Journal of Advanced Research Design 51, Issue 1 (2018) 14-25

Penerbit Akademia Baru

Journal of Advanced Research Design

Journal homepage: www.akademiabaru.com/ard.html
ISSN: 2289-7984

Heat Transfer Performance of Hybrid Nanofluid as Nanocoolant in Automobile Radiator System

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ARTICLE INFO

Article history:
Received 15 October 2018
Received in revised form 21 November 2018
Accepted 27 November 2018
Available online 29 December 2018

Keywords:
Graphene, erosion-corrosion, water pump, coolant, tribological impact

ABSTRACT

In automobile cooling system, mixture of water and ethylene glycol is widely used as coolant. For many years, nanofluid has been reported to enhance thermal properties of conventional heat transfer fluid due to dispersion of solid particles which exhibit superior thermal conductivity. Many past researchers found significant improvement of heat transfer rate in automobile cooling system by adopting nanofluid as coolant. However, most of them reported on drawback of using nanofluid such as low stability, high cost and high pressure drop but not trobological impact. Thus, this research tends to determine stability, thermophysical properties, hydrothermal performance and erosion-corrosion effect of a novel hybrid nanofluid in automobile cooling system. Stability test of proposed nanofluid will be evaluated based on zeta potential and absorbance value. After that, thermophysical properties measurement of nanofluid will be carried out using the most stable preparation method. Hydrothermal performance of the novel nanofluid will be evaluated using Goodness factor. For erosion-corrosion study, working parameters and procedures followed ASTM D2809-09 standard. Each pump surface profile was inspected using 3D imaging microscope to obtain surface change details. In addition, precise weight measurement was carried out to determine total material loss due to various coolants. It was observed that corrosion effect was about the same for base coolant and nanocoolants. Material loss due to erosion-corrosion effect was increased with increasing concentration of graphene nanoplatelets in coolant. Based on ASTM 2809-09 standard, erosion-corrosion damage on impeller using these nanocoolants was found to be minimal and can be considered to be incorporated in future cooling system.

1. Introduction

For few decades until today, vehicle engine system is becoming more advanced due to men's incessant pursue of higher performance engines. However, heat generated from engine block system is a huge drawback. In a car engine cooling system, coolant is initially pumped into engine

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block system from radiator. Then the coolant absorbs heat generated from engine blocks and flow back to radiator when it reached certain temperature. At the last stage, coolant flowing inside the radiator will be cooled by surrounding air with the aid of fan behind the radiator [18-19].

