MXene-graphene hybrid nanoflakes as friction modifiers for outboard engine oil

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Abstract. MXenes are a relatively new type of two-dimensional materials which remain largely unexplored in terms of tribological applications. In this research, hybrid comprising Ti3C2-NG (MXene-Nitrogen-doped Graphene) is synthesized in an attempt to enhance the thermal and tribological properties of Outboard Marine Engine Oil. Oil samples were prepared using the two-step method which involved optimization of mixing technique and followed by tests according to ASTM standards. Results revealed that the thermal conductivity of the oil is enhanced by 6.62% for 15 minutes high shear blending whereas the viscosity is reduced by 4.71%. The decrease in viscosity could be as a result of pockets of debilitated intermolecular bonds in oil due to nanoparticles addition. Further, the Newtonian behaviour oil remains unchanged with the addition of nanoparticles. However, increasing shear rate revealed dilatant behaviour of the nanofluids corresponding to Taylor-Couette flow. The hybrid nanoflakes doesn’t significantly alter the anti-friction and anti-wear behaviour of the oils although the coefficient of friction is decreased in the presence of 0.01 wt.% Ti3C2 additive nanoparticle by a marginal <1%.

1. Introduction
The According to the Food and Agriculture Organization (FAO), over 4.6 million fishing vessels operate in the world and out of which 64% are engine-powered in 2014. Fishing activity along coastal line of ASEAN countries contribute significantly to carbon emissions and affect aquatic life. At the same time, the rapid development of maritime transport, driven by international trade and seafood
industry, has led to increase in the usage of marine engines. Furthermore, extreme engine conditions in rescue operations to reach the rescue area quickly through rough seas requires superior lubrication[1]. Hence, improvement of marine engine oil is vital to enhance engine performance and efficiency.

For better performance of engines, lubricants are required to have a strong film protection against metal-to-metal contact, avoid film rupture at high loads and high temperatures, reduced scuffing, pitting and rolling contact fatigue. Marine lubricants are also required to offer high residual fuel compatibility and total base number (TBN) reserve and retention properties. Lubricant additives which are chemical based improve lubricant properties, especially thermo-physical properties. Addition of nanometer sized (1-100 nm) particles to based oils is found to improve thermal and tribological properties of oils. Numerous works using different kinds of carbon allotropes nanoparticles, for example, carbon nanotubes (single-walled or multi-walled [2, 3]), graphene [4, 5] and graphene oxide [6, 7] to produce nanolubricants or nanocoatings show excellent enhancement of thermal properties. Graphene has outstanding in-plane thermal conductivity that can reach as high as 5200 W/m.K. When graphene oxide was added at a concentration of 0.25wt% to water, thermal conductivity improved by 47.5%. Since carbon family nanoparticles exhibit outstanding thermal conductivity and coefficient of heat transfer, their respective nanolubricants are expected to give better performance. Researchers have concluded that graphene that exists in two-dimensional (2D) nanostructures, possess better thermal conductivity, higher mechanical strength as well as improved electrical conductivity. Graphene, thus, indirectly contributes to more improvement in thermal conductivity in nanofluids, as compared with other analyzed nanofluids [8]. In previous study, graphene nanoparticles were synthesized and dispersed into API SN standard base engine oil to outperform conventional lubricants[9]. Results showed that graphene indicated enhancement in thermal and anti-wear properties by approximately 23% and 17%, respectively. At the same time, Graphene also plays an important role in improving the oxidative stability of the lubricants[10].

Besides graphene, development of other 2D nanoparticles is rapidly growing. Recently, a new family of transition metal nitrides, carbides or carbon-nitrides, known as MXene has shown properties better than existing 2D materials [11]. MXene originated from MAX phase, owing the formula \( \text{M}_{n+1}\text{AX}_n \) \( (n = 1, 2, 3) \), where M stands for early d-block transition metals, A denotes main group sp elements (aluminium or silicon) and X can be either C or N atoms, has been synthesized by wet HF treatment at room temperature. During selective etching of Al from Ti\(_3\)AlC\(_2\), Al atoms are substituted by O, OH and/or F atoms. The substitution of Al layer has weakened the \( \text{M}_{n+1} \) and X bonding, thus, preparing the layer to loss A element to become MXene. This young class of 2D materials has becoming research attention to explore further since MXenes is known as graphene analogue nanomaterials. Furthermore, this material offers great electrical properties, high mechanical strength and shows superior energy storage behavior [12-15]. Moreover, the recent discovery of MXene reveals that this material has the potential of becoming lubricant properties enhancer [16, 17].

