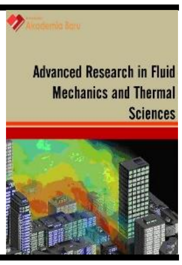
Penerbit Akademia Baru

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage: www.akademiabaru.com/arfmts.html
ISSN: 2289-7879



A Review on Factors Affecting Heat Transfer Efficiency of Nanofluids for Application in Plate Heat Exchanger

Open Access

Haziqatulhanis Ibrahim[1], Norazlianie Sazali[1,2,*], Ahmad Syahiman Mohd Shah[3], Mohamad Shaiful Abdul Karim[3], Farhana Aziz[4], Wan Norharyati Wan Salleh[4*]

1 Faculty of Mechanical Engineering, Universiti Malaysia Pahang, 26600 Pekan, Pahang, Malaysia
2 Centre of Excellence for Advanced Research in Fluid Flow (CARIFF), Universiti Malaysia Pahang, Lebuhraya Tun Razak, 26300 Gambang, Kuantan, Pahang, Malaysia
3 Faculty of Electrical and Electronics Engineering, Universiti Malaysia Pahang, 26600 Pekan, Pahang, Malaysia
4 Advanced Membrane Technology Research Centre (AMTEC), School of Chemical and Energy, Faculty of Engineering, Universiti Teknologi Malaysia, 81310 Skudai, Johor Darul Takzim, Malaysia

ARTICLE INFO

Article history:
Received 3 May 2019
Received in revised form 1 August 2019
Accepted 9 August 2019
Available online 15 August 2019

Keywords:
Nanofluid; plate heat exchanger; heat transfer; specific heat; viscosity

ABSTRACT

With the rapid advancement in science and technology, the enhancement in heat transfer is also making its way forward towards modern nanotechnology. It was noted that heat transfer efficacy of heat exchangers depends on the working fluid and nanofluid were discovered to enhance the heat transfer, making nanofluid our focus in this review. While shell and tube heat exchanger type were given attention since past decades, there are scarce on nanofluid application in plate heat exchanger. To add, thermophysical properties of nanofluids such as specific heat, viscosity, thermal conductivity and its heat transfer coefficient are very important for heat transfer application in heat exchangers. Therefore, this review article will cover the compilation of information and data collected from numerous previous researchers.

1. Introduction

Heat exchanger is an equipment that allows thermal energy transfer between two fluids or more. The two fluids having different temperature will be separated in either cold side or hot side through a separating medium to achieve an ideal thermal equilibrium in the process of heat transfer. There are many types of heat exchanger available in the market such as shell and tube, plate fin and also plate heat exchanger [1]. Currently, PHE are gaining more attention due to its advantages. First application of plate heat exchanger (PHE) in 1921 employed in dairy production has since been developed to other areas and are widely used in current era. Having advantages of high thermal efficiency, low cost and the compactness itself makes PHE to be the preferences in many engineering applications [2]. PHE is made up of several thin plates arranged in parallel form with a frame to hold the plates. There are other plates pattern of PHE such as zig zag and chevron. However, chevron plate

* *Corresponding author.*
E-mail address: azlianie@ump.edu.my (Norazlianie Sazali)

structure with corrugated design is the most commonly used surface in this type of heat exchanger [3].

Heat exchangers need a working fluid to transfer heat from or to the applied fluids. Importantly, for an ideal working fluid, it should have high thermal capacity, low viscosity and low cost. Most common working fluid in heat exchangers application is water. Having properties of high specific heat with low viscosity at a very low cost brings advantages to the heat transfer application industry. However, the drawback of using water as a base fluid is that high heat transfer rate requires larger size of heat exchangers. Therefore, through scientific study, numerous researchers tried to modify the heat transfer fluid to produce higher efficiency of working fluid. This was when nanofluids came into the light. A group of researchers had joint forces and discover a new material called nanofluids [3–5]. Nanofluids term is referring to small nano-sized particles having average size from 1 to 100nm that have been diffused in a working base fluid. Metal was known to have higher thermal conductivity than water and thus, became a potential candidate for nanofluids preparation [6]. This concept of suspending the nano particles into base fluid was a revised attempt from previous research of diffusing micron size particles into fluids [7]. This attempt had significantly improved the thermos-physical properties of fluids. As for preparation of nanofluids, it can be synthesised by one-step method or two-step method elaborated elsewhere [6,8].

Available studies on nanofluid application in heat exchanger are mostly using shell and tube heat exchanger. For plate heat exchanger, existing literatures focuses on using water as the process fluids. Thus, this paper aims to outline several factors that can contribute to the augmentation of heat transfer efficiency by summarizing works from previous researchers. Some of the existing research works showed contradictory findings, in which it produced a decreasing or an unchanged heat transfer performance. Due to the complex nature of nanofluid, it is very important to understand its properties and thermal behavior. Other than that, enhancement technique suggested in recent literature could be applied to increase the heat transfer efficiency [9,10].

