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Thermal performance evaluation for different type of metal oxide water based nanofluids

Tang Tsz Loong [a], Hamidon Salleh [a,*], Amir Khalid [b], Hasan Koten [c]

[a] Centre for Energy and Industrial Environment Studies (CEIES), Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia, 86400, Parit Raja, Batu Pahat, Johor, Malaysia

[b] Centre of Automotive and Powertrain Technology, Faculty of Engineering Technology, Universiti Tun Hussein Onn Malaysia, Pagoh Education Hub, Johor, 84600, Malaysia

[c] Mechanical Engineering Department, Istanbul Medeniyet University, 34700, Istanbul, Turkey

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ABSTRACT

Nanofluid as advanced coolant able to enhance capability heat transfer of cooling system, but with abnormal enhancement of viscosity of nanofluids have raised doubt on its thermal performance in practical application. In present paper, a thermal performance analysis has been conducted on various types of metal oxide water based nanofluids. The evaluated metal oxide water based nanofluids were Al_2O_3, CuO, MgO, TiO_2, SiO, ZnO, and ZrO_2 water based nanofluids. A performance factor is defined under fully developed laminar pipe flow with heat transfer to evaluate the thermal performance of nanolfuids. A systematic data reduction method to organize the experimental data of thermal conductivity and viscosity of various nanofluids is presented in this paper. Based on the comparison of enhancement of thermal conductivity and viscosity, thermal performance of various types of nanofluids is evaluated and their ranking is presented.

1. Introduction

Heat transfer capability of conventional coolant such as water, ethylene glycol and engine oil can be improved by dispersing nanoparticles into them. The thermal conductivity of coolant with suspended nanoparticles was first studied by Murshed et al. [1] and later the term “Nanofluids” coined by Chol [2] to describe this type of coolant. As the advancement of nanotechnology, the nanoparticles become less expensive and easy to obtain. Therefore, many researches have been done to study application of nanofluids especially in heat transfer field. Nanofluids have been found as a candidate to bring promising hope in development of energy-efficient coolant for engineering system and it is expected to bring huge contribution in miniaturization technology [3]. Material frequently adopted for nanoparticle to disperse in base fluids includes oxides such as alumina, silica, copper oxide and zinc oxide, and metals such as copper and gold. Carbon nanotubes and diamond nanoparticles have also been adopted to prepare nanofluids. The volumetric fraction of the nanoparticles used in research is usually below 5 % [4]. Abnormal increase of the thermal conductivity relative to base fluids is observed in nanofluids. Eastman et al. [5] revealed that about 40 % enhancement of thermal conductivity as 0.3 vol% of copper nanoparticle is suspended in ethylene glycol. Das et al. [6] found that thermal conductivity enhancement 10–25 % with 1–4 vol % alumina nanoparticles suspended in water. Moreover, they also revealed that the thermal conductivity of alumina-water based

* Corresponding author.
E-mail addresses: gd160030@siswa.uthm.edu.my (T.T. Loong), hamidon@uthm.edu.my (H. Salleh), amirk@uthm.edu.my (A. Khalid), hasan.koten@medeniyet.edu.tr (H. Koten).

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Nomenclature

List of symbols

C	Specify heat capacity
C_k	Thermal conductivity enhancement ratio
C_μ	Viscosity enhancement ratio
d_p	Nanoparticles diameter size
D	Diameter of circular pipe
ΔP	Pressure drop
h	Convective heat transfer coefficient
k	Thermal conductivity
L	Length of pipe
Nu	Nusselt number
PP	Pumping power
PF	Performance factor
q	Heat flux
q_T	Total heat removed
T	Temperature
Q	Volumetric flow rate

Greek symbols

η	Figure of merit
φ	Volume fraction of nanoparticles
μ	Viscosity
ρ	density

Subscript

f	Base fluid
nf	Nanofluid
np	Nanoparticle

nanofluids is strongly dependent on temperature. Besides abnormal augmentation of thermal conductivity, unusual viscosity increment for nanofluids also has been observed. Pak and Cho [7] measured the viscosity of alumina-water based nanofluids at 1 to 10 vol%, and found it higher than prediction of Brikman-Einstein or Batchelor viscosity model. Maïga et al. [8] also had same observation that the enhancement of viscosity is higher than usual as investigated alumina-water based nanofluids.

To apply nanofluids in practical heat transfer application, it is necessary to study the effect of nanofluids on pumping power of cooling system. Since, pressure drop is significantly surge in cooling system due to the abnormal viscosity enhancement of nanofluids. The heat transfer enhancement caused by additional nanoparticles in base fluids is not advantageous if the increment of required pumping power of nanofluids is more predominant. Therefore, a thermal performance analysis is required to evaluate the potential of nanofluids since the efficiency of nanofluids is not only convective heat transfer alone, but also the pressure drops need to be concerned in the evaluation. In present paper, previous results of thermal conductivity and viscosity of metal oxides-water based nanofluids are summarized and the thermal performances of these nanofluids are evaluated. The thermal performance of nanofluids is characterized by defined performance factor under fully developed laminar pipe flow. The metal oxides-water based nanofluids are considered in this paper because they are easy to prepare and low cost compare to metallic based nanofluids. The experimental data of thermal conductivity and viscosity of metal oxides-water based nanofluids from various papers are organized in a consistence manner according to the data reduction methodology presented in present paper. Based on the performance factor and organized results from various papers, the thermal performance of Al_2O_3, CuO, MgO, TiO_2, SiO, ZnO, ZrO_2 water based nanofluids were evaluated and ranking of them is presented. As a result, it is expected that the presented thermal performance analysis will be helpful to select appropriate type of metal oxides-water based nanofluids in the practical applications.