Titanium carbide (Ti\(_3\)C\(_2\)) is the most common establishment for MXene type that has been studied, especially in structural composites applications [18, 19]. Ti\(_3\)C\(_2\) belongs to ternary carbides group and possess appealing multi-functional behaviours. This novel material features stable thermal properties, as offered by ceramic-type materials, as well as electrical conductivity and machinability, as presented by metal-type materials. Barsoum et al. were the first researchers to report on thermal conductivity (~37-40 W/mK) of bulk Ti\(_3\)C\(_2\) in 1999 [20]. Development of 2D-MAXene nanostructures and synthesized into nanofluid, with propylene glycol as the base fluid, exhibited around 45% improvement in thermal conductivity at the temperature of 323 K [21]. The outstanding properties of Ti\(_3\)C\(_2\) suspended in the fluid has potential to outperform the general heat transfer fluids. Although many hybrid graphene nanoparticle [22, 23] have been explored as lubricant additives, hybrid graphene-MXene in lubricants has never been investigated.

Generally, wear mechanisms for spherical nano-inclusions include deposition in the ridges and valleys and nano-film formation between the contacting surfaces. Although adhesion of nanoparticles and agglomeration is common, the morphological transformation is rarely prominent for spherical particles. Existing reports on graphene-based lubricants have limited the investigation to evaluating the thermo-physical properties only. The morphological behaviour of graphene and other 2D materials
after high-shear mixing still remains unexplored. Therefore, the present study aims to investigate the thermo-rheological performance of graphene-MXene based lubricants as well as their morphological transformation during high-shear mixing. The combined effect of both graphene and MXene could produce a far better lubricant with enhanced thermo-physical and wear properties. This research will focus on the synthesis of a stable nanolubricant using hybrid graphene and MXene, meeting certified FC-W grades of National Marine Manufacturers Association (NMMA). Thermo-physical properties of the nanolubricant will be examined in detail using ASTM standards as well as the impact of high-shear mixing on the morphology of graphene-MXene will be investigated.

2. Methods and Materials

2.1. Hybrid Nanoparticles Synthesis and characterization
Hummer’s method was employed to produce graphene oxide (GO) and Nitrogen doping was carried out. Ti$_3$C$_2$ was exfoliated from MAX phase clay. As-prepared NG and MXene were mixed using an agate mortar with a mass ratio of 1:0.5. The powder was subjected to further pyrolysis at 900 °C for 1 hour under nitrogen flow. The pyrolysed sample was acid washed for 6 hour to remove unreacted species and the dried sample was labelled as NG-MXene. Transmission electron microscopy (HR-TEM) and X-ray Diffraction (XRD) pattern were used to characterize the prepared nanoparticles.

2.2. Nanolubricant Preparation
The samples were prepared by using the two-step method, as no surfactant was used. 0.01 wt.% of nanolubricants was prepared by dispersing each of the nanoparticles in marine engine oil meeting NMMA certified FC-W specifications.

2.3. Thermo-physical and Tribological Characterization of Nanolubricants
The KS-1 single-needle sensor (diameter: 1.3mm, length: 60mm), which connects to a microprocessor, was used to measure the thermal conductivity of the fluids [24]. The MCR 302 rheometer (Anton Paar, Austria), which is a stress-controlled rotational rheometer, was used to measure the dynamic viscosity of the nanolubricant. Four ball tribometer (Ducom) was used to measure the wear properties following the standard test ASTM D 4172. Weld load test was conducted for all lubricants using ASTM D 2783 at 1770 rpm speed, 25°C temperature, for 10 sec duration.

