Supplementary Information for the paper:

Nanofluids for Solar Thermal Collection and Energy Conversion

Mohammed Abdullah Hussain[1], Sumith Yesudasan[2*] and Sibi Chacko[1]

[1] School of Engineering and Physical Sciences, Heriot-Watt University, Dubai, UAE

[2] Department of Engineering Technology, Sam Houston State University, Huntsville, TX, USA

Author emails:

Mohammed Abdullah Hussain: mah11@hw.ac.uk

*Sumith Yesudasan: sumith.yesudasan@shsu.edu

Sibi Chacko: c.sibi@hw.ac.uk

This document contains additional information that we used in conducting the simulation and experiments.

Table 1 - Commonly used nanoparticles (left) and base fluids (right) used to synthesize nanofluids [4]

Nanoparticle Materials	Base Fluids
Aluminium Oxide - Al_2O_3	Ethylene Glycol
Copper Oxide - CuO	Ethylene Oxide
Iron(III) Oxide - Fe_2O_3	Ethanol
Magnesium Oxide - MgO	Glycerol
Silicon dioxide - SiO_2	Kerosene
Titanium dioxide - TiO_2	Toluene
Zinc oxide - ZnO	Water
Silver - Ag	
Aluminium - Al	
Gold - Au	
Copper - Cu	
Iron - Fe	
MWCNTs	

Table 2 - Specific heat capacity models

Model	Expression	Remarks	φ (%)	d_p (nm)	T (ºC)
Pak and Cho (1)	$c_{p,nf} = c_{p,f}(1-\varphi) + c_{p,p}\varphi$	Theoretical Equation	-	-	-
Xuan and Roetzel (2)	$c_{p,nf} = \frac{\rho_f\, c_{p,f}\,(1-\varphi) + \rho_p\, c_{p,p}\,\varphi}{\rho_{nf}}$	Theoretical Equation	-	-	-
Sekhar and Sharma (3)	$c_{p,nf} = c_{p,f}\, 0.8429 \left(1+\frac{T_{nf}}{50}\right)^{-0.3037} \left(1+\frac{d_p}{50}\right)^{0.4167} (1+\varphi)^{2.272}$	Empirical Equation	0-4	15-50	20-50

Table 3 - Thermal conductivity models

Model	Expression	Remarks	φ (%)	d_p (nm)	T (ºC)
Pak and Cho (1)	$k_{nf} = k_f\,(1 + 7.74\,\varphi)$	Empirical Equation	-	13	25
Bruggeman (4)	$k_{nf} = 0.25\,k_f\left[(3\varphi - 1)\frac{k_p}{k_f} + [3(1 - \varphi) - 1] + \sqrt{\Delta_B}\right]$ $\sqrt{\Delta_B} = \left[(3\varphi - 1)\frac{k_p}{k_f} + (3(1 - \varphi) - 1)\right]^2 + 8\frac{k_p}{k_f}$	Theoretical Equation Valid for high-volume concentrations, spherical particles and random distributions. No limitation on the concentration For low concentrations, the Bruggeman model shows almost the same result as the Maxwell–Garnett's model.	-	-	-
Mintsa et al. (5)	$k_{nf} = k_f\,(1 + 1.72\varphi)$	Empirical Equation	0-18	36, 46	20-50
Hamilton–Crosser (6)	$k_{nf} = k_f\frac{k_p + (n-1)k_p + (n-1)\varphi(k_p - k_f)}{k_p + (n-1)k_f + \varphi(k_f - k_p)}$	Theoretical Equation Valid for spherical and non-spherical particles. For spherical nanoparticles, n = 3 (also called Wasp or Maxwell Model) For cylindrical nanoparticles, n = 6.	0-4	-	-
Lu and Lin (7)	$k_{nf} = k_f\,(1 + 2.25\varphi + 2.27\varphi^2)$	Theoretical Equation Valid for spherical nanoparticles	-	-	-
Yu and Choi (8)	$k_{nf} = k_f\frac{k_p + 2k_p + 2\varphi(k_p - k_f)(1+\beta)^3}{k_p + 2k_f + \varphi(k_f - k_p)(1+\beta)^3}$ $\beta = \frac{h}{d_p * 0.5}$ Nanolayer thickness, $h = \frac{1}{\sqrt{3}}\left(\frac{4\,M_f}{\rho_f\,N_A}\right)^{1/3}$ Avagadro constant, $N_A = 6.023 \times 10^{23}$ per mol M_f = Molar mass of fluid $\left(\frac{g}{mol}\right)$ $k_{pe} = k_p\frac{[2(1-\gamma) + (1+\beta)^3(1+2\gamma)]\,\gamma}{-(1-\gamma) + (1+\beta)^3(1+2\gamma)}$ $\gamma = \frac{k_{layer}}{k_p}$	Theoretical Equation Modified Maxwell Model that considers nanolayer effect. Valid for spherical nanoparticles. Suggests the new approach that adding smaller (<10-nm diameter) particles could be potentially better than adding more particles	< 20	-	-
Chon et al. (9)	$k_{nf} = k_f\left(1 + 64.7\,\varphi^{0.746}\left(\frac{d_f}{d_p}\right)^{0.369}\left(\frac{k_p}{k_f}\right)^{0.746} Pr^{0.9955} Re^{1.2321}\right)$ $Re = \frac{\rho_f\,k_B\,T}{3\,\pi\,\mu_f^2 l_f}$ $Pr = \frac{c_{p,f}\,\mu_f}{k_f}$ l_f = fluid mean free path $k_B = 1.38 \times 10^{-23}\ m^2\,kg\,s^{-2}K^{-1}$	Empirical Equation Considers effect of Brownian motion of the nanoparticles in the nanofluid	1	11-150	20-70

