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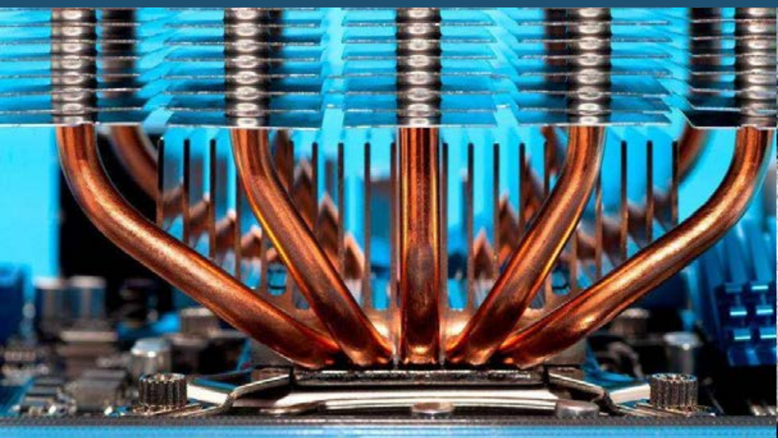
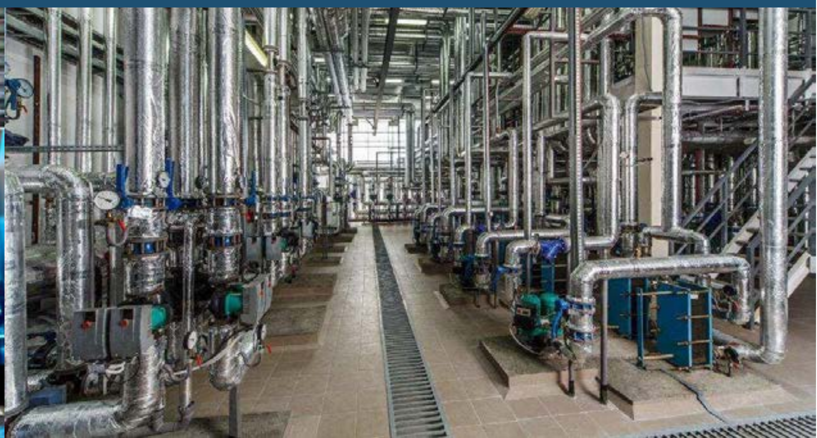
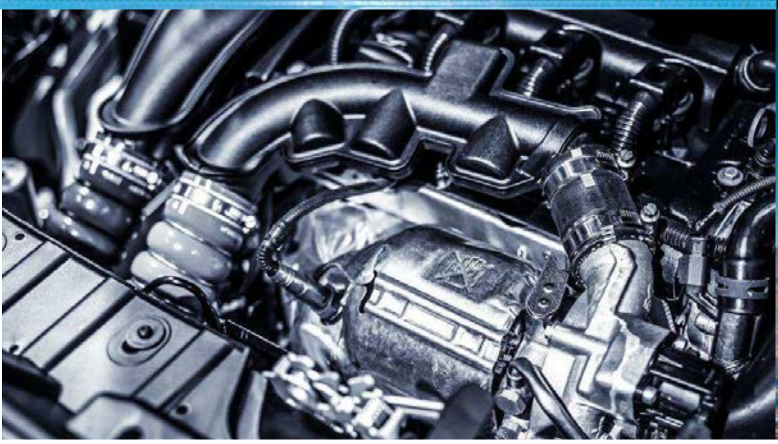
Handbook on Industrial Applications of Nanofluids in Energy Sector

DELIVERABLE 11







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Funded by the Horizon 2020 Framework Programme of the European Union

Title: Handbook on Industrial Applications of Nanofluids in Energy Sector

Deliverable 11

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Summary

The idea of this handbook was to open a call for possible contributions in the field of nanofluids industrial applications in the energy sector among the Nanouptake network.

A similar structure has been followed in all contributions with a limit of two pages: a) title, authors, affiliation, b) short description of the device c) effects following from employing nanofluids, d) design rules correlations, e) photos and plots, f) references and g) contact person.

A total of 27 contributions were received and distributed in different chapters covering various energy sectors: two-phase and heatpipes (4), heating & cooling (13), storage (1) and solar applications (7). An additional chapter has been dedicated to measurement of thermophysical properties (2).

The handbook will be distributed among the Nanouptake network and also to relevant industrial partners, with the objective of accelerating transfer of nanofluids knowledge from fundamental research to suitable and attractive industrial application in the energy sector.

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1.3. Nanoenhanced phase change materials development and characterization to improve the energy efficiency in buildings

1.4. Nanoparticle deposition via nanofluid pool boiling

Thermosyphon with graphene oxide nanofluids

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Heat transfer device

Two-phase closed thermosyphon is a passive heat transfer device consisting of a pipe divided into three sections: evaporator, adiabatic section and condenser (see: *Photos*). A small amount of working fluid placed in a pipe circulates in an evaporation - condensation closed loop. Heat from external source is absorbed in the evaporator and released in the condenser section. In contrast to conventional heat pipe, condensate returns to the evaporator due to the gravity forces. Thanks to phase change processes, device achieves high heat transfer efficiency. There is no need for additional mechanical parts and dimensions of the thermosyphon can be adapted to specific conditions.

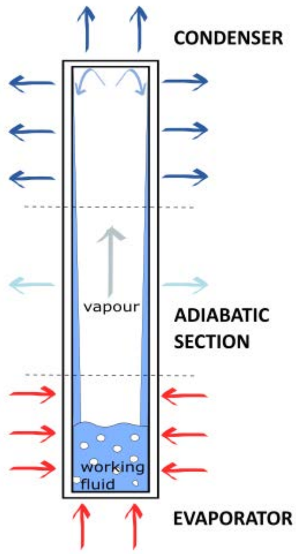
Effects following from employing nanofluids

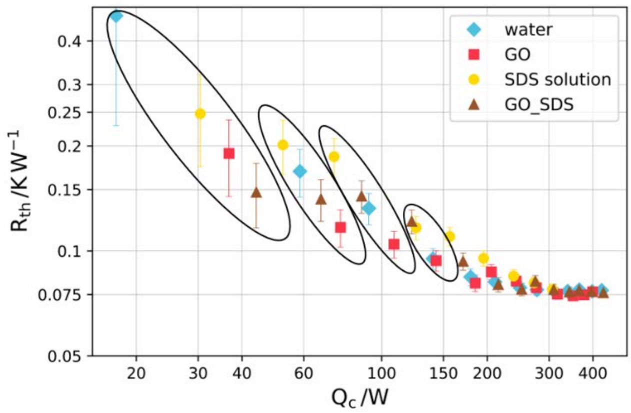
Overall thermal resistance of the device can be reduced by addition of properly selected nanoparticles, especially for low heating temperatures and small temperature differences between evaporator and condenser. It means that more heat can be transferred through the device working with graphene oxide nanofluid, although the inlet temperatures of heating and cooling water are the same (see: Photos and plots). Nanofluids shift the working point of the thermosyphon and affect boiling regimes.

Design rules correlations

Graphene oxide nanofluids enchance heat transfer capabilities at low temperatures of the evaporator section. The improvement is mainly caused by the deposited layer on the heating surface and the positive effect is limited to the evaporator. Nanofluid does not influence heat transfer process in the condenser section.

Photos and plots





The scheme (left) presents the operation principle of a two-phase closed thermosyphon. The diagram (right) shows the overall thermal resistance of the device versus heat released in the condenser for inlet cooling temperature of 15°C. Black ovals indicate the same working conditions (inlet temperatures of heating and cooling medium, pressure, volume fluxes). GO: 0.1g/l of graphene oxide flakes in water, SDS solution: 0.01g/l of sodium dodecyl sulfate in distilled water, GO_SDS: 0.1g/l of graphene oxide flakes and 0.01g/l of sodium dodecyl sulphate (surfactant) in water.

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Nanofluids applications in thermal management systems with pulsating heat pipes

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Heat transfer device

Pulsating heat pipes (PHPs) are considered a special type of heat pipe that operates by means of vapour plugs and liquid slugs of a saturated liquid and transports the heat from a source to a sink. They are built with a meandering capillary tube bent in several parallel segments, containing a certain amount of working fluid in saturated conditions. Since the slug/plug dynamics play an important role in this thermal device, PHPs operating with nanofluids have shown better performances (e.g., lower heat source temperatures) compared to that of their base fluid. The dispersed nanoparticles in the base fluid act as localized nucleation sites enhancing the vapour bubbles generation and displacing the liquid much more efficiently.

Effects following from employing nanofluids

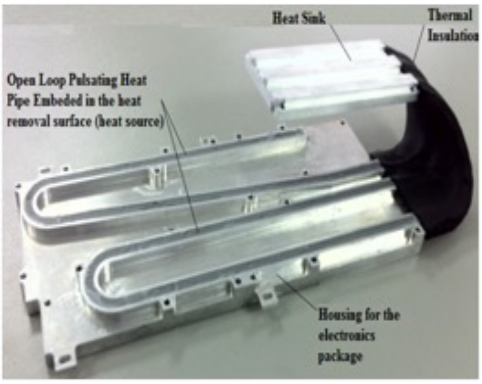
Comparing to solid bars with the same geometric characteristics, PHPs present a higher capability in transporting the heat from the source to the sink. The thermal performance of PHPs with nanofluids increases considerably (up to 5 times of the pure base fluid). It is found that using nanofluids in PHPs can result up to 25% decrease in heat source temperature and up to 50% increase in the thermal conductance when comparing the operation with the base fluid only. Real applications of PHPs with nanofluids have demonstrated their reliability under severe operation conditions and also stable operation with minimum indication of solid nanoparticles sedimentation.

Design rules correlations

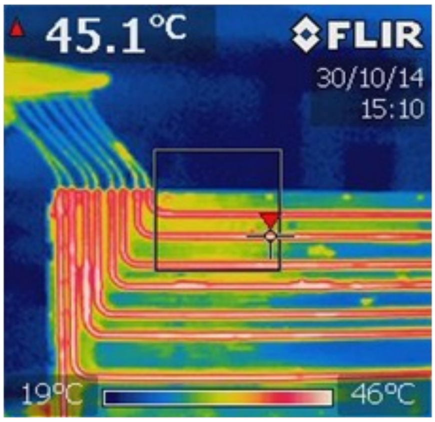
The selection of the base fluid and nanoparticles must be carefully evaluated in order to avoid the presence of non condensable gases (NCGs) during its operation. Chemical compatibility check must be performed for the nanofluid and the PHP's housing material as it will be operating under thermal cycling conditions at all times.

The use of surfactants must be avoided as it will contribute to the formation of NCGs. With nanofluids PHPs yield lower heat source temperature and a higher condensation capability, which directly contribute in increasing the thermal conductance (G) of this thermal device.