3. Results and discussion

3.1. Material Characterization
The synthesized material was characterized using XRD to validate the crystallinity and to identify the phase compositions of the G-MXene, Ti$_3$C$_2$ and Nitrogen doped graphene (N-G). Figure 1 shows the XRD pattern of the G-MXene, Ti$_3$C$_2$ and N-G nanocomposite. The XRD of G-MXene and Ti$_3$C$_2$ exhibit a reflection peak at 2θ≈26° which correspond to the weak graphite peak. This phenomenon might be due to the dense Ti$_3$C$_2$ coating on graphene, which could decrease the X-ray signal[25]. For both G-MXene nanocomposite and Ti$_3$C$_2$, their XRD characteristic reflection peaks exist at 9°, 17°, 26° and 62°, corresponding to the (002), (006), (008) and (110) planes of the Ti$_3$C$_2$[26]. These results further confirm the successful formation of hybrid nanocomposite. Furthermore, the XRD of N-G shows the presence of peak at 2θ=17° which confirms the attachment of MXene nanoparticles on the graphene sheet.
The microstructure and morphology of the G-MXene, Ti$_3$C$_2$ and NG powders were observed by high-resolution TEM (HRTEM), (Fig. 3). A sheet-like graphene structure was formed and consistent with the TEM analysis[27]. After nitrogen doping, as seen in Fig. 2, crumpled yet well-defined nanosheets are observed [28]. Fig. 3 indicated a clear 2D layered structure of the Ti$_3$C$_2$ after undergoing treatment and depicting electron-transparent thin morphology and a few layer structures of Ti$_3$C$_2$ [25]. The HRTEM image clearly shows that the G-MXene samples displayed a nanosheet morphology[29]. The diameter size distribution of samples unambiguously illustrates the formation of uniform ultra-small quantum dots. The average thickness of the multilayer nanosheet examined using TEM was approximately 1.5 nm and this implied that the composite was produced in nanosize [27, 30]. The size distribution was calculated by counting 100 particles, and the lateral sizes of the quantum dots were directly measured from the HRTEM images via Image J software.
Figure 2. High resolution TEM images of G-Mxene (A), Ti$_3$C$_2$ (B) and N-G (C) samples with nanosheet thickness 1.16 nm, 1.14 nm and 1.53 nm, respectively.

3.2. Thermal conductivity

In this study, investigation on the effect of temperature on the nanofluid’s thermal conductivity, containing the synthesized samples, was conducted as well as the impact of high shear blending time towards the thermal conductivity of nanofluids. It is known that the increasing temperature would increase nanolubricant thermal conductivity. As shown in Fig. 3, significant enhancements were observed to the $k$ values of all nanofluid samples compared to the base oil at all temperature. This result indicates that nanoparticles have the potential to improve the thermal conductivity in engine oil as the temperature increase. This trend could be well explained by the Brownian motion [31], where the nanoparticles tend to collide with each other more aggressively at higher temperature due to their kinetic energy. For example, at 5 minutes HSB, $k$ value enhancement at room temperature shows an improvement of 4.41%, 1.73% and 0.16% meanwhile at 60 °C, the thermal conductivity enhances up to 5.76%, 2.59% and 1.87% relative to the base oil for G-MXene, N-G and Ti$_3$C$_2$, respectively. It is evident that the $k$ values exhibit higher sensitivity at a higher temperature. This phenomenon may be due to fast molecular colliding at high temperatures compared to lower temperature [32]. This improvement also illustrates that at higher temperature the thermal conductivity could increase further which indicates promising result for application in an outbound engine.

It can also be observed from Fig. 3, that G-MXene hybrid nanofluid exhibits the highest enhancement of thermal conductivity at 60°C among all HSB variations, with 6.62% increment at 15 minutes HSB (figure not included). N-G [33] and Ti$_3$C$_2$ [21] are well known as high thermal conducting nanoparticles for their high aspect ratio. Hence, the hybridisation of both nanoparticles enhances the overall thermal conductivity of the output nanoparticles. Also, these deviations could be associated to the dependence of thermal conductivity to the several factors e.g. nanoparticle type, nanoparticle size that complimented well with Paul et al [34]. Nevertheless, prior to introducing the G-MXene with these nanofluids, reliable stability data is required as it inherently influences the thermal conductivity. Further studies under G-MXene nanolubricant and functionalized methods would aid for better understanding.
3.3. Rheology

