MINISTÉRIO DA CIÊNCIA E TECNOLOGIA
INSTITUTO NACIONAL DE PESQUISAS ESPACIAIS

Overall Review on the Application of Nanofluids in Passive Thermal Control Systems for Aerospace and Defense

Dr. Roger R. Riehl
roger.riehl@inpe.br
Two-Phase Thermal Control R&D
National Institute for Space Research – INPE/DMC/Satelite
+55 12 981 212 112

NANOUPTAKE, Trainning School 26th-28th October 2016 Castellon de la Plana,Spain

Av. dos Astronautas,1.758 - Jd. Granja - 12227-010 - Phone: 55-12-3206-4305 / Fax: 55 12 3208-6226
São José dos Campos - SP - Brasil http://www.dem.inpe.br/~rriehl - E-mail: roger.riehl@inpe.br

Agenda

- Loop Heat Pipe Development
- Pulsating Heat Pipe Development
- Importance of LHPs and PHPs Technologies
- Nanofluids Concept and Application
- Consideration About Nanofluids
- Testing With Nanofluids
- Results and Discussions
- Several Applications for Nanofluids
- Following Steps on Nanofluids R&D
- Concluding Remarks

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Loop Heat Pipe Development

- Objectives:
  - Establish a LHP development program for future Satellites and Defense systems
  - Define all technological steps
    - Manufacturing processes
    - Wick materials and working fluids investigation
  - Create a program to fulfill the current needs
  - Certify and qualify LHPs for space and defense applications
- Investigate new working fluids

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Pulsating Heat Pipe Development

- Objectives:
  - Better understand the theory behind PHPs for future development and application on Satellites and Defense
  - Define all technological steps
  - Create a program to fulfill the current needs
  - Certify and qualify PHPs for space and defense applications
- Investigate new working fluids

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Importance of LHPs and PHPs Technologies

- Growing need for heat dissipation
- Several applications on satellites and ground equipment:
  - Geo-stationary and low orbit satellites:
    - Telecommunications
    - Weather and Earth Observation
  - Defense and surveillance systems
    - Radars and radios

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Importance of LHPs and PHPs Technologies

- Different heat loads needed for LHPs and PHPs:
  - LHPs: up to 150 W
  - PHPs: up to 500 W
- Alternative working fluids (water, methanol, acetone)
- Operation Temperature Range: -40 to +150°C
- Integration on the structure is relevant

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Importance of LHPs and PHPs Technologies

- Other subjects are also investigated:
  - Ceramic and zirconia wick structures
  - Nanofluids applied to LHPs and PHPs (experimental and theoretical)
  - Fabrication and qualification procedures

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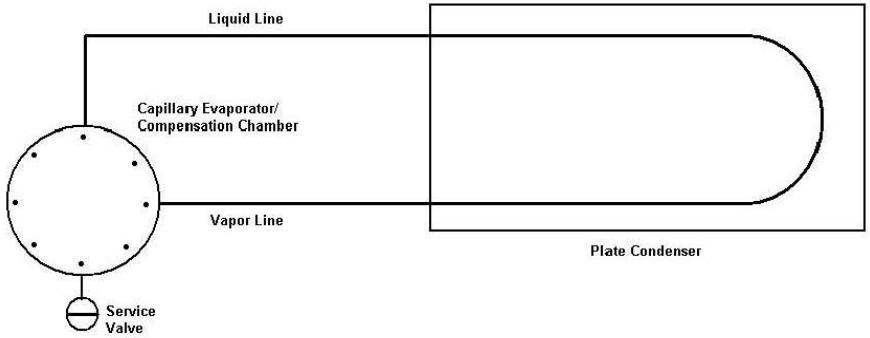
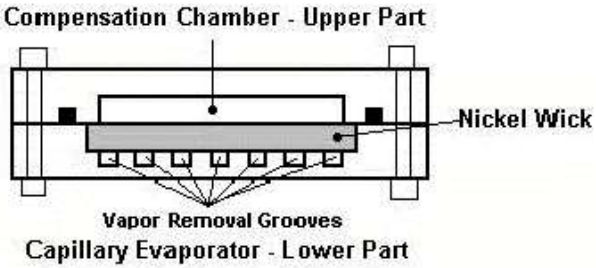
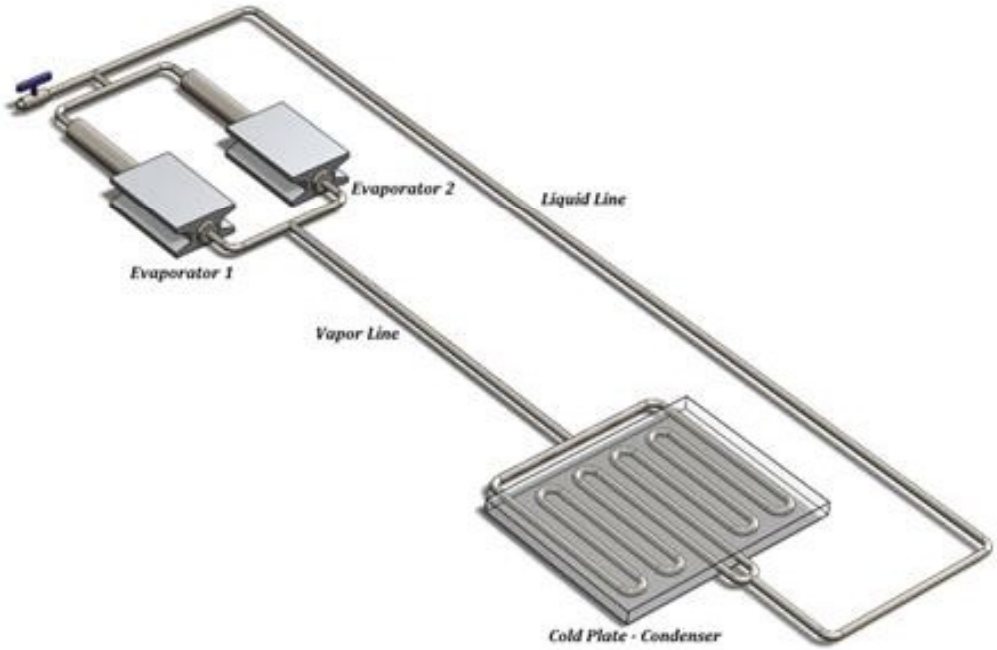
Loop Heat Pipe Designs







