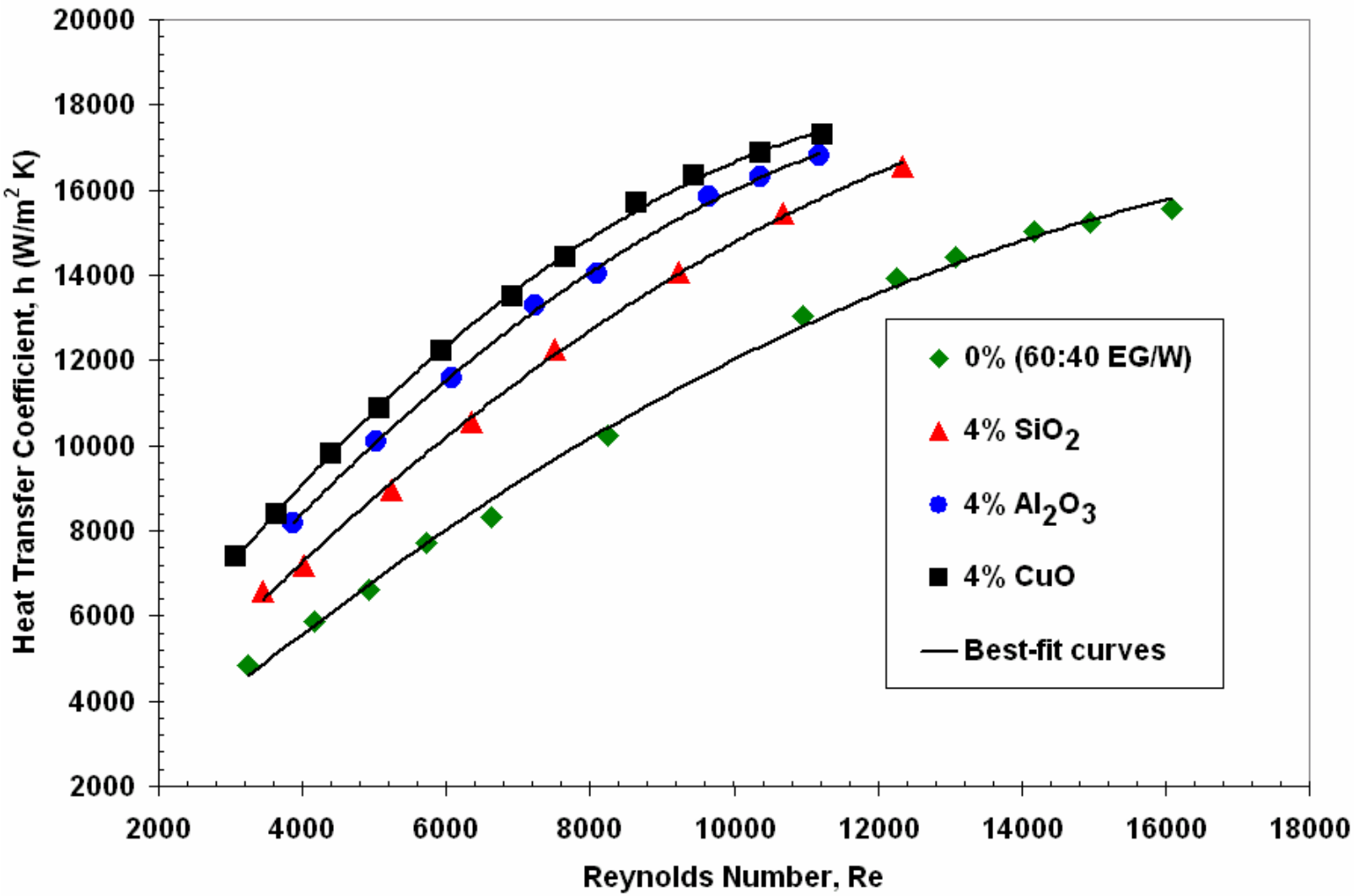
Source: Vajjha et al., 2010

Heat Transfer Coefficient Vs Reynolds Number



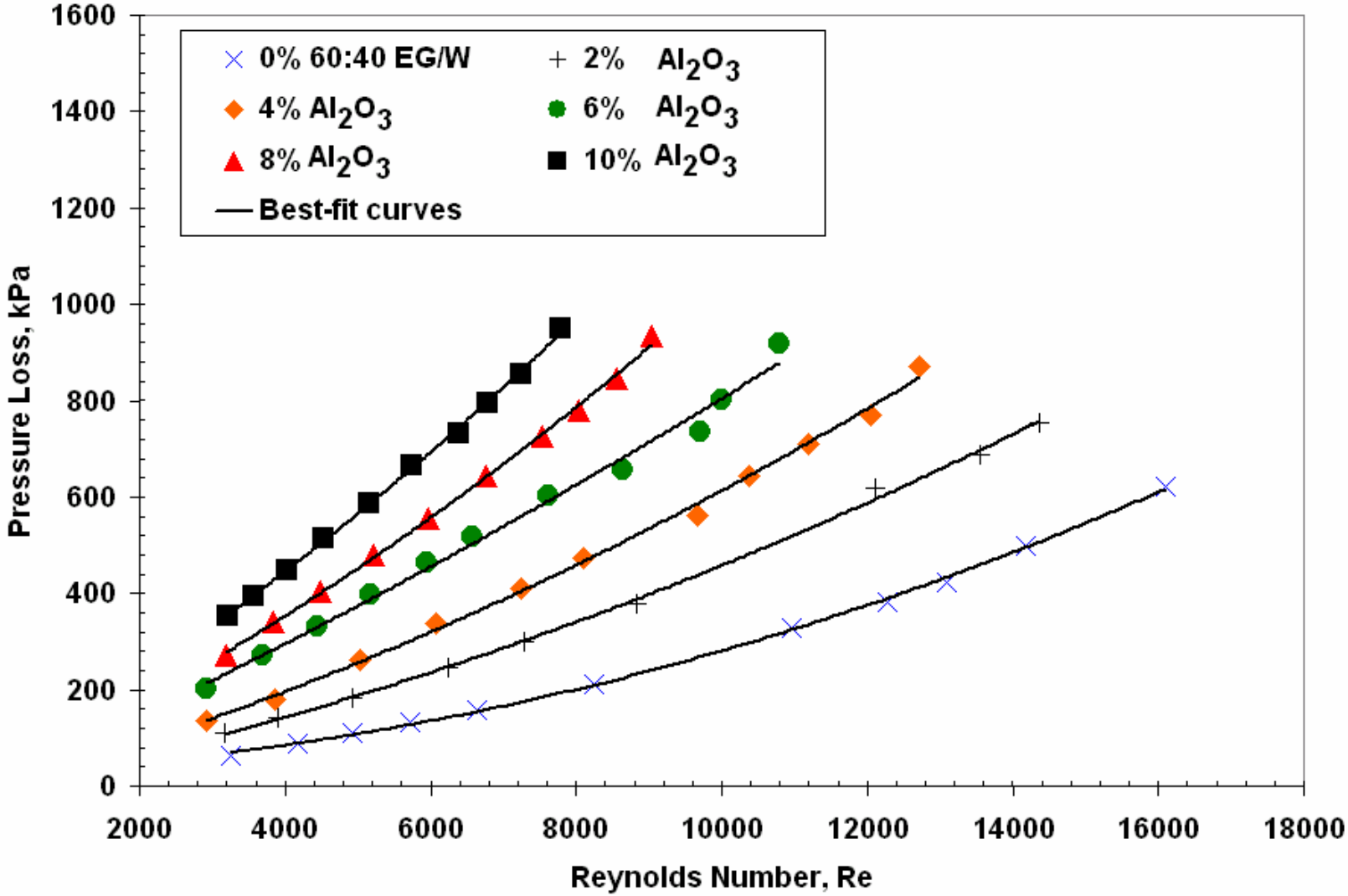
Source: Vajjha et al., 2010

Heat Transfer Coefficient Enhancement



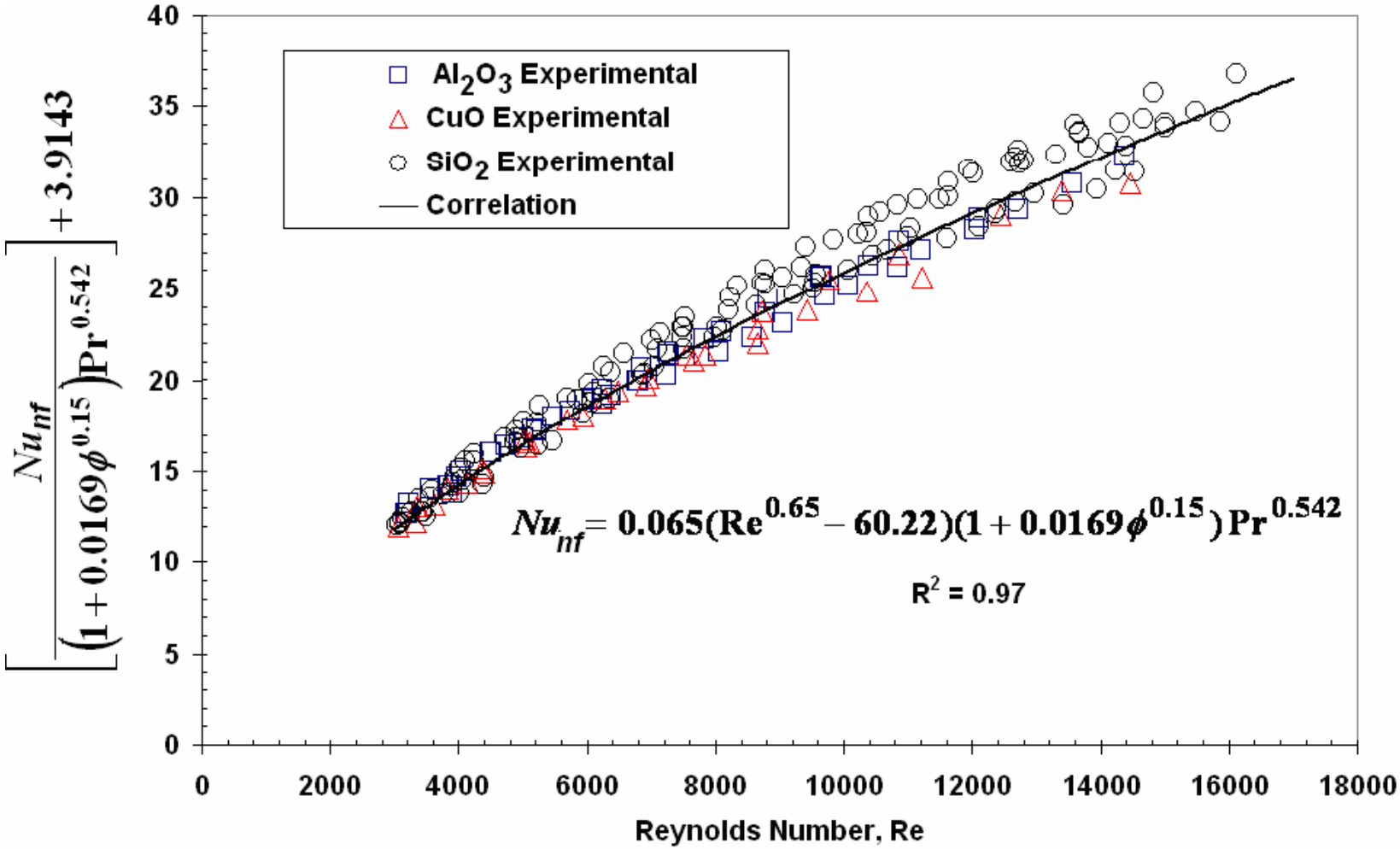
Source: Vajjha et al., 2010

Pressure Loss at Different Reynolds Number



Source: Vajjha et al., 2010

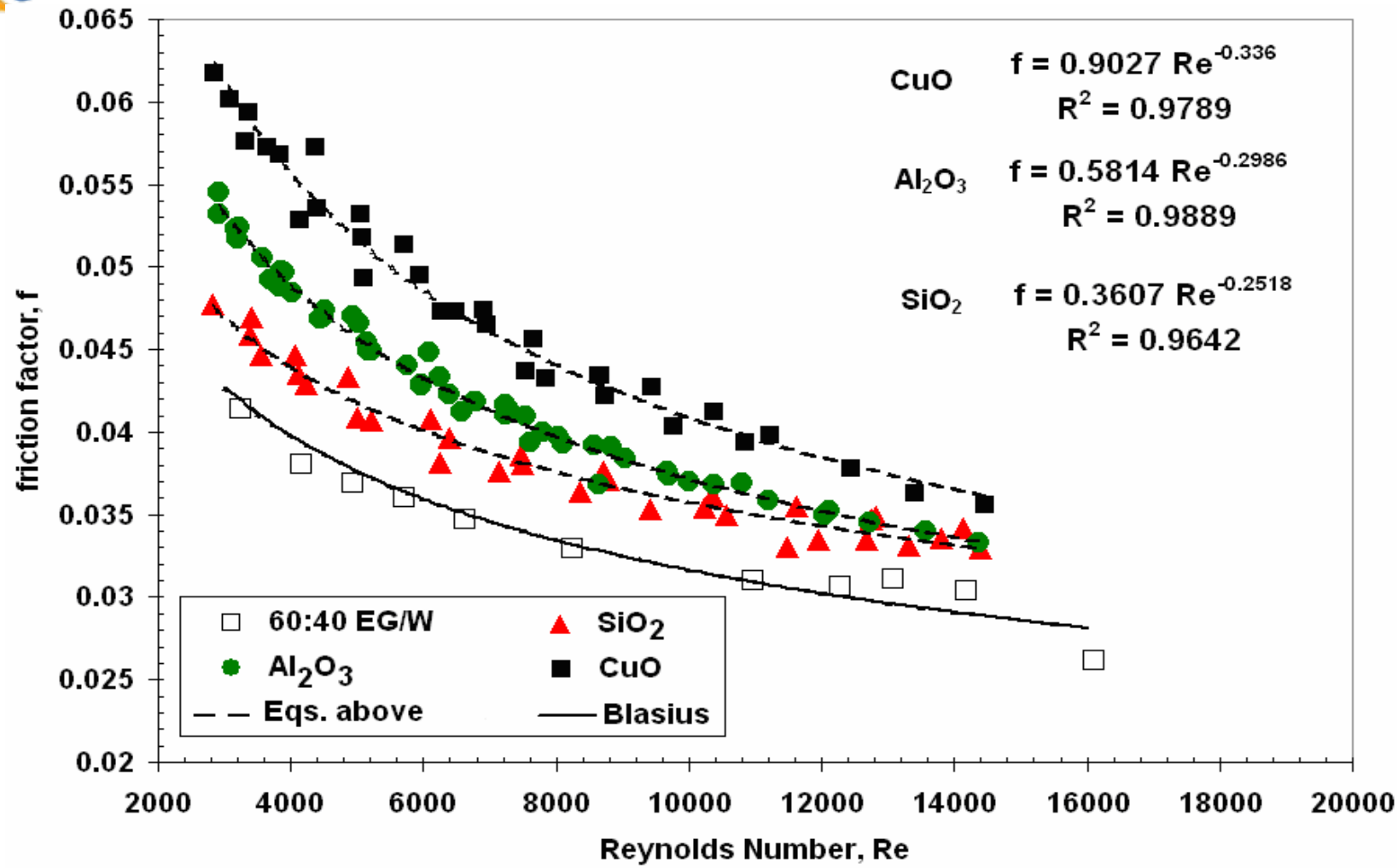
Nusselt Number Correlation for Nanofluids



