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Supplementary Information

Experimental investigation of heat transfer performance and frictional loss of functionalized trimethylolpropane tris [poly(propylene glycol), amine terminated] ether-treated graphene nanoplatelets (TMP-treated GNP) in a closed conduit flow

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Experimental apparatus

A straight seamless copper tube with a length of 1500 mm, 8 ± 0.2-mm outer diameter, and a 4-mm inner diameter was used as the test section. The test section was heated by using an Ultra-high-temperature heating flexible tape (Omega, USA) at a maximum power of 900 W, which was linked to PLC system to control the watts and ampere. Six type K thermocouples (Omega, Singapore) were mounted on the test section by using high temperature epoxy glue at 24cm equilateral axial distances on the outer surface of the test tube as shown schematically in Figure S1. The positioning of the thermocouples was done at outer surface of the cylindrical tube in order to avoid boundary layer interruption originating from the thermocouple probe protruding into the conduit inner surface. As shown in Figure S2.

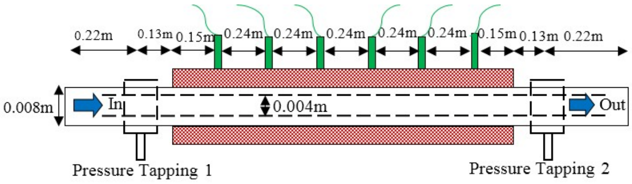

Figure S1: schematic view of the test section.

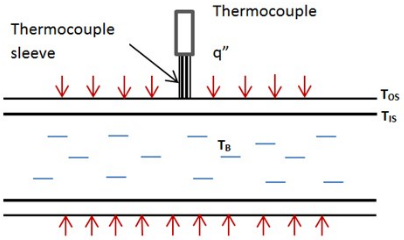

Figure S2. Schematic of temperature variation through heated wall.

However, by considering the convection and convective heat transfer process occur simultaneously for the present case. Further calibration test was needed to determine the exact temperature at the inner surface of the tube. A Wilson plot was therefore adopted to accomplish this task which is based on the equating the resistance between different sections of the heat transfer direction and determining the inner surface temperature via mathematical manipulation. Based on the figure S1, the inner diameter (ID) heat flux between different locations of the cross sectional direction can be formulated as follows:

Between TOS and TB

q" = U(TOS - TB)…………………………………………………………………….……..(S1)

Between TIS and TOS

$q'' = \frac{\lambda}{t}(Tos - Tis)$………………………………………………..…..$(S2)$

Between TIS and TB

q" = h (TIS - TB)………………………………………………..………………………..……(S3)

Combining the above equations into a single expression yields:

q" = U(TOS - TB) = $\frac{\lambda}{t}(Tos - Tis) =$ h (TIS - TB)……………………….……..(S4) further by rearranging equation no S4 the overall heat transfer coefficient U can described in terms of the distance between inner and outer conduit surface, t and effective thermal conductivity , λ such that

$$\frac{1}{U} = \frac{1}{h} + \frac{t}{\lambda} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (S5)$$

The aim of this exercise is to obtain the resistance between TOS and TIS (i.e . t/ λ) in order to solve the remaining equations.

By referring back to equation S1, thermal resistance between the above two points can be determined since TOS and TB are the measurable equations. However resistance between TIS and TB needs to be modeled to solve h. It is well known that the film heat transfer coefficient, h is function of liquid velocity. Therefore by adopting the dittus boelter equations which describes the heat transfer coefficient in-terms of fluid velocity, a simplified version of the relationship comes in the form of:

$h=ku^n \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (S6)$

where k represents the constant and u denotes the velocity.

Further substituting equations S6 into equation S5 results in the following equation:’

$$\frac{1}{U} = \frac{1}{k} u^{-n} + \frac{t}{\lambda} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (S7)$$

The above equation describes the overall heat transfer coefficient in-terms of wall resistance and bulk velocity. The equation in current form can now be solved by plotting the 1/U against 1/un to obtain both 1/k and t/λ. The exponential value associated with u was the subject of debate by previous researchers due to its strong dependent to prandtl number (Pr). However it was determined to be within the range of 0.78-0.85.