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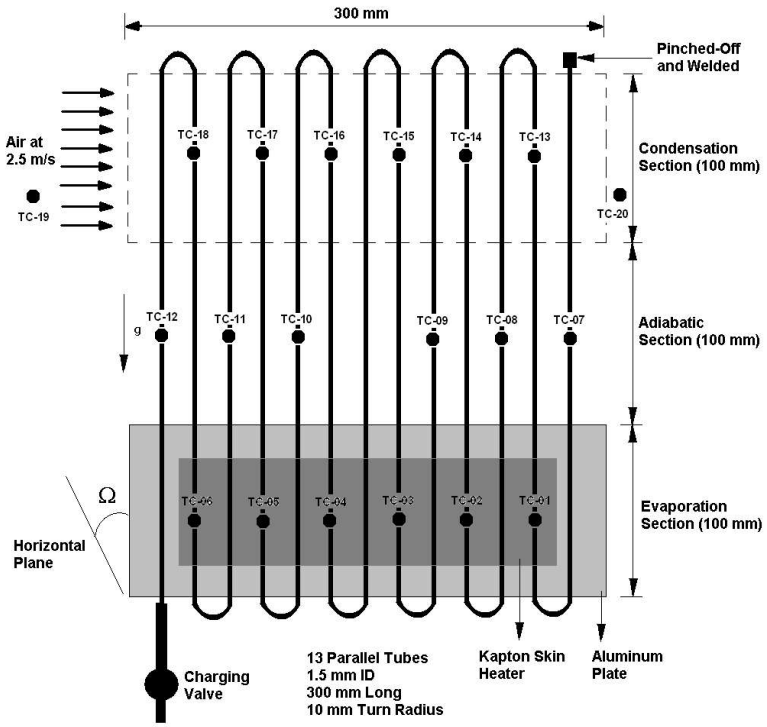
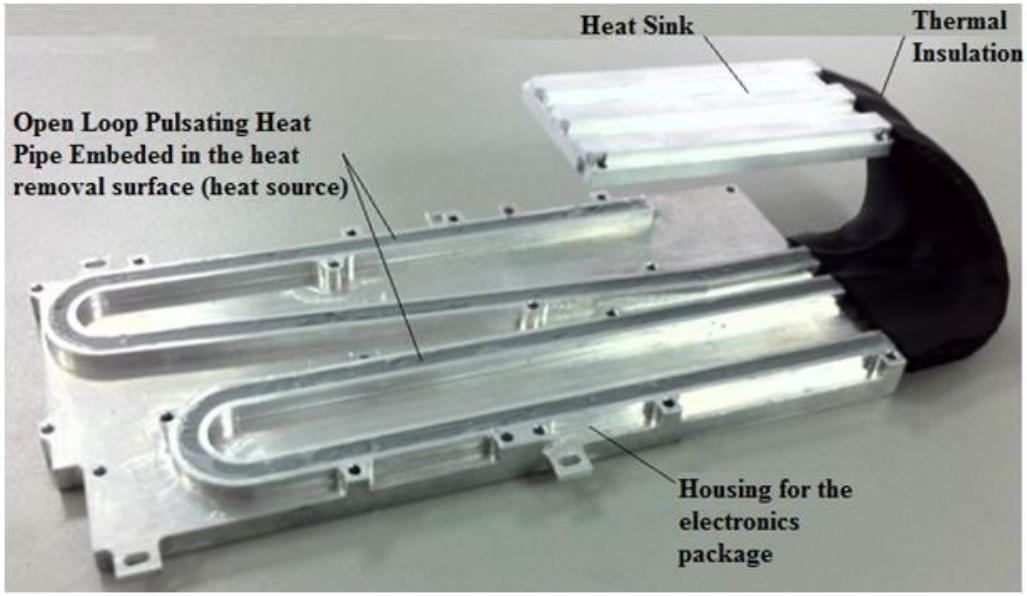
Pulsating Heat Pipe Designs





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Nanofluids Concept and Application

- Composed by a pure substance (base fluid) and solid nanoparticles:
  - Usually mixed with mass fractions up to 5%
  - Sizes below 100 nm
  - High purity: > 98%
- Influence on the properties:
  - May increase the liquid thermal conductivity by 20%
  - Improve heat transfer capability (proven on single-phase heat transfer devices)

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Nanofluids Concept and Application

- What are the effects on the other transport properties important for LHPs?
  - Liquid viscosity
  - Liquid density

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Nanofluids Concept and Application

- Two-phase model (V. P. Carey, 2008)

$$k_n = \frac{k_p + 2\ k_l + 2\left(k_p - k_l\right)\ f}{k_p + 2\ k_l - \left(k_p - k_l\right)\ f} k_l$$

Thermal Conductivity

$$\frac{1}{\rho_n} = \left(\frac{f}{\rho_p} + \frac{1-f}{\rho_l} \right)$$

Density

$$\mu_n = \mu_l \frac{1}{\left(1-f\right)^{2.5}}$$

Viscosity

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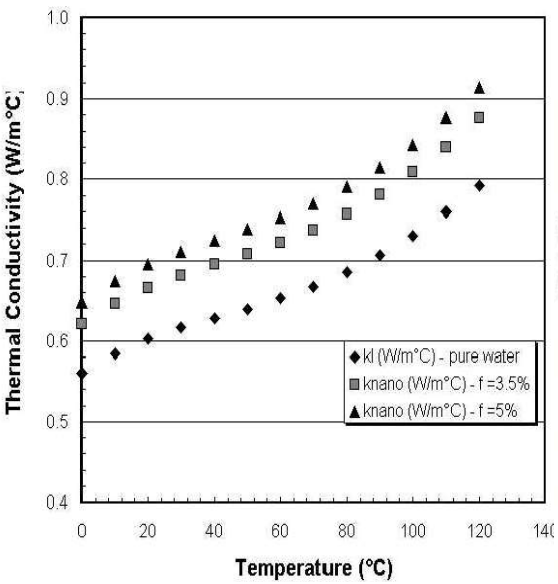
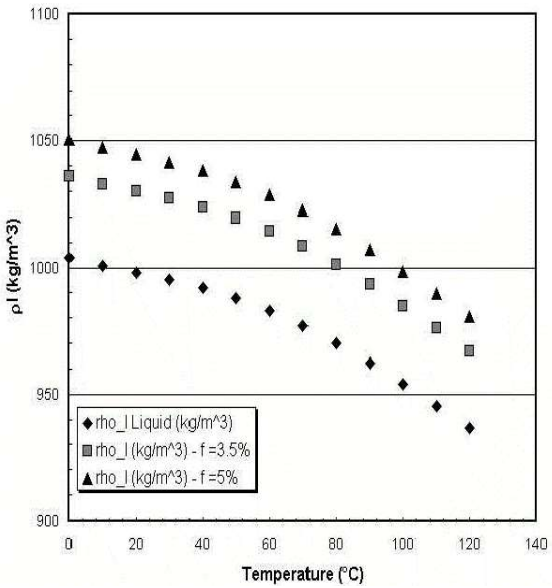
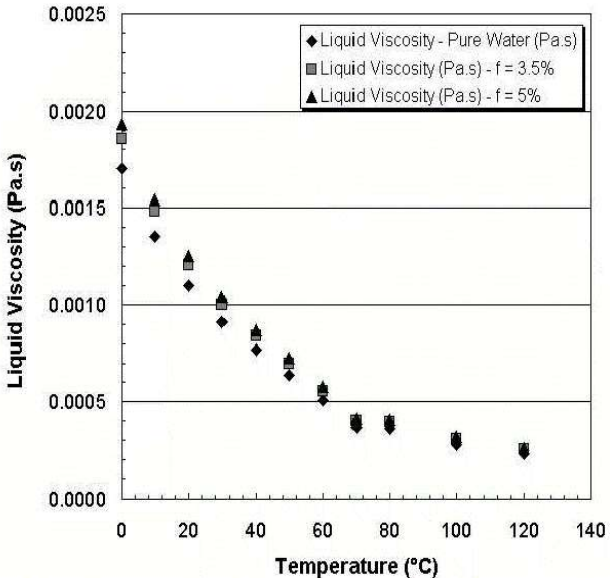
Nanofluids Concept and Application

Using Nickel Nanoparticles – 40 nm







Increase thermal conductivity by 10% for *f*=3.5% and 16.5% for *f*=5%

Increase liquid viscosity by 3.2% and 4.7%

Increase liquid viscosity by 9.3% and 13.7%

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Considerations About Nanofluids

- Nanofluid must be a homogeneous solution
- Solid nanoparticles cannot present sedimentation
- Nanofluid must be chemically compatible
- Wetting characteristics on wick materials must be observed
- Use of surfactants must be avoided

Wick Material	Water			Acetone			Methanol		
	Ni	**Cu**	**Al**	**Ni**	**Cu**	**Al**	**Ni**	**Cu**	**Al ****
Copper	**Poor**	**Good**	*	**Poor**	**Good**	**Poor**	**Poor**	**Good**	**Poor**
Nickel	**Good**	**Poor**	*	**Good**	**Poor**	**Poor**	**Good**	**Poor**	**Poor**
Polyethylene	**Poor**	**Poor**	*	**Poor**	**Poor**	**Poor**	**Poor**	**Poor**	**Poor**

* Water – Aluminum are incompatible substances – non-condensable gases are generated.
** Methanol – Aluminum have presented chemical incompatibility and unstable solubility.