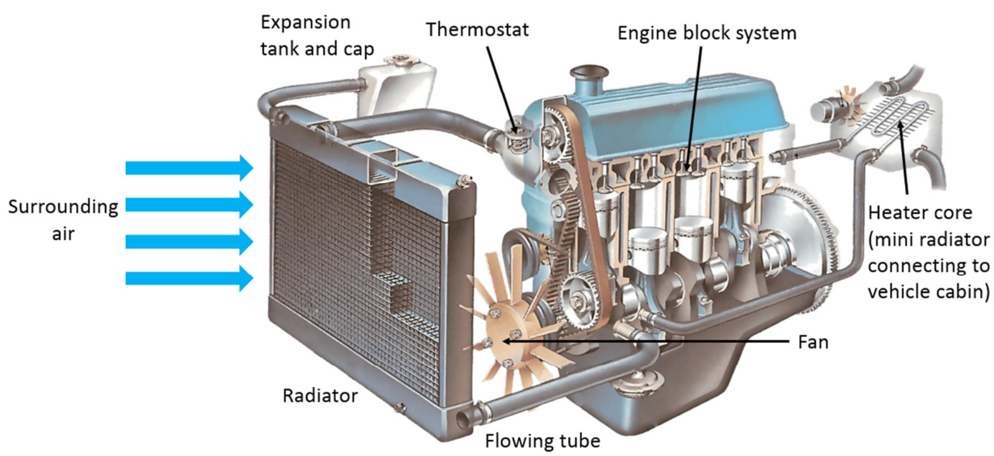

Fig. 1. Automobile engine cooling system

Failure of efficient heat transfer could lead to overheating of engine and next damaging engine block body. Thus, maintaining temperature of engine block system is crucial to strengthen its life span and performance. Radiator acts as heat exchanger in vehicle cooling system to transfer heat away from the engine block system to surrounding. In order to attract more users, many improvements have been done by engine companies on radiator system since back then, such as adding fins to increase surface area, changing radiator material and using different configuration of tubes. Nonetheless, there are limitations on these renovation in which few consequences have to be taken into consideration: size of radiator, burden on car, cost of material, durability of material and more.

In the history of development, water was first used as coolant in vehicle cooling system. In some countries with extremely cold weather, water tends to freeze and causes damage to flowing tubes and engine block due to its volume expansion. Then, antifreeze agent was introduced as additive to make up deficiencies of water that has unsatisfying freezing point and low boiling point. Increasing boiling point of coolant allows it to reach higher temperature without being boiled to vapor state, thus more heat can be absorbed and rejected in a cycle (vapor is poor heat conductor). Nowadays, water-ethylene glycol mixture is used as conventional automobile coolant because water and ethylene glycol alone are poor heat transfer fluid [20-22]. Table 1 and Figure 2 below show the properties of water, ethylene glycol and water-ethylene glycol mixture.

Table 1
Properties of water and ethylene glycol [1]

	Water	**Ethylene glycol**
Density (g/cm^3)	1.0	1.1132
Freezing Point (°C)	0	-12.9
Boiling Point (°C)	100	197.3
Viscosity (Ns/m^2)	1.002×10^{-3}	1.61×10^{-2}
Thermal Conductivity (W m/K)	0.609	0.258

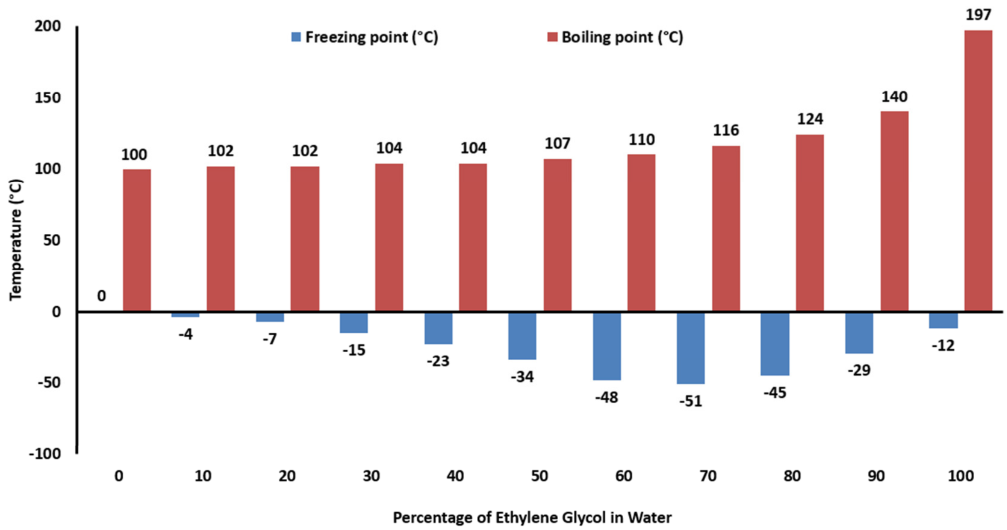

Fig. 2. Boiling and freezing points result from ratio of ethylene glycol in water

To further increase the capability of conventional coolant to transfer heat, nanofluid has become another alternative today. Up to authors' literature review, implantation of nanofluid into vehicle cooling system was initiated by Choi *et al*., [2] in 2001. They measured thermal conductivity of metal and metal oxide nanofluids and found that the measured values were much higher than expected values. Thus, they proposed that nanofluid could enhance vehicle thermal performance and this had led former researchers to start exploring the superior performance of nanofluid as coolant in automobile cooling system.

