Nanofluids Analysis Model – Basis for Comparison and Prediction

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Nanofluids Analysis Model - Basis for Comparison and Prediction

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Agenda

- **Introduction**
- **Use in Heat Pipe: Definition and Characteristics**
- **CuO-Water Nanofluids Characteristics**
- **Nanoparticle Size Characterization Process**
- **Reliability of Nanofluids**
- **Thermal conductivity models – CuO-Water Nanofluids**
- **Viscosity Models**
- **Results and Comments**
- **Conclusions**

Introduction

Thermal enhancement using nanofluids depend on several parameters:

1) Nanoparticle volume fraction (vol. %) or mass fraction (wt. %);

2) Nanoparticle shape and geometry – important information usually not available;

3) Operating temperature: causes positive influence for higher thermal enhancements;

4) Nanofluid preparation method (one-step or 2-steps); influences parameters related to stability, sedimentation levels, dispersibility, chemical compatibility of nanoparticles, thermal stability and addition of surfactants;

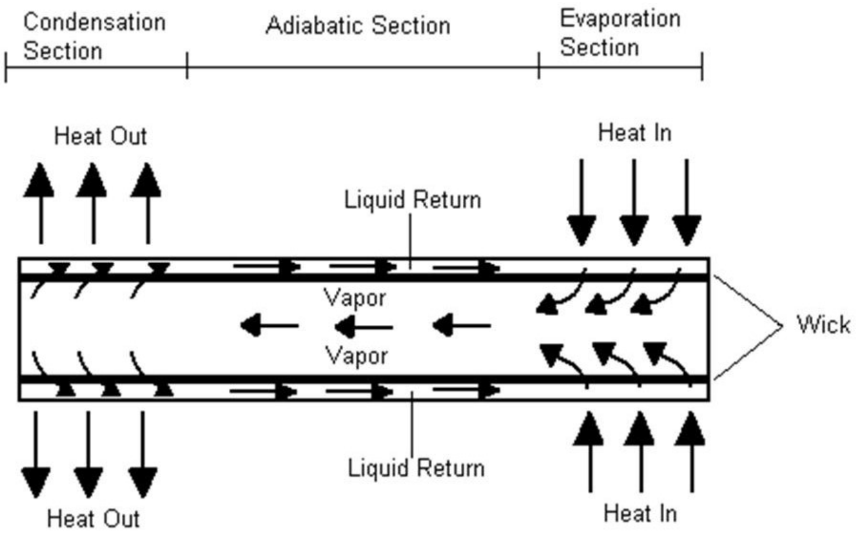
5) Type of application: pool boiling, evaporation/condensation, liquid cooling;

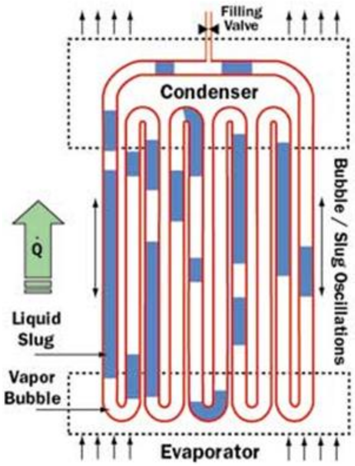
6) Nanoparticle sizes and distribution: important information often not considered;

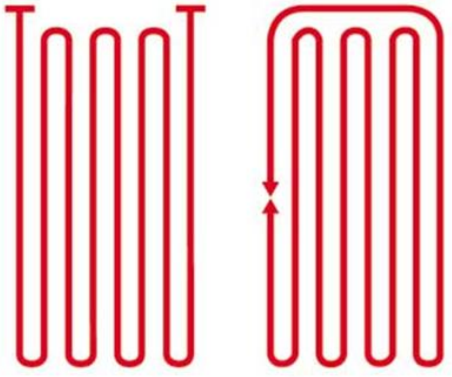
7) Operation at atmospheric or saturation condition present different results.