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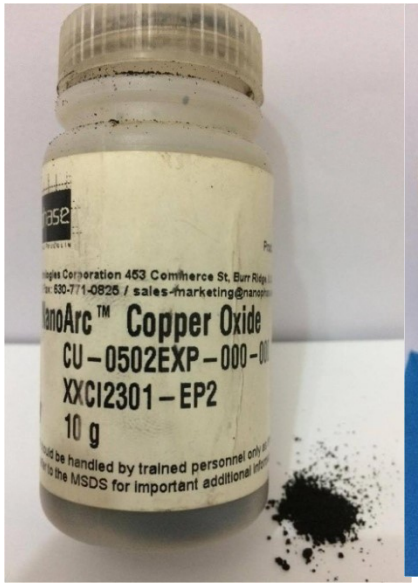
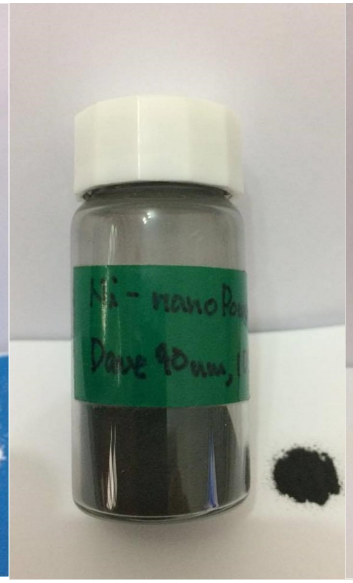
Considerations About Nanofluids





Copper Oxide	Aluminum Oxide	Nickel Oxide	Copper	Aluminum
Purity: 98%	Purity: 98%	Purity: 99.5%	Purity > 99.98%	
dp = 29 nm	dp = 36 nm	dp = 40 nm	dp = 2 nm	flakes: 2x3 nm

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Tests With Nanofluids - LHP

- De-ionized water and nickel oxide selected as the nanofluid combination
  - Due to the LHP characteristics
  - No use of surfactants due to chemical issues
- Necessary to agitate the nanofluid for 20~24 hours in ultrasonic bath
  - Required to form a nanolayer between the nanoparticles and the bulk liquid (Yu and Choi, 2003)

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Tests With Nanofluids - LHP

- Water-nickel nanofluid presents acceptable behaviour with nickel wick (LHP)
  - Wettability verification was performed
  - Nanofluid presents poor wettability on polyethylene and copper wicks
  - No separation of the nanoparticle from the water was verified during all tests

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Loop Heat Pipe Design

- Extense experience on design and tests of LHPs
- Known as reliable two-phase passive thermal control devices
- Miniature configuration is promissing and also reliable
- Flat evaporator design allows easy integration and a simple configuration

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Loop Heat Pipe Design

- Built with 316L SS
- Evaporator and compensation chamber are a single set
  - Total thickness is 8.0 mm
- Condenser is thermally connected to a cooling bath

Capillary Evaporator	**Liquid Line**	**Vapor Line**
Heat removal area: 3.0 cm^2 Number of grooves: 10	OD/ID(mm): 3.0/1.5 Length: 300 mm	OD/ID(mm): 3.0/1.5 Length: 200 mm
Nickel Wick Structure	**Compensation Chamber**	**Condenser**
Mean Pore size: 3 μm Porosity: 75 %	Total Volume: 6 cm^3	OD/ID(mm): 3.0/1.5 Length: 500 mm

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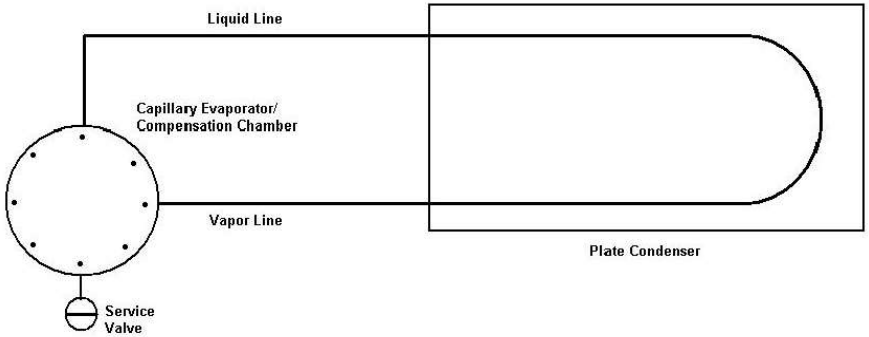
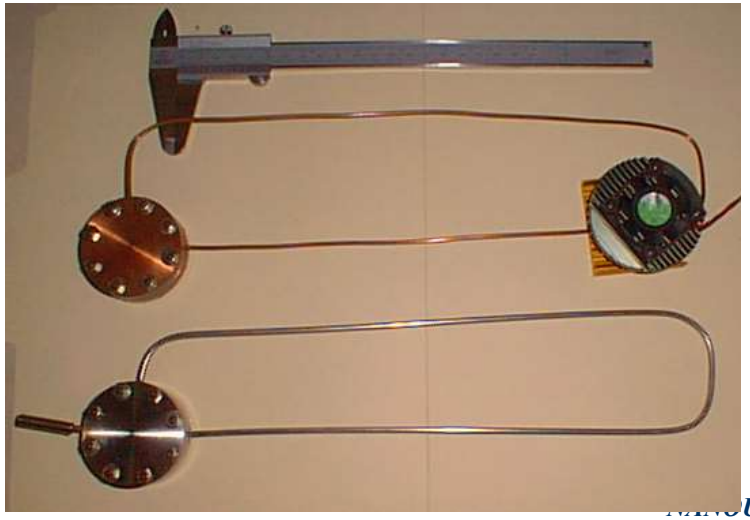
Mini-Loop Heat Pipe





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Results and Discussion - LHP

- First, the miniature LHP was tested with de-ionized water
- Concentrated heat flux on a area of 3.0 cm^2 resulted in high evaporator temperatures
- Reliable and constant operation for heat loads up to 40 W (maximum heat load tested)

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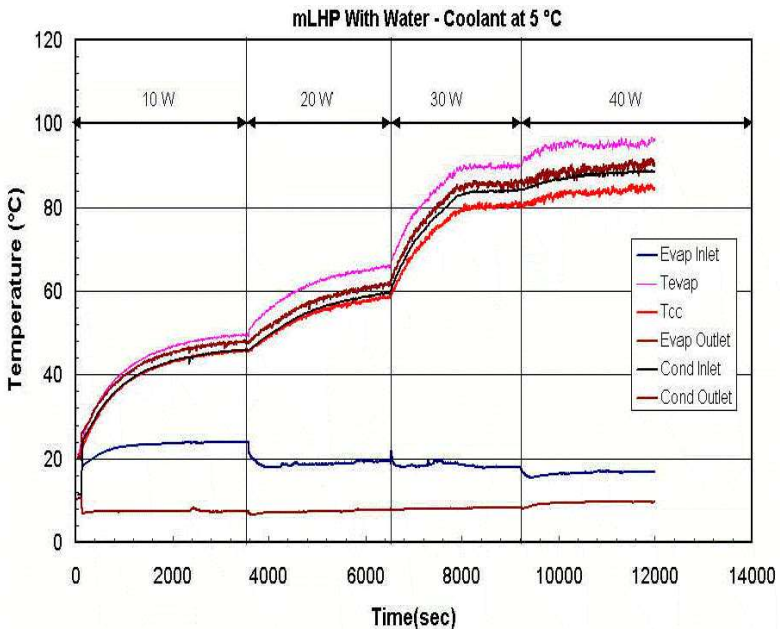
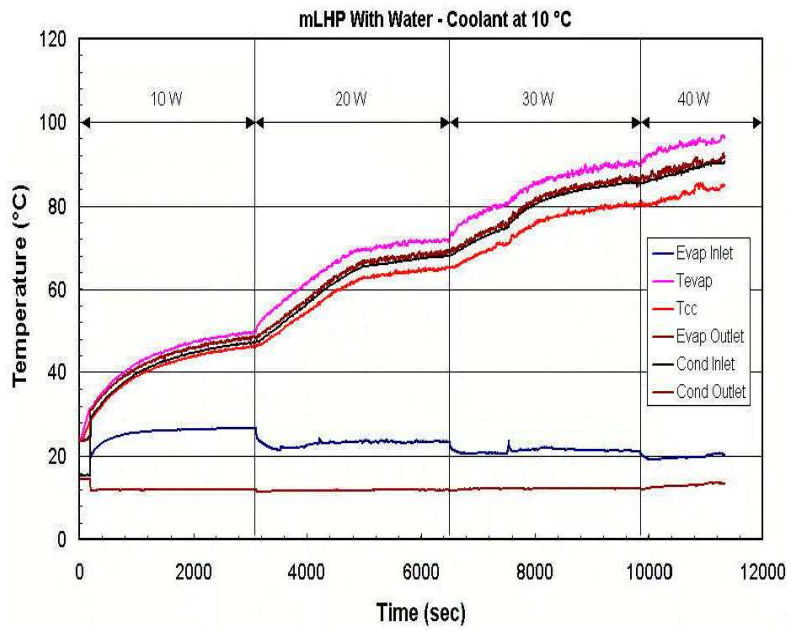
Results and Discussion - LHP