2. Theoretical study

The thermal conductivity of nanofluids is higher than base fluids but the mechanisms behind the thermal conductivity enhancement are remained unclear. However, the experimental thermal conductivity ratio of nanofluids and base fluids for small φ, k can be linearly fitted as Equation (1). Similarly, the viscosity ratio of nanofluids and base fluids can be written as Equation (2).

$$\frac{k_{nf}}{k_f} = 1 + C_k\varphi \tag{1}$$

$$\frac{\mu_{nf}}{\mu_f} = 1 + C_\mu \varphi \tag{2}$$

Prasher et al. [9] found that the enhancement of viscosity is greater than enhancement of thermal conductivity of nanofluids ($C_\mu > C_k$). Therefore, they conducted an analysis to evaluate the thermal performance of nanofluids to prove that there is still has great benefit to use nanofluids in practical application. In the analysis, a pipe with diameter D and length L being cooled by a fluid flowing through it as shown in Fig. 1 is considered.

A uniform heat flux, q is heated the pipe wall. The pressure at inlet and outlet of the pipe are P_{in} and P_{out} respectively. The P_{out} is always smaller than P_{in} because of the pressure drop due to friction between wall and fluid flow. The pressure drop is $\Delta P = P_{in}$-P_{out} and can be expressed as follow under laminar and fully developed flow conditions

$$\Delta P = \frac{128 \mu L}{\pi D^4} Q \tag{3}$$

where, μ, L, and Q are dynamic viscosity, length of circular pipe and volume flow rate respectively. One can define a figure of merit to compare the performance of the base fluid and nanofluid as

$$\eta = \frac{q_{T,nf} / PP_{nf}}{q_{T,f} / PP_f} \tag{4}$$

where, $q_{T,nf}$&$q_{T,f}$ are total heat removed by nanofluid and base fluid respectively, whereas PP_{nf}& PP_f are pumping power of nanofluid and base fluid respectively. The total heat removed can be obtained by $q_T = \pi qDL$ and the pumping power can be determined by $PP = Q\Delta P$. In order to compare the figure of merit for the nanofluid and the base fluid, it is assumed that the volumetric flow rate is same for both coolants under same pipe geometry (D and L are same) and same heat flux. Thus, the figure of merit reduced to as following

$$\eta = \frac{\Delta P_f}{\Delta P_{nf}} \geq 1 \tag{5}$$

The figure of merit must greater or equal to unity if the nanofluids have better efficiency compare to base fluids. Moreover, the convective heat transfer of nanofluids and base fluids can be expressed as following respectively

$$h_{nf} = \frac{Nu_{nf} k_{nf}}{D_{nf}} \tag{6}$$

$$h_f = \frac{Nu_f k_f}{D_f} \tag{7}$$

where Nu_{nf}& Nu_f are nusselt number of nanofluids and base fluids respectively, k_{nf}& k_f are thermal conductivity of nanofluids and base fluids respectively, and D_f& D_{nf} are the diameter of pipe for nanofluids flow and base fluids flow respectively. Nanofluids are expected to have higher convective heat transfer than base fluids, thus, their ratio is greater than unity ($h_{nf}/h_f > 1$). By combining Equation (4) and (5), one can obtained

$$\frac{Nu_{nf} k_{nf} D_f}{Nu_f k_f D_{nf}} > 1 \quad , \; for \frac{h_{nf}}{h_f} > 1 \tag{8}$$

By fourth powering and rearrange the relation 6, a new relation is formed

$$\left(\frac{Nu_{nf} k_{nf}}{Nu_f k_f}\right)^4 > \left(\frac{D_{nf}}{D_f}\right)^4 \tag{9}$$

The term of $(D_{nf}/D_f)^4$ can be expressed as Equation (8) by using Equation (1). Where μ_{nf}& μ_f are viscosity of nanofluids and base fluids respectively, L_{nf}& L_f are length of pipe for nanofluids flow and base fluids flow respectively and ΔP_{nf}& ΔP_f are pressure loss of nanofluids and base fluids respectively.

$$\left(\frac{D_{nf}}{D_f}\right)^4 = \frac{\mu_{nf}}{\mu_f} \frac{L_{nf}}{L_f} \frac{\Delta P_f}{\Delta P_{nf}} \tag{10}$$

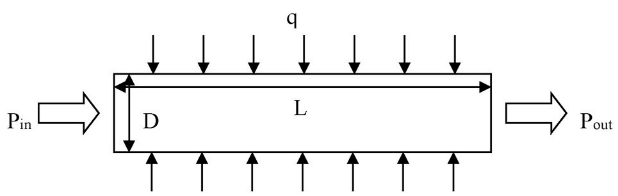


Fig. 1. Schematic of a pipe being cooled by a flowing coolant through it.