2. Studies on hybrid nanofluids

In past years, new class of working fluids for heat transfer enhancement known as hybrid nanofluids were widely utilized in lab scale studies [11]. Hybrid nanofluids are mixture of two or more nanoparticles incorporated in base fluid [12]. This combination of nanoparticles is able to overcome the drawback of single nanofluid usage due to positive features carried by each particle and is used to augment the overall heat transfer of fluid in heat exchanger. Ny and co-workers numerically investigated heat transfer using silver-graphene (Ag-Heg) nanofluids via CFD software. Similarly, Zainal *et al.,* conducted simulation analysis in order to evaluate the thermal performance of hybrid Ag-Heg/water nanofluids [12]. Their study discovered that heat transfer coefficient and Nusselt number decreased when they increase volume fraction if nanofluids from 0.1% to 0.9%. However, the performance comparison between pure water and hybrid nanofluids were not reported in their work. Not long ago, Yıldız studied the properties of Al_2O_3-SiO_2/water by employing established correlations and compared with its mono nanofluid properties [13]. They concluded that hybrid nanofluids can enhance the heat transfer performance at lower volume fraction compared to Al_2O_3/water nanofluid and SiO_2/water nanofluid. Consequently, lower volume fraction requires lower operating cost and is simple to operate. More literatures on recent hybrid nanofluids experiment can be found elsewhere [11].

3. Factors affecting heat transfer efficiency

3.1 Specific heat of nanofluids

According to Gupta *et al.*, specific heat is the amount of heat needed to increase temperature of a gram nanofluids by one degree centigrade [14]. It is used to study the performance of nanofluid in terms of its exergy and energy. Various researchers had conducted studies which shows that volume concentration of nanofluids affect its specific heat capacity [8,15,16]. Studies done by Pak and Cho on γ-Al_2O_3/water nanofluid shows a decrease in nanofluid specific heat to 2.27% from 1.1% when change in volume percentage from 1.34 to 2.78% [17]. Another research by Zhou and Ni on aluminium oxide/water nanofluids also concludes that 46% of heat capacity decrease when volume concentration is 21.7vol% [18]. Vajjha and Das carried out a research using various type of nanoparticles in ethylene glycol-water mixture have the same conclusion as the previous researchers [19]. They pointed that increase in volume concentration of nanofluid will decrease the specific heat capacity despite of using different type of base fluid.

Table 1 outlined the summary of past literatures discussing the relationship between volume concentration and specific heat capacity. Based on definition of specific heat capacity itself, it is known that low amount of heat capacity is desired so that the system will be more energy efficient. If base fluid used is not purely water such as hybrid base fluid, ethylene glycol or oil, the corresponding heat capacity can be affected by the concentration of base fluid. Referring to the table, aluminium oxide with various particle size shows a comparatively high heat capacity decrement in both water and ethylene glycol base fluid. Thus, it can be proven that aluminium oxide suspended in either water or ethylene glycol will possess a positive outcome in terms of specific heat.

Table 1
Summary of past literatures on specific heat of nanofluids

Nanoparticle	Working fluid	Particle size (nm)	Volume fraction (%Vol)	Specific heat Decrement (%)	References
Al_2O_3	Water	13	1.34-2.78	1.10-2.27	[17]
		45	21.7	46	[18]
		-	0-25	21-45	[20]
		40-50	0-4	3-18	[21]
	Radiator Coolant	13	1	14	[22]
	Ethylene Glycol/Water (60:40)	53	1-10	13	[19]
	Ethylene Glycol/Water (50:50)	45	2-6	5-16	[23]
	Lithium bromide/Water	35	0-0.1	17	[24]
CuO	Water	30	2-8	20	[25]
	Ethylene glycol	25-50	0.1-0.6	1.16-5.04	[26]
	Ethylene Glycol/Water (60:40)	29	1-6	24	[19]
SiO_2	Water	20	2-10	4-14.67	
	Ethylene Glycol	50	0.003-0.3	15	[27]
	Ethylene Glycol/Water (60:40)	30	1-10	10	[28]
	Ethylene Glycol/Water (60:40)	20	10	12	[29]
ZnO	Ethylene Glycol/Water (60:40)	77	1-7	4.23-18.08	[19]
MWCNT	Heat transfer oil	5-20	0.1-0.4	21.2-42.0	[30]

3.2 Viscosity of nanofluids

Another important factor in heat transfer application is viscosity of nanofluids. The pumping power of heat exchanger and value of pressure drop depends on the viscosity as it offers the resistance to shear stress. Along the years, researchers had proven that addition of nanoparticles in base fluid and the viscosity of base fluid are some of parameters that affects the viscosity of nanofluid. Al_2O_3 nanoparticle is the most common solid particle that is used to study the viscosity, varying its particle size and volume concentration, suspended in different type of base fluids. Lee et al. conducted a research on Al_2O_3/water nanofluids and obtain a 2.9% of viscosity enhancement at 0.01-0.3% volume concentrations [31]. Several other researchers perform the same type of study using different base fluid and noted a positive enhancement in viscosity. Sonawane et al. diffuses the alumina oxide nanoparticles in aviation turbine fuel and discover 38% of enhancement in viscosity [32]. Majority of studies reported that the viscosity will also increase with the increase in particle size. Based on the findings, it strengthens the statement that nanofluid viscosity is dependent on size of particles, type of base fluids and the volume concentration of nanofluid. The summary for previous researches is compiled in Table 2.