Longer startups when the coolant was set for 10 °C

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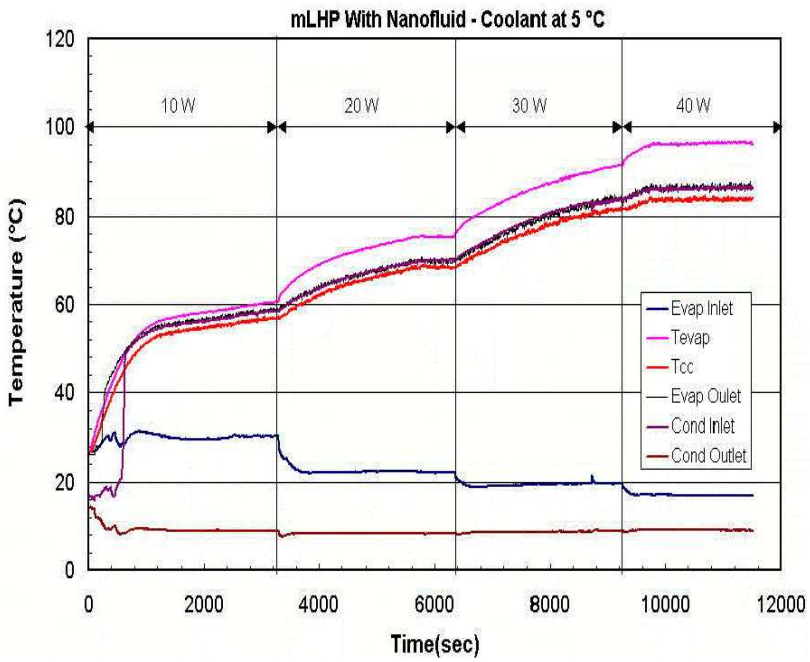
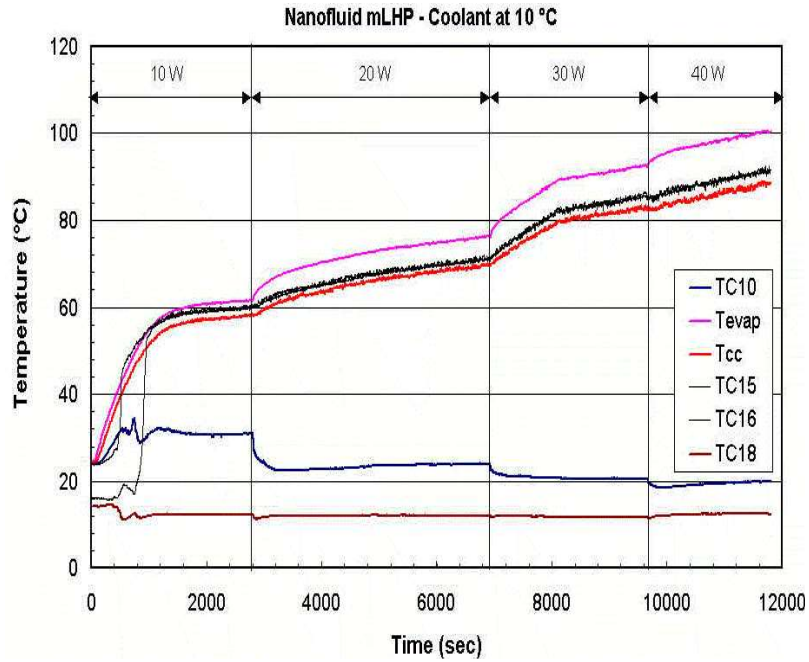
Results and Discussion - LHP





- Nickel nanofluid with concentration of 3.5%
- Longer startups when using nanofluids

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Results and Discussion - LHP

- Higher evaporator temperatures were observed when LHP was operating with the nanofluid
- Longer startups were also verified during all tests with the nanofluid
- Solid nanoparticles are acting against the capillary forces
  - Additional restrictions caused by the solid nanoparticles
  - Direct influence on the overall LHP performance

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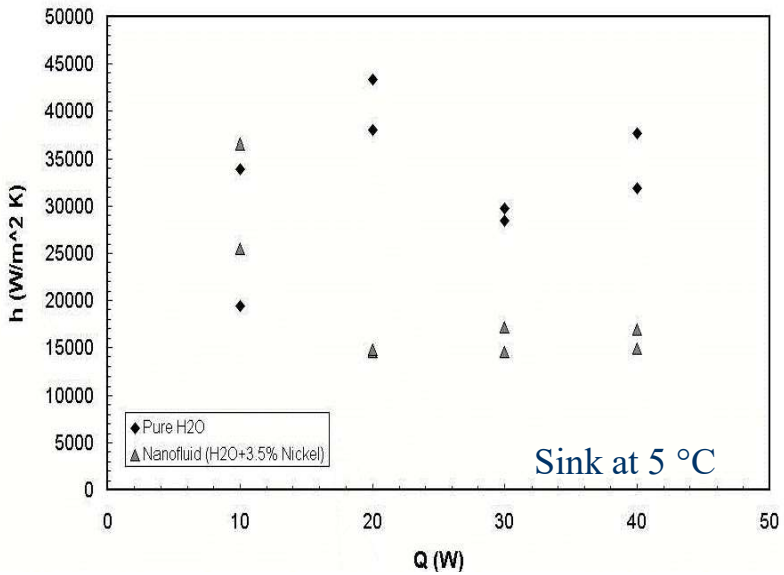
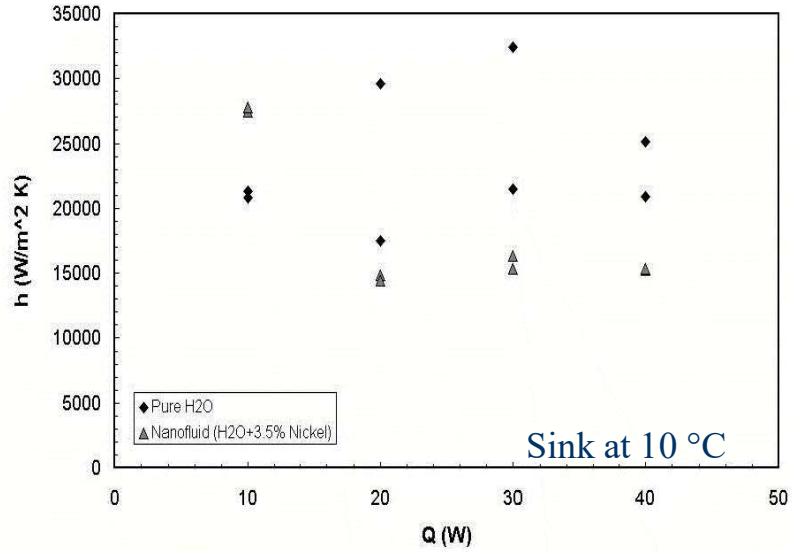
Effect on the Heat Transfer Coefficient - LHP





- When more liquid is present in the LHP, higher heat transfer coefficients were found
- When more vapour is present, the heat transfer coefficient is even less than when operating with pure water

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Effect on the Heat Transfer Coefficient - LHP

- At 10 W, the heat transfer coefficient is 33% greater with the nanofluid when compared with pure water
- For 40 W the heat transfer coefficient when using pure de-ionised water is 64% greater than when using the nanofluid
- For higher nanoparticle concentrations, the LHP would not operate

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Overall Effect on the LHP Performance

- Transport properties equations were evaluated on a steady-state model
- Nanoparticles were evaluated as another phase on the working fluid
  - Transport properties relations (Carey, 2008) were applied
- Simulations were compared with the experimental results