Thus, the relation 7 can rewritten as following

$$\left(\frac{k_{nf}}{k_f}\right)^4 \frac{\mu_f}{\mu_{nf}} \frac{L_f}{L_{nf}} > \frac{\Delta P_f}{\Delta P_{nf}} \left(\frac{Nu_{nf}}{Nu_f}\right)^4 \tag{11}$$

For the case where the pipe diameter and length of pipe remain unchanged where $L_f = L_{nf}$& $D_f = D_{nf}$, the pressure drop ratio $\Delta P_{nf}/\Delta P_f$ is actually equal to the figure of merit, thus, the relation 9 can be rewritten as

$$\left(\frac{k_{nf}}{k_f}\right)^4 \frac{\mu_f}{\mu_{nf}} > \eta \left(\frac{Nu_{nf}}{Nu_f}\right)^4 \tag{12}$$

For the favorable condition ($\eta > 1$) and the Nusselt number is constant in fully developed laminar pipe flow ($Nu_{nf} = Nu_f$), thus, above relation can be expressed as follow

$$\left(\frac{k_{nf}}{k_f}\right)^4 \frac{\mu_f}{\mu_{nf}} > 1 \tag{13}$$

By replacing the thermal conductivity ratio and viscosity ratio with Equation (1) and (2), an equation with C_k& C_μ can be obtained. Furthermore, with very small value of φ, by binomial expansion Equation (13) with substitution of Equation (1) and (2) can be reduced as

Table 1
Database for determination of enhancement coefficient C_k.

References	Nanoparticles	Volume fraction	d_p (nm)	Temperature (°C)	Number of data
[7]	Al_2O_3	$0.01 < \varphi < 0.045$	13	26.85	3
[11]	Al_2O_3	$0.005 < \varphi < 0.06$	36, 47	$27 < T < 37$	24
[12]	Al_2O_3	$0.03 < \varphi < 0.055$	28	23.85	3
[13]	Al_2O_3	$0.01 < \varphi < 0.034$	24.4	21.75	5
[6]	Al_2O_3	$0.01 < \varphi < 0.04$	38	$21 < T < 51$	12
[14]	Al_2O_3	$0.018 < \varphi < 0.04$	$8<d_p < 71$	$23 < T < 26$	15
[15]	Al_2O_3	$0.0027 < \varphi < 0.14$	20	$10 < T < 50$	9
[16]	Al_2O_3	$0.005 < \varphi < 0.01$	40	30	3
[17]	CuO	$0.001 < \varphi < 0.006$	50	26.85	6
[18]	CuO	$0.001 < \varphi < 0.14$	29	$22 < T < 40$	31
[6]	CuO	$0.005 < \varphi < 0.06$	28.6	$21 < T < 51$	12
[19]	CuO	$0.025 < \varphi < 0.1$	42.7	$15 < T < 35$	9
[15]	CuO	$0.026 < \varphi < 0.052$	33	$10 < T < 30$	5
[20]	TiO_2	$0.002 < \varphi < 0.02$	21	$15 < T < 35$	15
[21]	TiO_2	$0.005 < \varphi < 0.06$	21	$23 < T < 55$	9
[22]	TiO_2	$0.005 < \varphi < 0.043$	27	$18 < T < 87$	13
[15]	TiO_2	$0.006 < \varphi < 0.026$	40	$10 < T < 40$	8
[23]	TiO_2	$0.0024 < \varphi < 0.055$	$72<d_p < 76$	$20 < T < 80$	21
[24]	SiO_2	0.001	34	26.85	1
[25]	SiO_2	$0.01 < \varphi < 0.04$	17.5	22.35	4
[26]	SiO_2	$0.0045 < \varphi < 0.02$	12	21	2
[27]	SiO_2	$0.01 < \varphi < 0.025$	30	$25 < T < 50$	24
[28]	SiO_2	$0.024 < \varphi < 0.16$	10,20,30	24.85	7
[29]	SiO_2	$0.05 < \varphi < 0.2$	32	21	4
[30]	SiO_2	0.16	$10.7<d_p < 28.6$	21	3
[31]	SiO_2	$0.02 < \varphi < 0.2$	22	21	3
[32]	SiO_2	$0.01 < \varphi < 0.02$	20	25	2
[16]	SiO_2	$0.005 < \varphi < 0.01$	15	30	3
[33]	ZnO	$0.005 < \varphi < 0.01$	40	$20 < T < 60$	15
[34]	ZnO	0.01	10,30,60	20	3
[35]	ZnO	$0.01 < \varphi < 0.02$	30	$31 < T < 77$	8
[36]	ZnO	$0.0018 < \varphi < 0.02$	59,63	$10 < T < 71$	21
[37]	MgO	$0.0006 < \varphi < 0.011$	40	$24.7 < T < 60$	40
[38]	MgO	$0.0015 < \varphi < 0.0075$	40	$40 < T < 80$	20
[39]	MgO	0.000279	22.5	25	1
[40]	MgO	$0.0002 < \varphi < 0.0012$	20	26.85	5
[41]	MgO	$0.005 < \varphi < 0.06$	$20< d_p < 60$	24.7	16
[42]	ZrO_2	$0.005 < \varphi < 0.01$	20	20	3
[16]	ZrO_2	$0.005 < \varphi < 0.01$	25	30	3
[15]	ZrO_2	$0.0018 < \varphi < 0.098$	20	26.85	3
[43]	ZrO_2	$0.0001 < \varphi < 0.002$	30	$10 < T < 65$	60
[44]	ZrO_2	0.04	44	25	1
[45]	ZrO_2	0.005	25	25	1

$$\frac{(1+C_k\varphi)^4}{(1+C_\mu\varphi)} \approx 1+(4C_k-C_\mu)\varphi>1 \tag{14}$$

In Equation (14), a performance factor PF can be defined by the enhancement coefficient of thermal conductivity and viscosity as follow

$$PF = 4C_k - C_\mu > 0 \tag{15}$$

For a nanofluids with good thermal performance and be potential to be selected as heat transfer fluids, it should have a performance factor PF greater than 0 and the greater the performance factor means better thermal performance is expected as compared to conventional base fluids.