Use in Heat Pipes: Definition and Characteristics

- Heat pipes are thermal devices used to transfer heat at long distances in a very efficient way through capillary pumping.
- Pulsating heat pipes are wickless devices, operating by means of plug/slugs dynamics







(i) Open loop without flow check valve

(ii) Closed loop with flow check valve

CuO-Water Nanofluid Characteristics

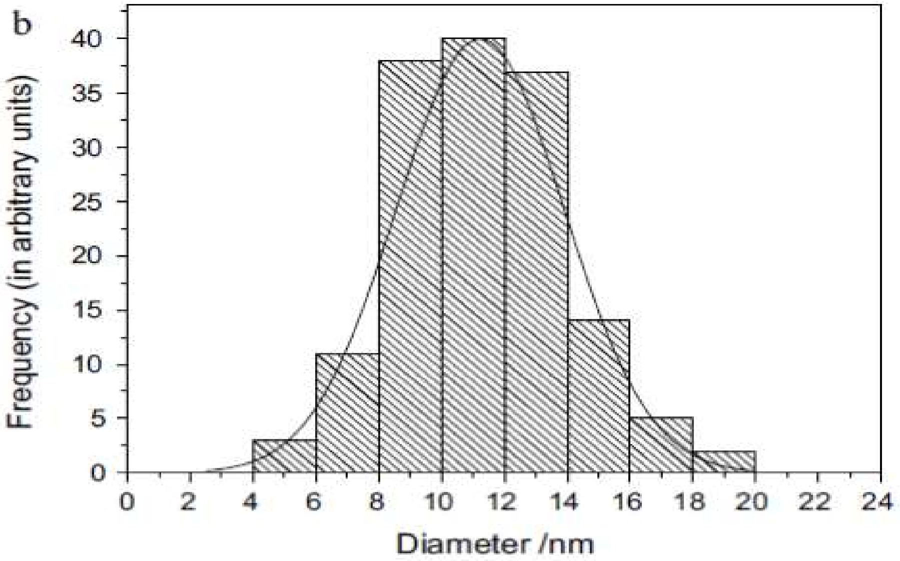
Nanofluid thermal enhancement can be affected by some parameters as: temperature, volume fraction, size of nanoparticles,, etc. Table below demonstrates some thermal enhancement ratios for CuO-water nanofluid experiments considering the variation of temperature and volume fraction.

Summary of measured thermal conductivity enhancement for CuO-water nanofluids influenced by change in temperature

Author (Ref.)	Temperature (°C)	Size of nanoparticle (nm)	Concentration (vol.%)	Enhancement ratio of k
Das et al.	21	28,6	1 to 4	1,07 - 1,14
	36	28,6	1 to 4	1,22 - 1,26
	51	28,6	1 to 4	1,29 - 1,36
Li & Peterson	28,9	29	2 to 6	1,35 - 1,36
	31,3	29	2 to 6	1,35 - 1,5
	33,4	29	2 to 6	1,38 - 1,51

Nanoparticle Size Characterization Process

The characterization process involves analysis and methods as Dynamic Light Scattering (DLS), Typical XRD (X-Ray Diffraction) patterns, SEM (Scanning Electrons Microscope) and TEM (Transmission Electron Microscope). After the characterization process it's possible to estimate over a volume concentration (vol.%) and the percentage of average nanoparticles at a certain size (nm)



High purity (CuO):
98% / 29 nm
~80% of particles
present this size

Ultra Pure (Cu):
>99.98% / 2 nm
> 95% of particles
present this size

Reliability of Nanofluids

For a reliable and stable nanofluid, two mandatory requirements are needed:

a) Nanoparticles dispersion: nanoparticles evenly dispersed in the base fluid;
b) Controlled surface charge: control of zeta potential;

The three most common methods in order to get a reliable stabilization and avoid clogging and sedimentation of nanoparticles:

1) Addition of surfactant or activator – **should be avoided in heat pipes**;
2) Modification of nanoparticle surface chemistry;
3) Ultrassonication for nanoparticles to avoid agglomeration.

Reliability of Nanofluids

Table demonstrates some relevant parameters related to ultrassonication process for obtaining a reliable nanofluid (*Marcelino et al,* "A Review on Thermal Performance of CuO-water Nanofluids Applied to Heat Pipes and Their Characteristics", *Itherm, May 27-30, 2016, Las Vegas NV USA).*

Nanoparticle size (nm)	Concentration	Stability process	Duration	Frequency
28,6	1 - 4 vol.%	Ultrasonic	11h	Not informed
10	0,003 vol.%	Ultrasonic	2 - 7h	Not informed
25	0,3	NA	NA	Not informed
25	0,1 wt%	Ultrasonic, pH control and surfactant addition	1h	Not informed
35,4	not informed	not informed	not informed	Not informed
50	0,5-2 wt%	Ultrasonic	10h	25-40Hz
50	0,5-2 wt%	Ultrasonic	10h	Not informed
50	0.5 / 1.0 / 1.5	Ultrasonic	1h	45Hz
50	0,5-2 wt%	Ultrasonic	10h	20-40Hz