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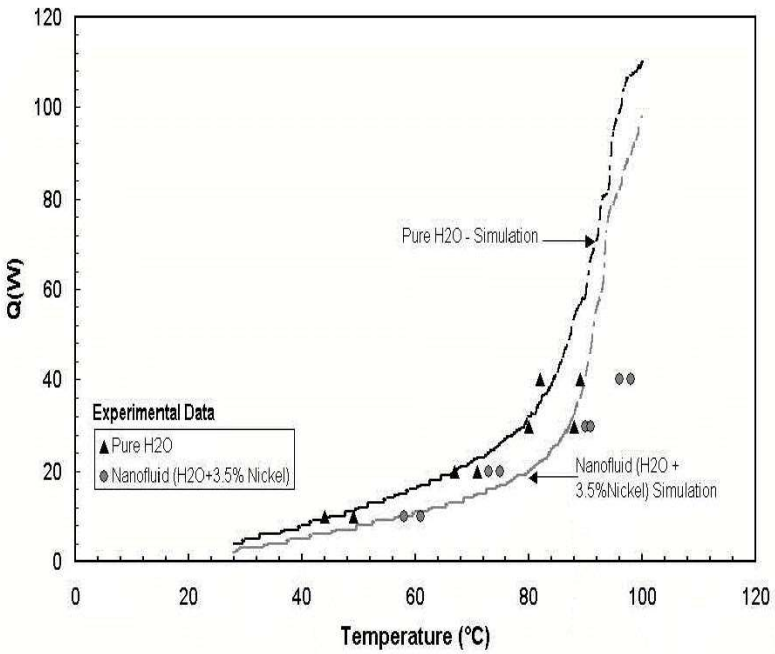
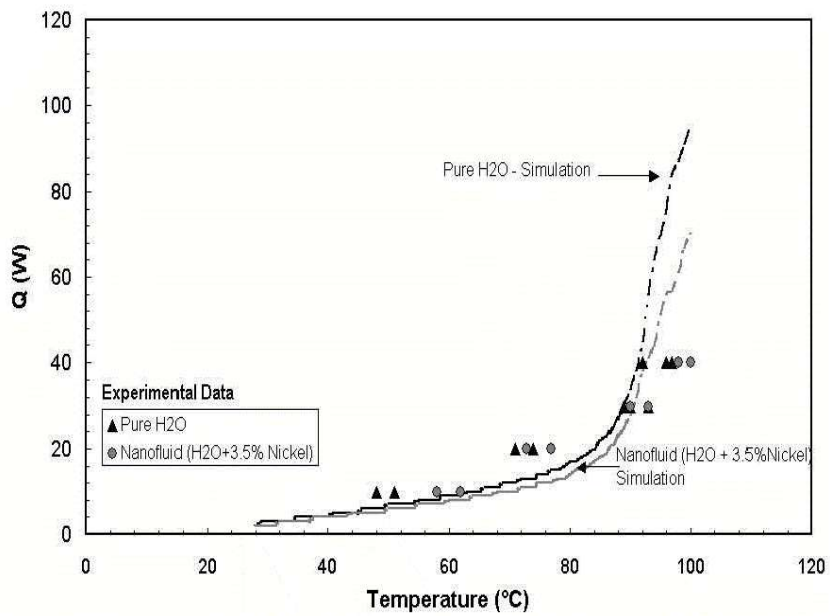
Overall Effect on the LHP Performance



Sink at 5 °C



Sink at 10 °C

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Overall Effect on the LHP Performance

- Using 3.5% by mass of nanoparticles is enough to compromise the overall LHP thermal performance
- Greater hydraulic loss of the nanofluid flowing across the porous wick also influences the entire LHP thermal performance
- For nanoparticles concentrations of 5%, the LHP presented unrealistic temperatures
  - LHP won't operate with this concentration

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Nanofluid Applied to PHP

- Fluid inventory does not change with applied power
- Presence of nanoparticles might assist on the improvement of the PHP thermal behaviour
- Previous evaluation (theoretical) of the PHP performance indicates improvements
- Tests were performed with de-ionized water and copper oxide nanoparticles
  - fraction of 5% by mass

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Nanofluid Applied to PHP

- PHPs have been considered today as important and reliable thermal management devices
- They can operate at any orientation without losing their heat transport capabilities
- Currently used in Space[1] and Surveillance[2,3] applications

- [1]Iwata, N., Ogawa, H., and Miyazaki, Y., "Temperature-Controllable Oscillating Heat Pipe," Journal of Thermophysics and Heat Transfer, Vol.25, No.3, pp.386-392, 2011
- [2]Riehl, R. R., Cachuté, L., "Thermal Control of Surveillance Systems Using Pulsating Heat Pipe and Heat Pipes", 49th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit11th International Energy Conversion Engineering Conference, 14-17 July 2013, San Jose, CA USA
- [3]Riehl, R. R., "Surveillance System Heat Transfer Enhancement Using Single-Phase Flow with Nanofluid", Heat Powered Cycles Conference, Netherlands, Sept 9-12, 2012.

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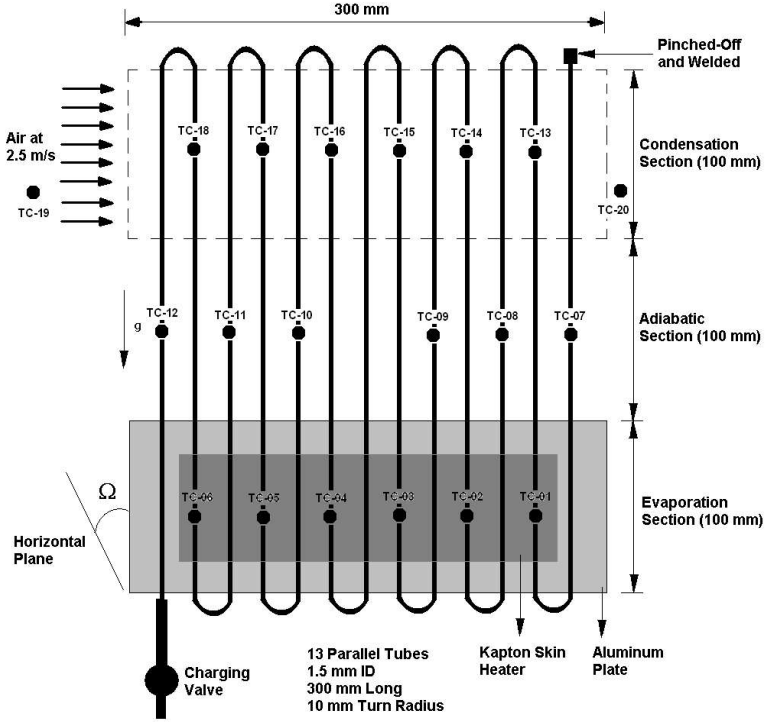
Nanofluid Applied to PHP

- Necessary to agitate using ultrasonic bath for 1.5 hs to obtain a homogeneous solution
  - Important to form a nanolayer between the particles and the base fluid (Yu and Choi, 2003)
  - No use of surfactants