3. Methodology

3.1. Database to perform thermal performance evaluation

As mentioned in previous section, the main objective of the present work is to evaluate the thermal performance of Al_2O_3, CuO, MgO, TiO_2, SiO, ZnO, ZrO_2 water based nanofluids. The thermal performance is evaluated by a performance factor as defined in Equation (15). The enhancement coefficients (C_k& C_μ) over the volume fraction domain have to determine first before the evaluation. To obtain the enhancement coefficients, experimental databases are obtained from the open literature as shown in Table 1 and 2. Table 1 is an experimental database to determine C_k where the database consists of thermal conductivity of various metal oxides based nanofluids with total 453 data points. Whereas, Table 2 is an experimental database to determine C_μ where the database consists of viscosity of various metal oxides based nanofluids with total 842 data points.

There are various factors affecting the thermal physics property of nanofluids. Thus, in order to summarize the data in a consistent manner to evaluate thermal performance of metal oxides based nanofluids. Several rules had been followed during the selection of published data to develop the databases.

Table 2
Database for determination of enhancement coefficient C_μ.

References	Nanoparticles	Volume fraction	d_p (nm)	Temperature (°C)	Number of data
[46]	Al_2O_3	$0.01 < \varphi < 0.09$	36, 37	$19 < T < 72$	148
[47]	Al_2O_3	$0.0001 < \varphi < 0.003$	30	21	6
[48]	Al_2O_3	$0.0001 < \varphi < 0.0031$	30	21	6
[12]	Al_2O_3	$0.01 < \varphi < 0.062$	43	23.85	6
[49]	Al_2O_3	$0.004 < \varphi < 0.13$	$13< d_p < 47$	20	35
[16]	Al_2O_3	$0.005 < \varphi < 0.01$	40	30	3
[46]	CuO	$0.01 < \varphi < 0.09$	29	$20 < T < 67$	112
[50]	CuO	$0.0016 < \varphi < 0.017$	11, 25	$10 < T < 50$	104
[51]	CuO	$0.0032 < \varphi < 0.017$	50	$24.7 < T < 80$	21
[52]	CuO	$0.001 < \varphi < 0.005$	40	$20 < T < 80$	21
[53]	CuO	$0.002 < \varphi < 0.03$	55	24	4
[54]	TiO_2	$0.0025 < \varphi < 0.012$	95	22	3
[20]	TiO_2	$0.002 < \varphi < 0.02$	21	$15 < T < 35$	15
[23]	TiO_2	0.0254& 0.0554	72,73	$10 < T < 70$	14
[22]	TiO_2	$0.01 < \varphi < 0.043$	27	$31 < T < 67$	12
[7]	TiO_2	$0.01 < \varphi < 0.032$	27	$19 < T < 67$	21
[32]	SiO_2	$0.01 < \varphi < 0.02$	20	25	2
[25]	SiO_2	$0.008 < \varphi < 0.03$	17.5	25	3
[26]	SiO_2	$0.004 < \varphi < 0.04$	12	21	3
[55]	SiO_2	$0.0008 < \varphi < 0.02$	$7< d_p < 40$	25	35
[56]	SiO_2	$0.0045 < \varphi < 0.04$	12	$20 < T < 50$	21
[16]	SiO_2	$0.005 < \varphi < 0.01$	15	30	3
[35]	ZnO	$0.005 < \varphi < 0.05$	30	22	4
[57]	ZnO	$0.003 < \varphi < 0.017$	40	$25 < T < 55$	12
[36]	ZnO	$0.000145 < \varphi < 0.0093$	59, 63	$10 < T < 70$	21
[33]	ZnO	$0.005 < \varphi < 0.02$	40	$20 < T < 60$	18
[58]	ZnO	$0.0025 < \varphi < 0.015$	37.5	$35 < T < 55$	11
[59]	MgO	$0.0025 < \varphi < 0.02$	40	26.85	42
[41]	MgO	$0.005 < \varphi < 0.02$	$20< d_p < 60$	50, 60	16
[60]	MgO	$0.0007 < \varphi < 0.0125$	20	$25 < T < 60$	40
[38]	MgO	$0.0015 < \varphi < 0.0075$	40	50, 60	8
[61]	MgO	$0.0002 < \varphi < 0.0012$	40	26.85	5
[62]	ZrO_2	$0.000125 < \varphi < 0.002$	30	$10 < T < 65$	60
[42]	ZrO_2	$0.005 < \varphi < 0.01$	20	20	3
[16]	ZrO_2	$0.005 < \varphi < 0.01$	25	30	3
[45]	ZrO_2	0.0054	25	25	1
[44]	ZrO_2	0.04	44	25	1

i. Only water-based nanofluids properties are presented because the main objective of current paper is to evaluate the thermal performance of metal oxides water based nanofluids
ii. Only two steps method is considered. Addition of surfactant and pH adjustment is acceptable in current evaluation because it is unavoidable for some production of metal oxides nanofluids. For some cases, dilution of purchased nanofluids is still considered as two steps method although the purchased nanofluid might be produced by one step method. This is because the sonication and stirring process are involved in the dilution process and the added nanofluids can seemingly as nanoparticles but just in watered form.
iii. Only spherical shape nanoparticles is considered. This is because the shape of nanoparticles has strong correlations to thermal physical properties.
iv. When there are multiple values at the same volume fraction due to surfactant and sonication time, the optimum value is selected. For the case, both viscosity and thermal conductivity are studied, Equation (15) is used to calculate the results and the property with optimum PF is selected. If only either one property is study, the optimum value is preferred.

