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Appendix A

Table A1 Summary of correlation for thermal conductivity of hybrid nanofluids

Nano-particle/ Base fluid	Working condition	Correlation	Author
-	-	$\frac{k_{nf}}{k_{bf}} = 1 + \frac{k_{p1}\phi_{p1}r_{bf}}{k_{bf}r_{p1}\left(1-\{\phi_{p1}+\phi_{p2}\}\right)} + \frac{k_{p2}\phi_{p2}r_{bf}}{k_{bf}r_{p2}\left(1-\{\phi_{p1}+\phi_{p2}\}\right)}$	Chougule and Sahu (2013)
Al_2O_3-Cu/ Water	ϕ=0.1-2%	$\frac{k_{nf}}{k_{bf}} = \frac{\frac{\phi_{p1}k_{p1}+\phi_{p2}k_{p2}}{\phi} + 2(1-\phi)k_{bf} + 2(\phi_{p1}k_{p1}+\phi_{p2}k_{p2})}{\frac{\phi_{p1}k_{p1}+\phi_{p2}k_{p2}}{\phi} + (2+\phi)k_{bf} - (\phi_{p1}k_{p1}+\phi_{p2}k_{p2})}$	Takabi and Salehi (2014)
Ag-MgO (equal)/ Water	ϕ=0-2%	$\frac{k_{nf}}{k_{bf}} = \frac{0.1747\times10^{5}+\phi}{0.1747\times10^{5} - 0.1498\times10^{6}\phi + 0.1117\times10^{7}\phi^{2} + 0.1997\times10^{8}\phi^{3}}$	Esfe et al. (2015a)
CNTs-Al_2O_3/ Water	T=27-57°C, ϕ=0-1%	$\frac{k_{nf}}{k_{bf}} = 1.05 + 0.005T + 0.06\phi + 0.0099\phi T +$ $0.00317T^{2} + 0.026\phi^{2} + 0.0034T^{2}\phi + 0.00735T\phi^{2}$	Esfe et al. (2015b)
MWCNT-Fe_3O_4 (equal)/ EG	T=25-50°C, ϕ=0.1-2.3%	$\frac{k_{nf}}{k_{bf}} = 1 + 0.0162\phi^{0.7038}T^{0.6009}$	Harandi et al. (2016)
ZnO-TiO_2 (equal) / EG	T=25-50°C, ϕ=0.0-3.5%	$\frac{k_{nf}}{k_{bf}} = 1 + 0.004503\phi^{0.8717}T^{0.7972}$	Toghraie et al. (2016)
MgO-fMWCNT/ EG	T=25-50°C, ϕ=0.0-0.6%	$\frac{k_{nf}}{k_{bf}} = 0.8341 + 1.1\phi^{0.243}T^{-0.289}$	Afrand (2017)
MgO-MWCNT/ EG	T=25-50°C, ϕ=0.0-0.6%	$\frac{k_{nf}}{k_{bf}} = 0.9787 + \exp\left(0.3081\phi^{0.3097} - 0.002T\right)$	Vafaei et al. (2017)
TiO_2-CuO-C/ EG	T=30-50°C, ϕ=0.5-2%	$\frac{k_{nf}}{k_{bf}} = 1 + 6.2299\left(\frac{\phi}{100}\right)^{0.9371}\left(\frac{T}{333}\right)^{10.2685}$	Akilu et al. (2017)
SWCNT-MgO (20:80)/ EG	T=30-50°C, ϕ=0-2%	$\frac{k_{nf}}{k_{bf}} = 0.90844 - 0.06613\phi^{0.3}T^{0.7} + 0.01266\phi^{0.31}T$	Esfe et al. (2017b)