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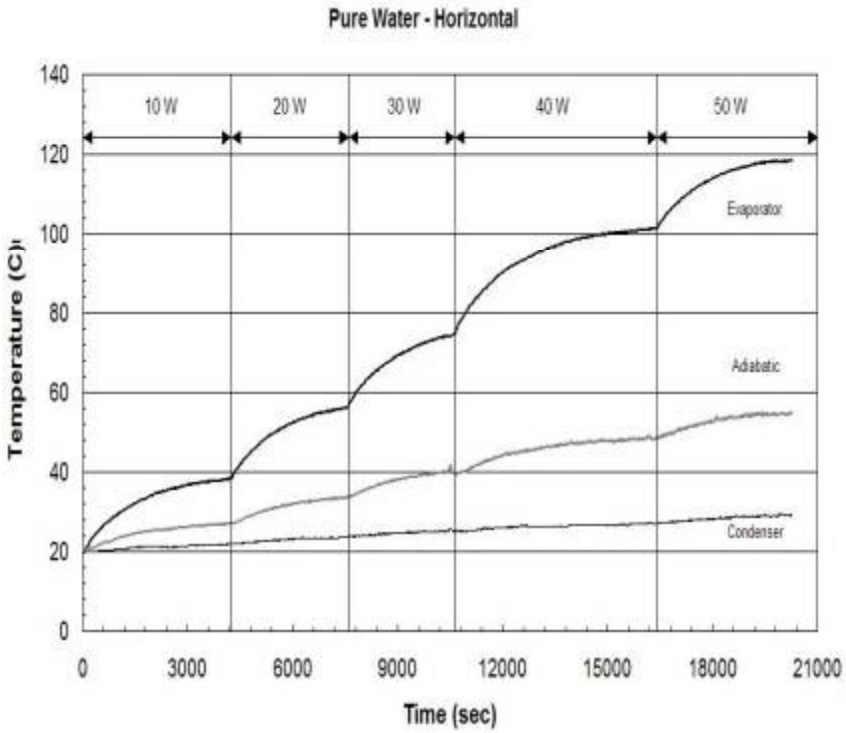
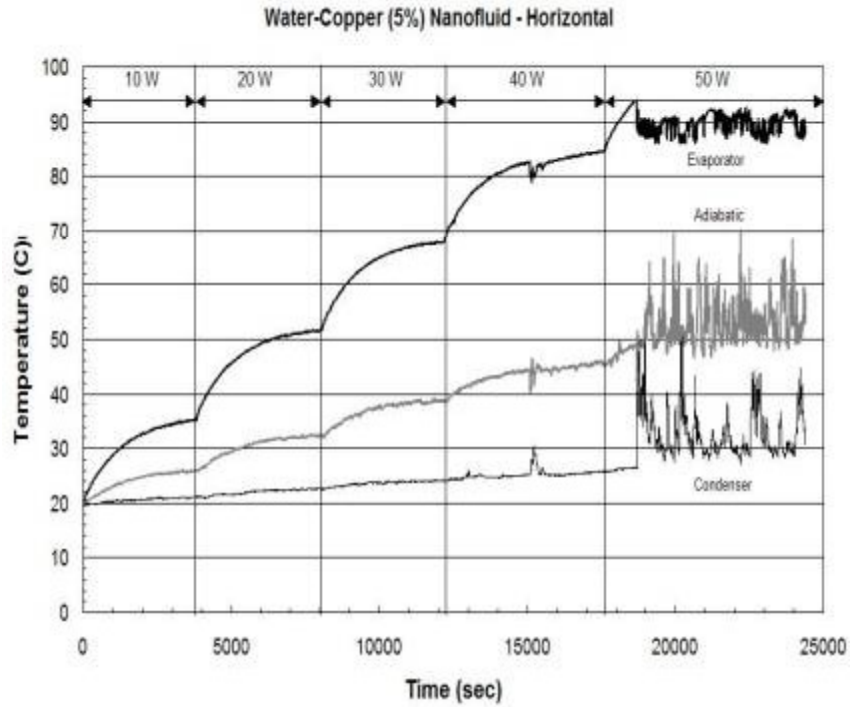
Overall Effect on the PHP Performance





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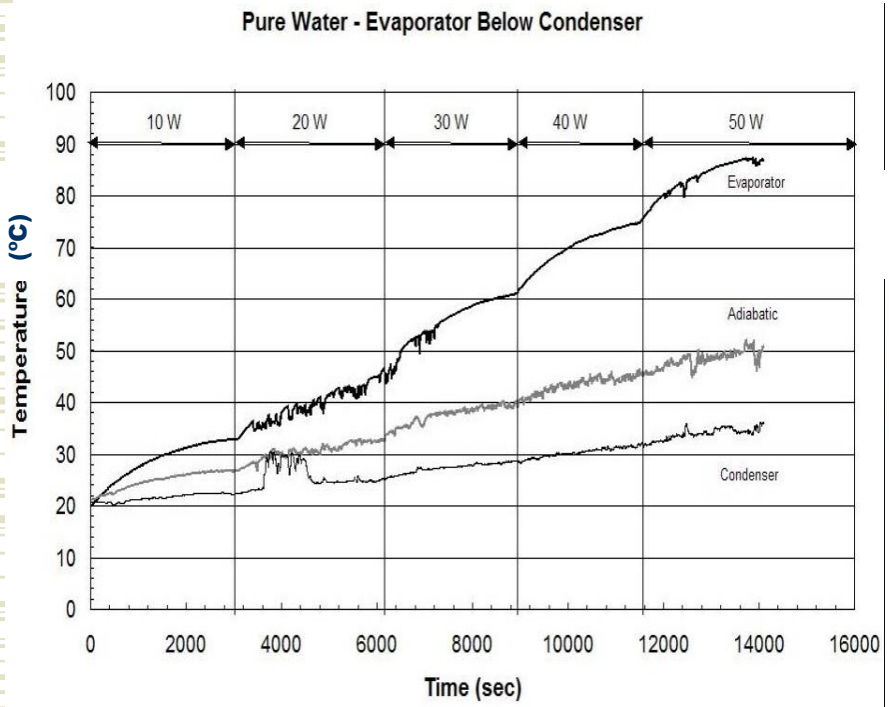
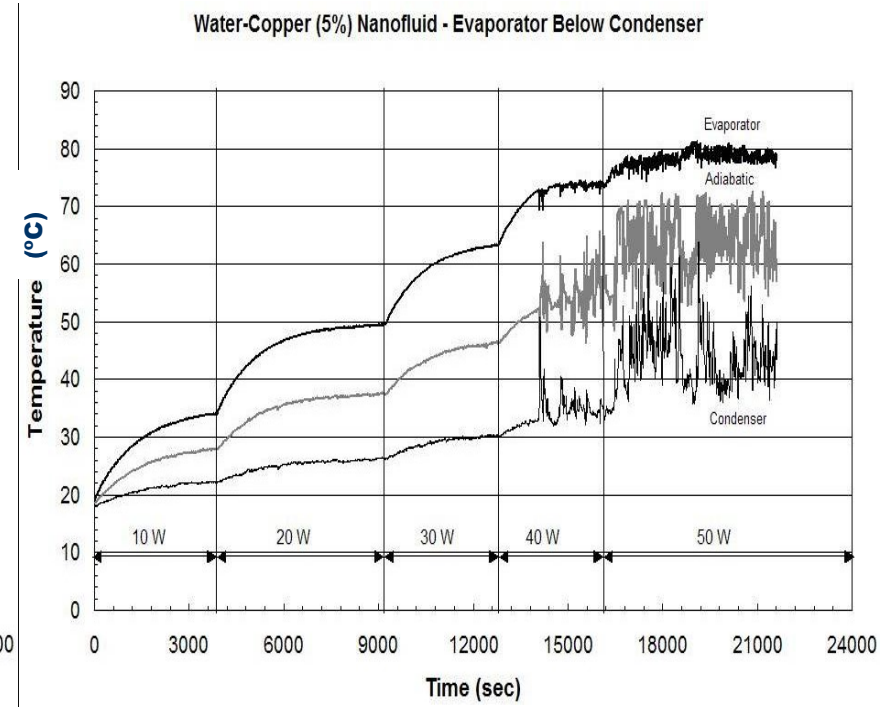
Overall Effect on the PHP Performance