$$Nu_{nf} = 0.065(\mathrm{Re}^{0.65} - 60.22)(1 + 0.0169\phi^{0.15})\,\mathrm{Pr}^{0.542}$$

Source : Vajjha et al., 2010

Friction Factor Correlation for Nanofluids



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

Source : Vajjha et al., 2010

Pumping Power Comparison For Equal Heat Transfer

Type of Fluid Parameters	60/40 EG /Water	2% Copper Oxide	2% Aluminum Oxide	2% Silicon Dioxide
Heat Transfer Coefficient (W/m2K)	10000	10000	10000	10000
Density (kg/m3)	1073.018	1181.557	1123.557	1095.957
Specific Heat (J/kg K)	3212.118	2917.350	3055.301	3112.169
Viscosity (mPa.s)	2.758	4.007	3.514	3.393
Thermal conductivity (W/m K)	0.36731	0.44039	0.43292	0.39277
Prandtl number (Pr)	24.122	26.543	24.798	26.885
Nusselt number (Nu)	91.749	76.523	77.844	85.800
Reynolds Number (Re)	7753	5115	5453	5815
Velocity (m/s)	5.914	5.147	5.060	5.342
Volumetric Flow Rate x 10E+5 m3/s	5.273	4.589	4.511	4.762
Reduction in Volumetric Flow Rate (%)	……	**12.974**	**14.439**	**9.677**
Mass Flow Rate x 10E+02 (kg/s)	5.658	5.422	5.069	5.219
Reduction in Mass Flow Rate (%)	……	**4.171**	**10.409**	**7.746**
friction factor (f)	0.03372	0.04206	0.03921	0.03768
Pressure Loss per Unit Length(kPa/m)	187.764	195.337	167.357	174.852
Pumping Power per Unit Length(W/m)	9.900	8.963	7.550	8.327
Reduction in Pumping Power (%)	…….	**9.464**	**23.738**	**15.888**