Table 2
Summary of past literatures on viscosity of nanofluids

Nanoparticle	Working fluid	Particle size (nm)	Volume fraction (%Vol)	Viscosity Increment (%)	References
Al_2O_3	Water	30 ± 5	0.01-0.3	2.9	[31]
		43	0.33-5.0	14-136	[20]
		36	2.1-12.2	10-210	[33]
		47	1-12	12-430	
		28	1-6	9-86	[34]
	ATF	30 ± 10	1	38	[32]
	Ethylene glycol	36	1.5	158	[35]
	Lithium bromide/Water	35	0-0.1	91.2	[24]
CuO	Water	29	4	92	[33]
	Ethylene glycol	10	0.18	15-23	[36]
	Ethylene glycol/Water	29	1	22	[29]
SiO_2	Ethylene glycol/Water	50	10	96	
ZnO	Water	90-210 (Rectangular)	0.5-5.0	5.3-68.6	[37]
	Ethylene glycol	10-20	0.2-5.0	15	[38]

Aluminium oxide nanoparticles show an excellent performance in heat transfer and from Table 3 below, it can be seen that various researchers derived correlations for Al_2O_3/water. Most of the correlations originate from Einstein's model in 1906. In 1952, Brinkman introduced a new correlation that can be used by wider volume concentration range that below 4%. Both theoretical and experimental correlations derived for viscosity determination only take base fluid viscosity and volume concentration into account. Thus, it can be proven that volume concentration of nanofluids and base fluid viscosity are dominating factors for this thermophysical properties.

Table 3
Empirical correlations for Viscosity calculation

Model	Information	Correlation	Reference
Theoretical	• Low particle volume fraction	$\mu_{nf}=\mu_{bf}(1+2.5\emptyset)$	[39]
	• Moderate particle concentration • Extended from Einstein formula • Spherical particles	$\mu_{nf}=\mu_{bf}\frac{1}{(1-\emptyset)^{2.5}}$	[40]
	• Rigid spherical particle • Brownian motion • Isotropic structure	$\mu_{nf}=\mu_{bf}(1+2.5\emptyset+6.2\emptyset^2)$	[41]
Experimental	• Al_2O_3/water	$\mu_{nf}=\mu_{bf}(1+7.3\emptyset+123\emptyset^2)$	[34]
	• Al_2O_3/water	$\mu_{nf}=\mu_{bf}(1+7.3\emptyset+123\emptyset^2)$	[42]
	• Al_2O_3/water	$\mu_{nf}=\mu_{bf}+\frac{\rho_{np}u_m d^2}{72C\delta}$ $\delta=\sqrt[3]{\frac{\pi}{6\emptyset}}d$	[43]
	• Only valid for Al_2O_3/water nanofluid • Includes nanoparticle size, concentration, temperature and capping layer effect	$\frac{\mu_{nf}}{\mu_{bf}}=\exp\left[m+\alpha\left(\frac{T}{T_0}\right)+\beta(\emptyset_h)+\gamma\left(\frac{d}{1-r}\right)\right]$	[44]

3.3 Thermal conductivity of nanofluids

Thermal conductivity is used to find out nanofluid potential. Many experimental and theoretical researches had been performed to study the deviation in thermal conductivity of nanofluids. Parameters involved in thermal conductivity determination includes degree of dispersion of nanofluids in working fluid, volume concentration and nanoparticles size and shape. Das et al. stated that when temperature increase, thermal conductivity will increase [45]. The study was conducted experimentally using Al_2O_3/water nanofluid with 4vol% and 38.4nm nanoparticle size. Few other researchers also proved the statement using the same type of nanofluid but varying the vol%, particle size and temperature.

In addition, studies also shows that thermal conductivity of nanofluids is higher than the base fluid [14]. The addition of solid nanoparticles in base fluid alters the Brownian motion mechanism that control the thermal behaviour of nanofluids. Therefore, thermal conductivity increases when nanoparticles is suspended into the base fluid. Yu et al. conduct a research using various type of base fluids but kept the other parameters constant to determine whether base fluid types will affect the thermal conductivity output [38]. They concluded that ethylene glycol shows an enhancement of 39% while propylene glycol as base fluid shows a 40% enhancement. Summary of past researches from various investigator regarding the thermal conductivity is as in Table 4 below.