Thermal Conductivity Models – CuO-Water Nanofluids

Thermal conductivity models - Koo and Kleinstreuer considers the Brownian motion for CuO-water nanofluids **up to 1% of volume fraction**.

$$K_{eff} = K_{static} + K_{Brownian}$$

K_{eff} = Thermal conductivity (W/m.K);
K_{static} = Thermal conductivity due to the intermolecular energetic potential (W/m.K);
$K_{Brownian}$ = Thermal conductivity due to Brownian motion (W/m.K).

Yimin and Xuan considers Brownian motion and Diffusion Limited Aggregation (DLA) theories for CuO-water nanofluid:

$$\frac{k_{eff}}{k_f} = \frac{k_p + 2k_f - 2\emptyset(k_f - k_p)}{k_p + 2k_f + \emptyset(k_f - k_p)} + \frac{\rho_p \emptyset C_p}{2k_f}\sqrt{\frac{k_b T}{3\pi r_c \eta}}$$

K_{eff} = Thermal conductivity (W/m.K);
K_f = Thermal conductivity of base fluid (W/m.K);
K_p = Thermal conductivity of nanoparticle (W/m.K);
Φ = Volume fraction of nanoparticles (vol. %);
C_p = Specific heat (J/Kg.K);
ρ_p = Density of nanoparticle (W/m.K);
r_c = Radius of aggregate or cluster (m);
η = Viscosity (Pa.s or cP).

Thermal Conductivity Models – CuO-Water Nanofluids

Author	Model	Comments
Maxwell **[4]**	$k_{eff} = k_p + 2k_f + 2\phi_p(k_p - k_f)$ $k_f = k_p + 2k_f - \phi_p(k_p - k_f)$	Based on spherical particles, random suspensions which must be under conduction solution theory through stationary conditions
Hamilton **[5]**	$k_{eff} = \dfrac{k_p + (n-1)k_f + (n-1)\phi_p(k_p - k_f)}{k_p + (n-1)k_f - \phi_p(k_p - k_f)}$	For high concentrations of spherical particles under conditions of differential effective medium (DEM) theory
Prasher et al. **[6]**	$k_{eff} = (1 + ARe^m Pr^{0.333}\phi_p)\left[\dfrac{k_p + 2k_f + 2\phi_p(k_p - k_f)}{k_p + 2k_f - \phi_p(k_p - k_f)}\right]k_f$	Obtained from Maxwell model and included the effects of correction generated by the Brownian motion
Koo and Kleinstreuer **[7]**	$k_{eff} = k_{static} + k_{Brownian}$ $k_{static} = \dfrac{k_p + 2k_f + 2\phi_p(k_p - k_f)}{k_p + 2k_f - \phi_p(k_p - k_f)}$ $k_{Brownian} = 5x10^4 \beta \phi_p \rho_p c_p \sqrt{\dfrac{k_B T}{\rho_p D}}(T, \phi_p)$	Considers the effects of surrounding liquid motion with random nanoparticles movement. Based on static Maxwell theory and dynamic effect of Brownian motion
Yu and Choi **[8]**	$k_{eff} = \dfrac{k_p + 2k_f + 2\phi(k_{pe} - k_f)(1+\beta)^3}{k_{pe} + 2k_f - \phi(k_{pe} - k_f)(1+\beta)^3} k_f$ $k_{pe} = \dfrac{2(1-\gamma)+(1+\beta)^3(1+2\gamma)\gamma}{-(1-\gamma)+(1+\beta)^3+(1+2\gamma)} k_p$	It was based on Maxwell model but addionally taking into account the effects of nanolayer thickness and thermal conductivity parameters

Viscosity Models

The first nanofluid viscosity models were based on Einstein's linear model (1906):

$$\mu_r = \frac{\mu_{nf}}{\mu_{bf}} = 1 + 2.5\phi$$

μ_r = Mixture viscosity relation;
μ_{nf} = Viscosity of nanofluid (Pa.s);
μ_{bf} = Viscosity of base fluid (Pa.s);
Φ = Volume fraction of nanoparticles (vol. %).