Photos and plots



PHP schematics for electronics cooling.



PHP infrared operation showing heat transport (temperature).

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Nanoenhanced phase change materials development and characterization to improve the energy efficiency in buildings

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Heat transfer device

Nanoenhanced PCM will store thermal energy to improve the energy efficiency of active building systems as domestic how water, heating and cooling systems, etc. The NEPCM developed where fully characterize in order to understand their reliability.

Composition: x-ray diffraction (XRD) was used to determine the nanoparticles composition after their synthesis. Moreover, Fourier transformed infrared (FT-IR) spectroscopy coupled to an attenuated total reflectance (ATR) allow the direct sample FT-IR measurements.

Viscosity: the viscosity of the NEPCM was measured by means of a rheometer (Brookfield RST-CPS) of both bio-based PCM doped.

Thermal stability of the NEPCM is measured by thermogravimetric analyses (TGA) in order to determine the max. working temperature.

Effective thermal conductivity: hot wire which is based on passing an electric pulse through a wire and it is heat due to the Joule effect.

Latent heat stored: by differential scanning calorimeters (DSC) which is one of the most powerful instruments to measure the thermophysical properties of a substance.

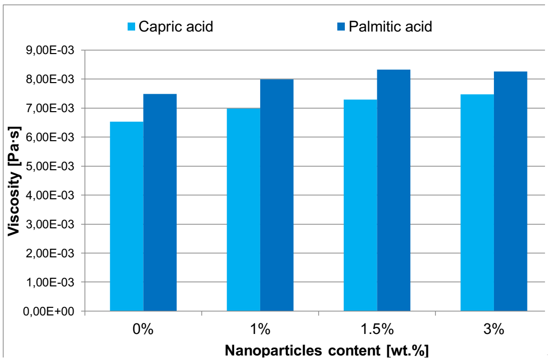
Effects following from employing nanofluids

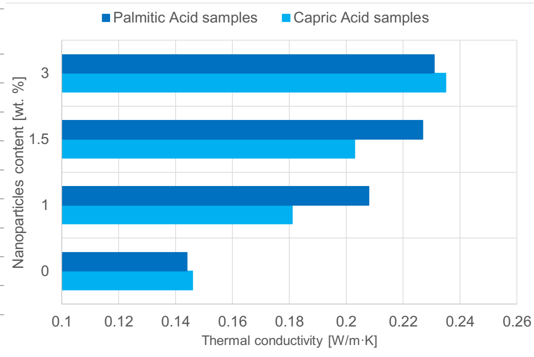
Whereas both NEPCM viscosities increased with nanoparticle content, the maximum increase is 7. In case of palmitic NEPCM the k stagnated after 1.5 wt.% while in capric NEPCM, the maximum increment achieved (55%) was measured at 3.0 wt.% nanoparticle. Latent heat storage capacity showed slighter increments.the composition remain constant as FT-IR results demonstrated. Moreover, TGA analysis proves the NEPCM thermal stability within the building application temperature range.

Design rules correlations

The thermophysical properties are improved when nanoparticles are added to the base-nanofluids which means that their final thermal application in building active systems will be improved from the energy efficiency point of view.

Photos and plots





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Nanoparticle deposition via nanofluid pool boiling

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Heat transfer device

This device is a simple boiling chamber in which the nanofluids boils over a heated surface. The latter is the surface to be coated. The heater is commonly made of copper and the electrical heating is used to heat up the uncoated surface. The nanofluid is kept at saturation temperature and during the boiling a thin layer of nanoparticles deposits and adheres over the surface.

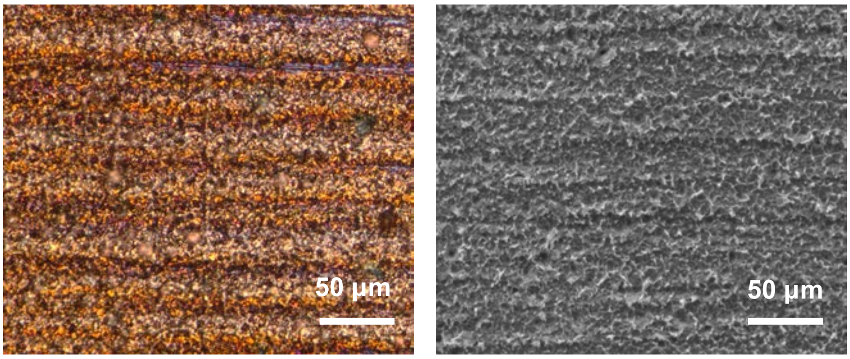
Effects following from employing nanofluids

During the nanofluid pool boiling, a thin layer of nanoparticles commonly deposits and adheres, which drastically modify the surface features (e.g. wettability) and the pool boiling characteristics of the surface.
The heat transfer enhancement in terms of critical heat flux can reach up to 400%; also, the heat transfer coefficient can be largely increased.

Design rules correlations

The boiling heat transfer behaviour of nanofluids has been extensively studied by many researchers who have observed some significant, though scattered, enhancements of the pool boiling CHF between 10% and 400%. There are also contrasting reports of significant deterioration in boiling performance.
Thus, the nanofluid/surface must be carefully selected on the basis of the specific characteristic or feature that it is expected for the given application.

Photos and plots



(a) (b)

Figure 1: (a) Microscope image and (b) SEM image of the sample after laser-roughening

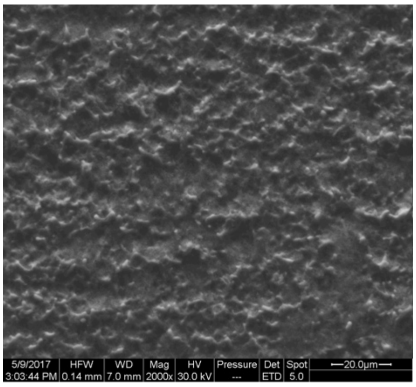


Figure 2: Coated (BOTTOM) surface after Cu/water nanofluid boiling on the copper surface.

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2. Heating and Cooling

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Laminar pipe flow with twisted tape

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Heat transfer device

Twisted tapes are inserts in pipe flow, which enhance heat transfer by inducing a secondary flow. They are standard devices and frequently applied in e.g. tube bundle heat exchangers.

Along the pipe main axis a twisted tape is inserted which splits the flow into two parallel running chambers. These chambers are turning around the central axis inducing therewith a radial force on the fluid. This radial force causes in each chamber a pair of counter rotating vortices which stretch along the chamber. Heat transfer is enhanced by exchanging fluid from the core of the chamber with fluid from outer regions of the chamber.

Effects following from employing nanofluids

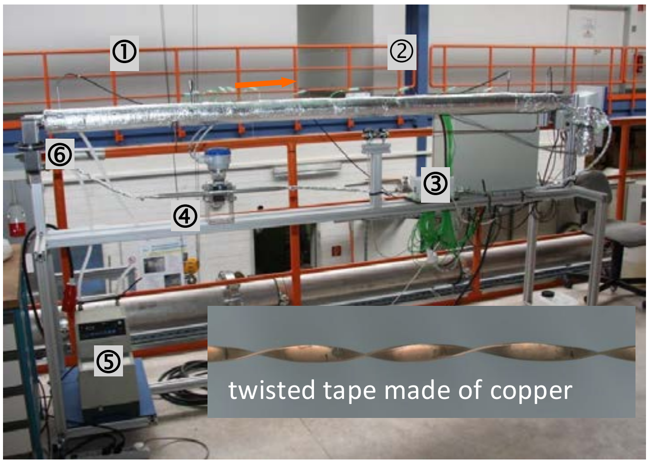
The radial force / acceleration acting on the fluid suppresses the development of turbulent motion. Flow remains laminar up to much higher Reynolds numbers as usually anticipated for straight pipes. Heat transfer is characterised as mixed convection. Depending on the actual Reynolds number heat transfer takes place partly via conduction and partly via convection due to the secondary motion. Adding nanoparticles enhances thermal conductivity of the fluid and enforces therewith conduction.

Design rules correlations

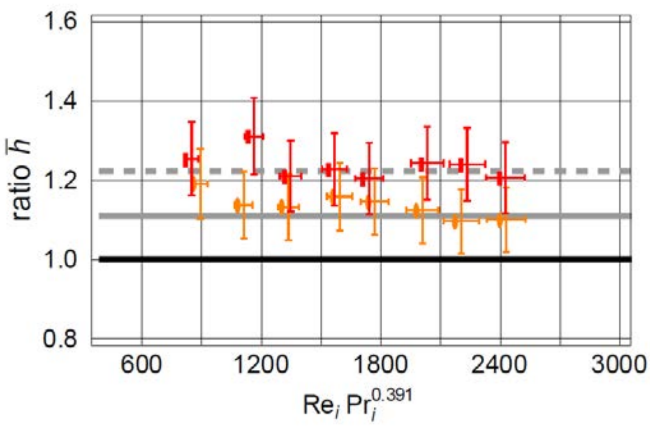
General design rule is: Heat transfer coefficient can be enhanced equivalent to increase of thermal conductivity of liquid by adding nanoparticles.

Nusselt number correlation for one test case utilising titania nanofluids is given in the reference.

Photos and plots



Test facility
① entrance length,
② test section,
③ pump,
④ flow meter,
⑤ thermostat,
⑥ heat exchanger.



Ratio of heat transfer coefficients (nanofluid / water).
Red 10 vol. % TiO_2 nanoparticles,
orange 5 vol. %.
Grey lines indicate increase of thermal conductivity.

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Turbulent forced-convective heat transfer nanofluids

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Heat transfer device

A wide variety of heat transfer mechanisms in industry is based on turbulent forced convective heat transfer in round pipes. Also, given their simple geometry and working functioning, it has been as a benchmark for the study of the heat transfer coefficient by using different flow regimes, fluids, heat fluxes, surface texturization, etc. Heat transfer coefficient can be experimentally calculated by measuring the temperature jump between the pipe outlet and the inlet (usually with immersed thermocouples) and the heat flux (from the heat power from an insulated heating band). Friction factor can be obtained by measuring pressure drop across the test section with a differential manometer).