Empirical correlations available for determination of thermal conductivity is summarised in Table 5. It is divided into two; theoretical and experimental correlations. Some of the correlations are based on theoretical findings. Commonly, the type of nanofluids used for this research is metal oxide suspended in conventional base fluids [46].

Table 4
Summary of past literatures on thermal conductivity of nanofluids

Nanoparticle	Working fluid	Particle size (nm)	Volume fraction (%Vol)	Thermal conductivity Increment (%)	References
Al_2O_3	Water	38.4	4	44 (21°C)	[45]
		43	0.33-3	9.7	[20]
		36	3.1-9	15 (20°C-40°C)	[46]
		13	1.3-43	33 (31.85°C-86.85°C)	[46]
		28	5.5	16	[34]
	Ethylene glycol	28	5	24.5	
	Ethylene glycol/Water	36	1.5	32.36 (60°C)	[35]
	Lithium bromide/Water	35	1	78.0	[24]
CuO	Water	29	3.3-9.3	15 (20°C-40°C)	[46]
	Ethylene glycol/Water	29	6	60 (90°C)	[19]
SiO_2	Ethylene glycol/Water	10	0.005-0.15	0.98-7.35	[47]
ZnO	Water	90-210 (rectangular)	0.5-5	3-19.8	[37]
	Ethylene glycol	15	5	26.5	[38]

Table 5
Empirical correlation for thermal conductivity of nanofluids

Model	Information	Correlation	References
Theoretical	-For liquid and solid suspension -Spherical particles	$k_{nf}=\frac{2k_{bf}+k_{np}+2\phi(k_{np}-k_{bf})}{2k_{bf}+k_{np}-\phi(k_{np}-k_{bf})}k_{bf}$	[48]
	-Spherical particles -Valid for high volume concentration nanofluid	$k_{nf}=\frac{1}{4}\left[(3\phi-1)k_{np}+(2-3\phi)k_{bf}\right]+\frac{k_{bf}}{4}\sqrt{\Delta}$ $\Delta=(3\phi-1)^2\left(\frac{k_{np}}{k_{bf}}\right)^2+(2-3\phi)^2+$ $2(2+9\phi-9\phi^2)\left(\frac{k_{np}}{k_{bf}}\right)$	[49]
	Brownian movement	$k_{nf}=\phi k_{np}+(1-\phi)k_{bf}$	[50]
Experimental	Al_2O_3/water	$\frac{k_{nf}-k_{bf}}{k_{bf}}=0.764\phi+0.0187(T-273.15)-0.462$	[51]
	Al_2O_3/water	$k_{nf}=(1+3\phi)k_{bf}$	[52]
	Al_2O_3/water	$\frac{k_{nf}}{k_{bf}}=\left(\frac{C_{p_{nf}}}{C_{p_{bf}}}\right)^a\left(\frac{\rho_{nf}}{\rho_{bf}}\right)^b\left(\frac{M_{bf}}{M_{nf}}\right)^c$ a=-0.023, b=1.358, c=0.125	[20]
	Al_2O_3/water	$\frac{k_{nf}}{k_{bf}}=1+4.4Re^{0.4}Pr^{0.66}\left(\frac{T}{T_{bf}}\right)^{10}\left(\frac{k_{np}}{k_{bf}}\right)^{0.03}\phi^{0.66}$	[53]

3.4 Convective heat transfer and Application of Nanofluid in Plate Heat Exchanger

Convective heat transfer is the amount of energy being transported between surface of solid in heat exchanger and nanofluid particles. Several factors that affects the value of convective heat are the type of nanofluid itself, specification geometry of plate heat exchanger and also the size and shape of nanoparticles. Based on theoretical and experimental studies, Tiwari et al. discovered 27% enhancement in overall heat transfer coefficient [2]. The type of nanofluid used in their study was aluminium oxide/water nanofluid with vol% ranging from 0.5% to 3%. Separate research done by Kabeel et al. and Jokar and O'Halloran using the same type of nanofluid and range of volume concentration but different size of nanoparticles shows a contradictory result [54,55]. When the particle sizing is 47nm, overall heat transfer coefficient shows an increment approximately 13% but when the sizing is 36nm, no significant enhancement was recorded. Increase in HTC was calculated with respect to water as working fluid. Table 6 shows the summary of past research works done by various researchers and Table 7 consist of empirical correlations that have been derived by the researchers.