3.2. Data reduction procedure for thermal performance evaluation

Previously, Lee et al. [10] had used similar methodology reduction to evaluate thermal performance of SiO_2–H_2O based nanofluids. They evaluated the nanofluids under same room temperature and without considered the effect of nanoparticles diameter size. However, same methodology reduction is not suitable in present case, because the majority papers studied on thermal physical properties of metal oxides in wide range of temperature and nanoparticles diameter. The temperature and nanoparicles size are important parameters of nanofluids. Thus, to account the effect of temperature and nanoparticles diameter size in the thermal performance evaluation, several steps are taken in the calculation.

1) Convert each relative thermal conductivity and viscosity data point found in open literatures to enhancement coefficients (C_k& C_μ) by apply Equation 16

$$C_k = \left(\frac{k_{nf}}{k_f} - 1\right)\frac{1}{\varphi} \& C_\mu = \left(\frac{\mu_{nf}}{\mu_f} - 1\right)\frac{1}{\varphi} \tag{16}$$

2) Extracted data points of C_k and C_μ respective to each type of metal oxide water based nanofluids from range of $0 < \varphi < 0.03$ and $20 < T < 50$.
3) Eliminate the negative C_k and C_μ
4) Apply Chauvenet's criterion to eliminate the C_k and C_μ with abnormal values (i.e. too large)
5) Arrange the extracted data points in form of $C_k = f\,(T, d_p)$ and $C_\mu = f\,(T, d_p)$. The repeated C_k and C_μ is averaged at the same (T, d_p).
6) Apply linear interpolation on specify points (d_P, T) to estimate C_k and C_μ on that points.
7) Calculate performance factor, PF by substitute obtained C_k and C_μ to Equation 15

The scatteredInterpolant () algorithm which found in Matlab software are used to perform the task of linear interpolation on the specific point (T, d_p). Furthermore, with aided of this algorithm, 3D surface graph of $C_k = f\,(T, d_p)$ and $C_\mu = f\,(T, d_p)$. can be plotted and the C_k and C_μ can be determined on each defined point (T, d_p). Fig. 2 illustrates the linear interpolated 3D surface of C_k and C_μ of MgO–H_2O based nanofluids on domain of d_p and T.

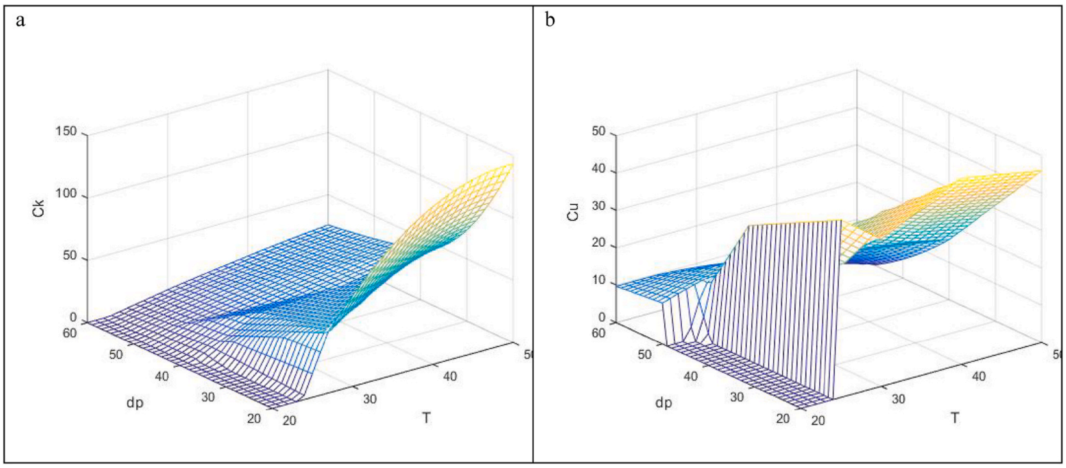


Fig. 2. Linear interpolated 3D surface of C_k and C_μ of MgO–H_2O based nanofluids (a) C_k versus d_p and T; (b) C_μ versus d_p and T.

Fig. 3 illustrates that the number of publication of nanoparticles diameter size based on the developed experimental database. As observed, the number of publication for 20–30 nm nanoparticles size is the highest; this indicates the particle size range between 20 and 30 nm is the most frequent used nanoparticles size among the range of particle diameter 0–100 nm. Thus, the average 25 nm is chosen as a compare basis in thermal performance evaluation of metal oxides based nanofluids. In general, the cooling units do not cool down the equipment to low temperature 22.2 °C which the comfort temperature for human. The acceptable operating temperature for most electrical devices is 40 °C or greater, excessive cooling can lead to energy wasting and unnecessary maintenance costs. Therefore, based on the mentioned reasons, the temperature 40 °C and particle diameter 25 nm is chosen as compare basis in the thermal performance analysis of Al_2O_3, CuO, MgO, TiO_2, SiO, ZnO, ZrO_2 water based nanofluids.