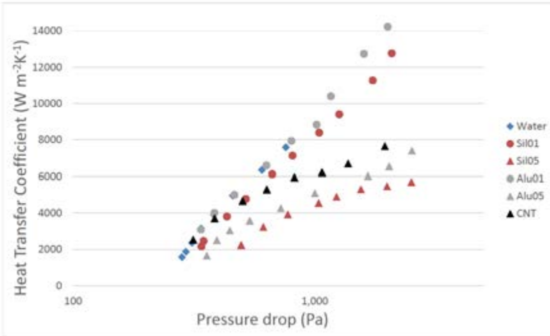
Effects following from employing nanofluids

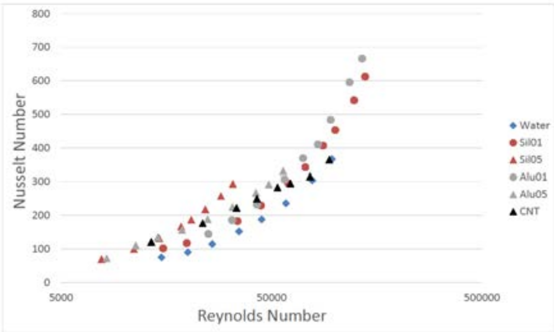
Nanofluids are expected to enhance the heat transfer coefficient given their enhanced thermal conductivity. But the viscosity of the nanofluid is also increased with the nanoparticle concentration, so the overall performance is determined by a balance between these two factors.

Design rules correlations

The heat transfer enhancement has been a topic of controversy, but nowadays it is accepted that the heat transfer and pressure drop fit properly to common heat transfer correlations such as the one proposed by Gnielinski, as long as their thermophysical properties are included into them. Up to now, the increase produced in Nanofluid viscosity is so high that the overall effect is a reduction of the heat transfer coefficient on a constant pumping power basis. For systems that require a fixed Reynolds number for their functioning, such as flow mixers and separators, the heat transfer for water based nanofluids can be enhanced as much as a 200% (270% pressure drop increase) for 5%wt silica nanoparticle concentration.

Photos and plots





Heat transfer performance of water based nanofluids with silica (1 and 5% w.t.), alumina (1 and 5% wt) and carbon nanotubes (0.125% wt). At a same nanoparticle concentration, CNTs provide the highest differences because of their huge viscosity increase. Alumina provides the lowest differences as they show the smallest viscosity increase.

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Annular tube flow

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Heat transfer device

The device is a vertical annular tube counter flow heat exchanger, in which the nanofluid flow in the inner tube (diameter 6 mm) and hot water flows in the outer section (diameter 13 mm). The water flow in the external side of the heat exchanger is set to flow downwards and the nanofluid upwards.

Effects following from employing nanofluids

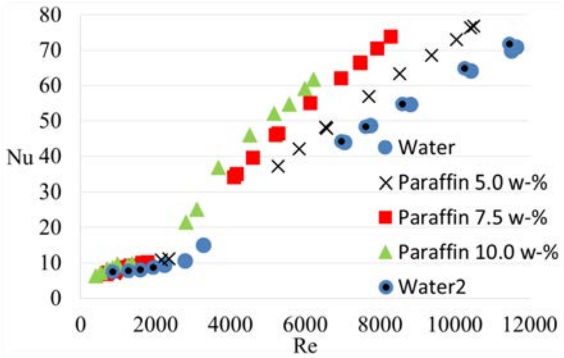
For water based nanofluids with SiO2, Al2O3, micelles, polystyrene and phase changing paraffin particles (PCM) an increase in heat transfer coefficient can always be detected if the performance of nanofluid and its base fluid is compared with each other based on constant Reynolds number. However, no improvement in solid particle nanofluids performance can be found if all changes in fluid properties are properly accounted for. The phase changing nanofluids (paraffin/water) instead can show somewhat improved performance compared to the base fluid.

The addition of nanoparticles increases the viscosity of base fluid and therefore the pressure losses increase. As a consequence, the overall efficiency (both increase in heat transfer and increase pressure losses are accounted for) of all nanofluids becomes lower than that of the base fluid.

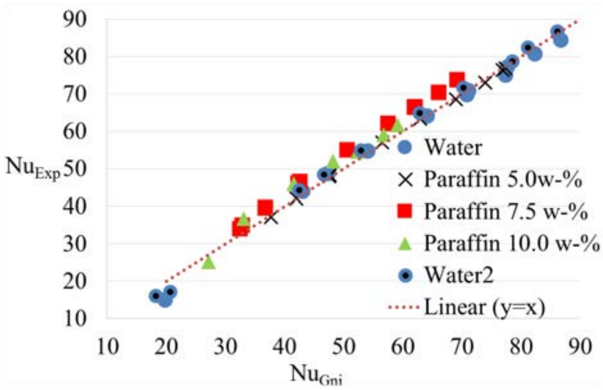
Design rules correlations

The applications in which the nanofluids studied with this device can show improved overall efficiency are related to a narrow operation temperature range (around the phase change temperature) of the PCM fluid. Then, addition of latent heat overcomes the weakening of other properties.

Photos and plots



The Nusselt numbers as a function of Reynolds numbers for phase changing paraffin nanofuids. [Sep1]



The convective heat transfer compared to the Gnielinski correlation (transition and turbulent regimes, *Re* > 3000) for phase changing paraffin nanofuids. [Sep1]

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Forced convective heat transfer by a tube-in-tube heat exchanger

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Heat transfer device

The experimental setup consists of three different circuits: the tested fluid loop, the heating loop and the cooling loop. The main element of the facility is a tube-in-tube heat exchanger of stainless steel. The tested fluid is pumped through the inner tube of the heat exchanger, cooling the hot water that flows through the annular section. The heating loop allows the hot water to return to its initial conditions by means of electric resistances, while the cooling loop allows the tested fluid to remove the gained heat by means of tap water that flows through another heat exchanger. Fours temperature sensors, two flow meters and a differential pressure sensor allow collecting all the test information. The convective heat transfer coefficients of the tested fluid can be obtained from the sum of thermal resistances.

Effects following from employing nanofluids

The use of nanofluids can improve the convective heat transfer in relation to the base fluid. Enhanced convective coefficients can be achieved for the same flow rate, leading to increases of the exchanged heat in the tube-in-tube heat exchanger. Furthermore, for a fixed Reynolds number, it is intended to achieve higher Nusselt numbers.

Design rules correlations

Enhancements of up to 15 %, 32 % and 7% for the convective heat transfer coefficient were achieved for different functionalized graphene nanoplatelet dispersions in water, a propylene glycol: water mixture and a commercial coolant, respectively.
Correlations for Nusselt number (Nu) as a function of Reynolds number (Re), Prandtl number and nanoadditive volume fraction were obtained for the mentioned nanofluid sets [1-3].

Photos and plots

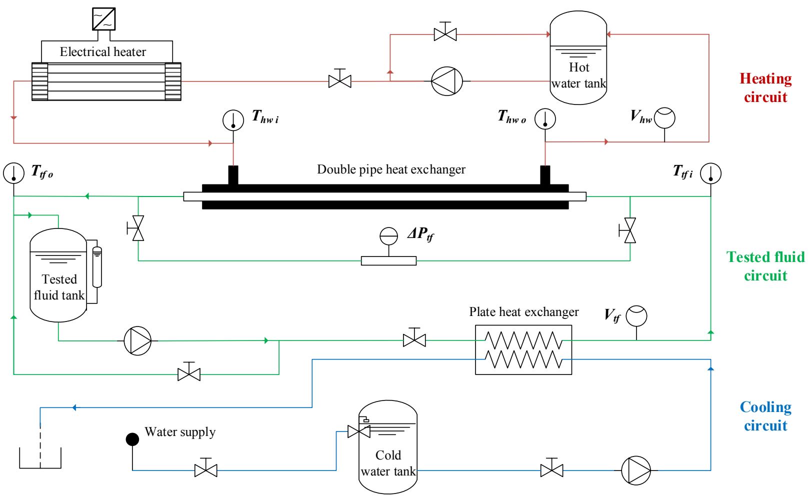
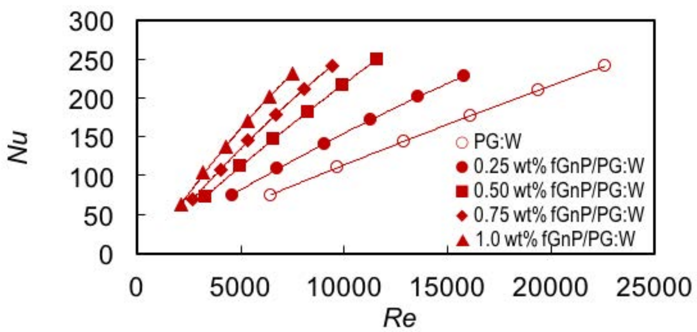


Diagram of the experimental facility [2]



Nu versus *Re* for functionalized graphene nanoplatelet (fGnP) dispersions in propylene glycol:water 30:70 wt% mixture (PG:W) [2]

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Mini and micro channels-based cooling of nanofluids

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Heat transfer device

Conventional coolants and cooling techniques are increasingly falling short in meeting the ever-rising cooling needs and thermal management challenges of modern high heat generating devices and systems. This is mainly due to the limitations in heat transfer capabilities like thermal conductivity (TC) and convective heat transfer coefficient (HTC) of traditional cooling media and also due to the lack of usages of small scale (mini/micro) channels in the thermal management systems [1]. Hence, the combination of nanofluids with enhanced TC and HTC and their flows in mini/micro channels can have great potential in advanced cooling applications. However, investigations on thermal transport of nanofluids in such small-scale channels are still scarce and more extensive studies are needed.

Effects following from employing nanofluids

Nanofluids showed significantly high HTC which increases further with increasing concentration of nanoparticles as well as with the flow rate (Re) as exemplified in Figure 1 for TiO2 (15nm)/DIW (deionized water) nanofluid. Representative results on HTC of various nanofluids in mini and micro channels are also briefly summarized in Table 1 which confirms that nanofluids have better cooling performance as compared to conventional fluids in those channels and cooling systems for industrial applications.

Design rules correlations

The convective cooling performance (HTC) of conventional fluids can greatly be increased by dispersing nanoparticles and by employing nanofluids in mini and micro channels-based systems. The HTC can further be increased with increasing the loading of nanoparticles (up to a critical concentration) as well as with Reynold number (Re). Since HTC is inversely proportional to the hydraulic diameter of the channel, very high heat transfer performance (as reported) can be achieved by using such small-scale channels with nanofluids.