$$\dot{q} = hA_s(T_w - T_{bm})$$

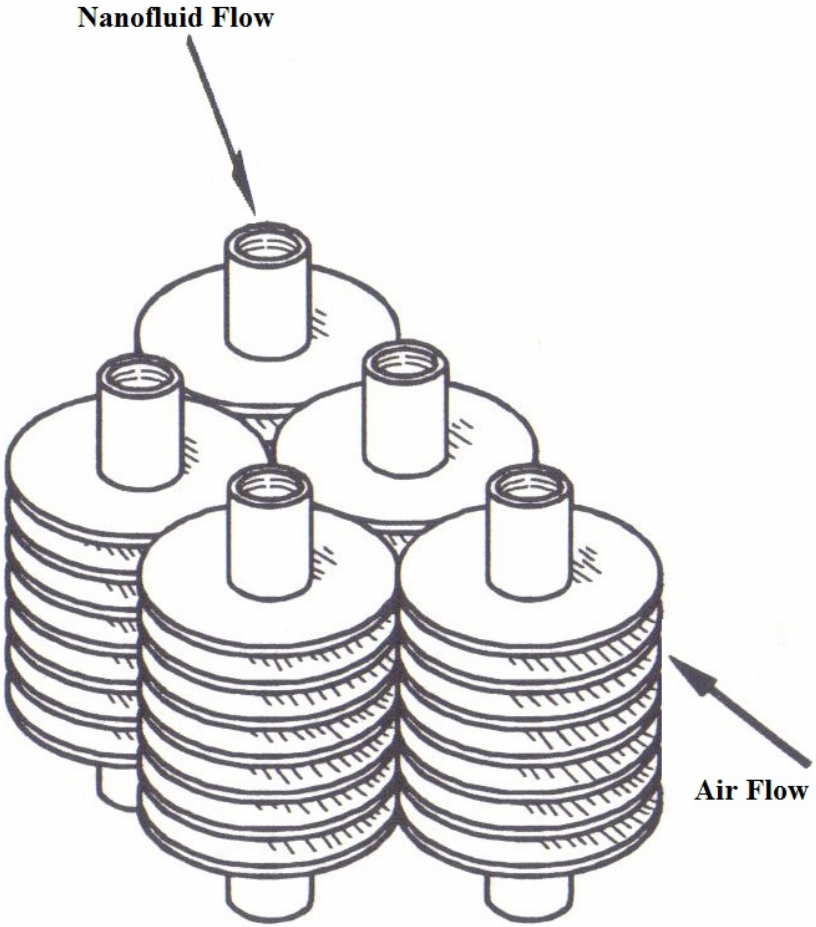
A_s and (T_w-T_{bm}) are constant.

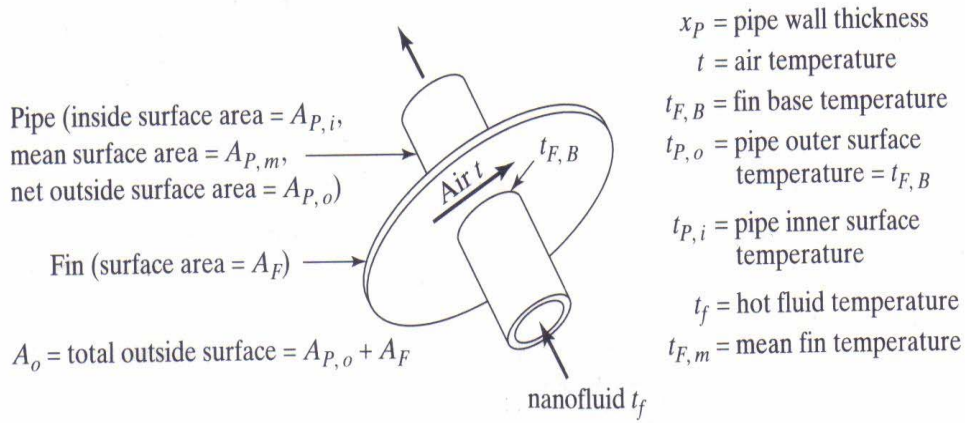
From experimental setup

ID=0.00337m

T_m=313K

Nanofluids to Air Heat Exchanger





Source: Thermal Environmental Engineering by Kuehn et al., 1998 (3rd Edition).