From literature, there is number of past researchers who studied in heat transfer performance of nanofluids in actual vehicle radiator [23-30]. The summary is tabulated in Table 2 below.

Despite nanofluid can enhance heat transfer performance of base fluid significantly, there are several drawbacks reported by past researchers such as low stability, high pressure drop and high cost. Anyhow, there are very few researchers reported the tribological impact of using nanofluid which could deal severe damage to their system. This is important as one of the reasons of engine overheating is due to severely eroded impeller which led to inefficiency in cooling process.

Celata *et al*., [16] tested erosion-corrosion effect on three different flat metal plates which include stainless steel AISI 316, copper and aluminium. In their experiment, they used water and different water-based nanofluids: 9 wt% TiO_2, 9 wt% Al_2O_3, 9 wt% ZrO_2, 3 wt% SiC and 3 wt% Al_2O_3. For their comparison purpose, they covered portion of the metal plate with erosion-resistant material so a reference point was created for showing the difference of plate thickness before and after erosion test using profilometer. The erosion effect due to different nanofluids is summarized in Table 3 below. In addition, they observed that TiO_2 caused least pump gears damage meanwhile 9 wt% Al_2O_3 caused the most severe damage. From their SEM image, they concluded that material removal by mechanical erosion is due to the use of nanofluids while water caused intergranular corrosion on the metals.

Rashidi *et al*., [17] investigated the synergistic effect of sea water and gamma-alumina nanoparticles on cylindrical carbon steel specimens using a hydrodynamically smooth rotating cylinder electrode. Sea water is produced using distilled water and sodium chloride with pH around 8.3. Diameter of nanoparticles is averagely sized 20 nm. From their results, nanoparticles were found to be a corrosion inhibitor but still had higher impact on erosion rate of low carbon steel when compared to sea water. Besides that, erosion-corrosion was found to contribute the most in material loss compared to pure corrosion and erosion, in both nanofluid and base fluid testing.

Table 2
Past studies on nanofluid used in actual vehicle radiator

Type of radiator	Nanofluid	Concentration	Enhancement compared to base fluid	Ref
Shell and tube heat exchanger	γ-Al_2O_3+water	0.3 vol.%	Nusselt number (29.8%) Overall heat transfer coefficient (19.1%)	[3]
	Al_2O_3 (20 nm)+ water	4 vol.%	Average heat transfer coefficient (11.94%)	[4]
Double pipe heat exchanger	Aluminum Nitride + EG	4 vol.%	Thermal performance (35%)	[5]
Double tube heat exchanger	Al_2O_3 (20 nm) + water	1 vol.%	Nusselt number (20%)	[6]
	TiO_2 (21 nm) + water	1 vol.%	Heat transfer coefficient (26%)	[7]
	γ-Al_2O_3 (20 nm) + water	0.2 vol.%	Heat transfer rate (7.32%)	[8]
	γ-Al_2O_3 (20 nm) + water	0.15 vol.%	Heat transfer coefficient (25%)	[9]
Air-cooled heat exchanger	Hybrid carbon (20-30 nm)+water	0.02 wt. %	Heat exchange capacity (13%) System efficiency factor (11.7%)	[10]
Double pipe U-bend heat exchanger	Fe_3O_4 (36 nm) + water	0.06 vol.%	Heat transfer enhancement (14.7%) Effectiveness (2.4%)	[11]
Cross flow heat exchanger	Fe_2O_3 + water and Al_2O_3 + water	0.65 vol.%	Heat transfer enhancement Fe_2O_3 (9%), Al_2O_3 (7%)	[12]
	Al (84 nm) + double-distilled water	0.3 vol.%	Effectiveness (11.57%) Heat transfer coefficient (18.39%)	[13]
Counter flow heat exchanger	Ag (30-90 nm) + water/EG (70:30)	0.45 vol.%	Convective heat transfer coefficient (42%)	[14]
Cone helically coiled tube heat exchanger	MWCNT (50-80 nm) + water	0.5 vol.%	Nusselt number (52%)	[15]