Table 4 - Viscosity models

Model	Expression	Remarks	φ (%)	d_p (nm)	T (ºC)
Einstein (10)	$\mu_{nf} = (2.5\varphi + 1)\mu_f$	Theoretical Equation Spherical Particles	≤ 2	-	-
Ho et al. (11)	$\mu_{nf} = \mu_f (1 + 2.93\varphi + 222.4\varphi^2)$	Empirical Equation	0–4	33	15-40
Maiga et al. (12)	$\mu_{nf} = \mu_f (1 + 7.3\varphi + 123\varphi^2)$	Empirical Equation	0-5	13, 28	25
Batchelor (13)	$\mu_{nf} = \mu_f (1 + 2.5\varphi + 6.2\varphi^2)$	Theoretical Equation Spherical Particles	-	-	-
Nguyen et al. (14)	$\mu_{nf} = \mu_f (1 + 0.025\varphi + 0.015\varphi^2)$	Empirical Equation Spherical Particles	1-9.4	36, 29	20-75
Brinkman (15)	$\mu_{nf} = \mu_f(1 - \varphi)^{-2.5}$	Theoretical Equation Spherical Particles	< 5	-	-
Masoumi et al. (16)	$\mu_{nf} = \mu_f + \frac{\rho_p V_B d_p^2}{72\, C\, \delta}$ $V_B = \frac{1}{d_p}\left(\frac{18\, k_B\, T}{\pi\, \rho_p\, d_p}\right)^{\frac{1}{2}}$ $k_B = 1.38 \times 10^{-23}\ m^2\ kg\ s^{-2} K^{-1}$ $C = \mu_f^{-1}[(C_1\, d_p + C_2)\varphi + (C_3\, d_p + C_4)]$ $C_1 = -1.133 \times 10^{-6}$ $C_2 = -2.771 \times 10^{-6}$ $C_3 = 9 \times 10^{-8}$ $C_4 = -3.93 \times 10^{-7}$	Empirical Equation	0-5	28, 36	22-65

References

1. Bock Choon Pak YoungIC. Hydrodynamic and Heat Transfer Study of Dispersed Fluids With Submicron Metallic Oxide. Exp Heat Transf J Therm Energy Transp Storage Convers. 2013;(January 2013):37–41.
2. Xuan Y, Roetzel W. Conceptions for heat transfer correlation of nanofluids. Int J Heat Mass Transf. 2000 Oct;43(19):3701–7.
3. Sekhar YR, Sharma KV. Study of viscosity and specific heat capacity characteristics of water-based Al 2 O 3 nanofluids at low particle concentrations. J Exp Nanosci. 2015 Jan 22;10(2):86–102.
4. Bruggeman DAG. Berechnung verschiedener physikalischer Konstanten von heterogenen Substanzen. I. Dielektrizitätskonstanten und Leitfähigkeiten der Mischkörper aus isotropen Substanzen. Ann Phys. 1935;416(7):636–64.
5. Mintsa HA, Roy G, Nguyen CT, Doucet D. New temperature dependent thermal conductivity data for water-based nanofluids. Int J Therm Sci. 2009 Feb;48(2):363–71.
6. Hamilton RL, Crosser OK. Thermal Conductivity of Heterogeneous Two-Component Systems. Ind Eng Chem Fundam. 1962 Aug;1(3):187–91.
7. Lu S, Lin H. Effective conductivity of composites containing aligned spheroidal inclusions of finite conductivity. J Appl Phys. 1996 May 1;79(9):6761–9.
8. Yu W, Choi SUS. The role of interfacial layers in the enhanced thermal conductivity of nanofluids: A renovated Hamilton-Crosser model. J Nanoparticle Res. 2004;6(4):355–61.

9. Chon CH, Kihm KD, Lee SP, Choi SUS. Empirical correlation finding the role of temperature and particle size for nanofluid (Al2O3) thermal conductivity enhancement. Appl Phys Lett. 2005 Oct 10;87(15):153107.
10. Einstein A. Eine neue Bestimmung der Moleküldimensionen. Ann Phys. 1906;324(2):289–306.
11. Ho CJ, Liu WK, Chang YS, Lin CC. Natural convection heat transfer of alumina-water nanofluid in vertical square enclosures: An experimental study. Int J Therm Sci. 2010 Aug;49(8):1345–53.
12. Maïga SEB, Nguyen CT, Galanis N, Roy G. Heat transfer behaviours of nanofluids in a uniformly heated tube. Superlattices Microstruct. 2004 Mar;35(3–6):543–57.
13. Batchelor GK. The effect of Brownian motion on the bulk stress in a suspension of spherical particles. J Fluid Mech. 1977 Nov 1;83(1):97–117.
14. Nguyen CT, Desgranges F, Roy G, Galanis N, Maré T, Boucher S, et al. Temperature and particle-size dependent viscosity data for water-based nanofluids – Hysteresis phenomenon. Int J Heat Fluid Flow. 2007 Dec;28(6):1492–506.
15. Brinkman HC. The Viscosity of Concentrated Suspensions and Solutions. J Chem Phys. 1952 Apr;20(4):571–571.
16. Masoumi N, Sohrabi N, Behzadmehr A. A new model for calculating the effective viscosity of nanofluids. J Phys Appl Phys. 2009 Mar 7;42(5):055501.