Table 6
Summary of past researches on Heat Transfer Coefficient of Nanofluid

Nanoparticle	Working fluid	Particle size (nm)	Concentration	Observation	Ref.
ZnO	Water	-	0.5-2 %vol	Enhancement range of 24%-28%	[3]
Al_2O_3	Water	45	0.5-3 %vol	Ratio of HTC approximately increase 27%	[2]
		45	2-4 %vol	Ratio of HTC approximately increase 11%	[21]
		47	1-4 %vol	Ratio of HTC approximately increase 13%	[54]
		36	1-4 %vol	No significant enhancement	[55]
		50	0.3%	Heat transfer enhancement of 46%	[56]
	Ethylene glycol	20	0.1-1 %vol	Enhancement range of 3%-49%	[57]
Ag	Water	16.2	0-10 mg/L	Enhancement of 36.6% at 2.5 mg/L	[58]
Graphene	Ethylene glycol/Water (50:50)	2	0.01-1 wt%	Maximum enhancement of 4%	[59]
CuO	Water	50	0.1-0.5 %vol	Enhancement of 52% at 0.3%vol	[60]

Table 7
Empirical correlations for Heat Transfer Coefficient

Information	Correlation	References
• Experimental • Turbulent flow • Al_2O_3/water • $10^4 < Re < 10^5$ • $6.5 < Pr < 12.3$	$Nu=0.021\,Re^{0.8}Pr^{0.5}$	[17]
• Experimental • Turbulent flow • Al_2O_3/water • $3000 < Re < 1.6x10^4$ • $0 < \emptyset < 10$vol%	$Nu=0.065(Re^{0.65}-60.22)(1+0.0169\emptyset^{0.15})\,Pr^{0.542}$	[28]
• Numerical • Laminar flow • Al_2O_3/water • $Re \leq 1000$ • $6.0 < Pr < 753$	For constant temperature: $Nu = 0.28\,Re^{0.35}Pr^{0.35}$ For constant wall heat flux: $Nu=0.086\,Re^{0.55}Pr^{0.5}$	[42]

• $0< \phi < 10vol\%$		
• Numerical • Turbulent flow • $104<Re< 5x10^5$ • $6.6 < Pr < 13.9$ • $0< \phi < 10vol\%$	$Nu=0.085\ Re^{0.71}Pr^{0.35}$	[61]
• Numerical • Fully-developed turbulent flow	$Nu=\frac{\left(\frac{f}{8}\right)(Re-1000)Pr}{1+\delta^{+}\sqrt{\left(\frac{f}{8}\right)}\left(Pr^{\frac{2}{3}}-1\right)}$	[62]

4. Conclusions

In conclusion, nanofluids exerts superior thermal properties that can enhance heat transfer process. Utilization of nanofluids in heat exchanger is expected to replace conventional working fluids used in current industries. However, plate heat exchanger is a complex system that need a thorough studies in order to be successfully applied in a real scale heat exchanger. Optimum conditions for each parameter such as specific heat capacity, nanofluids viscosity, heat transfer capacity and thermal viscosity of nanofluids must be defined for maximum heat transfer efficiency. Theoretical and experimental studies done by past researchers were able to demonstrate its behaviour and narrowing the research gap in heat transfer by plate heat exchanger.

Acknowledgement
Authors would like to extend their gratitude to Universiti Malaysia Pahang and Ministry of Education (MOE) with reference no. RDU170367. The authors would also like to show our gratitude to Associate Professor Dr Agus Saptoro from Curtin University Malaysia for his insight in this topic.

References
[1] Bahiraei, Mehdi, Reza Rahmani, Ali Yaghoobi, Erfan Khodabandeh, Ramin Mashayekhi, and Mohammad Amani. "Recent research contributions concerning use of nanofluids in heat exchangers: a critical review." *Applied Thermal Engineering* 133 (2018): 137-159.
[2] Tiwari, Arun Kumar, Pradyumna Ghosh, and Jahar Sarkar. "Performance comparison of the plate heat exchanger using different nanofluids." *Experimental Thermal and Fluid Science*49 (2013): 141-151.
[3] Kumar, Vikas, Arun Kumar Tiwari, and Subrata Kumar Ghosh. "Characterization and performance of nanofluids in plate heat exchanger." *Materials Today: Proceedings* 4, no. 2 (2017): 4070-4078.
[4] Taherian, Hessam, Jorge L. Alvarado, and Ehsan M. Languri. "Enhanced thermophysical properties of multiwalled carbon nanotubes based nanofluids. Part 1: Critical review." *Renewable and Sustainable Energy Reviews* 82 (2018): 4326-4336.
[5] Suganthi, K. S., and K. S. Rajan. "Metal oxide nanofluids: Review of formulation, thermo-physical properties, mechanisms, and heat transfer performance." *Renewable and Sustainable Energy Reviews* 76 (2017): 226-255.
[6] Lee, Y. K. "The use of nanofluids in domestic water heat exchanger." *J. Adv. Res. Appl. Mech* 3, no. 1 (2014): 9-24.
[7] Das, Sarit Kumar, Stephen US Choi, and Hrishikesh E. Patel. "Heat transfer in nanofluids—a review." *Heat transfer engineering* 27, no. 10 (2006): 3-19.
[8] Babar, Hamza, and Hafiz Muhammad Ali. "Towards hybrid nanofluids: preparation, thermophysical properties, applications, and challenges." *Journal of Molecular Liquids* (2019).
[9] Muhammad, Nura Mu'az, and Nor Azwadi Che Sidik. "Utilization of Nanofluids in Minichannel for Heat Transfer and Fluid Flow Augmentation: A Concise Research Design." *Journal of Advanced Research Design* 50, no. 1 (2018): 18–29.
[10] Abu Bakar, Saidu Bello, Nor Azwadi Che Sidik, and Wei Xian Hong. "Numerical Prediction of Laminar Nanofluid Flow in Rectangular Microchannel." *Journal of Advanced Research Design* 50, no. 1 (2018): 1–17.
[11] Huminic, Gabriela, and Angel Huminic. "Hybrid Nanofluids for Heat Transfer Applications – A State-of-the-Art Review." *International Journal of Heat and Mass Transfer* 125 (October 2018): 82–103.