DWCNT-SiO2 / EG	T=30-50°C, ϕ=0.03-1.71%	$\frac{k_{nf}}{k_{bf}}=0.9896-0.07122\phi+\left(0.02705\phi^{0.7685}T^{0.627}\right)$ $+1.531\times10^{-5}T^{2}$	Esfe et al. (2017c)
SiO2-TiO2/ Water-EG (60:40)	T=30-80°C, ϕ=0.5-3.0%	$\frac{k_{nf}}{k_{bf}}=\left(1+\frac{\phi}{100}\right)^{5.5}\left(\frac{T}{80}\right)^{0.01}$	Nabil et al. (2017)
CuO-SWCNT (50:50)/ Water-EG (60:40)	T=20-50°C, ϕ=0.02-0.75%	$\frac{k_{nf}}{k_{bf}}=1+0.04056\phi T-0.003252(\phi T)^{2}$ $+0.0001181(\phi T)^{3}-0.000001431(\phi T)^{4}$	Rostamian et al. (2017)
MWCNT-CuO/ Water	T=25-50°C, ϕ=0.0-0.6%	$\frac{k_{nf}}{k_{bf}}=0.907\exp(0.36\phi^{0.3111}+0.000956T)$	Zadkhast et al. (2017)
TiO2-MWCNTs/ Water+EG	T=20-50°C, ϕ=0.05-1%	$\frac{k_{nf}}{k_{bf}}=0.006\left(\phi^{1.099}\right)T^{1.051}+1.014$	Akhgar and Toghraie (2018)
Al2O3-SiO2/water	T=25-50°C, ϕ=1-3%	$k_{nf}=0.607-0.005\phi_{1}+0.009\phi_{1}^{2}+0.109\varphi_{2}-0.059\phi_{2}^{2}$ $+0.013\phi_{2}^{3}$	Moldoveanu et al. (2018)
SiO2-TiO2/Water +EG	T=30-80°C, ϕ=1%	$\frac{k_{nf}}{k_{bf}}=1.17(1+R)^{-0.1151}\left(\frac{T}{80}\right)^{0.0437}$ Where R is the mixture ratio	Hamid et al. (2018)
ZnO-Ag (50:50) /water	T=25-50°C, ϕ=0.125-2%	$\frac{k_{nf}}{k_{bf}}=1+0.0008794\phi^{0.5899}T^{1.345}$	Esfahani et al. (2018)
MWCNTs-SiC/ Water+EG	T=25-50°C, ϕ=0-0.75%	$\frac{k_{nf}}{k_{bf}}=0.0017\phi^{0.698}T^{1.386}+0.981$	Kakavandi and Akbari, 2018
f-MWCNT-Fe2O3/water	T=30-60°C, ϕ=0.01-0.3 wt%	$k_{nf}=0.785T^{0.1268}\phi_{p1}{}^{0.026}\phi_{p2}{}^{0..0903}$	Balaga et al. (2019)
GO-Al2O3/ Water	T=25-50°C, ϕ=0.1-1%	$\frac{k_{nf}}{k_{bf}}=0.0031\left(T^{1.185}\right)\left(\phi^{0.863}\right)+1.006$	Taherialekouhi et al. (2019)
Al2O3-Fe2O4/ 10w40	T=25-65°C, ϕ=0.25-4 wt%	$\frac{k_{nf}}{k_{bf}}=0.113\times1.011^{T}\times wt^{0.376}+0.921$	Sulgani et al. (2019)

TiO_2-MWCNTs/ EG-water	T=20-60°C, ϕ=0.0625-1%	$\frac{k_{nf}}{k_{bf}} = 1 + 0.0187\phi^{0.6719}T^{0.6913}$	Moradi et al. (2020)