4. Results and discussions

The experimental data points of enhancement ratio of thermal conductivity and viscosity obtained from various literature in range $0 < \varphi < 0.03$ and $20 < T < 50$. are shown in Fig 4 and 5 respectively. The enhancement coefficients of C_k and C_μ at 40 °C and particles size 25 nm are denoted as C_k (40,25) and C_μ(40,25) respectively. These values are presented on the Figures and the plotted line based on C_k (40,25) and C_μ(40,25) are located between maximum and minimum bound of C_k and C_μ. These enhancement coefficients are predicted by linear interpolation on point (40 °C, 25 nm). By utilizing these values, performance factor can be calculated based on Equation (15). The calculated PF of each metal oxide water based nanofluids under same 40 °C and 25 nm is illustrated in Fig. 6.

The performance factor PF greater than 0 indicates that the nanofluids has better heat transfer performance than base fluid, the larger the PF, the better nanofluids compared to its base fluid. As seen in Fig. 6, one can notice all nanofluids except ZrO_2–H_2O based nanofluids performed better than pure water and the best option is MgO–H_2O water based nanofluids. The best scenario of MgO–H_2O based nanofluids is attributed to the high thermal conductivity of MgO nanoparticles as it is the highest among other metal oxides as shown in Table 3. However, ZrO_2 particles possess higher thermal conductivity than SiO_2 but ZrO_2 based nanofluids is located in the lowest ranking with a negative PF. This is attributed to the high viscosity enhancement of ZrO_2 based nanofluids with approximately $C_\mu = 188.39$ as observed in Fig. 5f.

As mentioned previously, Lee et al. [10] had calculated the performance factor of SiO_2–H_2O based nanofluids under room temperature and negative performance factor are obtained in their analysis. Different studies can be found in the literature [67–72]. However, in current thermal performance analysis, a small positive PF is obtained for SiO_2–H_2O based nanofluids at 40 °C. This shows that the increment of temperature does increase the PF since the thermal conductivity of nanofluids increase and viscosity decrease as temperature rises. However, the thermal performance of SiO_2–H_2O based nanofluids is the second lowest as compare to other type of nanofluids. This is because the poor thermal conductivity of SiO_2 nanoparticles, it possesses the lowest value as compare to other metal oxides as shown in Table 3.

Furthermore, both nanoparticles size and temperature of nanofluids are crucial to thermal performance of nanofluids. To study the effect of them on heat transfer performance, the MgO–H_2O based nanofluids with various particles sizes and temperature are illustrated in Fig. 7. As observed Fig. 7b, the thermal performance of MgO–H_2O based nanofluids increase as used nanoparticles size decrease. This is attributed to the decrement of viscosity enhancement over volume fraction as particles loading size become smaller. Furthermore, the thermal performance of MgO–H_2O based nanofluids is escalated as the working temperature rises as observed in Fig. 7a. This is because of the intensified of particles Brownian effect caused by the rising temperature has escalated the thermal conductivity drastically and the viscosity of nanofluids also decreases as the temperature increases, these combination of effects caused increasing in thermal performance.

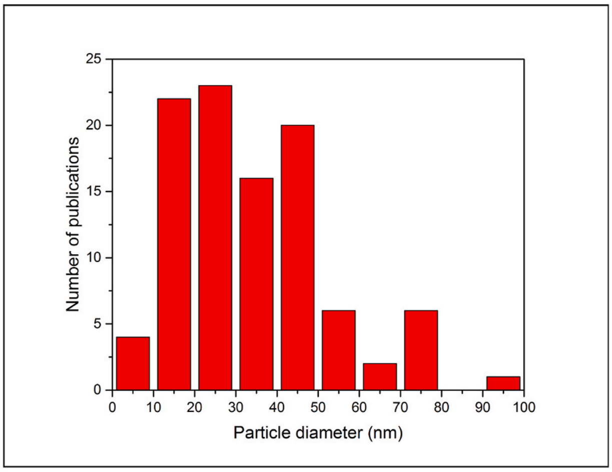
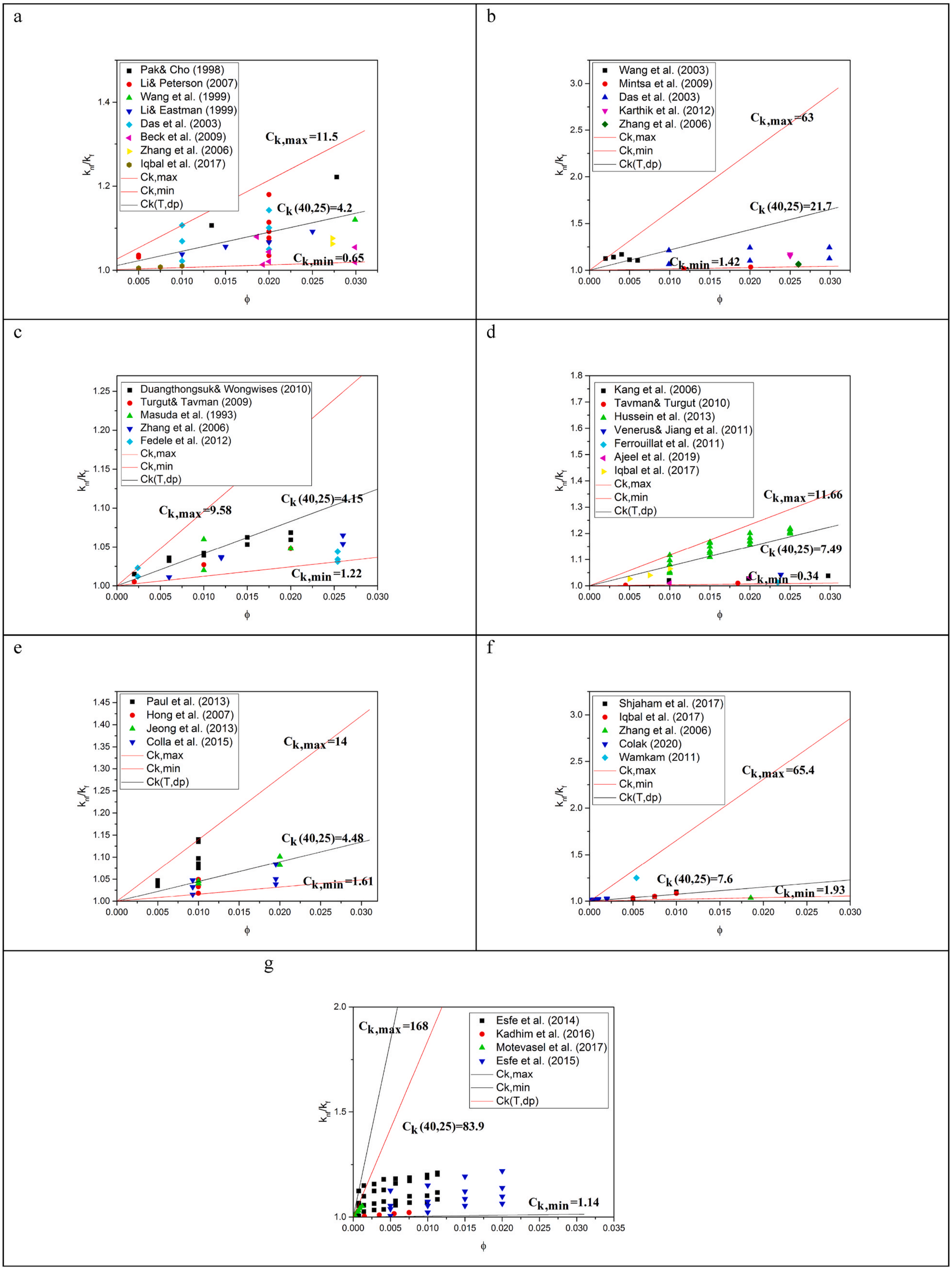


