Supplementary Information

Transformer oil based hexylamine-multiwalled carbon nanotubes coolant with optimized electrical, thermal and rheological enhancements

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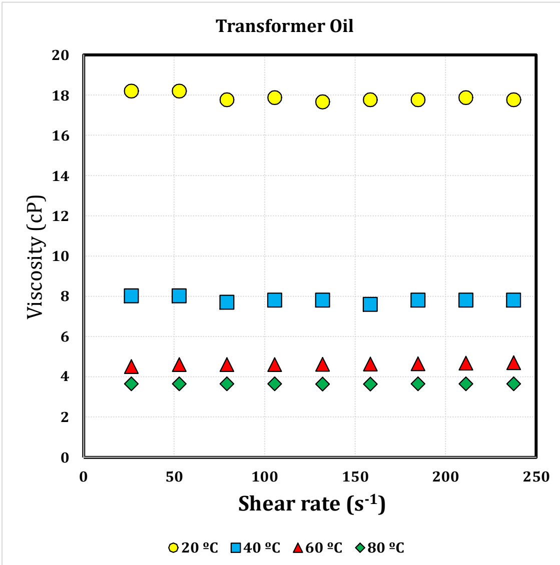
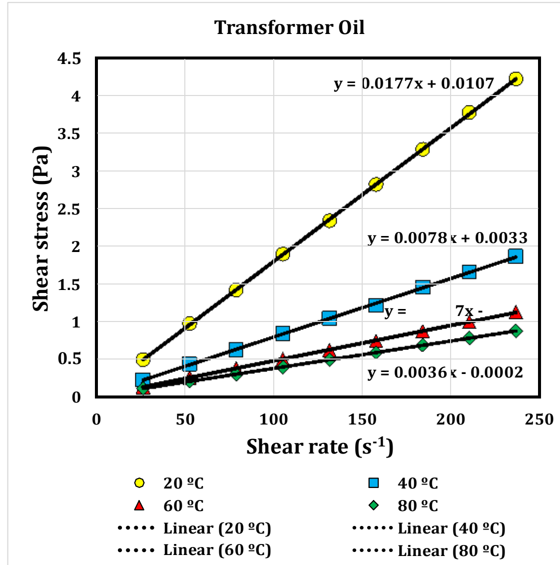
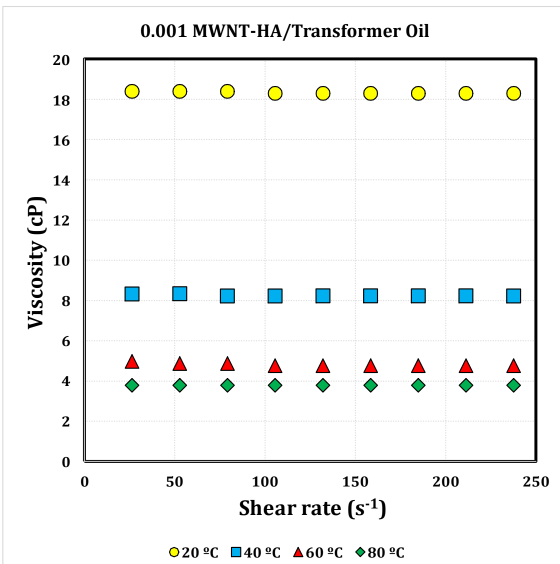
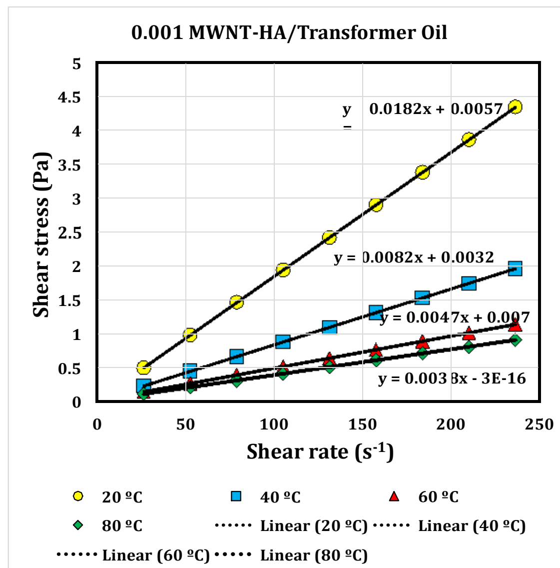
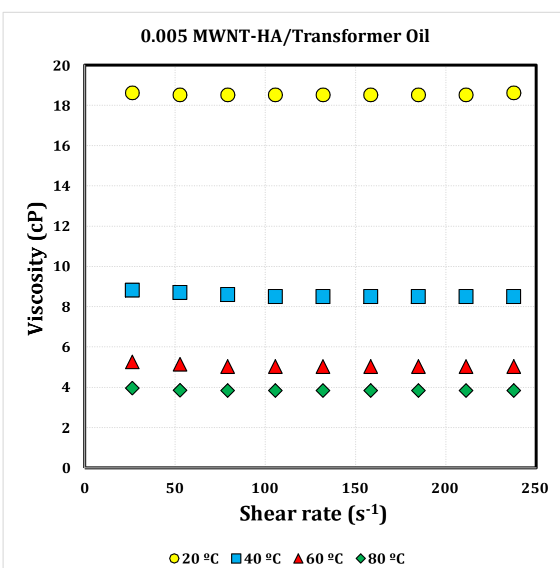