[12] Zainal, S., C. Tan, C. J. Sian, and T. J. Siang. "ANSYS Simulation for Ag/HEG Hybrid Nanofluid in Turbulent Circular Pipe." *Journal of Advanced Research in Applied Mechanics* 23, no. 1 (2016): 20–35.

[13] Yıldız, Çağatay, Müslüm Arıcı, and Hasan Karabay. "Comparison of a Theoretical and Experimental Thermal Conductivity Model on the Heat Transfer Performance of Al_2O_3-SiO_2/Water Hybrid-Nanofluid." *International Journal of Heat and Mass Transfer* 140 (September 2019): 598–605.

[14] Gupta, Munish, Vinay Singh, Rajesh Kumar, and Z. Said. "A review on thermophysical properties of nanofluids and heat transfer applications." *Renewable and Sustainable Energy Reviews* 74 (2017): 638-670.

[15] Lei, Gang, Weirong Li, and Qingzhi Wen. "The convective heat transfer of fractal porous media under stress condition." *International Journal of Thermal Sciences* 137 (2019): 55-63.

[16] Sajid, Muhammad Usman, and Hafiz Muhammad Ali. "Recent advances in application of nanofluids in heat transfer devices: a critical review." *Renewable and Sustainable Energy Reviews* 103 (2019): 556-592.

[17] Pak, Bock Choon, and Young I. Cho. "Hydrodynamic and heat transfer study of dispersed fluids with submicron metallic oxide particles." *Experimental Heat Transfer an International Journal* 11, no. 2 (1998): 151-170.

[18] Zhou, Sheng-Qi, and Rui Ni. "Measurement of the specific heat capacity of water-based Al_2O_3 nanofluid." *Applied Physics Letters* 92, no. 9 (2008): 093123.

[19] Vajjha, Ravikanth S., and Debendra K. Das. "A review and analysis on influence of temperature and concentration of nanofluids on thermophysical properties, heat transfer and pumping power." *International Journal of Heat and Mass Transfer* 55, no. 15-16 (2012): 4063-4078.

[20] Chandrasekar, M., S. Suresh, and A. Chandra Bose. "Experimental investigations and theoretical determination of thermal conductivity and viscosity of Al_2O_3/water nanofluid." *Experimental Thermal and Fluid Science* 34, no. 2 (2010): 210-216.

[21] Pandey, Shive Dayal, and V. K. Nema. "Experimental analysis of heat transfer and friction factor of nanofluid as a coolant in a corrugated plate heat exchanger." *Experimental Thermal and Fluid Science* 38 (2012): 248-256.

[22] Elias, M. M., I. M. Mahbubul, R. Saidur, M. R. Sohel, I. M. Shahrul, S. S. Khaleduzzaman, and S. Sadeghipour. "Experimental investigation on the thermo-physical properties of Al2O3 nanoparticles suspended in car radiator coolant." *International Communications in Heat and Mass Transfer* 54 (2014): 48-53.

[23] Kulkarni, Devdatta P., Ravikanth S. Vajjha, Debendra K. Das, and Daniel Oliva. "Application of aluminum oxide nanofluids in diesel electric generator as jacket water coolant." *Applied Thermal Engineering* 28, no. 14-15 (2008): 1774-1781.

[24] Jung, Jung-Yeul, Eung Surk Kim, Youngsuk Nam, and Yong Tae Kang. "The study on the critical heat flux and pool boiling heat transfer coefficient of binary nanofluids (H_2O/LiBr+ Al_2O_3)." *International journal of refrigeration* 36, no. 3 (2013): 1056-1061.

[25] Pantzali, M. N., A. G. Kanaris, K. D. Antoniadis, A. A. Mouza, and S. V. Paras. "Effect of nanofluids on the performance of a miniature plate heat exchanger with modulated surface." *International Journal of Heat and Fluid Flow* 30, no. 4 (2009): 691-699.

[26] Zhou, Le-Ping, Bu-Xuan Wang, Xiao-Feng Peng, Xiao-Ze Du, and Yong-Ping Yang. "On the specific heat capacity of CuO nanofluid." *Advances in mechanical engineering* 2 (2010): 172085.