Fig. 3. Number of publication of nanoparticles diameter size based on experimental databases.



(caption on next page)

Fig. 4. Graphs of k_{nf}/k_f vs φ of (a) Al_2O_3; (b) CuO; (c) TiO_2; (d) SiO_2; (e) ZnO; (f) ZrO_2; (g) MgO water based NF.

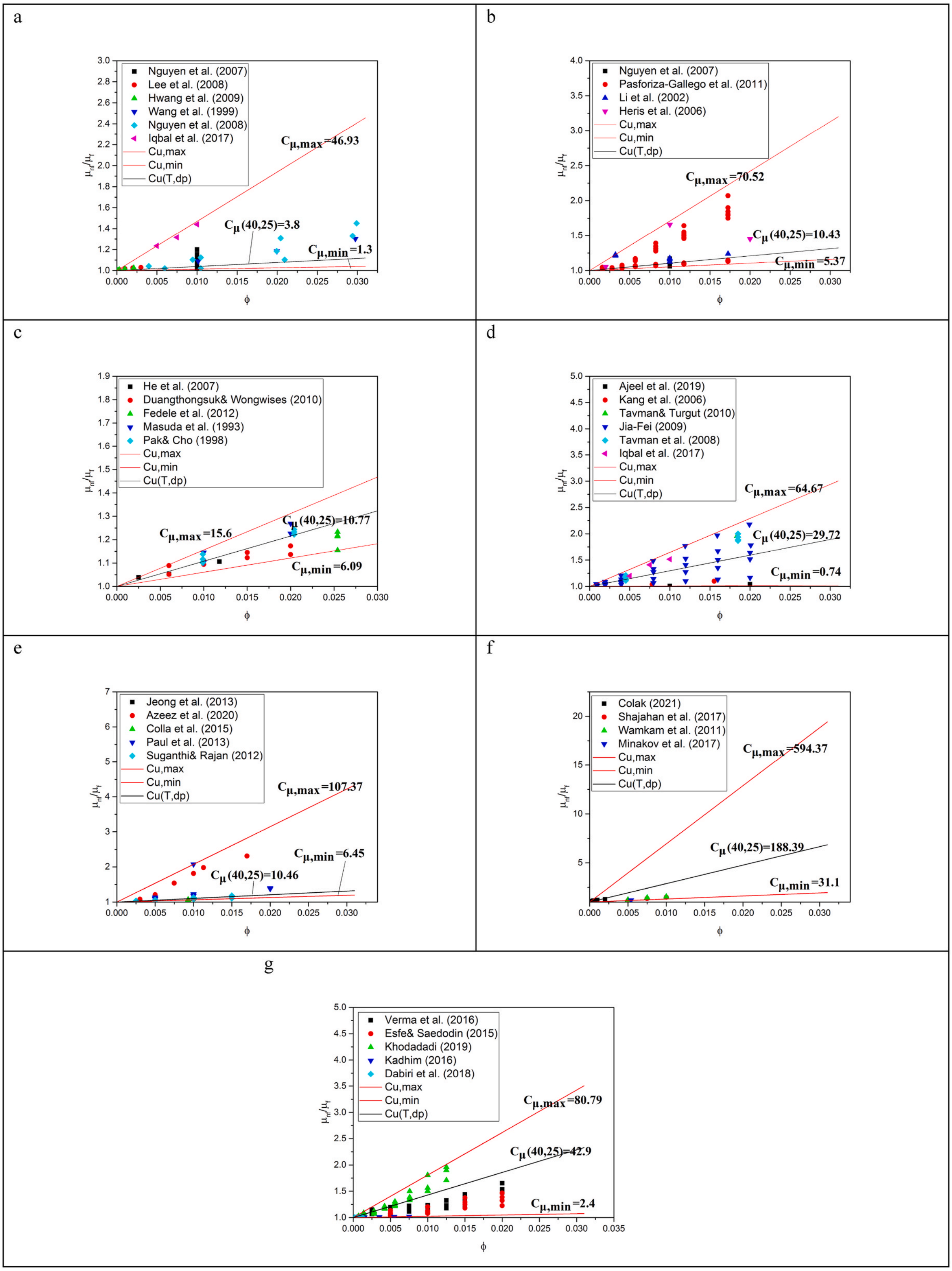


Fig. 5. Graphs of μ_{nf}/μ_f vs φ of (a) Al_2O_3; (b) CuO; (c) TiO_2; (d) SiO_2; (e) ZnO; (f) ZrO_2; (g) MgO water based NF.

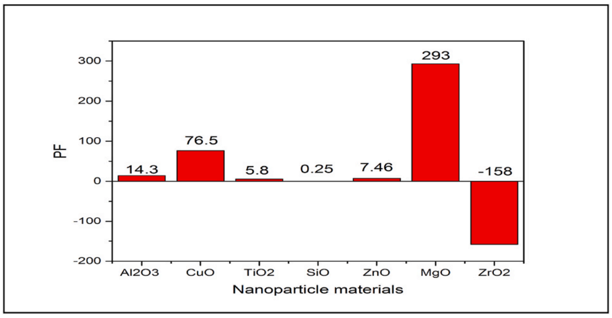


Fig. 6. Performance factors with respect to different type of metal oxides water based nanofluids.

Table 3
Thermo-physical properties of metal oxides.

Metal Oxide	k (*W/m.k*)	ρ (*kg/m*^{3})	C_p (J/kg)
Al_2O_3	36.0 [27]	3880 [27]	773 [27]
CuO	33 [63]	6000 [63]	551 [63]
MgO	48.4 [64]	3585 [64]	903 [64]
TiO_2	8.4 [27]	4175 [27]	692 [27]
ZnO	13 [65]	5600 [65]	504.9 [66]
SiO_2	1.4 [27]	2200 [27]	745 [27]
ZrO_2	2.75 [43]	5.89 [43]	455 [43]

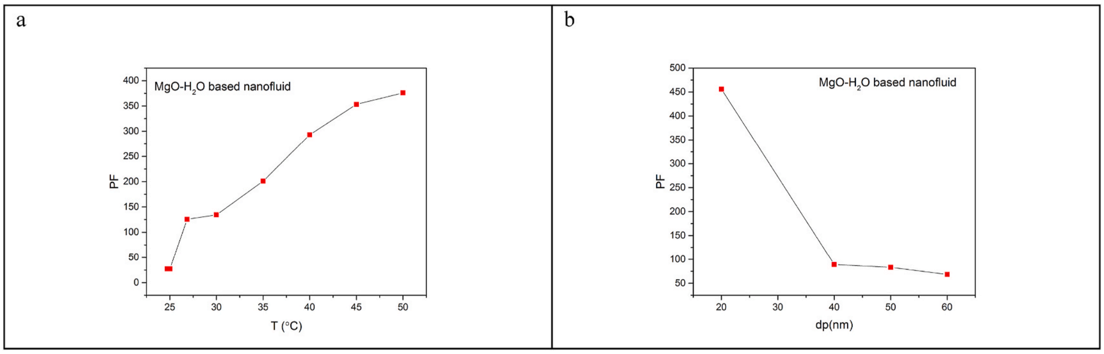


Fig. 7. Variation of performance factors of MgO–H_2O based nanofluids to (a) Temperature; (b) Nanoparticles Diameter.

5. Conclusion

Thermal performance analysis has been performed to evaluate heat transfer performance of Al_2O_3, CuO, MgO, TiO_2, SiO, ZnO, and ZrO_2 water based nanofluids. Databases of enhancement thermal conductivity and viscosity are developed and summarized from open literature. Thermal performance factor defined under heat pipe laminar flow condition is adopted to study the heat transfer performance of various type of metal oxides water based nanofluids. The major findings can be drawn as follows.

1. Based on the statistical result from the experimental database, the most used nanoparticles sizes are in range of 20–30 nm. The average of 25 nm is taken as compare basis in thermal performance evaluation.
2 40 °C is the acceptable operating temperature of electronic cooling.
3. Thus, PF calculation is done on 40 °C and 25 nm by means of 3 dimensional linear interpolation
4. The performance factor of Al_2O_3, CuO, TiO_2, SiO, ZnO, ZrO_2, MgO water based nanofluids are 14.3, 76.5, 5.8, 0.25, 7.46, 29.3& −158 respectively. This indicates that the all mentioned metal oxide based nanofluids excerpts ZrO_2 water based nanofluids are advantageous as a heat transfer fluids.
5. Particles size and working temperature affect thermal performance of nanofluids. Refer to MgO–H_2O based nanofluids, the thermal performance enhances as particle size decreases and temperature increases.

Credit author statement

All authors have contributed to the all parts.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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