Photos and plots

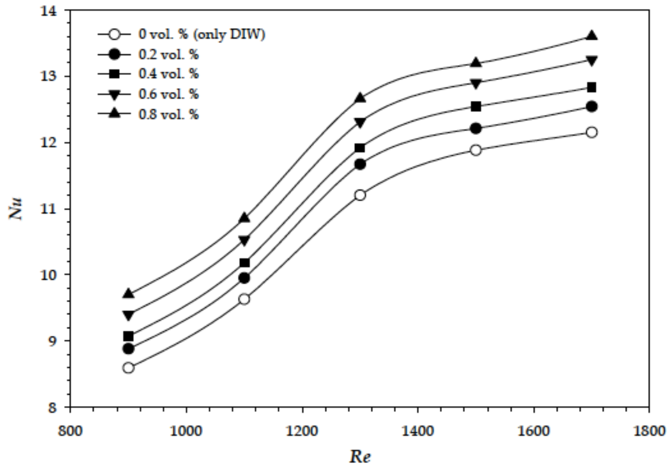

Figure 1: Nu Vs Re (TiO_2/DIW nanofluid at various concentrations)

Table1: Selective results on the convective cooling of nanofluids in mini- and micro-channels [2]

Nanofluids	Mini/Micro Channel (ID)	***Re*** range	Main results
CNT/W	Micro (355 μm)	2-17	*h* increased >100% at 1.1 CNT vol.%.
MWCNT/W	Mini (4.5 mm)	800-1200	*h* enhanced up to 370%.
Al_2O_3/W	Micro (50μm)	5-300	*h* enhanced up to 100% at entrance.
TiO_2/DIW	Mini (4 mm)	900-1700	*Nu* increased 13% at 0.8 vol.% of TiO_2 and at *Re* =1100.
Al_2O_3/W; Carbon/W	Mini (4.57mm)	800-6500	At entrance, *h* increased up to 20% for Al_2O_3 and 8% for carbon.
CuO and SiO_2 /EG+W	Mini (3.14 mm)	3000-16000	At *Re*=10000, *h* increased 29% for SiO_2 and 43% for CuO.
Al_2O_3/W	Mini (1.09 mm)	500-4500	*h* increased up to 21% at the entrance.

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Performance of nanofluids in helically coiled heat exchangers

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Heat transfer device

Helically coiled tubes and double-pipe helical heat exchangers are widely used due to their high heat transfer coefficient and compact design. Centrifugal force in the helical coils induces a secondary flow field with a couple of vortices in the tube cross section, which drives the fluid in the central part towards the outer wall and then flows back along the side walls to the inner wall, and therefore enhances the heat transfer performance.

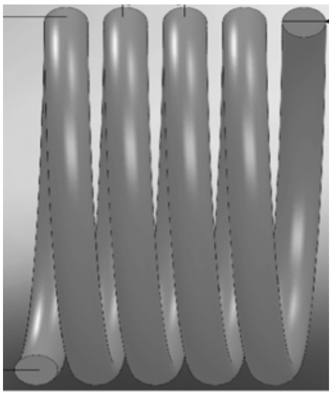
Effects following from employing nanofluids

Alumina/water and multi-walled carbon nanotube (MWCNT)/water nanofluids were tested in double-pipe helical heat exchangers. Both the viscosity and thermal conductivity increase with nanoparticle concentrations. The thermal conductivity increase by nanoparticles is beneficial for heat transfer, whereas the secondary flow intensity induced by centrifugal forces might be mitigated by nanoparticles due to the larger viscosity and density of the nanofluids compared to those of the base fluid. No anomalous heat transfer enhancement exists in our cases for both laminar flow and turbulent flow.

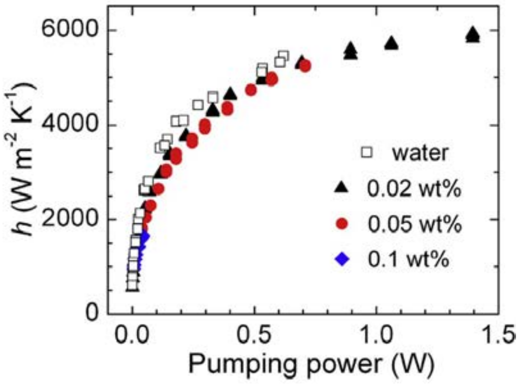
Design rules correlations

1) The enhancement in heat transfer coefficient is generally equivalent to the enhancement in thermal conductivity by adding nanoparticles.
2) Heat transfer enhancement comparison for nanofluids over their base fluids based on equal Reynolds number can be misleading, which over-estimates the actual heat transfer largely.
3) The newly developed correlation (Wu et al. correlation) and the Seban and McLaughlin correlation can reproduce the thermal behaviours of base fluids and nanofluids accurately for laminar flow and turbulent flow, respectively.

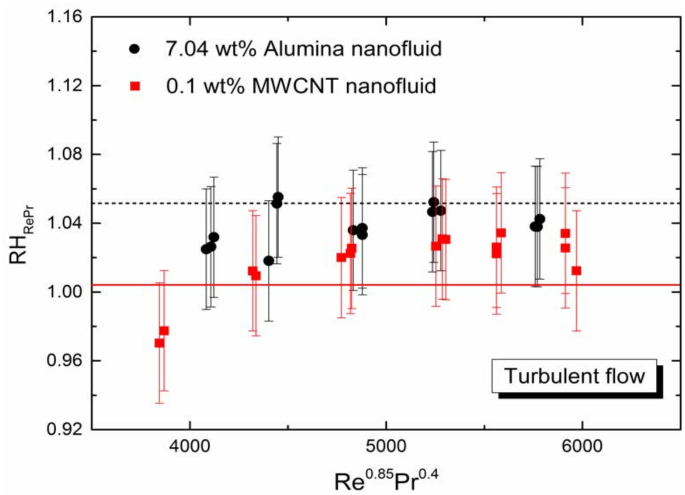
Photos and plots



Helically coiled tube



Heat transfer comparison at fixed pumping power for MWCNT nanofluids



Heat transfer enhancement by nanofluids

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Performance of nanofluids in brazed plate heat exchangers

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Heat transfer device

Plate heat exchangers are widely used in multiple applications from heating, cooling and heat recovery to evaporation and condensation. In general, plate heat exchangers have higher heat transfer coefficients and higher compactness than shell-and-tube heat exchangers. The plate surfaces are corrugated which creates turbulence and enhanced mixing and as a result the heat transfer coefficient is high. The corrugation also improves the stiffness of the plates.

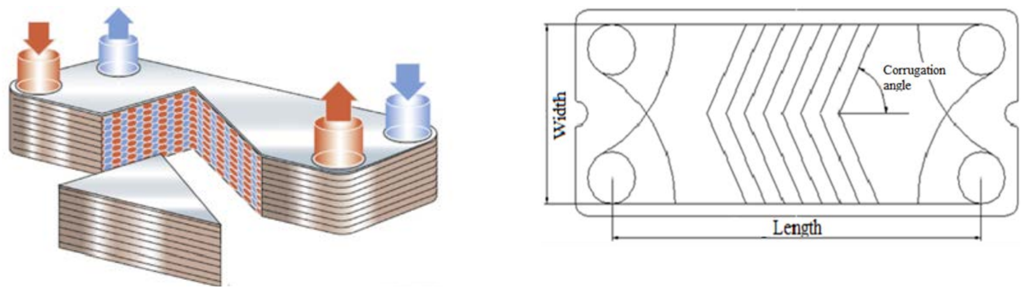
Effects following from employing nanofluids

Alumina/water, multi-walled carbon nanotube (MWCNT)/water, and graphene nanoplatelets (GnP)/water-ethylene glycol nanofluids were tested in plate heat exchangers. Both the viscosity and the thermal conductivity were measured, increasing with nanoparticle concentrations. Accordingly, Nusselt number and pressure drop increase with increasing nanoparticle concentrations. Thermophysical properties of nanofluids are the main factors influencing the heat transfer performance. The sharp increase in viscosity makes high concentrations of nanofluids ineffective as heat transfer fluids. GnP nanofluids have an optimum range of weight concentration (0.05 – 0.1%) in which the heat transfer shows maximum enhancement.

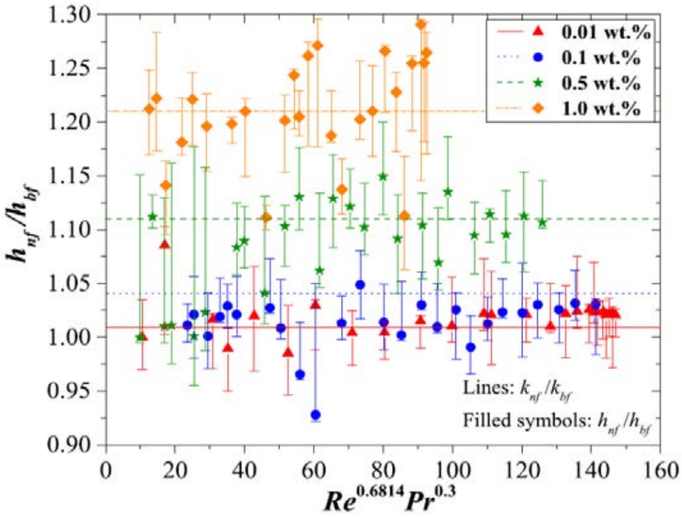
Design rules correlations

1) The improvement of heat transfer performance achieved by adding nanoparticles equals the increase of their thermal conductivities in comparison with the base fluid.
2) To maximize the advantages of nanofluids, the trade-off between the thermal conductivity and the viscosity of nanofluid is crucial for the performance improvement.
3) The correlations for predicting the heat transfer coefficient and friction factor in plate heat exchangers were obtained and fitted the experimental data very well, and can be applied to both the base fluids and the nanofluids.

Photos and plots



Brazed plate heat exchanger



Heat transfer enhancement for GnP nanofluids

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Ionanofluids potential use in heat exchangers

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Heat transfer device

The main application of nanofluids in real life applications refers heat exchangers. Thus, to increase the overall heat transfer performance of a heat exchanger, a new fluid with high thermal properties particularly thermal conductivity must be developed and this can be achieved by adding high conductive nanoparticles in conventional fluids. The ionanofluids (INFs) are introduced as new fluids by adding solid nanoparticles to ionic liquids (IL). In this application, the ionanofluid flows in a 0.12 m diameter pipe with uniform velocity and temperature [1]. The CFD code used for this analysis is Ansys Fluent [2] and more information on laminar modelling and equations can be found in [1].

Effects following from employing nanofluids

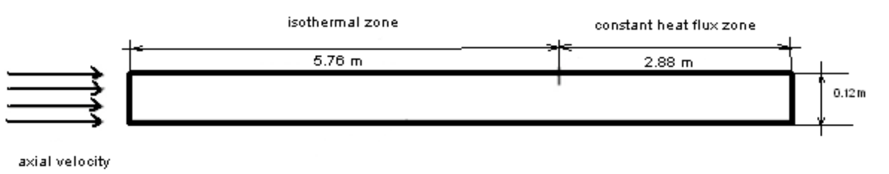
The effects of the nanoparticle concentration and flow rate on heat transfer augmentation are estimated for different ionanofluids and Reynolds numbers. Firstly, the results obtained for the convective heat transfer coefficient improvement at heating in connection with nanoparticles volume fraction were discussed [1]. Finally, the roles played by the volume fraction and types of nanoparticles are analyzed.