Viscosity models specifically investigated for CuO-water nanofluid:

Kulkarni et al. (2006):

$$\ln(\mu_{nf}) = A\frac{1}{T} - B$$

μ_{nf} = Dynamic viscosity of nanofluid (cP);
A and B = Parameters in function of volume fraction;
T = Temperature (K).

Mahbudul et al. (2011):

$$\mu_{nf} = \mu_{bf}(1.475 - 0.319\phi + 0.051\phi^2 + 0.009\phi^3)$$

μ_{nf} = Viscosity of nanofluid (Pa.s);
μ_{bf} = Viscosity of base fluid (Pa.s);
Φ = Volume fraction (vol. %)

Viscosity Models

Author	Model	Comments
Einstein [14]	$\mu_{eff} = (1 + 2.5\phi_p)\mu_f$	Based on phenomenological hydrodynamic equation for infinitely diluted suspensions of spheres with no interaction between spheres. Works well for maximum volume concentration of 2%
Brinkman [15]	$\mu_{eff} = \frac{1}{(1+2.5\phi_p)^{2.5}}\mu_f = (1 + 2.5\phi_p + 4.375\phi_p^2 + \cdots)\mu_f$	Extended Einstein's model by considering the effect of addition of one solute molecule to an existing solution.
Buongiorno [16]	$\mu_{eff} = (1 + 39.11\phi_p + 533.9\phi_p^2)\mu_f$ $\mu_{eff} = (1 + 5.45\phi_p + 108.2\phi_p^2)\mu_f$	Curve fitting from experimental data of Al2O3-water nanofluid
Nguyen et al. [17]	$\mu_{eff} = \mu_f 0.904 e^{0.148\phi_p}$ $\mu_{eff} = (1 + 0.025\phi_p + 0.015\phi_p^2)\mu_f$	Curve fitting from experimental data of Al2O3-water nanofluid
Chen et al. [18]	$\mu_{nf} = \mu_{bf}\left[1 + 10.6\phi_p + (10.6\phi_p)^2\right]$	Adjusted model for experimental versus theoretical data by considering the rheological effects of shear-rate
Kulkami et al. [19]	$ln(\mu_{eff}) = A\left(\frac{1}{T}\right) - B$ $A = 20587\phi_p^2 + 15857\phi_p + 1078.3$ $B = -107.12\phi_p^2 + 53.54\phi_p + 2.8715$	Curve fiting from experimental CuO-water: 5%< Φ_p <15% dp=29 nm; 278 < T(K) < 323; shear rate = 100 l/s
Namburu et al. [20]	$log(\mu_{eff}) = Ae^{-BT}$ $A = -0.29956\phi_p^3 + 6.738\phi_p^2 - 55.444\phi_p + 236.11$ $B = -6.4745\phi_p^3 + 140.03\phi_p^2 - 1478.5\phi + 20341$	Curve fitting from experimental data of Al2O3-ethylene-glycol nanofluid: 1% < Φ_p <10%; dp=53 nm; 278<T (K)<323
Adedian et al. [21]	$\mu_{nf} = \frac{\mu_{bf}}{\left(1 - \frac{5}{2}\phi_p\right)}$	Extention of Einstein's equation for obtaining good agreement in volume concentration ranges of up to 18-20% in suspension system non-interacting with spherical particles.
Meybodi et al. [22]	$\mu_{nf} = \mu_{bf}\frac{A_1 + A_2 exp\left(\frac{\phi_p}{S}\right) + A_3\left[exp\left(\frac{\phi_p}{S}\right)\right]^2 + A_4\left[exp\left(\frac{\phi_p}{S}\right)\right]^3}{A_5 + A_6\frac{ln(S)}{T} + A_7\frac{[ln(S)]^2}{T}}$ $A_1 = 1.3354064976x10^2$ $A_2 = -3.4382413843x10^2$ $A_3 = 2.9011804759x10^2$ $A_4 = -78993120761x10^1$ $A_5 = 9.1161630781x10^{-1}$ $A_6 = 3.2330142333x10^1$ $A_7 = -1.1732514460x10^1$	Model obtained from experimental data, which takes into account volume concentration, nanoparticles size and temperature