The flow behaviors of hybrid nanofluids were explored at variable shear rates and temperatures as a function of shear stress, as shown in Fig. 4. A linear pattern of shear stress variation with shear rate can be seen for every hybrid sample at all temperatures. From Fig. 4, it can be deduced that nanolubricant showed Newtonian behavior at lower temperature. Comparable behaviors were seen in the study done by Motahari et al. [35] for MWCNT-SiO$_2$/20W50 motor oil and Afrand et al. [36] for Fe$_3$O$_4$-Ag/EG hybrid nanofluid. This is a vital criterion, especially for convective heat transfer. Although at a higher temperature (110 °C) all nanofluids show inclination towards non-Newtonian nature, however, it is insignificant in shear stress with respect to shear rates. The further increment of temperature anticipates a change from the Newtonian to non-Newtonian behavior of the nanofluids. Besides, the flow curves indicated that the difference in shear stress became larger between low and high temperature as the shear rates increase.
Figure 4. Flow curves versus shear rates at different temperatures for (a) G-Mxene and (b) base lubricant

Fig. 5 shows the variation in viscosity of G-MXene nanofluid compared with base marine engine oil as a function of shear rate at different temperature. Most of the previous studies concluded that the dynamic viscosity increased with addition of nanoparticles to the conventional engine oils. Contrary to these studies, the results revealed that the addition of G-MXene, N-G and Ti$_3$C$_2$ nanoparticles to marine engine oil reduced the viscosity below the viscosity of the base lubricant, at all temperature. Addition of G-MXene nanoparticles presented the highest reduction in term of viscosity up to 4.71%, 4.70%, 2.59%, 3.68% and 4.59% at 30 °C, 50 °C, 70 °C, 90 °C and 110 °C, respectively. The trends are consistent at all temperature tested over the entire shear rate of 1s$^{-1}$ to 1500 s$^{-1}$. 
3.4. Anti-wear properties

Results indicate that addition of Graphene MXene hybrid additive does not have significant enhancement in anti-friction property of lubricant. The coefficient of friction for the lubricant and its variant also show similar behaviour. Friction coefficient is calculated according to IP-239. Increment in test load increase the coefficient of friction. The coefficient of friction for 0.01% G-MXene is found to be increased by 6.5%. Whereas the friction coefficient with N-G as lubricant additive is increased by 10.2%. On the other hand, the coefficient of friction for marine engine oil with 0.01% Ti$_3$C$_2$ additive has enhanced anti-friction property with reduction of µ by ~0.8%. The wear scar diameter (WSD) depends on the magnitude of the wear and the load bearing capacity of the lubricant. As observed, the presence of G-MXene nano particles resulted in small WSD compared to standalone N-G and Ti$_3$C$_2$ additive and base oil. Weld load test was conducted for all lubricants using ASTM D 2783 at 1770 rpm speed, 25°C temperature, for 10 sec duration. The result from ASTM D 2783 shows that there is no improvement in the load carrying capacity for marine engine oil with or without additive.

4. Conclusion

Marine engine oil with N-G, MXene and G-MXene additive with 0.01% wt are analysed for thermal conductivity, viscosity and frictional coefficient and compared with properties of conventional engine oil. It can be concluded that there is significant enhancement to the k values of all hybrid nanofluid samples compared to the base oil at all temperature and the conductivity improves as the temperature increase. G-MXene hybrid nanolubricant exhibits the highest enhancement of thermal conductivity with up to 6.62% increment in conductivity. All hybrid nanolubricants show shear thinning for nanofluids which is due to low shear rate, therefore reducing fluid viscosity. However, the changes are not significant to be considered as a non-Newtonian fluid. Results show that G-MXene nanoparticles presented the highest reduction in viscosity, up to 4.71%, compared to N-G and Ti$_3$C$_2$ nanoparticles to marine engine oil. Wear properties analysis show that oil with G-MXene hybrid additive depicts the
frictional coefficient in between the oil with N-G and MXene additive, and higher than base engine oil. Result shows reduction in scar diameter with addition of NG-MXene hybrid, enhancing the anti-wear properties of lubricant. Nevertheless, application of NG-MXene with these nanofluids influences the thermal conductivity, viscosity and frictional properties of fluid. Further studies are required to investigate the discrepancy between the tribological findings of this study and the previous works.