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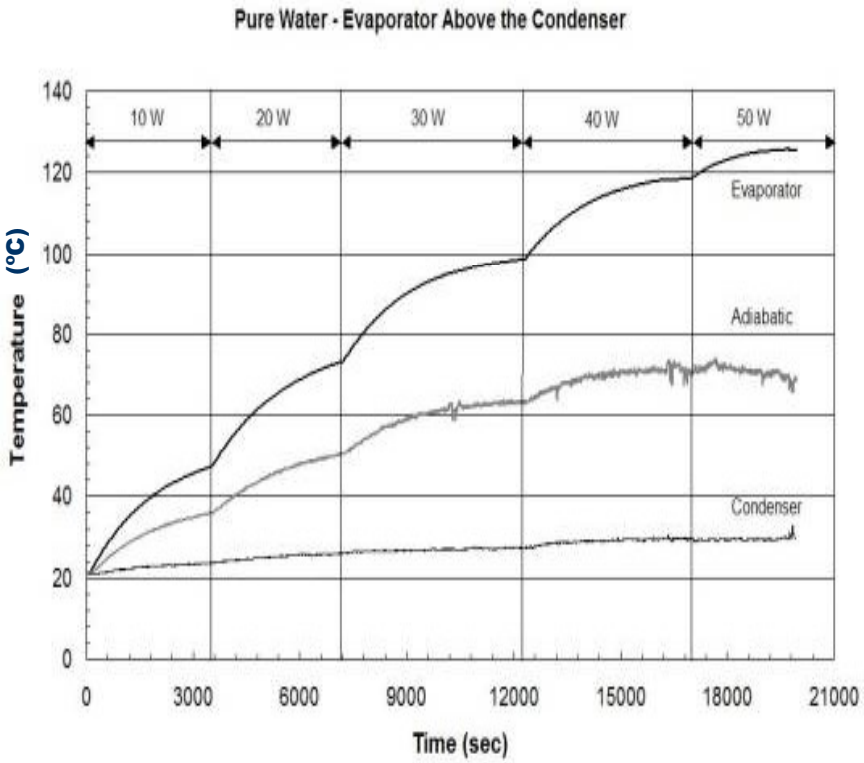
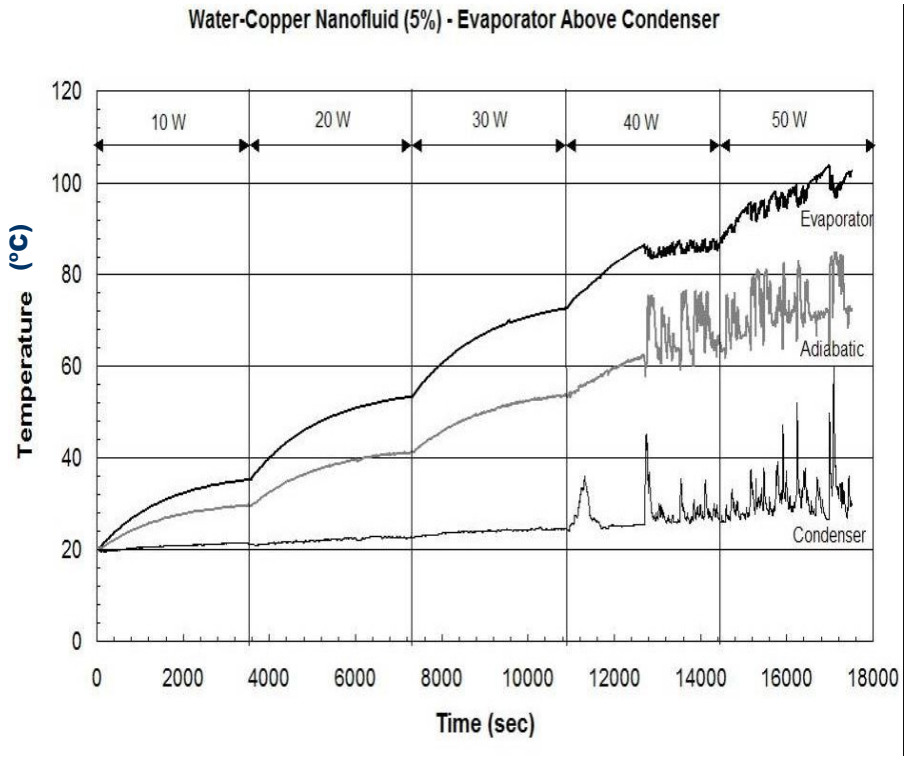
Overall Effect on the PHP Performance





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Several Applications for Nanofluids

- Surveillance (Defense) systems have been equipped with different heat pipes' designs (i.e. open loops PHPs);
- Heat pipes applied to industrial needs for thermal management;

Heat Pipe capacity: 2 kW each

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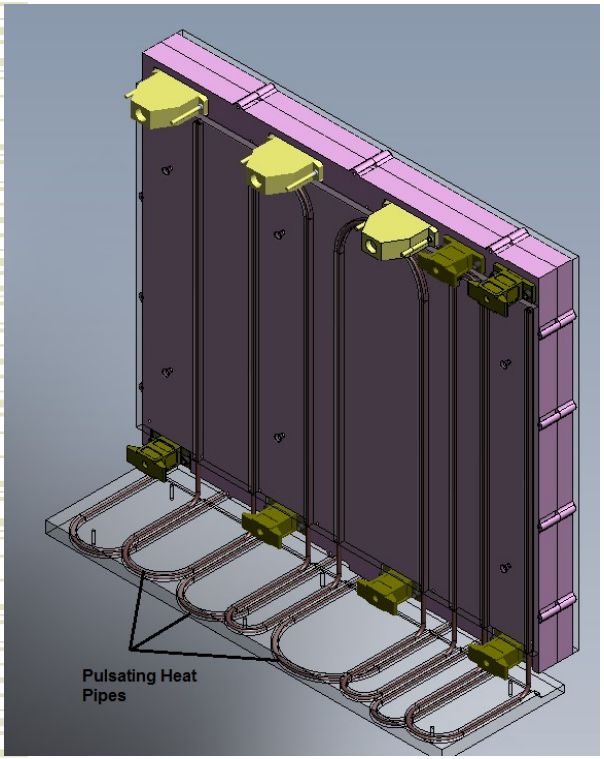
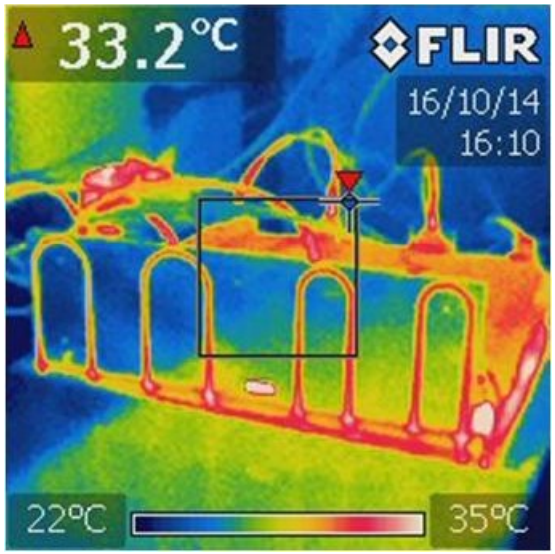
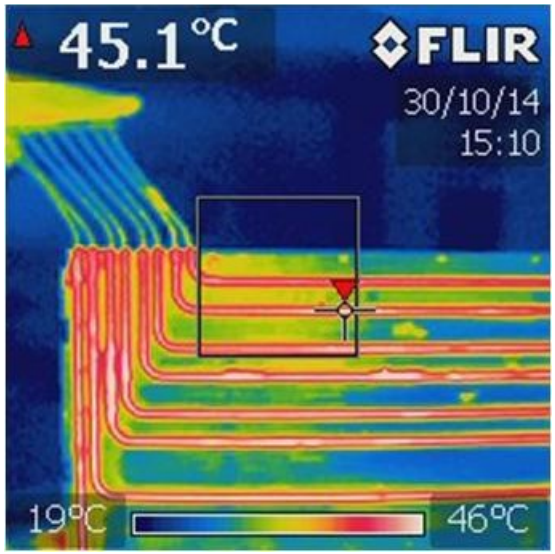
Several Applications for Nanofluids







Up to 450 W of heat dissipation

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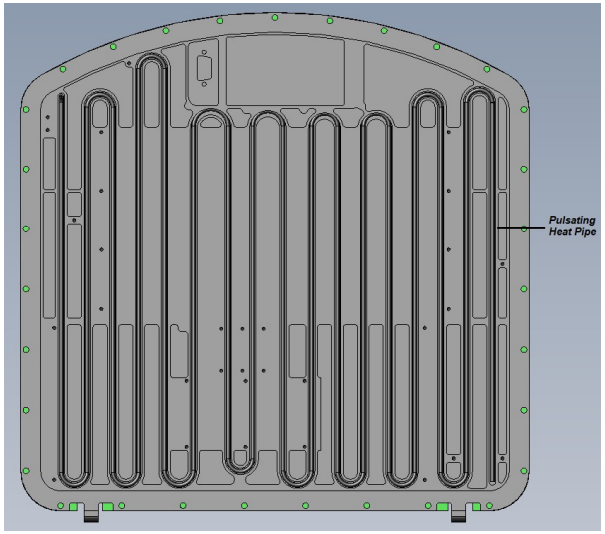
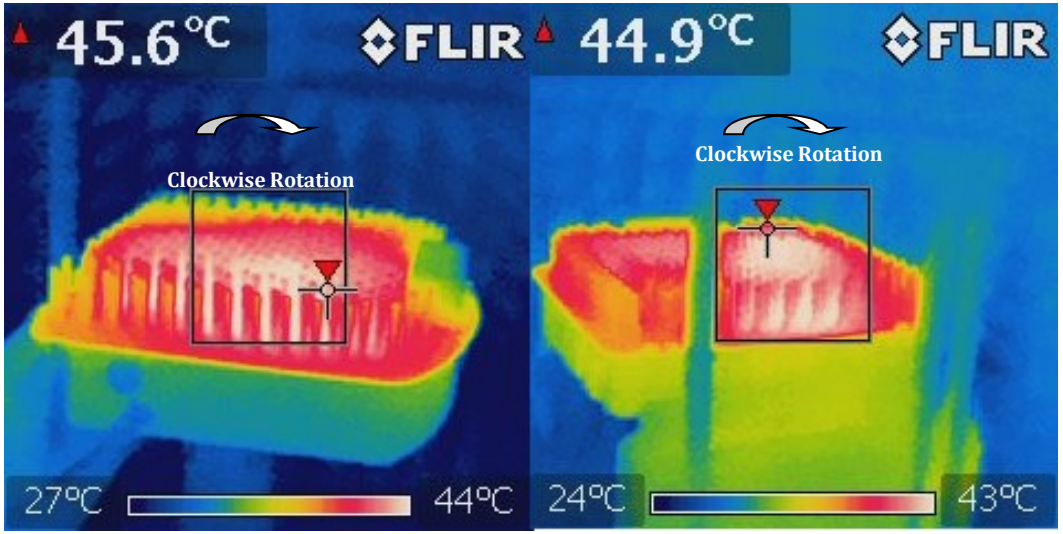
Several Applications for Nanofluids