As shown in literature, the use of nanofluid could cause thinning of material by erosion. Thus, this research includes erosion-corrosion damage of various nanofluids on vehicle cooling system since there are very few related studies published. As for novelty obtained from literature gap, authors propose a novel hybrid nanofluid and tend to determine its stability, thermophysical properties and hydrothermal performance in this research.

Table 3
Erosion effect of various nanofluids on different metals

Nanofluid	Erosion effect on metals
TiO_2	No effect on copper and stainless steel.
	Some effect on aluminium, but water caused more material loss.
Al_2O_3	No effect on stainless steel.
	Small effect on copper.
	Extreme large effect on aluminium, about 300 times more than effect of water.
ZrO_2	No effect on stainless steel.
	Large effect on copper.
	Very large effect on aluminium.
SiC	Small effect on all tested metals.

2. Methodology
2.1 Preparation of Nanofluid

From most past studies, nanofluids were prepared using two-step method due to lower cost, simpler procedures and more amount of nanofluids can be produced in a single time. Hence, the same method will be implemented for all nanofluids in this research.

Titanium oxide (TiO_2) nanopowder was purchased from US Research Nanomaterial, Inc. The TiO_2 nanopowder has purity of 99.9%, bulk density of 3900 kg/m^3 and 18 nm of diameter. For graphene nanoplatelets (GnP), it was purchased from Cheap Tubes. The details of graphene nanoplatelets (GnP) are shown below.

Table 4
Properties of graphene nanoplatelets

Thickness	< 4 nm
Purity	> 99 wt%
Number of layers	< 4 layers

Sodium sulphate, sodium chloride and sodium bicarbonate were first mixed into distilled water with quantity of 148 ppm, 165 ppm and 138 ppm respectively. The mixture (corrosive water) was then kept at room temperature. For base coolant, 2 L of conventional car coolant was poured into corrosive water in volume ratio of 1:5. For nanocoolant (nanofluid), graphene nanoplatelets were added into base coolant with different concentrations, stirred at 500 rpm for 30 minutes and followed by homogenizing. For hybrid nanocoolant, TiO_2 and GnP will be mixed at 50:50 weightage ratio.

Stability for all samples will be inspected from time to time to observe the slope of deterioration. The best surfactant and sonication time for each nanofluid will be chosen as the best preparation criteria based on the least deterioration of stability. All nanofluids will be prepared again based on the new criteria and thermophysical properties measurement will be carried out using specified apparatus listed in Table 5.

Table 5
Apparatus used for preparation and properties measurement of nanofluids

Device	**Function**
Decagon KD2-Pro Thermal Analyzer	To measure thermal conductivity of nanofluid
Ultrasonic homogenizer NUH-5	To homogenize nanofluid through sonication
Heating bath EWB-20	To maintain temperature of sample
Magnetic stirrer MS-170	To stir mixture of nanoparticles and base fluid
Viscometer WVS-2M	To measure viscosity of nanofluid

2.2 Experiment Setup

This research consists of two test rigs: for erosion-corrosion and heat transfer study, which presented in Figure 3 and 4 respectively. Most objectives of this research will be accomplished using test rig for heat transfer study. The test rig for erosion-corrosion study will be dissembled and modified by adding other components for heat transfer study.