[27] Starace, Anne K., Judith C. Gomez, Jun Wang, Sulolit Pradhan, and Greg C. Glatzmaier. "Nanofluid heat capacities." *Journal of Applied Physics* 110, no. 12 (2011): 124323.

[28] Vajjha, Ravikanth S., Debendra K. Das, and Praveen K. Namburu. "Numerical study of fluid dynamic and heat transfer performance of Al_2O_3 and CuO nanofluids in the flat tubes of a radiator." *International Journal of Heat and fluid flow* 31, no. 4 (2010): 613-621.

[29] Namburu, P. K., D. P. Kulkarni, A. Dandekar, and D. K. Das. "Experimental investigation of viscosity and specific heat of silicon dioxide nanofluids." *Micro & Nano Letters* 2, no. 3 (2007): 67-71.

[30] Pakdaman, M. Fakoor, M. A. Akhavan-Behabadi, and P. Razi. "An experimental investigation on thermo-physical properties and overall performance of MWCNT/heat transfer oil nanofluid flow inside vertical helically coiled tubes." *Experimental thermal and fluid science* 40 (2012): 103-111.

[31] Lee, Ji-Hwan, Kyo Sik Hwang, Seok Pil Jang, Byeong Ho Lee, Jun Ho Kim, Stephen US Choi, and Chul Jin Choi. "Effective viscosities and thermal conductivities of aqueous nanofluids containing low volume concentrations of Al2O3 nanoparticles." *International Journal of Heat and Mass Transfer* 51, no. 11-12 (2008): 2651-2656.

[32] Sonawane, Sandipkumar, Kaustubh Patankar, Ankit Fogla, Bhalchandra Puranik, Upendra Bhandarkar, and S. Sunil Kumar. "An experimental investigation of thermo-physical properties and heat transfer performance of Al_2O_3-Aviation Turbine Fuel nanofluids." *Applied Thermal Engineering* 31, no. 14-15 (2011): 2841-2849.

[33] Nguyen, C. T., F. Desgranges, Gilles Roy, Nicolas Galanis, Thierry Maré, S. Boucher, and H. Angue Mintsa. "Temperature and particle-size dependent viscosity data for water-based nanofluids–hysteresis phenomenon." *International Journal of Heat and Fluid Flow* 28, no. 6 (2007): 1492-1506.