Transformer Oil
Viscosity (cP)
Shear rate (s-1)
20 ºC 40 ºC 60 ºC 80 ºC


Transformer Oil
Shear stress (Pa)
Shear rate (s-1)
y = 0.0177x + 0.0107
y = 0.0078x + 0.0033
y = 0.0036x - 0.0002
20 ºC
40 ºC
60 ºC
80 ºC
Linear (20 ºC)
Linear (40 ºC)
Linear (60 ºC)
Linear (80 ºC)


0.001 MWNT-HA/Transformer Oil
Viscosity (cP)
Shear rate (s-1)
20 ºC 40 ºC 60 ºC 80 ºC


0.001 MWNT-HA/Transformer Oil
Shear stress (Pa)
Shear rate (s-1)
0.0182x + 0.0057
y = 0.0082x + 0.0032
y = 0.0047x + 0.007
y = 0.0038x - 3E-16
20 ºC
40 ºC
60 ºC
80 ºC
Linear (20 ºC)
Linear (40 ºC)
Linear (60 ºC)
Linear (80 ºC)


0.005 MWNT-HA/Transformer Oil
Viscosity (cP)
Shear rate (s-1)
20 ºC 40 ºC 60 ºC 80 ºC

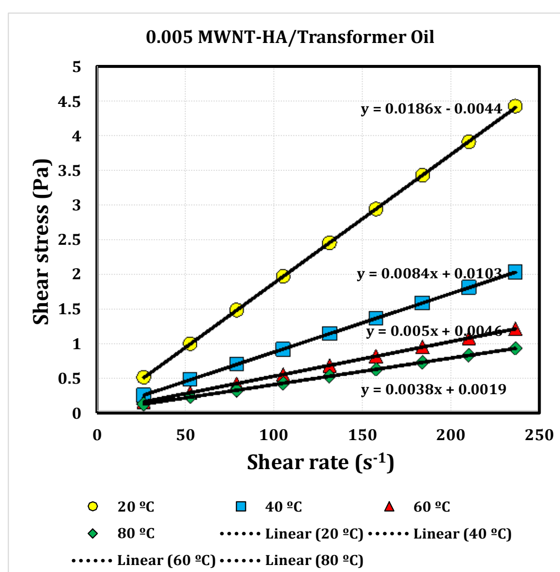

0.005 MWNT-HA/Transformer Oil
Shear stress (Pa)
Shear rate (s-1)
y = 0.0186x - 0.0044
y = 0.0084x + 0.0103
y = 0.005x + 0.0046
y = 0.0038x + 0.0019
20 ºC
40 ºC
60 ºC
80 ºC
Linear (20 ºC)
Linear (40 ºC)
Linear (60 ºC)
Linear (80 ºC)

Figure S1. The viscosity of pure TO and MWNT-HA based TO coolants at different weight concentrations and shear rates.

Table S1. Rheological properties of the pure transformer oil

Viscosity at 20 °C	17.754 cP
Viscosity at 40 °C	7.807 cP
Density at 20 °C	0.843 ∘C/gr Cm^{-3}
Flash point	150 ∘C
Pour point	Lower than -45 °C
Breakdown voltage	57 kV

Table S2. Zeta potential and associated suspension stability 1.

Z potential (mv)	**Stability**
0	Little or no stability
15	Some stability but settling lightly
30	Moderate stability
45	Good stability, possible settling
60	Very good stability, little settling likely

A summary of experimental studies on the thermal conductivity of TO-based nanofluids is listed in Table S3 which increase the possibility of sediment. As compared with recent studies[2], the present work reaches higher enhancement in thermal conductivity at similar experimental condition. For example, Patel et al. [3] obtained 10, 11.5, 14 and 17% enhancements in the thermal conductivities of TO-based nanofluids by the addition of Al_2O_3 at 20, 30, 40 and 50 °C, respectively. Such enhancements are obtained for 3% Al2O3 loading, while we work at very low weight fractions of 0.001 and 0.005. In fact, the strategy of the present study is the utilization of low concentration of highly-soluble MWNT-HA in TO to avoid sediment, since the bulk fluid in the transformer is motionless.