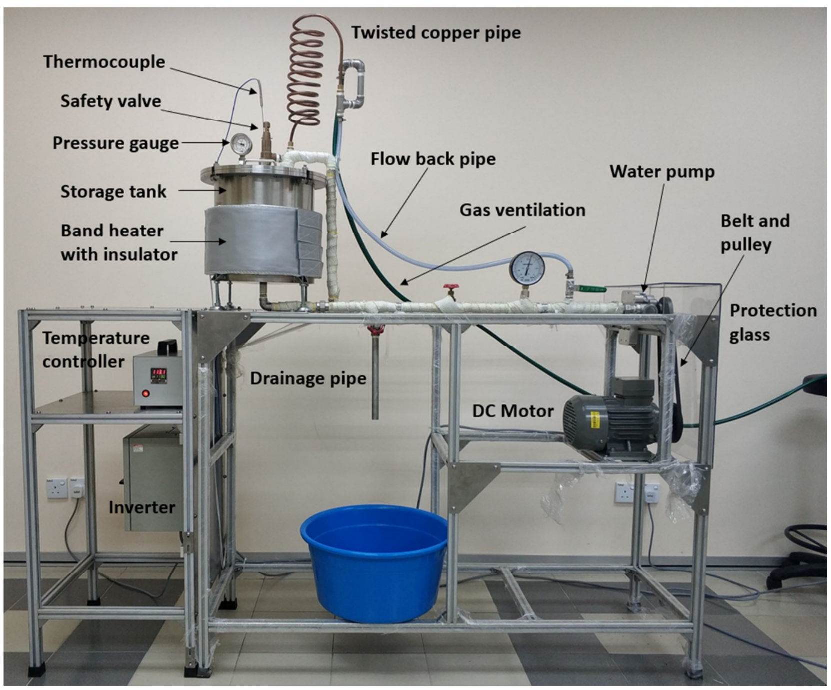

Fig. 3. Test rig for erosion-corrosion study

Figure 3 presents the experiment setup used in this research. Stainless steel 304 pipes were used to prevent corrosion and erosion attack due to long duration testing. Total length and internal diameter of pipes are about 2.6 m and 1.5 cm respectively. Glass wool was wrapped around the pipes as insulator to minimize heat loss to surrounding. The 25 L tank is made up of stainless steel 304 with thickness of 11 mm and several openings were made on the tank cover to install pressure gauge, thermocouple, safety valve, flow back pipe and coolant feeder. Pressure gauges were placed above tank and before pump inlet to obtain system pressure and pump inlet pressure. Three-phase DC motor with 2 horsepower, 380 V and 2715 rpm was used. An inverter (Schneider ATV312) was installed between motor and power source so the speed of motor can be varied. Shimaden SRS10A temperature controller (250 V, AC) with accuracy of 0.1 ℃ was used. Constant heat flux was supplied to the tank by employing a band heater (Sakaguchi E.H VOC. Corp.) with rated power of 1400 W, 240 V and maximum heating temperature of 300 ℃. Glass wool of 25 mm thickness was applied on band heater for reducing heat loss and safety purpose. Twisted copper pipe was placed above safety valve to allow condensation of steam back into liquid droplet and flow back into flowing pipe.