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References
[1] Anand M, Hadfield M, Thomas B and Cantrill R 2017 The depletion of ZDDP additives within marine lubricants and associated cylinder liner wear in RNLI lifeboat engines Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications 231 162-70
[2] Esfe M H, Firouzi M and Afrand M 2018 Experimental and theoretical investigation of thermal conductivity of ethylene glycol containing functionalized single walled carbon nanotubes Physica E: Low-dimensional Systems and Nanostructures 95 71-7
[3] Khalil W, Mohamed A, Bayoumi M and Osman T 2017 Thermal and Rheological properties of industrial mineral gear oil and paraffinic oil/CNTs nanolubricants Iranian Journal of Science and Technology, Transactions of Mechanical Engineering 1-7
[4] Rasheed A, Khalid M, Javeed A, Rashmi W, Gupta T and Chan A 2016 Heat transfer and tribological performance of graphene nanolubricant in an internal combustion engine Tribology International 103 504-15
[5] Kamel B M, Mohamed A, El Sherbiny M and Abed K 2016 Rheology and thermal conductivity of calcium grease containing multi-walled carbon nanotube Fullerences, Nanotubes and Carbon Nanostructures 24 260-5
[6] Ali M K A, Xianjun H, Abdelkareem M A, Gulzar M and Elsheikh A 2018 Novel approach of the graphene nanolubricant for energy saving via anti-friction/wear in automobile engines Tribology International 124 209-29
[7] Mungse H P and Khatri O P 2014 Chemically functionalized reduced graphene oxide as a novel material for reduction of friction and wear The Journal of Physical Chemistry C 118 14394 402
[8] Yarmand H, Gharehkhani S, Ahmadi G, Shirazi S F S, Baradaran S, Montazer E, Zubir M N M, Alehashem M S, Kazi S and Dahari M 2015 Graphene nanoplatelets–silver hybrid nanofluids for enhanced heat transfer Energy conversion and management 100 419-28
[9] Rasheed A K, Khalid M, Javeed A, Rashmi W, Gupta T C S M and Chan A 2016 Heat transfer and tribological performance of graphene nanolubricant in an internal combustion engine Tribology International 103 504-15
[10] Rasheed A K, Khalid M, Walvekar R, Gupta T C S M and Chan A 2015 Study of graphene nanolubricant using thermogravimetric analysis Journal of Materials Research 31 1939-46
[11] Lei J-C, Zhang X and Zhou Z 2015 Recent advances in MXene: Preparation, properties, and applications Frontiers of Physics 10 276-86
[12] Naguib M, Mochalin V, Barsoum M and Gogotsi Y G 2014 MXenes: A New Family of Two Dimensional Materials Advanced Materials 26
[13] Naguib M, Mashtalir O, Carle J, Presser V, Lu J, Hultman L, Gogotsi Y and Barsoum M W 2012 Two-dimensional transition metal carbides ACS nano 6 1322-31
[14] Tang Q, Zhou Z and Shen P 2012 Are MXenes promising anode materials for Li ion batteries? Computational studies on electronic properties and Li storage capability of Ti3C2 and Ti3C2X2 (X= F, OH) monolayer Journal of the American Chemical Society 134 16909-16
[15] Lukatskaya M R, Mashtalir O, Ren C E, Dall’Agne Y, Rozier P, Taberna P L, Naguib M, Simon P, Barsoum M W and Gogotsi Y 2013 Cation intercalation and high volumetric capacitance of two-dimensional titanium carbide Science 341 1502-5

[16] Chakraborty P, Das T, Naifday D, Boeri L and Saha-Dasgupta T 2017 Manipulating the mechanical properties of Ti2C MXene: Effect of substitutional doping Physical Review B 95 184106

[17] Hong Ng V M, Huang H, Zhou K, Lee P S, Que W, Xu J Z and Kong L B 2017 Recent progress in layered transition metal carbides and/or nitrides (MXenes) and their composites: synthesis and applications Journal of Materials Chemistry A 5 3039-68

[18] Mahesh K, Balanand S, Raimond R, Mohamed A P and Ananthakumar S 2014 Polyaryletherketone polymer nanocomposite engineered with nanolaminated Ti3SiC2 ceramic fillers Materials & Design 63 360-7

[19] Barsoum M W and El-Raghy T 2001 The MAX phases: Unique new carbide and nitride materials: Ternary ceramics turn out to be surprisingly soft and machinable, yet also heat tolerant, strong and lightweight American Scientist 89 334-43

[20] Barsoum M, El-Raghy T, Rawn C, Porter W, Wang H, Payzant E and Hubbard C 1999 Thermal properties of Ti3SiC2 Journal of Physics and Chemistry of Solids 60 429-39