Table A2 Summary of correlation for the viscosity of hybrid nanofluids

Nanoparticle/ Basefluid	**Working condition**	**Correlation**	**Author**
Ag-MgO (50:50)/ Water	ϕ=0-2%	$\frac{\mu_{nf}}{\mu_{bf}} = 1 + 32.795\phi - 7214\phi^2 + 714600\phi^3 - 0.1941\times 10^8\phi^4$	Esfe et al. (2015)
MWCNT - ZnO (15:85)/ Engine oil	T=5-55°C, ϕ=0.125-1.0%	$\mu_{nf} = 796.8 + 76.26\phi + 12.88T$ $+0.7965\phi T - 196.9\sqrt{T} - 16.53\phi\sqrt{T}$	Asadi and Asadi (2016)
MWCNT-SiO_2 (equal portion)/ SAE40	T=25-60°C, ϕ=0-1%	$\frac{\mu_{nf}}{\mu_{bf}} = 0.00337 + \exp(0.07731\phi^{1.452}T^{0.3387})$	Afrand et al. (2016)
MWCNT-MgO (20:80)/ SAE50	T=25-50°C, ϕ=0-2%	$\frac{\mu_{nf}}{\mu_{bf}} = (328201T^{-2.053}\phi^{0.09359})$	Asadi et al. (2016)
MWCNT-Al_2O_3 (25:75)/ SAE40	T=25-50°C, ϕ=0-2%	$\frac{\mu_{nf}}{\mu_{bf}} = 1.123 + 0.3251\phi - 0.08994T + 0.002552T^2$ $-0.00002386T^3 + 0.9695\left(\frac{T}{\phi}\right)^{0.01719}$	Dardan et al. (2016)
MWCNT-MgO/EG	T=30-60°C, ϕ=0.1-1.0%	$\frac{\mu_{nf}}{\mu_{bf}} = \left[0.191\phi + 0.240\left(T^{-0.342}\phi^{-0.473}\right)\right]$ $\times\exp\left(1.45T^{0.120}\phi^{0.158}\right)$	Soltani and Akbari (2016)
TiO_2-CuO/C EG	T=30-50°C, ϕ=0.5-2vol%	$\frac{\mu_{nf}}{\mu_{bf}} = 0.9653 + 77.4567\left[\frac{\phi_v}{100}\right]^{1.1558}\left[\frac{T}{333}\right]^{0.6881}$	Akilu et al. (2017)
SiO_2-TiO_2/ Water+EG	T=30-80°C, ϕ=1vol%	$\frac{\mu_{nf}}{\mu_{bf}} = 1.42(1+R)^{-0.1063}\left(\frac{T}{80}\right)^{0.2321}$	Hamid et al. (2018)
MWCNT-Al_2O_3, (50:50) water+EG (20:80)	T=25-50°C, ϕ=0.0625-1vol%	$\frac{\mu_{nf}}{\mu_{bf}} = A + (B\phi^C) + (\phi^D)^5$ A, B, C and D depend on temperature.	Afshari et al. (2018)

ZnO-Ag (50-50) /Water	T=25-50°C, ϕ=0.125-2vol%	$\frac{\mu_{nf}}{\mu_{bf}} = a_o + a_1\phi + a_2\phi^2 + a_3\phi^3$ a_o, a_1, a_2 and a_3 depend upon temperature.	Ruhani et al. (2019)
CuO-MWCNTs/ water+EG (70:30)	T=20-60°C, ϕ=0.025-1vol%	$\frac{\mu_{nf}}{\mu_{bf}} = 0.50013 + 0.019722T + 4.23872\phi - 0.052336T\phi$	Tian et al. (2020)
γ-Al_2O_3 - MWCNT / water	T=20-50°C, ϕ=0.1vol%	$\mu_{nf} = 1.41467 + 5.197\times10^{-3}R - 1.37\times10^{-2}T$ Where, R is the ratio of hybrid nanoparticles	Giwa et al. (2020)

Appendix B

Uncertainty analysis

Equations to find out the uncertainty for various parameters is based on the procedure of **Kline and McClintock, 1953,** have been included in this section:

Heat transfer rate, $\dot{Q}$:

$$\frac{\Delta\dot{Q}}{\dot{Q}}=\sqrt{\left(\frac{\Delta\dot{V}}{\dot{V}}\right)^2+\left(\frac{\Delta\rho}{\rho}\right)^2+\left(\frac{\Delta c_p}{c_p}\right)^2+\left(\frac{\Delta(T_{out}-T_{in})}{(T_{out}-T_{in})}\right)^2}=\pm 2.87\%$$

Thermal resistance, R:

$$\frac{\Delta R}{R}=\sqrt{\left(\frac{\Delta(T_s-T_m)}{(T_s-T_m)}\right)^2+\left(\frac{\Delta\dot{Q}}{\dot{Q}}\right)^2}=\pm 2.88\%$$

Thermal effectiveness, ε_{th}:

$$\frac{\Delta\varepsilon_{th}}{\varepsilon_{th}}=\sqrt{\left(\frac{\Delta(T_s-T_{in})_{hnf}}{(T_s-T_{in})_{hnf}}\right)^2+\left(\frac{\Delta(T_s-T_{in})_{bf}}{(T_s-T_{in})_{bf}}\right)^2}=0.13\%$$