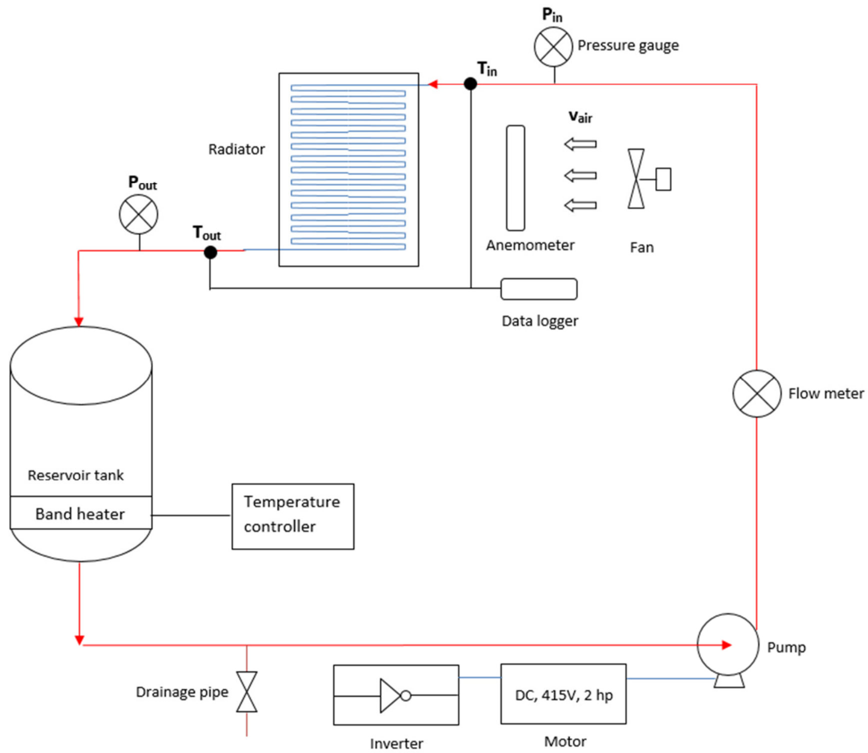

Fig. 4. Schematic diagram of test rig for heat transfer study

Table 6
Differences between test rigs in Figure 3 and 4

Difference	**Test rig for corrosion-erosion study (Figure 3)**	**Test rig for heat transfer study (Figure 4)**
Size of coolant tank	25 Liters	3 Liters
Thermocouple	One (in coolant tank)	Three (another two at radiator)
Pressure transducer	Two (in tank and before pump inlet)	Four (another two at radiator)
Flow meter	No	Yes
Components	Without radiator and cooling fan	With radiator, cooling fan and data logger

2.3 Experimental Procedure for Erosion-corrosion Study

Cleaning process was performed before each test was carried out. Firstly, a flushing pump was installed to circulate tap water in the system. The pump speed was adjusted to around 2675 rpm and run for 5 min, for three times. Digital tachometer TM-4100 with resolution of 0.1 rpm was used and three readings were taken to ensure rotational speed accuracy. The system was drained and filled with another cleaning solution. The cleaning solution which made up of water, oxalic acid and citric acid was then heated and controlled at about 80°C with the pump operating at 2675 rpm for 60 min. The system was drained and cleaned with tap water for 5 minutes (for three times). Cool tap water was then mixed with sodium carbonate and circulated in the system no more than 10 min to avoid the formation of carbonates on copper components. The system was drained and cleaned with tap water. A portion of last flushed water was mixed with 5 wt% calcium chloride and if precipitation or turbidity was observed, system cleaning with tap water was repeated until clear mixture was obtained.

Every impeller was weighted and inspected using 3D microscope before installing the whole pump for each test. The system was first filled with 12 L of corrosive coolant prepared earlier, followed by these three conditions:

1. Pump speed with 4600 rpm
2. 35 to 38°C coolant temperature
3. Pump inlet pressure with gage reading of 6.8 kPa vacuum by adjusting throttling valve.

After achieving conditions above, coolant temperature was further increased to 113°C and the position of throttling valve was remained untouched till the end of experiment. The temperature controller was calibrated two times at 113°C to maintain temperature of coolant all the time. The whole system was operated continuously for 100 hours. When the experiment was completed, pump cover and impeller were cleaned with distilled water and dried for microscopic inspection and weight measurement.