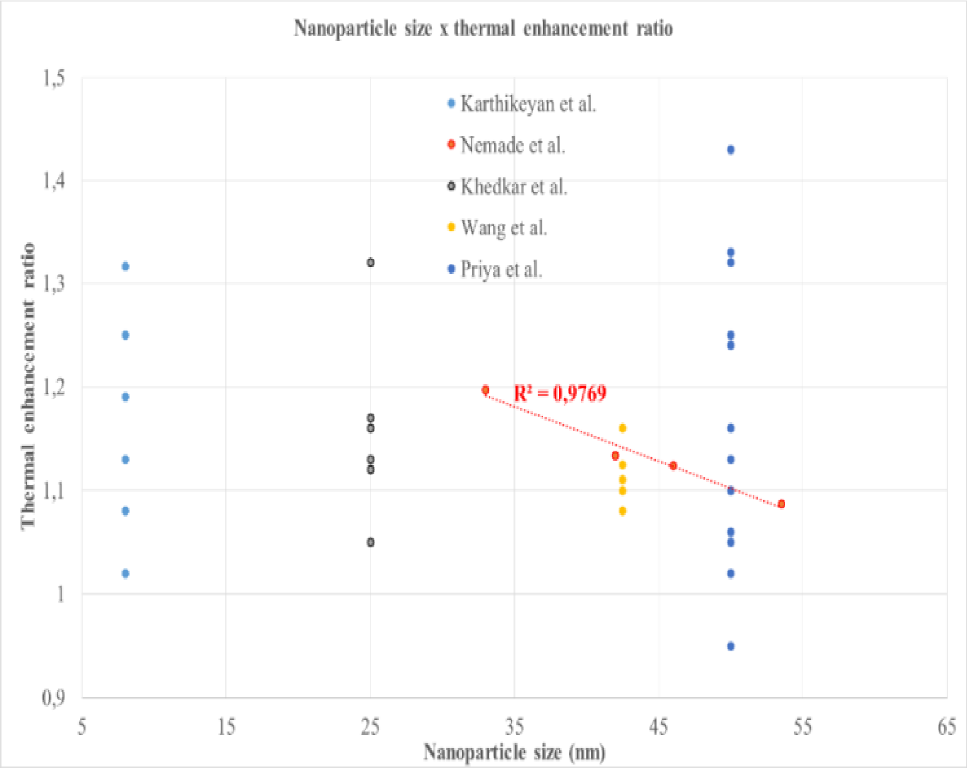
Results and Comments

Different nanoparticle sizes applied in CuO-water nanofluid and their respective thermal enhancement ratios.

Author [Ref]	CuO Nanoparticle Size (nm)	Thermal Enhancement ratio	Volume fraction (vol. %)	Temperature (°C)	Sonication time (h)
Karthikeyan et. al [16]	8	1,02	0,02	20	0,5
	8	1,08	0,09	20	0,5
	8	1,13	0,1	20	0,5
	8	1,19	0,3	20	0,5
	8	1,25	0,8	20	0,5
	8	1,316	1	20	0,5
Nemade et. al [17]	33	1,197	0,5	55	1
	42	1,134	0,5	55	0,75
	46	1,124	0,5	55	0,5
	53,5	1,087	0,5	55	0,25
Khedkar et al. [18]	25	1,05	0,01	26	1,5
	25	1,12	0,02	26	1,5
	25	1,13	0,03	26	1,5
	25	1,16	0,04	26	1,5
	25	1,17	0,05	26	1,5
	25	1,32	0,075	26	1,5
Wang et al. [19]	42,5	1,08	0,02	25	not informed
	42,5	1,1	0,04	25	
	42,5	1,11	0,1	25	
	42,5	1,125	0,15	25	
	42,5	1,16	0,4	25	
Priya et al. [20]	50	1,02	0,004	28	6
	50	1,06	0,008	28	6
	50	1,1	0,012	28	6
	50	1,13	0,016	28	6
	50	1,05	0,004	50	6
	50	1,16	0,008	50	6
	50	1,25	0,012	50	6
	50	1,32	0,016	50	6
	50	0,95	0,004	55	6
	50	1,24	0,008	55	6
	50	1,33	0,012	55	6
	50	1,43	0,016	55	6