Equations for Heat Exchanger Analysis

Heat transfer rate from a heating coil circulating nanofluid to air

$$\dot{Q} = U_o A_o \Delta t_m$$

Rate of heat transfer from the nanofluid to the pipe

$$\dot{Q} = h_i A_{P,i} (t_f - t_{P,i})$$

Rate of heat transfer through the pipe wall

$$\dot{Q} = \frac{k_P A_{P,m} (t_{P,i} - t_{P,o})}{x_P}$$

Rate of heat transfer from the pipe and fin to the air

$$\dot{Q} = h_{c,o} (A_{P,o} + \eta A_F)(t_{P,o} - t)$$

Overall heat transfer coefficient

$$U_o = \frac{1}{\frac{A_o}{A_{P,i} h_i} + \frac{A_o x_P}{A_{P,m} k_P} + \frac{1-\eta}{h_{c,o}(A_{P,o}/A_F + \eta)} + \frac{1}{h_{c,o}}}$$

Typical Data for Heat Exchanger:

$A_{P,i}$= pipe inside area; $A_{P,m}$= pipe mean area; $A_{P,O}$= pipe net outside area; A_F= Fin area;

A_O= total outside area; All areas are in square meter per lineal meter of tube.

$A_{P,i}$ = 0.03536 m^2 $A_{P,m}$ = 0.0375 m^2 $A_{P,o}$ = 0.03658 m^2 A_F = 0.948 m^2

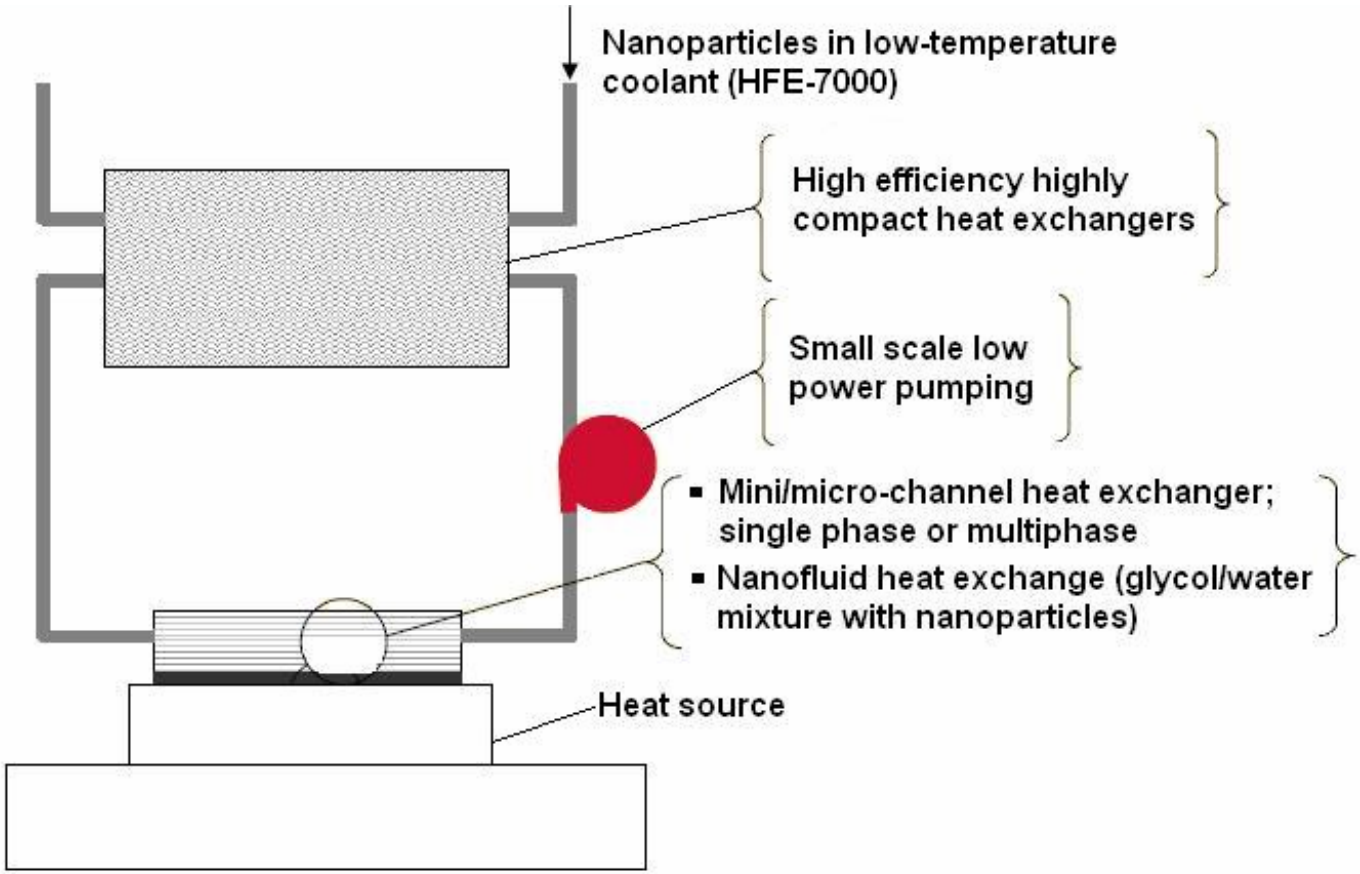
A_o = 0.9845 m^2 d_i = 0.0112593 m $h_{c,o}$ = 113W/m^{2}K T_f = 298 K