2.3 Experimental Procedure for Heat Transfer Study

The parameters are limited to inlet temperature (30 – 90 ^{o}C), nanofluid concentration (0.01 – 1 wt%), volume flow rate (2 – 10 L/min) and Reynolds number (5000 – 20000). At the end of experiment, data will be collected in term of temperature and pressure using data logger and sensor. Before analysing collected data, validation of experimental data based on Dittus-Boelter correlation will be carried out using water to ensure reliability and accuracy of the experimental setup. Collected data is required for computing thermal and hydraulic properties such as Nusselt number, heat transfer coefficient and friction factor. Besides that, thermal and flow performance between base fluid and nanofluid in the cooling system will be compared to obtain the percentage of enhancement due to the dispersion of nanoparticles into base fluid, which is one of the objectives of this research. There is some other information such as length of pipe, thermophysical properties of flowing fluid, and air speed are required to compute other parameters. Some important parameters in this research are listed in Table 7 below.

After that, all data computed will be transformed into graph form to observe relationship between desired parameters. To determine the optimum value of performance, heat transfer coefficient and friction factor obtained will be computed to Goodness factor, in which higher value indicates better ratio of heat transfer performance over pressure drop. Lastly, optimization of input parameters will be performed using response surface design in Minitab software.

Table 7
Important variables and respective formulae

Variable	Formulae	
Reynolds number	$Re = \frac{\rho v d}{\mu}$	(1)
Prandtl number	$\Pr = \frac{\mu \cdot c_p}{k}$	(2)
Dittus-Boelter equation	$Nu_{db} = 0.023 Re^{0.8} Pr^{0.3}$	(3)
Nusselt number	$Nu = \frac{hd}{k}$	(4)
Actual heat transfer	$\dot{Q}_{actual} = \dot{m} c_p \left(T_{nf,in} - T_{nf,out}\right)$	(5)
Overall heat transfer coefficient	$U = \frac{\dot{Q}}{A_s F \Delta T_{lm}}$	(6)
Actual heat transfer	$\dot{Q}_{actual} = \varepsilon C_{min}\left(T_{nf,in} - T_{air,in}\right) = \varepsilon \dot{Q}_{max}$	(7)
Effectiveness of cross-flow heat exchanger	$\varepsilon = 1 - \exp\left\{\frac{[NTU]^{0.22}}{c}\left[\exp(-c * [NTU]^{0.78}) - 1\right]\right\}$	(8)
Darcy friction factor	$f = \frac{\Delta P}{\left(\frac{L}{D}\right)\left(\frac{\rho v^2}{2}\right)}$	(9)
Chilton and Colburn J-factor analogy	$j = \frac{Nu}{Re \cdot Pr^{\frac{1}{3}}}$	(10)
Goodness Factor	Goodness factor = $\frac{j}{f}$	(11)

3. Results

There are some results obtained after running few samples for erosion-corrosion study. Every impeller was inspected using Hirox KH-8700 3D digital microscope. Low range high resolution MXG-2016Z lens with 20-160x magnification was used. In accordance to ASTM D2809-09, maximum depth of eroded part represents rating of a coolant. For each impeller, blade with the most corroded or eroded surface was chosen for study. Surface profiles of all blades were obtained by scanning top surface of the blades, as shown in Figure 5.