(*) average nanoparticle size

Results and Comments

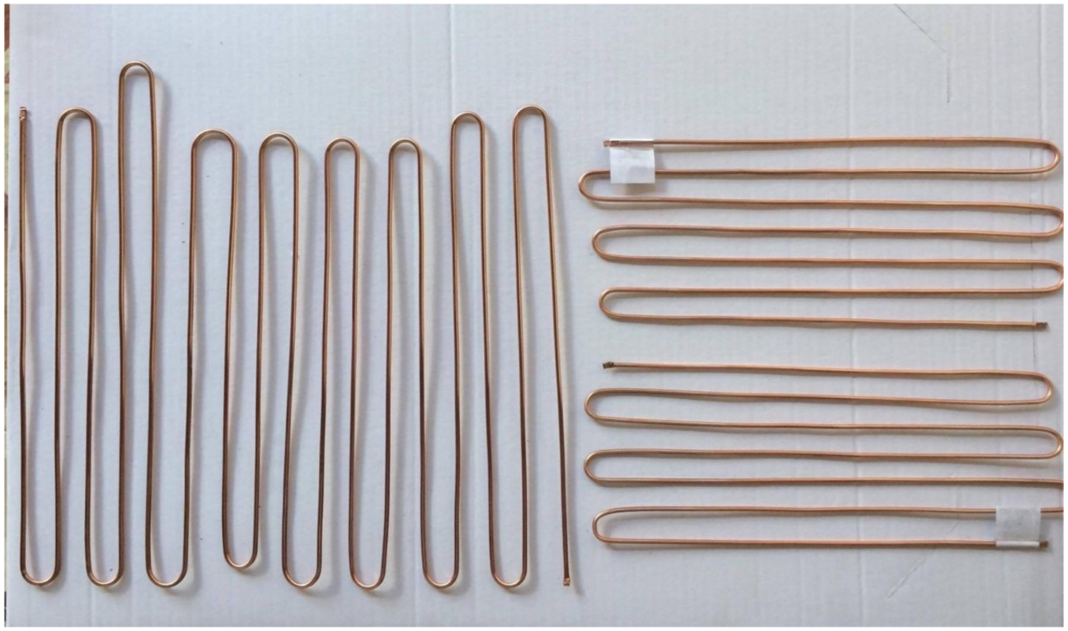


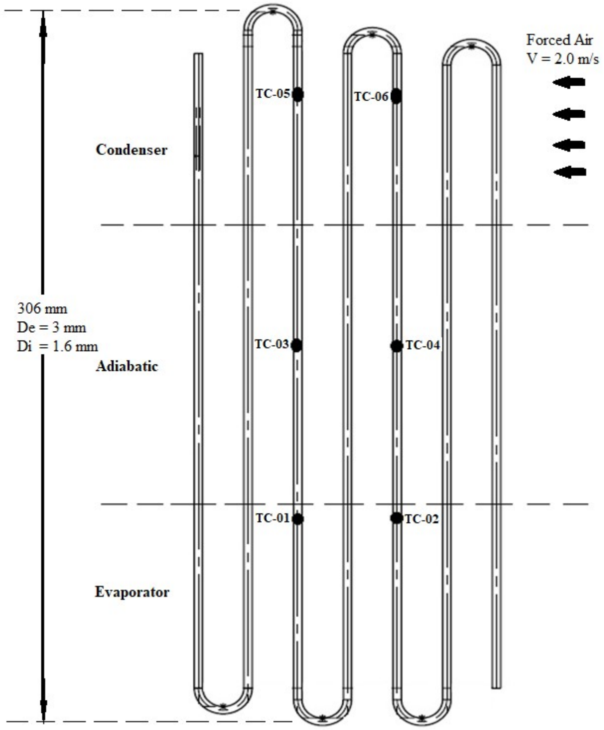
With a fixed nanoparticle size and by varying other parameters (e.g. sonication time, volume fraction, etc.), it is possible to obtain similar thermal enhancement ratios between two nanofluids with different nanoparticle sizes.

No general model available due to variations of nanoparticles sizes and distribution, as well as purity – requires statistical treatment.

Results and Comments

Pulsating Heat Pipe: applied in the thermal control of radio frequency (RF) components in radars.