Source: Thermal Environmental Engineering by Kuehn et al., 1998 (3rd Edition)

Surface Area Comparison For Equal Pumping Power

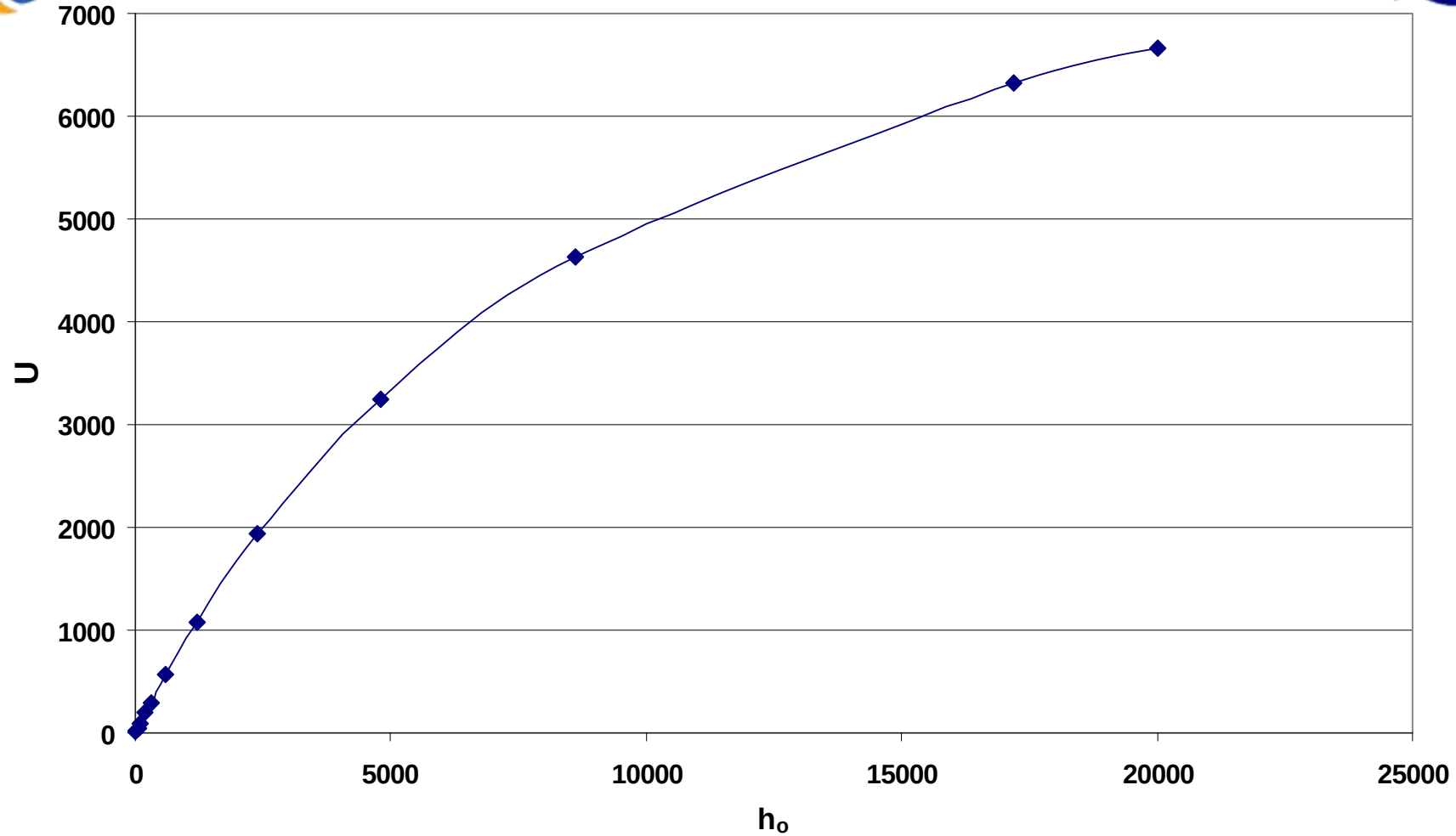
Component	60:40 EG/Water	1% Copper Oxide	1% Aluminum Oxide	1% Silicon Oxide
Pumping Power/Unit Length (W/m)	**10**	**10**	**10**	**10**
Velocity (m/s)	2.1883	2.0891	2.1287	2.1340
Reynolds Number	6290	5456	5596	5349
Prandtl number (Pr)	37.133	36.875	36.738	40.457
Nusselt number (Nu)	88.521	96.478	98.340	99.769
Inside heat transfer coefficient, h_i	2822.127	3409.704	3458.614	3331.069
Inside Surface Resistance x 10E3 $R_i = A_o / A_{P,i} h_i$	9.867	8.166	8.051	8.359
Pipe Wall Resistance x 10E5 $R_P = A_o x_P / A_{P,m} k_P$	4.651	4.651	4.651	4.651
Fin Resistance x 10E3 $R_F = \frac{1}{h_{c,o}} \left(\frac{1-\eta}{\eta + A_{P,o} / A_F} \right)$	3.778	3.778	3.778	3.778
Outside Surface Resistance x 10E3 $R_o = 1/h_{c,0}$	8.805	8.805	8.805	8.805
Total Resistance x 10E3 $R_t = R_i + R_P + R_F + R_o$	22.496	20.795	20.680	20.988
Overall Heat Transfer Coeff. U_o	44.453	48.087	48.356	47.646
% Increase in U_o	……	**8.176**	**8.780**	**7.183**
% Reduction in Area	……	**8.176**	**8.780**	**7.183**

Thermal Systems For Heat Transfer in Space Systems