The heat transfer behavior of INFs can be accurately defined in terms of convective heat transfer coefficient (*h*) that was extracted from the post-processing module of the CFD software [2].

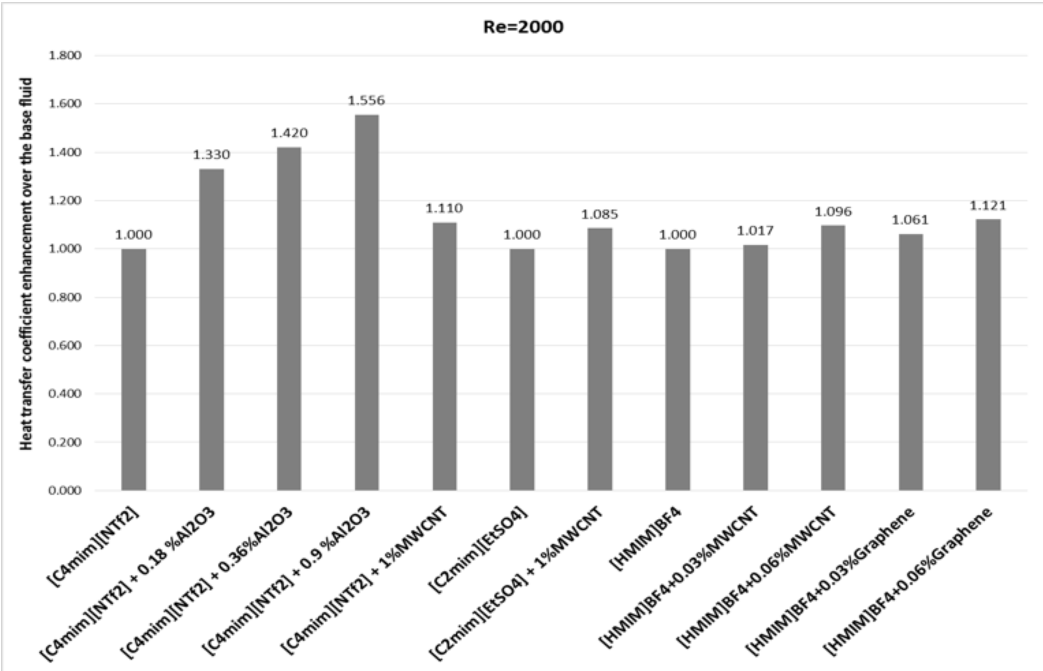
Design rules correlations

The numerical analysis revealed that in general, with increasing flow, the convective heat transfer coefficient increases considerably [1]. Moreover, it seems that the thermal conductivity plays a bigger role compared to that of the viscosity for their convective performance in heat exchange systems at laminar regime. The maximum increase in heat transfer coefficient is attained by adding Al_2O_3 nanoparticles to [C_4mim][NTf_2] IL and, adding low concentration of MWCNT or graphene to various ILs, the convective HTC increase is between 1.7 – 12.1% in regard to the base IL [1]. Further discussion, related correlations and results can be found in our earlier study [1].

Photos and plots



A schematic of the problem geometry



Representative results of enhanced HTC of INFs (see Ref. [1] for more)

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2. Ansys software

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Automotive cooling circuits with nanofluids

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Heat transfer device

The automotive cooling circuit allows to transfer toward the external ambient the large amount of heat that the engine generates to avoid overheating. The cooling circuit consists in the engine (heating system), a hydraulic pump and the car radiator. The rapid development of vehicle engine performance with a strong demand in producing high-efficiency engine at low cost have determined the need to increase the cooling rate. Traditional approach of enhancing the cooling rate by using fins and microchannels has already showed to their limit. Furthermore, heat transfer fluids such as water and ethylene glycol have very low thermal conductivity. Then the nanofluids, nano-coolant, represent a potential substitute of conventional coolants in engine cooling system.

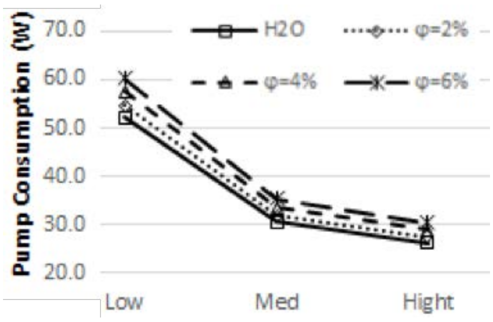
Effects following from employing nanofluids

Nanofluids have a higher thermal conductivity than the traditional coolants employed in automotive; the convective heat transfer inside the cooling system is improved and the mass flow rate can be reduced with radiator volume reduced. The reduction of mass flow rate compensates the pressure drops increase. Some erosion effects could be present but the use of nanoparticles in graphite can reduce the effect.

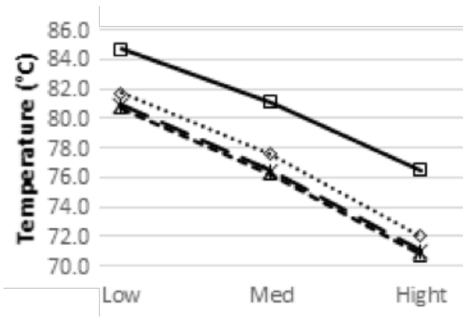
Design rules correlations

The increase in convective heat transfer inside the radiator is between 10% and 50% and the suggested volumetric concentration is <1% In this condition the pressure drops are limited. Different nanofluids can be employed with water/ ethylene glycol base fluid. Some improvements are obtained using hybrid nanofluids and applying magnetic forces.

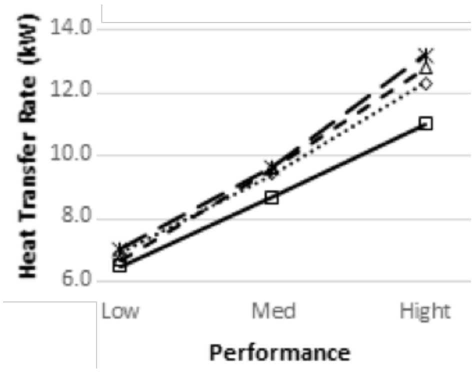
Photos and plots



Pumping consumption for different nanoparticles concentrations.



Outlet radiator temperature for different nanoparticles concentrations.



Heat transfer rate for different nanoparticles concentrations.

In the figures Low=1500 RPM;

Medium=2000 RPM;

High=2500 RPM for water containing

0 - 2 - 4 - 6 vol% alumina (Al_2O_3)

nanoparticles

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NANOUPTAKE COST ACTION (CA 15119) Working Group Meeting, Naples, Italy, 28th – 29th May 2018

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Magnetic fluid for cooling of transformers

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Heat transfer device

A single-phase power transformer with a nominal power of 5 kVA was designed and equipped with temperature sensors (type T thermocouples connected to a precision measuring instrument and data logger). Temperature distribution at various locations in the transformer under load was monitored when cooling the transformer with conventional transformer oil and with magnetic fluid. When designing the transformer, the attention was paid to providing good conditions for the possible thermomagnetic convection in the magnetic fluid. In order to increase the stray magnetic field and create more space for the convection, the transformer with a gap between the primary and secondary winding and between the winding and the core was constructed.

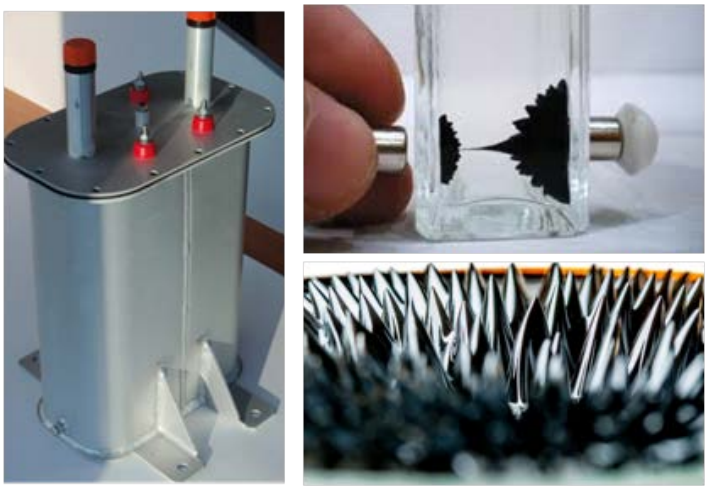
Effects following from employing nanofluids

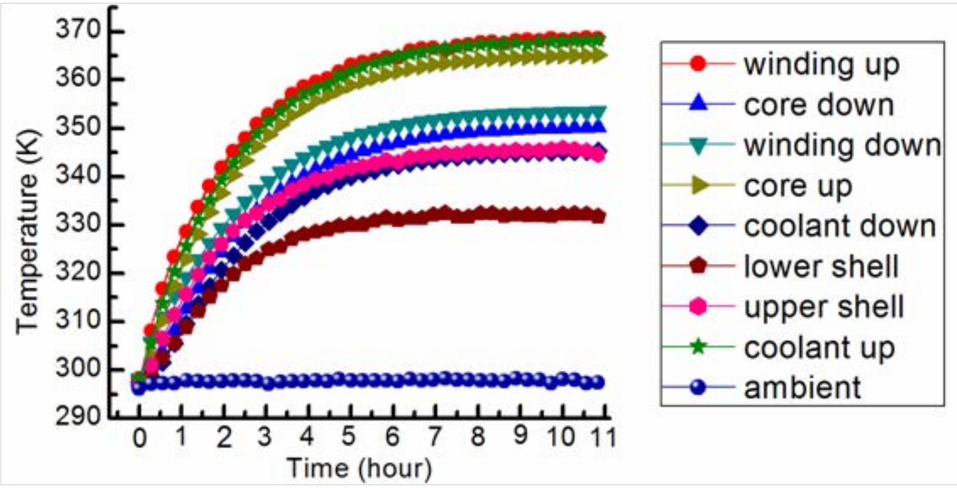
Transformer oils are used to cool and insulate electric transformers. However, due to their low thermal conductivity the heat transfer is not so effective. Suspension of magnetic nanoparticles in transformer oil is known as a magnetic fluid with remarkably enhanced heat transfer properties. Beside the increased thermal conductivity, the more effective heat transfer in transformers relies on the induced thermomagnetic convection due to the transformer stray magnetic field. When magnetic fluid close to the transformer core and winding is heated up, its magnetic susceptibility decreases and colder magnetic fluid is attracted to the core, so inducing the convection without any mechanical pumping.

Design rules correlations

Average operating temperature of the transformer filled with magnetic fluid (iron oxide solid volume fraction 0.93 %) is about 1.1 K, as compared to the cooling with the transformer oil.