Clockwise Rotation

Up to 200 W of heat dissipation

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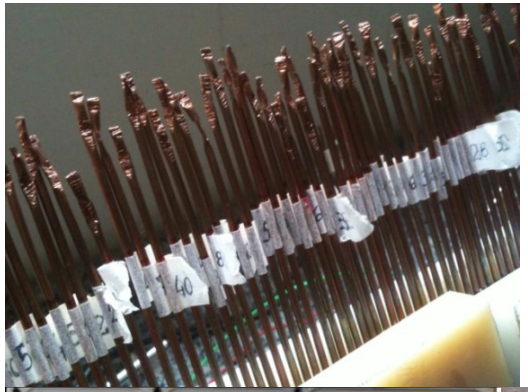
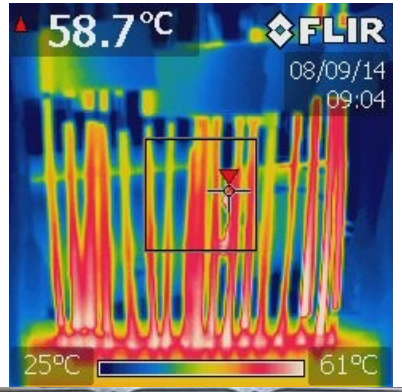
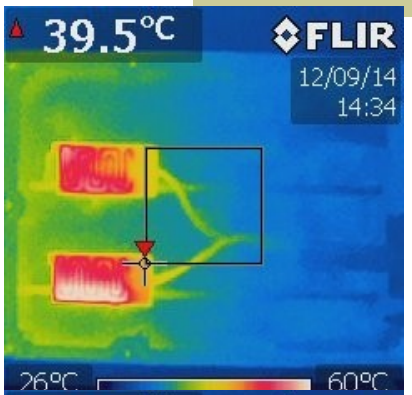
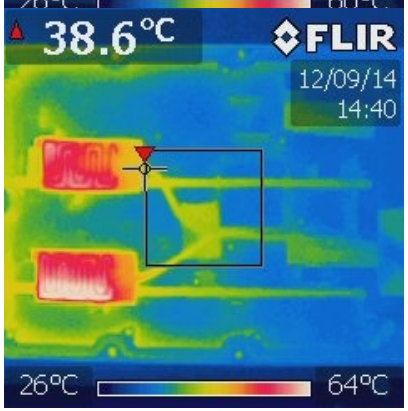
Several Applications for Nanofluids









Up to 12 W of heat dissipation on each heat pipe

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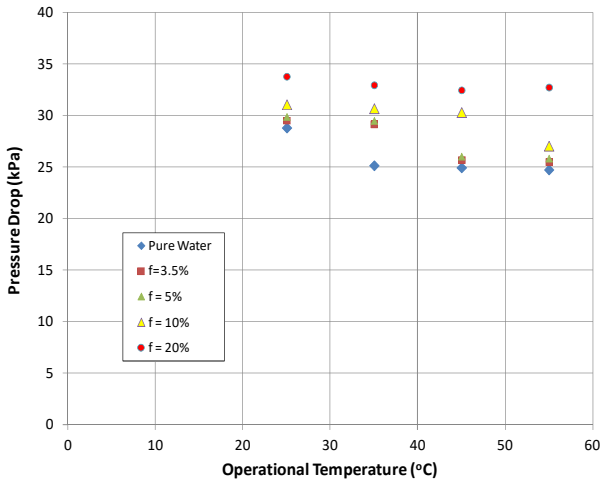
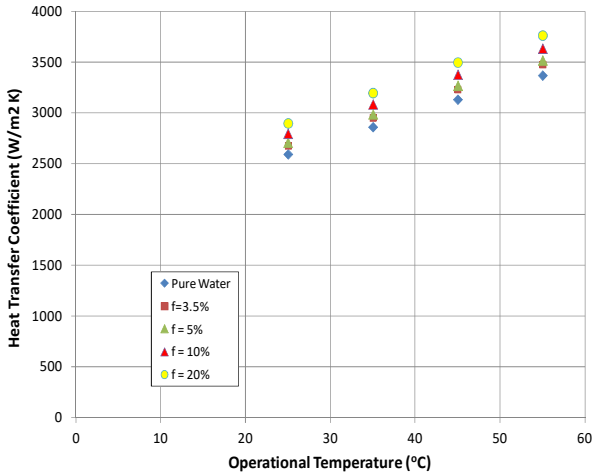
Several Applications for Nanofluid

- Considerable enhancement on the heat transfer capabilities have been obtained when operating single-phase thermal management systems. However, pressure drop requires attention.





- Source: Riehl, R. R., "Surveillance System Heat Transfer Enhancement Using Single-Phase Flow with Nanofluid", Heat Powered Cycles Conference, Netherlands, Sept 9-12, 2012.

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Following Steps on Nanofluids R&D

- Results related to nanofluids R&D and applications are rather scattered
- Differences on applied methodologies for preparation, data reduction, etc lead to mixed conclusions
- Results obtained for a given nanofluid condition cannot be compared to another nanofluid's results under the same conditions

NO "GENERAL" APPLICATION

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Following Steps on Nanofluids R&D

- Currently there is a need to obtain a statistical model to bring the results to a common base line for comparison
- Such a model would allow better understanding of different nanofluids under the same application
  - Further investigation is necessary for better understanding the impacts over each percentage of the statistical nanoparticle size distribution versus thermal enhancement ratio
  - The main objectives are to allow a better definition on ultrasonic bath times, nanoparticles sizes and volume fraction use, etc
- Along with the current nanoparticles, investigations using graphene nanoparticles are undergoing

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São José dos Campos - SP - Brasil http://www.dem.inpe.br/~rriehl - E-mail: roger.riehl@inpe.br

Concluding Remarks

- Nanofluids are an important contribution to enhance the thermal performance of current equipment
- Several investigations have addressed the potentials on using Nanofluids
- Great interests are found for thermal management devices used in Space and Defense applications
- Substantial gain on passive and active thermal control devices capabilities are important for new designs

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Concluding Remarks

- Nanoparticles are important when high volume of base fluid is in the LHP
- Increases the heat transfer coefficient (at lower heat loads) but results in higher evaporator temperature
  - Effect caused by additional hydraulic losses
- High concentrations of nanoparticles are not benefical to the overall LHP operation
- Should be considered for devices operating without a wick structure

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Concluding Remarks

- For the PHP, the use of nanofluid shows important enhancement on the device's thermal management capabilities
- Lower evaporator section temperatures were obtained when using the nanofluid, as the presence of nucleation sites were enhanced by the solid nanoparticles
- Additional applications have been under development:
  - Nanoparticles for improvement of optical characteristics on surfaces
    - Change on heat emissions by radiation: direct impact on IR imaging
    - Change on radar signature of objects

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Thank You !

Questions ?

Dr. Roger R. Riehl
roger.riehl@inpe.br
Two-Phase Thermal Control R&D
National Institute for Space Research – INPE/DMC/Satelite
+55 12 981 212 112

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