Calibration for each thermocouple was conducted with water as the base fluid. The results were plotted with respect to overall heat transfer coefficient against exponential velocity as shown in Figure S3 (a) until (f). The wall resistance (λ/t) values for each of the thermocouple were obtained from intercept on y-axis. The value of the exponents, n along with λ/t values are presented in Table S1. Furthermore, the specifications and the accuracy of the measuring equipment used in the present experimental setup are presented in Table S2.

Table S1. λ/t value for each thermocouple installed on the test section.

Thermocouple No	***λ/t***	*n*
1		0.8
2		0.8
3		0.8
4		0.8
5		0.8
6		0.8

Table S2. Specifications and errors for the measuring devices utilized in the present study.

Measured parameter	Type of measuring device	Range	Error
Surface temperature	Type K thermocouple	0–300C	±0.10C
Bulk temperature	RTD (PT-100) sensor	0–200 C	±0.10C
Fluid flow rate	N-FLO-25 Electromagnetic Flow Meter	0.1–15 m/s	±0.5%
Fluid pressure drop	Invensys foxboro pressure transmitter	0–1500 kPa	±0.075%
Cooling unit	WiseCircu DAIHAN Scientific Refrigerated circulating bath	2.2 kW	±0.10C
Pump	Araki magnetic pump	0-12 l/m	N/A