Photos and plots





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Solar Absorption Cooling Systems with Nanofluids

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Heat transfer device

An appealing solution for air conditioning in summer time is the solar cooling system. The Increasing of the efficiency of solar collectors helps to reduce the cost of heat energy absorbed by the collectors. A solar collector is a heat exchanger that converts radiant solar energy into heat. There are different types of solar collectors such as the flat plate, evacuated tube, parabolic trough and dish collectors. Each type has its own working principles and its efficiency. A Solar Cooling system converts solar energy for space cooling and refrigeration. Absorption cooling systems are reliable and can be driven by low-grade thermal energy. The main advantage of absorption chillers is their higher coefficient of performance than other thermally operated refrigeration cycles, i.e., adsorption or desiccant cooling systems. One of the major challenges in solar based cooling systems is to reduce the unnecessary consumption of auxiliary energy and other parasitic energy losses from electrical devices.

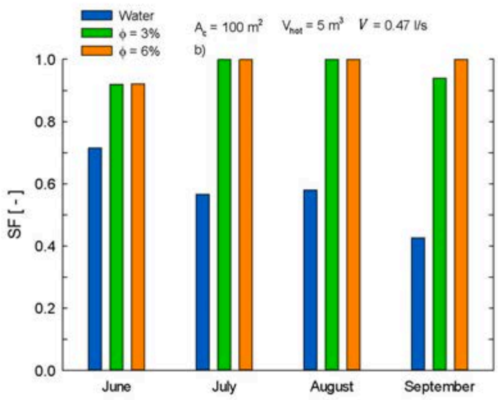
Effects following from employing nanofluids

According to the existence of metal or metal oxides nanoparticles, the thermal conductivity of the nanofluids are higher compared to the water and therefore, the thermal efficiency of the flat plate solar collectors would be enhanced in the case of using nanofluids as a working fluid.

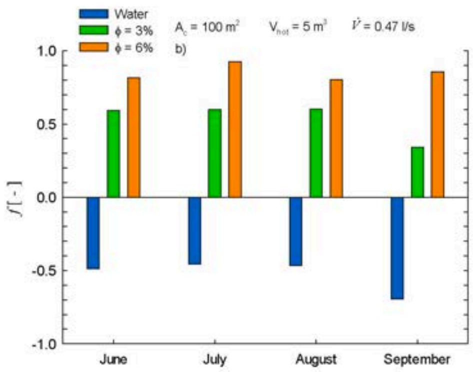
Design rules correlations

With respect of the base fluid, nanofluids as working fluids in a solar collector improve of solar thermal gain from collectors of about 300%, reduce the energy consumption of the auxiliary boiler of over 70%. A negative effect is the increase of the energy pumping consumption that can be greater than 10%.

Photos and plots



Solar fraction values at different months for several nanoparticle volume concentrations and solar field area values.



Primary energy savings values at different months for several nanoparticle volume concentrations and solar field area values.

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Nanofluids use in home appliances

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Heat transfer device

Household appliances efficiency has improved very much in the last years. Nowadays it becomes more and more difficult to improve it with the current devices technologies. Therefore, developing a new technology is necessary to bring the efficiency to the next level.

Since the thermal conductivities of solids (metals) are several magnitude orders higher than liquids, Nanofluids (very dilute suspensions of Nanoparticles in liquids - very low concentration, usually <1%wt-) could enhance the heat transfer of the complete system.

Effects following from employing nanofluids

Home appliances using vapour compression cycles could benefit for the use of Nanofluids. Improvement in terms of heat transfer thanks to the application of Nanofluids instead of ordinary liquids are expected. The main advantage of this heat transfer enhancement would be a higher global energy efficiency of the appliance.

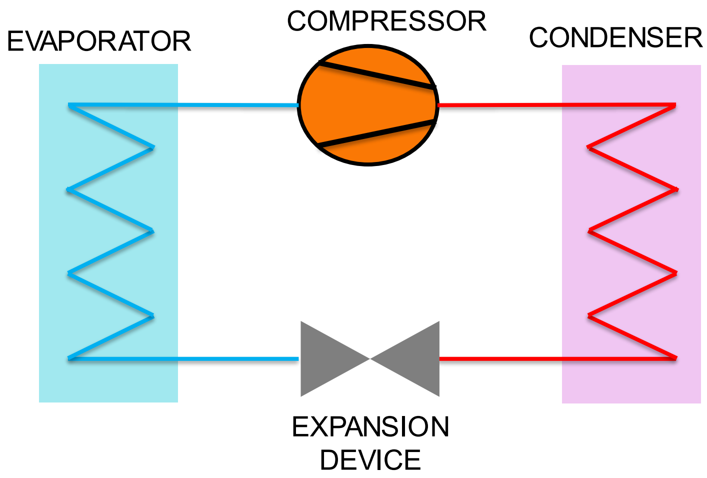
Design rules correlations

Nanofluids behaviour does not correspond to the established and predictable laws currently in place for the technology of heat and cold; even the experts have some difficulties with the equations formulated.

Furthermore, some contradictions between the results obtained by different investigators appear in the literature, currently hindering the adoption of industrial strategies for possible incorporations into industrial processes with guaranteed success.

Photos and plots

Some difficulties are nowadays clear in the development of engineering designs and calculation for systems and equipments with nanorefrigerants and nanolubricants. Especially considering the current heat exchange systems designed and calculated with formulas for fluids without solid particles inside. Therefore, a new development with new engineering formulas will be necessary to the use of NanoFluids in these systems.



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In the literature, several patents and papers in the field of Nanofluids (and their heat transfer) analyse the influence of nanoparticles concentration, sizes, etc. However, there is no state of the art, neither patents about phase change Nanofluids, as, for example, the Nanorefrigerants used in vapour compression cycles, where evaporation and condensation processes are present.

On the other hand, no bibliography exists about long-term stabilization Nanofluids neither about stability after long time on/off cycles.

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Turbulent pipe flow at high temperatures

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Heat transfer device

The methodology to measure the convective heat transfer coefficient for thermal oils at temperatures up to 250ºC combines an experimental closed loop that allows laminar and turbulent flow in a straight pipe with circular cross section and constant heat flux together with experimental measurements of the thermophysical properties of the analysed fluids.
The test section consists of a round stainless steel pipe with an inner diameter of 7 mm. A current source (350 A) produced Joule heating on the pipe walls over a length of 2 m. Inlet and outlet fluid temperatures were measured with thermocouples, as well as outer wall temperatures in 10 different locations along the test section. The facility also includes the required instrumentation for measuring the heat transfer coefficient at different Reynolds.

Effects following from employing nanofluids

The addition of small nanoparticles to obtain a nanofluid modify the thermophysical properties of the original fluid, allowing the improvement of the single-phase convective heat transfer coefficient.

Design rules correlations

The heat transfer coefficient of a nanofluid consisting of 1 wt.% of tin nanoparticles in Therminol 66 was measured. The measured enhancements in the facility of the convective heat transfer coefficient, using experimental values of the thermophysical properties and for a Reynolds of 20.000 were 9.9% for 140ºC and 6.8% for 200ºC, when comparing the nanofluids with respect to the base fluid.

Photos and plots

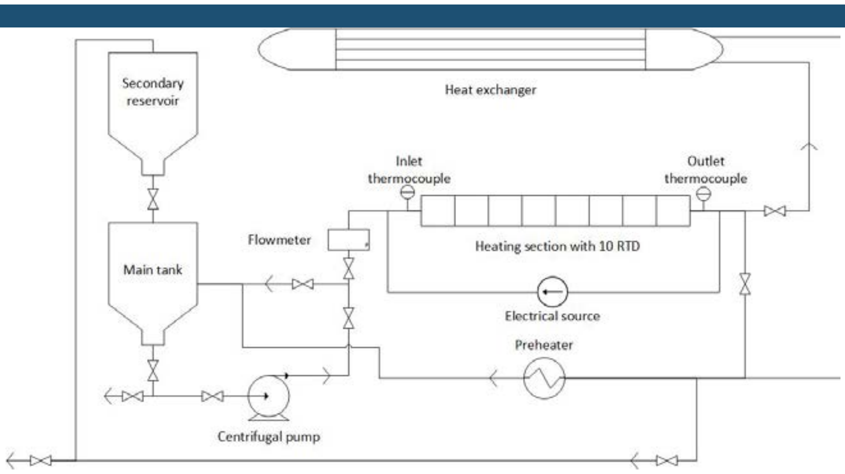
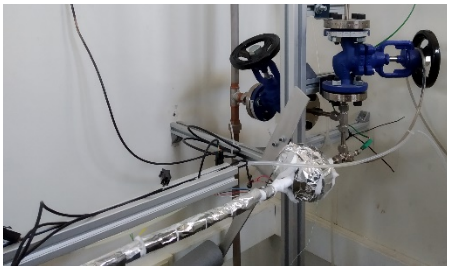
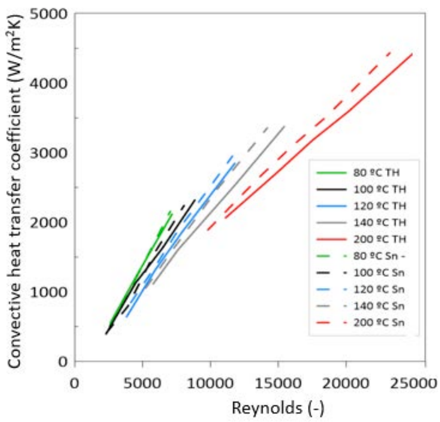


Diagram and photos of the experimental set-up





Heat transfer coefficient versus *Re* at different temperatures (from 80° to 200°C) for base fluid (Therminol 66, TH) and nanofluid (1 wt.% tin nanoparticles, Sn)

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3. Storage

3.1. Thermal storage of molten salts with nanoencapsulated PCMs

Thermal storage of molten salts with nanoencapsulated PCMs

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Heat transfer device

Concentrated Solar Power (CSP) plants concentrate solar radiation to generate electricity with the advantage of including a Thermal Energy Storage (TES) system in order to handle the intermittencies of solar availability and prevent the gap between energy supply and power demand. Molten salts are currently used as TES material and thermal energy storage is achieved mainly by sensible heat storage. In sensible heat storage processes there is no phase change happening and materials experience a raise in temperature. The relation between the change in temperature and the stored heat is given by the specific heat.