Hydraulic diameter, d_h:

$$\frac{\Delta d_h}{d_h}=\sqrt{\left(\frac{\Delta w_{ch}}{w_{ch}}\right)^2+\left(\frac{\Delta h_{ch}}{h_{ch}}\right)^2+\left(\frac{\Delta(w_{ch}+h_{ch})}{(w_{ch}+h_{ch})}\right)^2}=\pm 1.02\%$$

Mean velocity, u_m:

$$\frac{\Delta u_m}{u_m}=\sqrt{\left(\frac{\Delta\dot{V}}{\dot{V}}\right)^2+\left(\frac{\Delta w_{ch}}{w_{ch}}\right)^2+\left(\frac{\Delta h_{ch}}{h_{ch}}\right)^2}=\pm 0.78\%$$

Effective area, A:

$$\frac{\Delta A}{A}=\sqrt{\left(\frac{\Delta(w_{ch}+2h_{ch})}{(w_{ch}+2h_{ch})}\right)^2+\left(\frac{\Delta L_{ch}}{L_{ch}}\right)^2}=\pm 1.2\%$$

Reynolds number, Re:

$$\frac{\Delta \mathrm{Re}}{\mathrm{Re}}=\sqrt{\left(\frac{\Delta\rho}{\rho}\right)^2+\left(\frac{\Delta u_m}{u_m}\right)^2+\left(\frac{\Delta d_h}{d_h}\right)^2+\left(\frac{\Delta\mu}{\mu}\right)^2}=\pm 3.10\%$$

Heat transfer coefficient, h:

$$\frac{\Delta h}{h}=\sqrt{\left(\frac{\Delta\dot{Q}}{\dot{Q}}\right)^2+\left(\frac{\Delta A}{A}\right)^2+\left(\frac{\Delta(T_s-T_m)}{(T_s-T_m)}\right)^2}=\pm 3.11\%$$

Effectiveness, ε:

$$\frac{\Delta\varepsilon}{\varepsilon}=\sqrt{\left(\frac{\Delta h_{hnf}}{h_{hnf}}\right)^2+\left(\frac{\Delta h_{bf}}{h_{bf}}\right)^2}=\pm 4.38\%$$

Nusselt number, Nu:

$$\frac{\Delta Nu}{Nu}=\sqrt{\left(\frac{\Delta h}{h}\right)^2+\left(\frac{\Delta d_h}{d_h}\right)^2+\left(\frac{\Delta k}{k}\right)^2}=\pm 3.83\%$$

Friction factor, f:

$$\frac{\Delta f}{f}=\sqrt{\left(\frac{\Delta d_h}{d_h}\right)^2+\left(\frac{\Delta(\Delta p)}{\Delta p}\right)^2+\left(\frac{\Delta L_{ch}}{L_{ch}}\right)^2+\left(\frac{\Delta\rho}{\rho}\right)^2+\left(\frac{2\Delta u_m}{u_m}\right)^2}=\pm 2.76\%$$

Pumping Power, P_p:

$$\frac{\Delta P_P}{P_P}=\sqrt{\left(\frac{\Delta\dot{V}}{\dot{V}}\right)^2+\left(\frac{\Delta(\Delta p)}{\Delta p}\right)^2}=\pm 0.56\%$$

Coefficient of performance, COP:

$$\frac{\Delta COP}{COP}=\sqrt{\left(\frac{\Delta\dot{Q}}{\dot{Q}}\right)^2+\left(\frac{\Delta P_P}{P_P}\right)^2}=\pm 2.92\%$$

Figure of merit, FOM:

$$\frac{\Delta FOM}{FOM}=\frac{1}{3}\times\sqrt{\left(\frac{3\Delta\varepsilon}{\varepsilon}\right)^2+\left(\frac{\Delta P_{P,hnf}}{P_{Phnf}}\right)^2+\left(\frac{\Delta P_{P,bf}}{P_{P,bf}}\right)^2}=\pm 4.39\%$$