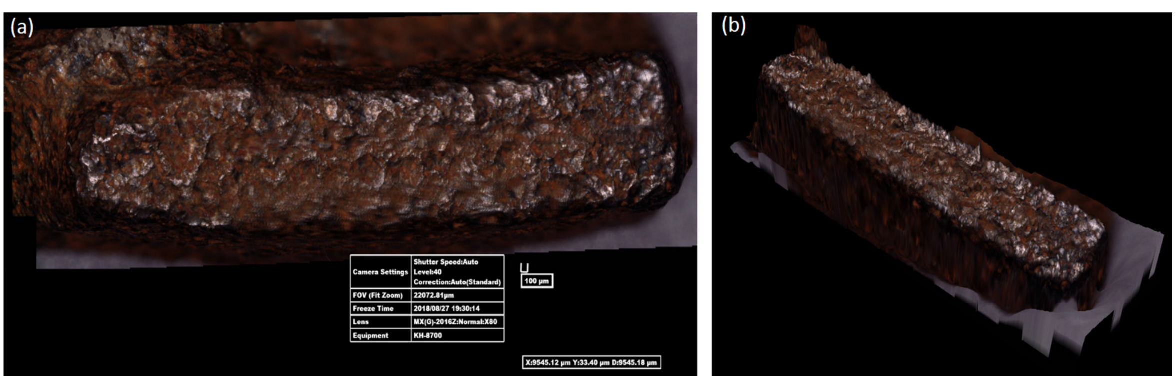

Fig. 5. (a) 2D (b) 3D representation of blade

Before determining the deepest eroded part of each blade, width of blade (before testing) was divided into several sections from respective contour profile as shown in Figure 6. After 100 hours testing, sections (before testing) that close to the deepest pitting in contour profile (after testing) were chosen for study.

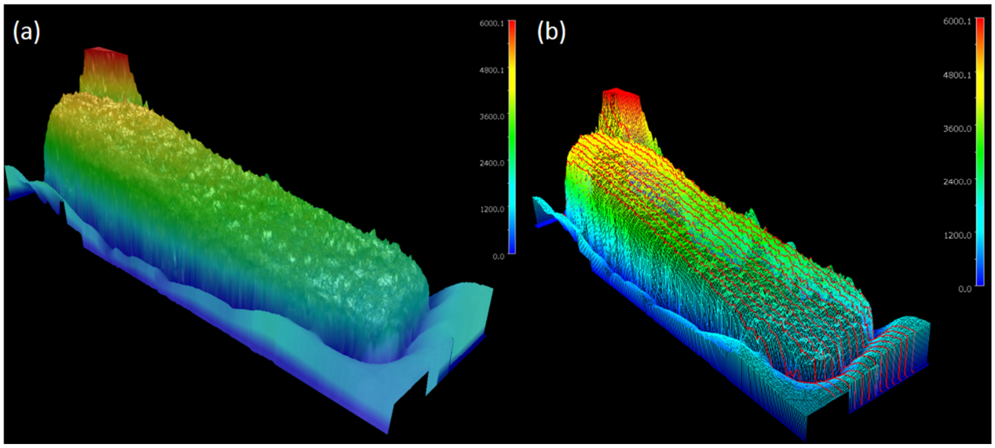

Fig. 6. Contour of a sample blade before testing (a) Original (b) After divisions

This study involved dynamic corrosive environment only, thus weight loss due to pure erosion and pure corrosion is not available. Weight loss due to erosion-corrosion effect for base coolant and nanocoolants are shown in Table 8 below. This result is in line with past study which used sea water containing alumina nanoparticles, where nanofluid showed more material loss in erosion-corrosion phenomena [17].

Table 8
Rating of erosion-corrosion damage on aluminum impeller

Sample	Rating based on ASTM D2809-09 standard	Observation on the impeller surface and maximum eroded depth	Material loss (gram)
Base coolant	9/10	Less than 100 μm, with minimal erosion and general corrosion.	0.0809
20_ppm_nf	8/10	Less than 400 μm, with light erosion and general corrosion.	0.2581
40_ppm_nf	8/10	Less than 400 μm, with light erosion and general corrosion.	0.9825

4. Conclusions

1)The corrosion effect is almost similar for all coolants.
This is due to low concentration of GnP that could not act as a strong barrier against the oxygen atoms diffusing onto impeller surface.

2)Material loss due to erosion-corrosion effect in nanocoolant is more than that of base coolant and it is higher when concentration of nanoparticles is increased.

The highly turbulent environment contributed to high collision energy of GnP which exacerbates material loss compared to base coolant. Thus, the effect is intensified when number of nanoparticles is increased.

In future work, we will continue synthesizing hybrid nanofluid with high stability and compare its erosion-corrosion damage and hydrothermal performance with mono nanofluid used in this research. It is important to determine various aspects such as cost, drawbacks, stability, advantage, optimum ratio in order to commercialize nanofluid in daily applications.

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