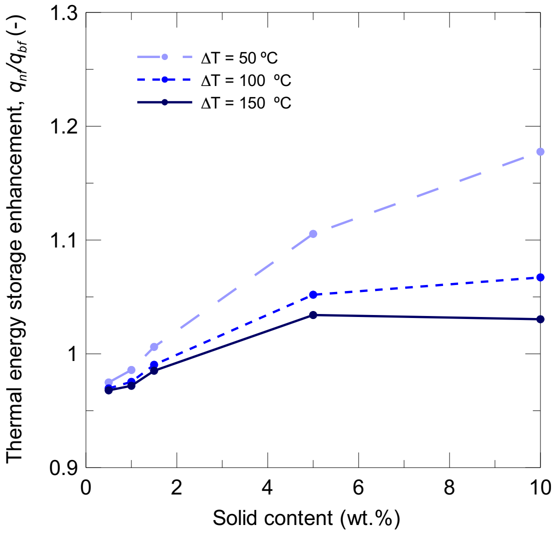
Effects following from employing nanofluids

The addition of nanoencapsulated phase change materials (nePCMs) can improve the thermal energy storage of molten salts or any base fluid due to the contribution of the phase change enthalpy of the nanoparticle nuclei and the latent heat storage.
For molten salt based nanofluids, the addition of nanoparticles usually leads to a decrease in the specific heat although increases can be achieved under some experimental conditions. In spite of the change in the specific heat and thus the sensible heat storage, the contribution of the phase change enthalpy and the latent heat storage can increase the total thermal energy storage of the fluid.

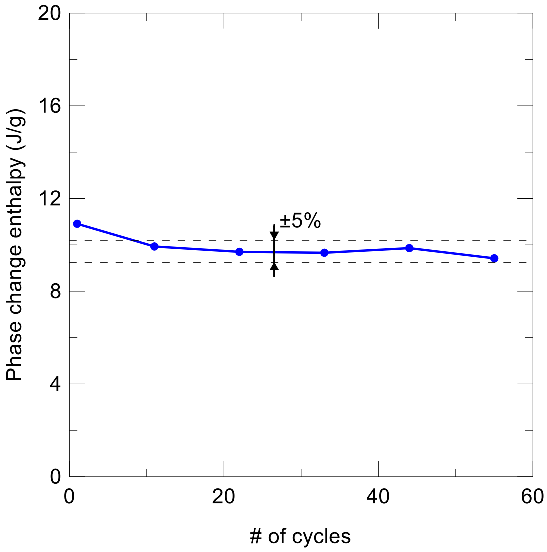
Design rules correlations

The phase change enthalpy of the nePCMs must be suitable for the intended application. Al-Cu metal alloy nanoparticles (T=546.74ºC), encapsulated by an alumina passivation shell, can be dispersed in solar salt (60% $NaNO_3$-40% KNO_3). As the solid content is increased, the latent heat storage can overcome the sensible heat decrement and maximum energy storage of 17.8% at constant volume basis can be achieved at 10 wt.% of nePCM for a working temperature range of 50ºC.

Photos and plots



Evolution of the total thermal storage enhancement with solid content of Al-Cu nePCM on a constant volume basis.



Evolution of phase change enthalpy with thermal cycling for a solar salt based nanofluid with 10 wt.% of Al-Cu nePCM to corroborate thermal stability.

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4. Solar Application

4.1. Hybrid nanofluids potential use on parabolic trough collectors

4.2. Dark nanofluids for solar applications

4.3. Melanin particles for solar thermal energy conversion

4.4. Nanofluid-based optical limiters

4.5. Solar steam generation via nanofluid

4.6. Nanofluids based on 2D nanomateriales for concentrating solar power

4.7. Direct absorption solar collectors (DASC) with nanofluids

Hybrid nanofluids potential use on parabolic trough collectors

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Heat transfer device

The main application of nanofluids in solar systems refers to solar collectors. Hence, to increase the overall heat transfer performance of a solar system, a new fluid have to be considered by adding high conductive solid nanoparticles. The hybrid nanofluids are introduced in the pipe with uniform velocity and temperature, and exit the pipe with high temperature due to solar radiation heating in the parabolic trough. Due to the low heat flux from the sun, the fluid flow is estimated to be laminar. The heat flux is not uniform around the pipe perimeter: the upper half is subjected to direct solar radiation (qupper) while the lower half is subjected to concentrated heat flux (qlower) as a benefit of the parabolic trough. The actual concentrated solar radiation (qlower) is equal to the direct solar ration multiplied by the concentration ratio (GR) of the collector (qlower = GR qlower). The pipe length is 10 times higher than the pipe diameter (L=10D), so, the problem can be considered as laminar forced convection in fully developed conditions.

In the present study, the hybrid nanofluid base fluid is water or 60EG:40W.

Effects following from employing nanofluids

The water based hybrid nanofluids provides acceptable heat transfer augmentation with less pressure drop penalty. Nevertheless, the addition of nanoparticles to 60EG:40W is not recommended due to higher increase in pressure drop penalty.

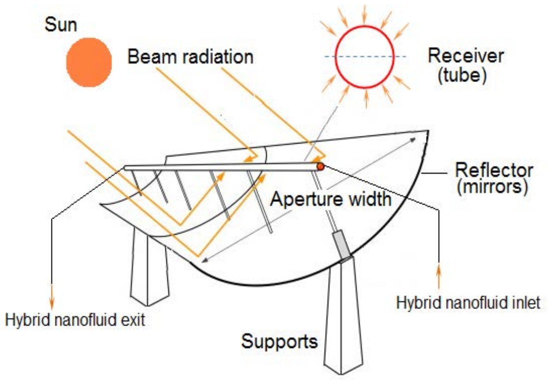
The water based hybrid nanofluids with 2% Ag-MgO offers the highest values in collector efficiency while the Re increases.

Finally, hybrid nanofluids are very good candidates for solar energy applications, even if the studies in the literature are limited.

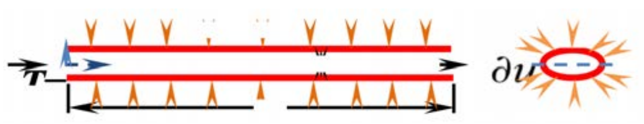
Design rules correlations

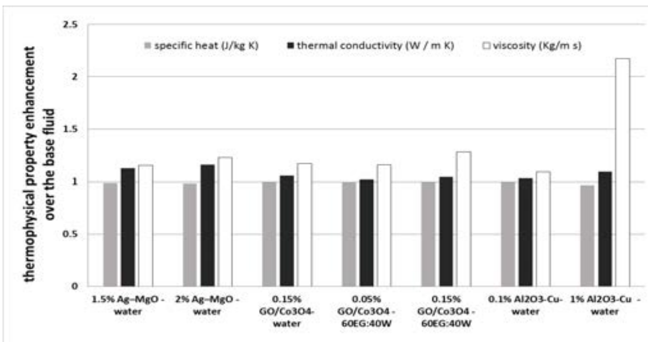
It was found that the peak enhancement in the Nusselt number has been established with both 2% Ag-MgO/water and 0.15% GO/Co_3O_4/60EG:40W hybrid nanofluid. Plus, Ag-MgO-water hybrid nanofluid with a volume concentration of 2% (at a Re = 2000) provides the maximum efficiency enhancement of the solar collector (up to 60%). Further discussion and correlations are given in the references.

Photos and plots



A view and a schematic diagram of the problem showing coordinates orientation with the hybrid nanofluid flow inside the tube of the parabolic trough.





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Dark nanofluids for solar applications

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Heat transfer device

Conventional solar collectors operating at low-mid temperatures consist of a sunlight absorbing (dark) coating deposed on a solid surface exchanging heat with a working fluid. To reduce energy losses due to thermal re-radiation by the heated absorber, a vacuum insulation of the absorbing surface is typically required. This scheme can be significantly simplified by the use of a dark fluid working at the same time both as volumetric light absorber and heat exchanger and flowing in a transparent channel.

Effects following from employing nanofluids

Nanofluids (i.e. fluids with nanometer-sized nanoparticles in suspension) have given a new pulse to the concept of Direct Absorption Solar Collectors (DASCs). With the proper choice of nanoparticles and base fluids, it is possible to obtain a nanofluid with the following characteristics:

1) high sunlight absorption level in a tailorable length, optimized for the geometry/architecture of the system of interest;

2) volumetric sunlight absorption with reduced emittance losses (to be compared to the surface absorption of conventional systems;

3) stability under thermal cycles and sunlight irradiation;

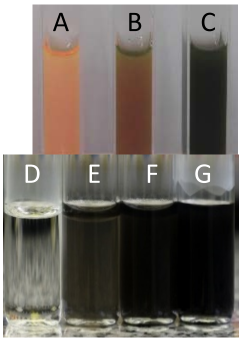
4) sunlight absorption and heat transfer tasks carried out by the same component (the nanofluid).

Design rules correlations

General design rule is: the proper choice of type and concentration of nanoparticles in the fluid allow to obtain the full sunlight absorption in the desired length.

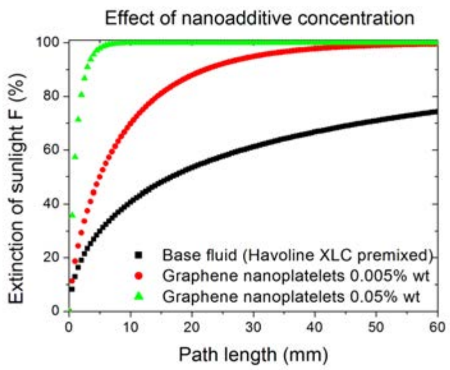
Photos and plots

Examples of dark nanofluids in heat transfer fluids:



(A) pure base fluid (Havoline XLC premixed); (B) Base fluid with 0.005% wt graphene nanoplatelets; (C) Base fluid with 0.05% wt graphene nanoplatelets (samples provided by L. Lugo, University of Vigo, Spain);

(D) pure base fluid (ethylene glycol); (E) Base fluid with 0.0025% wt graphite/nanodiamond mixture; (F) Base fluid with 0.0050% wt graphite/nanodiamond mixture; (G) Base fluid with 0.0100% wt graphite/nanodiamond mixture (samples provided by G. Zyla, University of Rzeszow, Poland).



Extinction of sunlight F(x) as a function of the path length x within the nanofluid. I(λ): sunlight spectrum; α(λ): nanofluid spectral extinction coefficient; λ: wavelength; λ_{min}=300 nm; λ_{MAX}=3000 nm

$$F(x) = 1 - \frac{\int_{\lambda_{\min}}^{\lambda_{MAX}} I(\lambda)\cdot e^{-\alpha(\lambda)x}\,d\lambda}{\int_{\lambda_{\min}}^{\lambda_{MAX}} I(\lambda)\,d\lambda}$$

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Melanin Particles for Solar Thermal Energy Conversion

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Heat transfer device

Rising energy costs, pronounced urban heat-island effect and global warming increase the need for intelligent solar heat management solutions. New Biomaterial (micro to nanoparticles, having a narrow particle size distribution), melanin, extracted from ink sac of a Cephalopoda animal, provides solutions for efficient management of solar devices, both for heat transfer fluids, with enhanced thermal properties, as well as pigment for solar selective absorbing lacquer or paint. The working principle without nanofluids of these types of paints is on the market, namely in domestic and small industry applications.