Performance evaluation criteria, PEC:

$$\frac{\Delta PEC}{PEC} = \pm\frac{1}{3}\times\sqrt{\left(\frac{3\Delta N_{hnf}}{Nu_{hnf}}\right)^2+\left(\frac{3\Delta Nu_{bf}}{Nu_{bf}}\right)^2+\left(\frac{\Delta f_{hnf}}{f_{hnf}}\right)^2+\left(\frac{\Delta f_{bf}}{f_{bf}}\right)^2} = \pm 5.57\%$$

Mass flow rate: $\dot{m}$

$$\frac{\Delta\dot{m}}{\dot{m}} = \sqrt{\left(\frac{\Delta\rho}{\rho}\right)^2+\left(\frac{\Delta\dot{V}}{\dot{V}}\right)^2} = \pm 2.06\%$$

Total entropy generation rate, δ_{gen}:

$$\frac{\Delta S_{gen}}{S_{gen}} = \sqrt{\left(\frac{\Delta\dot{m}}{\dot{m}}\right)^2+\left(\frac{\Delta c_p}{c_p}\right)^2+\left(\frac{\Delta(T_{out}/T_{in})}{(T_{out}/T_{in})}\right)^2+\left(\frac{\Delta\dot{m}}{\dot{m}}\right)^2+\left(\frac{\Delta(\Delta p)}{\Delta p}\right)^2+\left(\frac{\Delta\rho}{\rho}\right)^2+\left(\frac{\Delta T_m}{T_m}\right)^2+\left(\frac{\Delta\dot{Q}}{\dot{Q}}\right)^2+\left(\frac{\Delta T_s}{T_s}\right)^2}$$

$$= \pm 5.05\%$$

List of Publications:

Journals

1. Vivek Kumar, Jahar Sarkar, Two-phase numerical simulation of hybrid nanofluid heat transfer in minichannel heat sink and experimental validation, International Communications in Heat and Mass Transfer 91 (2018) 239–247. (IF-3.971)
2. Vivek Kumar, Jahar Sarkar, Research and development on composite nanofluids as next generation heat transfer medium, Journal of Thermal Analysis and Calorimetry 137 (4) 1133–1154. (IF-2.731)
3. Vivek Kumar, Jahar Sarkar, Numerical and experimental investigations on heat transfer and pressure drop characteristics of Al_2O_3-TiO_2 hybrid nanofluid in minichannel heat sink with different mixture ratio, Powder Technology 345 (2019) 717–727. (IF-4.142)
4. Vivek Kumar, Jahar Sarkar, Experimental hydrothermal characteristics of Al_2O_3-MWCNT hybrid nanofluid in minichannel heat sink with different nanoparticle ratios, Applied Thermal Engineering 165 (2020) 114546. (IF-4.725)
5. Vivek Kumar, Jahar Sarkar, Effect of different nanoparticles mixture dispersed nanofluids on hydrothermal characteristics in minichannel heat sink, Advanced Powder Technology 31 (2020) 621–631. (IF-4.217)
6. Vivek Kumar, Jahar Sarkar, Experimental hydrothermal behavior of hybrid nanofluid for various particle ratios and comparison with other fluids in minichannel heat sink, International Communications in Heat and Mass Transfer 110 (2020) 104397. (IF-3.971)
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Conferences

1. Vivek Kumar, Jahar Sarkar, Effect of inlet temperature and heat flux on the performance of minichannel using various hybrid nanofluids: Experimental Study, Proceedings of the 25th National and 3rd International ISHMT-ASTFE, Heat and

Mass Transfer Conference (IHMTC-2019), December 28-31, 2019, IIT Roorkee, India.

2. Vivek Kumar, Jahar Sarkar, Experimental heat transfer and pressure drop of Al_2O_3-graphene hybrid nanofluid in minichannel heat sink, 1st International conference on nanofluids (ICNF) & 2nd European symposium on nanofluids (ESNF), June 26-28, 2019, Castellon, Spain.
3. Vivek Kumar, Gaurav Verma, Jahar Sarkar, Numerical analysis of mini/microchannel heat transfer characteristics using different nanofluids, Proceedings of the 24th National and 2nd International ISHMT-ASTFE, Heat and Mass Transfer Conference (IHMTC-2017), December 27-30, 2017, BITS Pilani, Hyderabad, India. DOI: 10.1615/IHMTC-2017.1750.