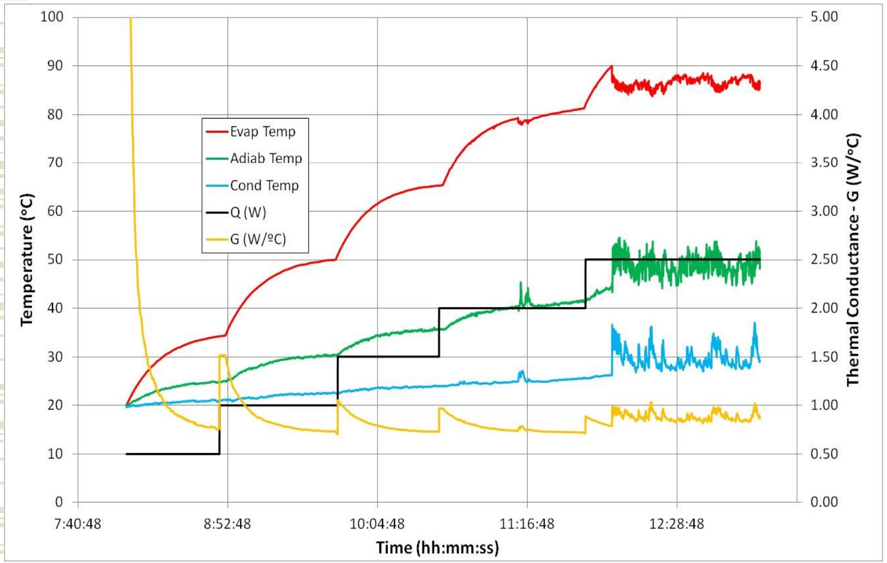


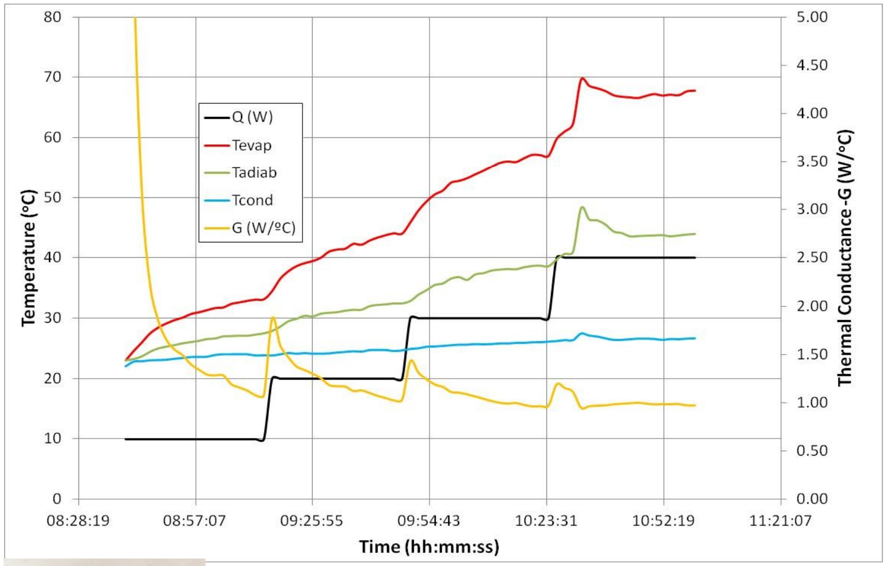


1st ENSf, 8th 11th October 2017 Lisbon, Portugal

Results and Comments

Pulsating Heat Pipe: the combination of smaller particle size, geometry (shape) and higher purity results in a more stable operation – Copper-Methanol nanofluid (3.5% w.t.)





High purity (CuO): 98% / 29 nm
~80% of particles present this size
< 60% of particles are spheres

Ultra Pure (Cu): >99.98% / 2 nm
> 95% of particles present this size
> 95% of particles are spheres

Conclusions

- For heat pipes application, models can show great variation in experimental results if they were conceived for atmospheric or saturation conditions;
- Wide variations on results related to the use of a given nanoparticle size and mixing techniques on the thermal enhancement;
- Further investigation is necessary for better understanding the impacts over each percentage of the nanoparticle size distribution versus thermal enhancement ratio and pressure drop influence;
- The addition of solid nanoparticles in the base fluid causes the increase on the nanofluid's viscosity, increasing the overall pressure drop – requires proper evaluation;
- More stable operation obtained with smaller particles with higher purity;
- Statistical treatment becomes a requirement to normalize results for better analysis.

Heat Powered Cycles Conference 2018
16.-19.09.2018

Heat Powered Cycles Conference
Center of Energy Technology, University of Bayreuth, Germany

Extended Abstracts Deadline: 18 Nov 2017

https://heatpoweredcycles.org/

Thank You !

Questions ?

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