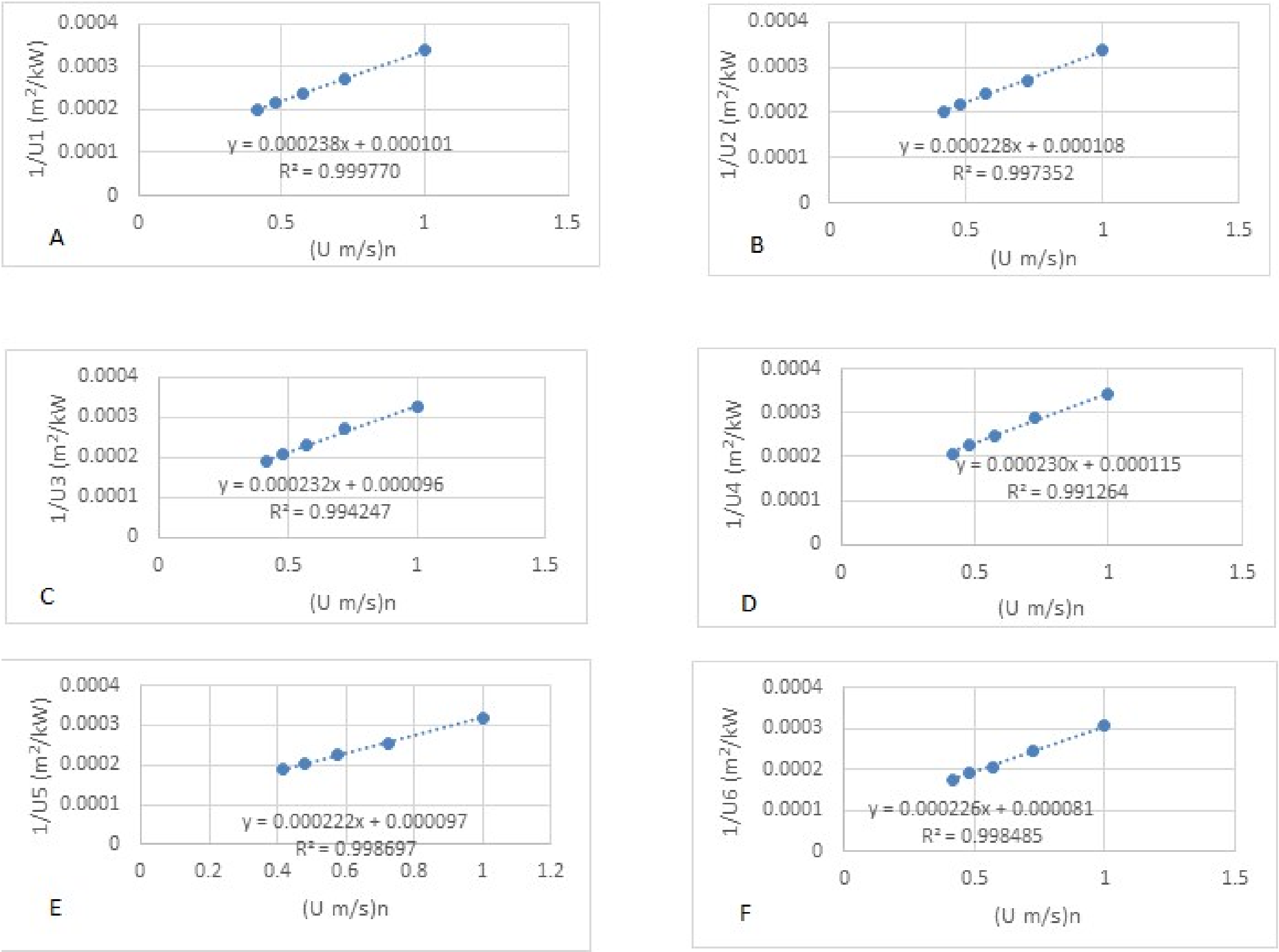

Figure S3. Plot of 1/U against u^n for thermocouple number (a) 1, (b) 2, (c) 3, (d) 4, (e) 5, (f) 6 enumerated from the upstream of the rest section. The calibration experiment was conducted with water at bulk temperature of 30^0C.

Cleaning procedure and effect on thermal performance.

After completion of one nanofluid test run, the loop is drained completely and flushed several times to remove the remaining nanoparticles. It is preferred in many cases to use an alternative solvent family which consists of the aqueous solution of the chelating agent. Thus the agent should not have the potential to damage the equipment during or after cleaning. Two chelating agents are used in this experiment as described in Table 4.

Table S3. Cleaning agent used for test rig.

Chelating agent	Specification	Preparation procedure	Times of washing
Decon 90	Surface active cleaning agent, and/or radioactive decontaminant, for laboratory, medical and industrial applications	Prepare a 2–5% solution of Decon 90 with water	3 times
Degreaser cleaner 5213 + antifoam 9000	Water-based formula dissolves grease and grime from almost any surface	Prepare a 4% solution of with water	3 times

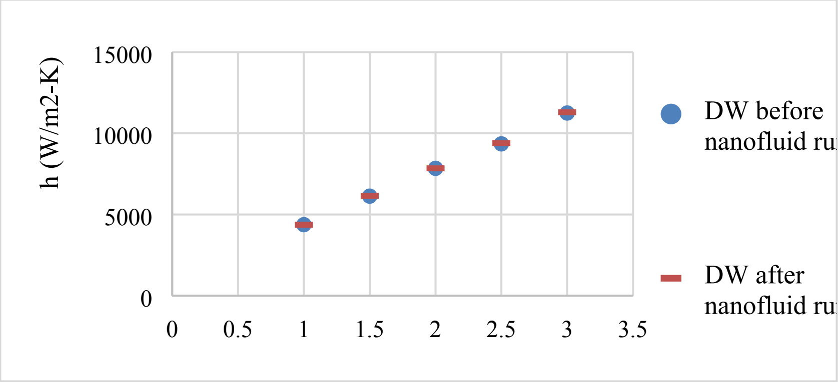

Figure S4. Variation of heat transfer coefficient with velocity for DW retest.

During cleaning, at a steady solution temperature of 30^{0}C, the degreaser + antifoam and then Decon 90 are pumped into the system separately several times. After each run, the loop is cleaned and flushed by using DW three times, each for duration of 25 minutes. However in order to ensure of that there are no surface modifications or fouling of the system, a DW run is once again performed and compared to theory. Fig. 17 presents the heat transfer coefficient as a function of velocity, before and after cleaning runs, for DW at a bulk temperature of 30^{0}C. It is observed that the data are reproducible, and that the test rig is highly accurate and attains an error of <1%. It is therefore felt that no notable modifications of the tube surface occur due to the use of nanofluids.