Table S3. Summary of experimental studies on thermal conductivity of TO-based nanofluids.

Authors [Ref.]	Particle Material/ Base fluids	Fraction (vol% or wt%)	Particle size(nm)	Additives	Enhancement (%) in Thermal Conductivity
Xuan & Li [4]	Cu/Transformer oil	2.5-7.5	100	Oleic acid	12-43
Patel et al. [3]	Al_2O_3/ Transformer oil	0.5-3	45	-	3-10 at 20 °C 4.5-11.5 at 30 °C 6.5-14 at 40 °C
		0.5-3	31		8-17 at 50 °C

	CuO Transformer oil				5-12.5 at 20 °C
					7-17.5 at 30 °C
					8-19.5 at 40 °C
		0.5-3	80		9.5-26 at 50 °C
	Cu/Transformer oil				13-27.5 at 20 °C
					13.5-29 at 30 °C
					15-33 at 40 °C
		0.5-3	80		16-38 at 50 °C
					9-18.5 at 20 °C
	Al/Transformer oil				9.5-24 at 30 °C
Choi et al. [5]	Al_2O_3	0.5 1.0 2.0 4.0		--	5% 8% 12.5% 20% (Room Temperature)
Choi et al. [5]	AIN	0.5		--	8% (Room Temperature)
Beheshti et al. [2]	MWNT-COOH	0.001 0.01 0.001 0.01 0.001 0.01	15nm * 30 µm	-	<1% at 30 °C ~1% at 30 °C <6% at 60 °C <8% at 60 °C ~ 0% at 70 °C <0% at 70 °C
Present Study	MWNT-HA	0.001 0.005 0.001 0.005 0.001 0.005	30nm * (5-15) µm		2.56% at 30 °C 3.2% at 30 °C 6.87% at 60 °C 7.78% at 60 °C 9.14% at 70 °C 9.85% at 70 °C

Table S4 also shows a comparison of the natural convection and forced convection heat transfer coefficients of nanofluids with different nanoparticles loading. The convective heat transfer coefficient of MWNT-HA/TO nanofluid was compared with those of other nanoparticles-based TO nanofluids reported in the literature. Obviously, the present samples had a relatively high natural convection and forced convection heat transfer coefficients in comparison to other nanoparticles loading in TO at similar weight fraction, in particular, as compared with MWNT-COOH/TO nanofluids [2] at similar experimental conditions. Our results showed the natural convection and forced convection heat transfer coefficient enhancements of 23 and 28% at weight fraction of 0.005, which demonstrate a significant increase at a very low concentration.

Table S4. Summary of experimental studies on convective heat transfer properties of nanofluids

Authors [Ref.]	Particle Material/ Base fluids	Fraction (vol% or wt%)	Particle size(nm)	Additives	Enhancement (%)
Beheshti et al. [2]	MWCNT-COOH/ Transformer oil	0.001-0.01%wt	15*30000	-	10.04-16.42 at 50W 10.85-11.83 at 70W 16.78-18.82 at 90 W 12.94-14.01 at 120 W 9.27-10.46 at 150 W (Free Convection) 5.78-12.92 at 50W 12.08-15.94 at 70W 6.57-11.72 at 90W 4.35-7.1 at 120W 6.55-9.17 at 150W (Force Convection)
Choi et al. [6]	Al_2O_3/ Transformer oil AlN/ Transformer oil	0.5 0.5	13 50	Oleic acid	20 overall heat transfer coefficient (U)
Chun et al. [7]	Al_2O_3/ Transformer oil	0.5	~43 27-43 7	-	13 10 25 Laminar (h)
Rajesh et al. [8]	Al/Transformer oil	0.5	100		70 heat transfer coefficient
Present Study	MWNT-HA	0.001-0.005 0.001-0.005	30nm * (5-15) µm	---	12-23% Free Convection 13-28% Forced Convection

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1. L. Vandsberger, McGill University, 2009.
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3. H. E. Patel, T. Sundararajan and S. K. Das, *Journal of Nanoparticle Research*, 2010, **12**, 1015-1031.
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5. C. Choi, H. S. Yoo and J. M. Oh, *Current Applied Physics*, 2008, **8**, 710-712.
6. C. Choi, H. Yoo and J. Oh, *Current Applied Physics*, 2008, **8**, 710-712.
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