[21] Mahesh K, Linsha V, Mohamed A P and Ananthakumar S 2016 Processing of 2D-MAXene nanostructures and design of high thermal conducting, rHEO-controlled MAXene nanofluids as a potential nanocoolant Chemical Engineering Journal 297 158-69

[22] Meng Y, Su F and Chen Y 2016 Supercritical Fluid Synthesis and Tribological Applications of Silver Nanoparticle-decorated Graphene in Engine Oil Nanofluid 6 31246

[23] Soo Hui Q, Rashmi W, Khalid M, Gupta T C S M, Nabipoor M and Mohammad Taghi H 2017 Thermal conductivity and electrical properties of hybrid SiO 2 -graphene naphthenic mineral oil nanofluid as potential transformer oil Materials Research Express 4 015504

[24] Hong K, Hong T-K and Yang H-S 2006 Thermal conductivity of Fe nanofluids depending on the cluster size of nanoparticles Applied Physics Letters 88 031901

[25] Li M, Han M, Zhou J, Deng Q, Zhou X, Xue J, Du S, Yin X and Huang Q 2018 Novel Scale Like Structures of Graphite/TiC/Ti3C2 Hybrids for Electromagnetic Absorption Advanced Electronic Materials 4 1700617

[26] Feng W, Luo H, Wang Y, Zeng S, Tan Y, Zhang H and Peng S 2018 Ultrasonic assisted etching and delaminating of Ti3C2 MXene Ceramics International 44 7084-7

[27] Muniandy S, Dinshaw I J, Teh S J, Lai C W, Ibrahim F, Thong K L and Leo B F 2017 Graphene-based label-free electrochemical aptasensor for rapid and sensitive detection of foodborne pathogen Analytical and bioanalytical chemistry 409 6893-905

[28] Yang L, Zheng W, Zhang P, Chen J, Zhang W, Tian W and Sun Z 2019 Freestanding nitrogen doped d-Ti3C2/reduced graphene oxide hybrid films for high performance supercapacitors Electrochimica Acta

[29] Zhao D, Chen Z, Yang W, Liu S, Zhang X, Yu Y, Cheong W-C, Zheng L, Ren F and Ying G 2019 MXene (Ti3C2) Vacancy Confined Single-Atom Catalyst for Efficient Functionalization of CO2 Journal of the American Chemical Society

[30] Xu Q, Ding L, Wen Y, Yang W, Zhou H, Chen X, Street J, Zhou A, Ong W-J and Li N 2018 High Photoluminescence Quantum Yield of 18.7% by Nitrogen-Doped Ti3C2 MXene Quantum Dots Mater. Chem. C

[31] Qing S H, Rashmi W, Khalid M, Gupta T, Nabipoor M and Hajibeigy M T 2017 Thermal conductivity and electrical properties of hybrid SiO2-graphene naphthenic mineral oil nanofluid as potential transformer oil Materials Research Express 4 015504

[32] Akilu S, Baheta A T and Sharma K 2017 Experimental measurements of thermal conductivity and viscosity of ethylene glycol-based hybrid nanofluid with TiO2-CuO/C inclusions Journal of Molecular Liquids 246 396-405

[33] Mehrali M, Sadeghinezhad E, Rosen M A, Akhiani A R, Latibari S T, Mehrali M and Metselaar H S C 2016 Experimental investigation of thermophysical properties, entropy generation and
convective heat transfer for a nitrogen-doped graphene nanofluid in a laminar flow regime

[34] Paul G, Philip J, Raj B, Das P K and Manna I 2011 Synthesis, characterization, and thermal property measurement of nano-Al95Zn05 dispersed nanofluid prepared by a two-step process International Journal of Heat and Mass Transfer 54 3783-8

[35] Motahari K, Moghaddam M A and Moradian M 2018 Experimental investigation and development of new correlation for influences of temperature and concentration on dynamic viscosity of MWCNT-SiO2 (20-80)/20W50 hybrid nano-lubricant Chinese Journal of Chemical Engineering 26 152-8

[36] Afrand M, Toghraie D and Ruhani B 2016 Effects of temperature and nanoparticles concentration on rheological behavior of Fe3O4–Ag/EG hybrid nanofluid: an experimental study Experimental Thermal and Fluid Science 77 38-44