Adopted from Ortega (2006) NSF ITHERM Presentation

U_o For Gas to Liquid vs. Liquid to Liquid



$$\dot{Q} = U * A * (LMTD)$$

$$U \approx \frac{1}{\frac{1}{h_i} + \frac{1}{h_o}}; h_i = 10000$$

Conclusions

- The CuO nanofluid showed the highest heat transfer coefficient and highest pressure loss followed by the Al_2O_3 nanofluid, then the SiO_2 nanofluid and the lowest values were for the base fluid.

- Al_2O_3 nanofluid showed the optimum behavior. Recommend low volumetric concentration of about 2%. Results in reduction in fluid volume flow rate up to 14%, mass flow rate up to 10% and pumping power up to 24% on an equal heat transfer basis compared to the base fluid.

- A heat exchanger surface area reduction up to 8% is possible on an equal pumping power basis by these nanofluids.

- 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.

- Reduction of material volume and power will lead to less environmental pollution.

Acknowledgement

- Financial Support: Graduate School, University of Alaska Fairbanks

  Department of Mechanical Engineering, UAF

  Alaska NASA EPSCoR, Alaska NSF EPSCoR

- CEM Staff Kala Hansen, Eric Johansen, Tom McCarty

- Petroleum Development Lab, UAF

Thank You

Questions ???