[34] Wang, Xinwei, Xianfan Xu, and Stephen U. S. Choi. "Thermal conductivity of nanoparticle-fluid mixture." *Journal of thermophysics and heat transfer* 13, no. 4 (1999): 474-480.
[35] Sundar, L. Syam, E. Venkata Ramana, Manoj K. Singh, and Antonio CM Sousa. "Thermal conductivity and viscosity of stabilized ethylene glycol and water mixture Al_2O_3 nanofluids for heat transfer applications: An experimental study." *International Communications in Heat and Mass Transfer* 56 (2014): 86-95.
[36] Shima, P. D., John Philip, and Baldev Raj. "Influence of aggregation on thermal conductivity in stable and unstable nanofluids." *Applied Physics Letters* 97, no. 15 (2010): 153113.
[37] Jeong, Jisun, Chengguo Li, Younghwan Kwon, Jaekeun Lee, Soo Hyung Kim, and Rin Yun. "Particle shape effect on the viscosity and thermal conductivity of ZnO nanofluids." *International journal of refrigeration* 36, no. 8 (2013): 2233-2241.
[38] Yu, Wei, Huaqing Xie, Lifei Chen, and Yang Li. "Investigation of thermal conductivity and viscosity of ethylene glycol based ZnO nanofluid." *Thermochimica Acta* 491, no. 1-2 (2009): 92-96.
[39] Einstein, Albert. "Eine neue bestimmung der moleküldimensionen." *Annalen der Physik* 324, no. 2 (1906): 289-306.
[40] Brinkman, H. C. "The viscosity of concentrated suspensions and solutions." *The Journal of Chemical Physics* 20, no. 4 (1952): 571-571.
[41] Batchelor, G. K. "The effect of Brownian motion on the bulk stress in a suspension of spherical particles." *Journal of fluid mechanics* 83, no. 1 (1977): 97-117.
[42] Maiga, Sidi El Becaye, Samy Joseph Palm, Cong Tam Nguyen, Gilles Roy, and Nicolas Galanis. "Heat transfer enhancement by using nanofluids in forced convection flows." *International journal of heat and fluid flow* 26, no. 4 (2005): 530-546.
[43] Masoumi, N., N. Sohrabi, and A. Behzadmehr. "A new model for calculating the effective viscosity of nanofluids." *Journal of Physics D: Applied Physics* 42, no. 5 (2009): 055501.
[44] Masoud Hosseini, S., A. Moghadassi, and Dale Henneke. "A new dimensionless group model for determining the viscosity of nanofluids." *Journal of Thermal Analysis and Calorimetry*100, no. 3 (2010): 873-877.
[45] Roetzel, W., Li, M., & Luo, X. (2002). Dynamic behaviour of heat exchangers. *Advanced Computational Methods in Heat Transfer*.
[46] Mintsa, Honorine Angue, Gilles Roy, Cong Tam Nguyen, and Dominique Doucet. "New temperature dependent thermal conductivity data for water-based nanofluids." *International journal of thermal sciences* 48, no. 2 (2009): 363-371.
[47] Mostafizur, R. M., M. H. U. Bhuiyan, R. Saidur, and AR Abdul Aziz. "Thermal conductivity variation for methanol based nanofluids." *International Journal of Heat and Mass Transfer*76 (2014): 350-356.
[48] Maxwell, James Clerk. *A treatise on electricity and magnetism*. Vol. 1. Oxford: Clarendon Press, 1873.
[49] Bruggeman, Von DAG. "Berechnung verschiedener physikalischer Konstanten von heterogenen Substanzen. I. Dielektrizitätskonstanten und Leitfähigkeiten der Mischkörper aus isotropen Substanzen." *Annalen der physik* 416, no. 7 (1935): 636-664.
[50] Bhattacharya, P. S. S. K., S. K. Saha, A. Yadav, P. E. Phelan, and R. S. Prasher. "Brownian dynamics simulation to determine the effective thermal conductivity of nanofluids." *Journal of Applied Physics* 95, no. 11 (2004): 6492-6494.
[51] Li, Calvin H., and G. P. Peterson. "The effect of particle size on the effective thermal conductivity of Al_2O_3-water nanofluids." *Journal of Applied Physics* 101, no. 4 (2007): 044312.
[52] Timofeeva, Elena V., Alexei N. Gavrilov, James M. McCloskey, Yuriy V. Tolmachev, Samuel Sprunt, Lena M. Lopatina, and Jonathan V. Selinger. "Thermal conductivity and particle agglomeration in alumina nanofluids: experiment and theory." *Physical Review E* 76, no. 6 (2007): 061203.
[53] Corcione, Massimo. "Empirical correlating equations for predicting the effective thermal conductivity and dynamic viscosity of nanofluids." *Energy Conversion and Management*52, no. 1 (2011): 789-793.
[54] Kabeel, A. E., T. Abou El Maaty, and Y. El Samadony. "The effect of using nano-particles on corrugated plate heat exchanger performance." *Applied Thermal Engineering* 52, no. 1 (2013): 221-229.
[55] Jokar, Amir, and Steven P. O'Halloran. "Heat transfer and fluid flow analysis of nanofluids in corrugated plate heat exchangers using computational fluid dynamics simulation." *Journal of Thermal Science and Engineering Applications* 5, no. 1 (2013): 011002.
[56] Tamilselvan, K., B. Sivabalan, R. Prakash, M. Manojprasath, and A. Mahabubadsha. "Experimental Analysis of Heat Transfer Rate in Corrugated Plate Heat Exchanger Using Nanofluid in Milk Pastuerization Process." *International Journal of Engineering and Applied Sciences* 4, no. 5.
[57] Zamzamian, Amirhossein, Shahin Nasseri Oskouie, Ahmad Doosthoseini, Aliakbar Joneidi, and Mohammad Pazouki. "Experimental investigation of forced convective heat transfer coefficient in nanofluids of Al_2O_3/EG and

CuO/EG in a double pipe and plate heat exchangers under turbulent flow." *Experimental Thermal and Fluid Science* 35, no. 3 (2011): 495-502.

[58] Pourhoseini, S. H., N. Naghizadeh, and H. Hoseinzadeh. "Effect of silver-water nanofluid on heat transfer performance of a plate heat exchanger: An experimental and theoretical study." *Powder Technology* 332 (2018): 279-286.

[59] Wang, Zhe, Zan Wu, Fenghui Han, Lars Wadsö, and Bengt Sundén. "Experimental comparative evaluation of a graphene nanofluid coolant in miniature plate heat exchanger." *International Journal of Thermal Sciences* 130 (2018): 148-156.

[60] Ahmad, S. A., Javed, M. N., Saeed, M. Z., Syed, H., & Aslam, M. A. (2016). Experimental Investigation of plate heat exchanger using Nanofluid. *International Research Journal of Engineering and Technology*, *3*(10), 28–34.

[61] El Bécaye Maïga, Sidi, Cong Tam Nguyen, Nicolas Galanis, Gilles Roy, Thierry Maré, and Mickaël Coqueux. "Heat transfer enhancement in turbulent tube flow using Al2O3 nanoparticle suspension." *International Journal of Numerical Methods for Heat & Fluid Flow* 16, no. 3 (2006): 275-292.

[62] Buongiorno, Jacopo. "Convective transport in nanofluids." *Journal of heat transfer* 128, no. 3 (2006): 240-250.