Effects following from employing nanofluids

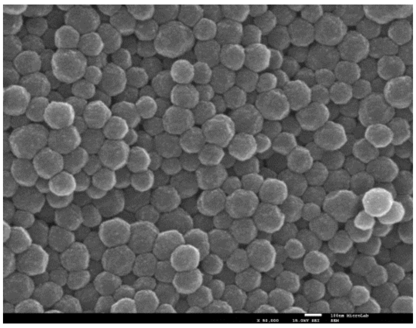
Efficiency of direct solar collectors can be increased as much as 12%, without selective absorbing paint. Melanin is also a very efficient heat storage material (high heat capacity between 60 and 120 °C) and it is a by-product or even waste-product from Cephalopoda animals for the food industry.

Nanofluid (1 wt% of melanin in water) has higher heat capacity and thermal conductivity than corresponding nanofluids with copper or graphite nanoparticles. Material is renewable and cheaper. No reactivity known.

Design rules correlations

Heat transfer coefficient and solar collector's efficiency can be enhanced, due to increase of heat capacity and thermal conductivity of nanofluid, without significant increase of viscosity and density.

Photos and plots



(SEM) image of melanin obtained from *Sepia officinalis* after isolation according to the method of the present invention, magnified 50 000 X.
Average size 138 nm, narrow PSD.

	Water	Melanin	Copper	Graphite
Heat capacity at 100 ºC (J/gK)	4.21	25	0.4	0.7
Heat capacity of 1 wt % in water nanofluid		4.39	4.14	4.15

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3. S. I. C. Vieira, M. Araújo, R. André, P. Madeira, M. Humanes, M. J. V. Lourenço and C. A. Nieto de Castro, Sepia melanin: a new class of nanomaterial with anomalously high heat storage capacity obtained from a natural nanofluid, J. Nanofluids 2, (2013) 104–111. http://dx.doi.org/10.1166/jon.2013.1040

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Nanofluid-based optical limiters

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Heat transfer device

The efficient manipulation of optical beams is required for many application fields (optical communications, optical computing, security, etc.). Light intensity is one of the most important parameters needing to be predictably controlled. Passive control techniques are considerably simpler than active ones, as they can be obtained using a single component working, at the same time, as sensor, processor and actuator. Optical limiters are passive devices able to control the amplitude of an optical signal. Their characteristic is that optical transmission changes with input intensity: a given light transmission at weak radiation input intensities turns into a lower transmission at high intensities. They are important for eye and optical sensors protection, with application in different fields e.g. military and security.

Effects following from employing nanofluids

Nanofluids (i.e. fluids with nanometer-sized nanoparticles in suspension) are advantageous as optical limiting materials thanks to their liquid form, which facilitate the production of devices of any shape, the simple material replacement e.g. in case of device refurbishment, change of the wavelength of interest, etc. With the proper choice of nanoparticles and base fluids, it is possible to obtain a nanofluid with the following characteristics:

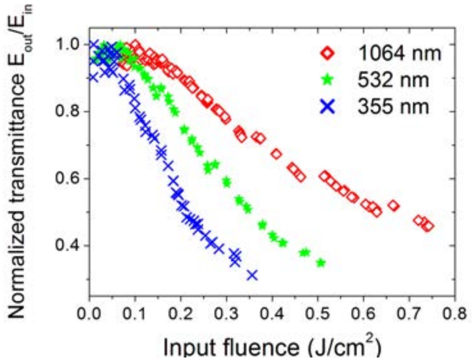
1) optical limiting operation at the wavelength of interest;

2) energy threshold for optical limiting in the range of interest.

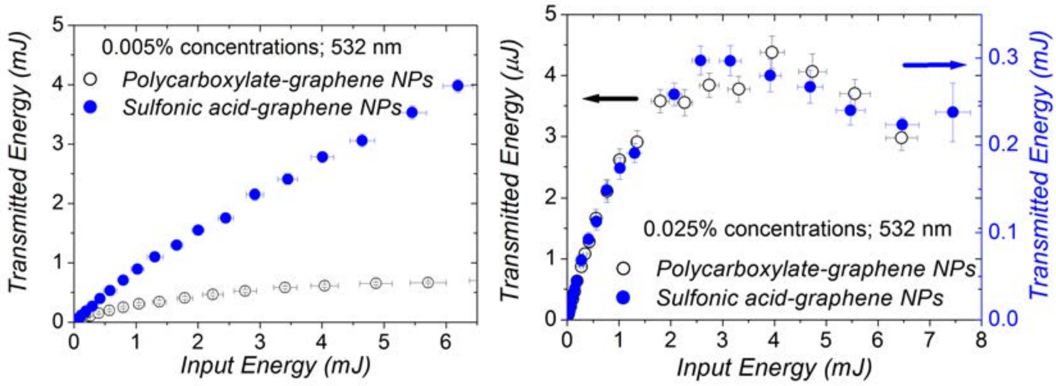
Design rules correlations

General design rule is: the proper choice of 1) type and 2) concentration of nanoparticles in the fluid and 3) of the basefluid allow to obtain the desired optical limiting behavior.

Photos and plots



Normalized transmittance, i.e. the ratio between output and input energies, normalized to its maximum value of nanodiamond suspensions with 0.005% wt concentration at 355, 532 and 1064 nm light wavelength [1]. In the linear regime, the normalized transmittance is unity, and decreases in the optical limiting regime.



Optical limiting is evidenced also considering the dependence of Transmitted Vs Input energy. The plots refer to differently-functionalized graphene nanoplatelets under 532 nm wavelength [2].

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Solar Steam Generation via nanofluid

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Heat transfer device

To study the effect of solar radiation on steam generation via nanofluids, a set-up is fabricated as shown in Fig. 1. For indoor experiments, a solar simulator is used. The effects of various solar radiation intensities and nanofluid concentrations on the amount of evaporation are investigated.

Effects following from employing nanofluids

Water can only absorb solar energy in the infrared wavelength range (700-1000nm), while a large portion of the solar energy is in the visible range (400-700nm). Among the recent various methods, there has been a growing interest in terms of using nanofluids for the direct absorption of solar power due to their promising high efficiencies in solar energy harvesting. In fact, direct and volumetric fluid absorption of solar energy via nanoparticles can minimize the convection heat transfer losses to achieve higher efficiencies.

Design rules correlations

General design rule is: The light absorption of water can be enhanced by adding nanoparticles.

Photos and plots

Test facility

① Solar simulator,

② *Aperture,*

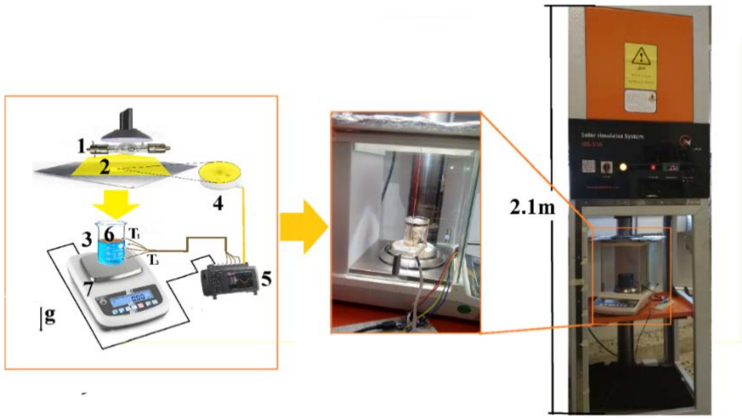
③ *nanofluid sample,*

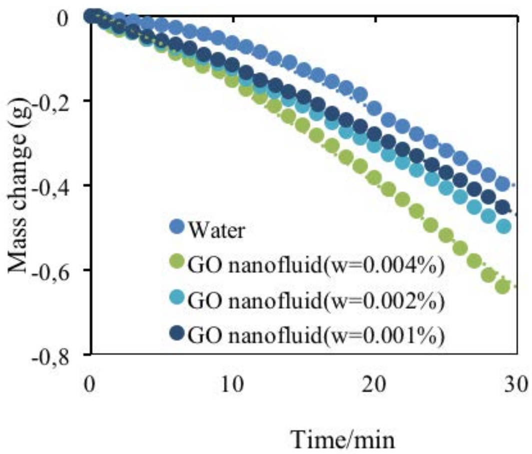
④ Pyranometer,

⑤ Data logger,

⑥ Glass container,

⑦ Balancer





This figure shows time variations of the reduced mass of the GO nanofluid at different nanoparticle concentrations compared to that of water exposed to the light intensity of 3.5 Suns

It can be seen that increasing the nanoparticle concentration enhances the evaporation rate, and The evaporation rate of the nanofluid with the highest GO concentration (0.004% wt.) is about 1.25 $kg.m^{-2}.hr^{-1}$, which is 1.6 times more than that of water.

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Nanofluids based on 2D nanomaterials for Concentrating Solar Power

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Heat transfer device

Solar energy is the most abundant energy resource on earth. It is a source of renewable energy that is environmentally-friendly and easily available in the whole world. More specifically, Concentrating Solar Power (CSP) has been one of the most appealing option in recent decades. CSP is a type of clean, renewable energy with global technical potential of almost 3000000 TWh/year and capable of reducing an average of 1 kg of GHC emissions for each kW generated.

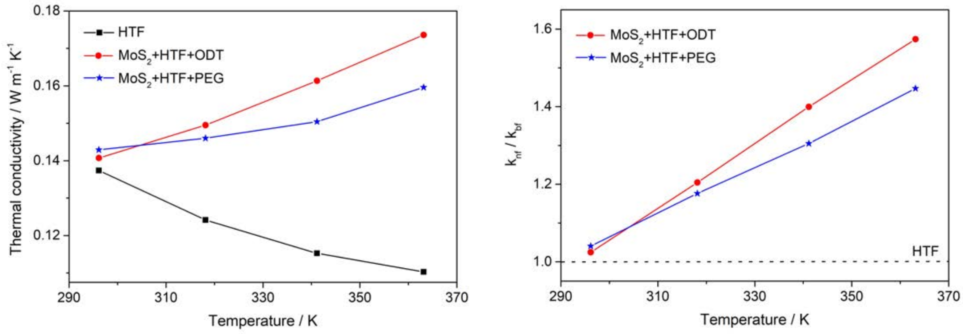
Effects following from employing nanofluids

Nanofluids (i.e. the colloidal suspension of a nanomaterial in a base fluid) are advantageous as heat transfer fluid in CSP. Specifically, nanofluids based on 2D nanomaterials show interesting features for this application. First, the 2D morphology lead to the production of highly stable nanofluids over the time, being this one of the most important issue to reach for nanofluid application. Second, the high thermal conductivity of 2D-nanomaterial, such as MoS2, WS2, h-BN… leads to prepare nanofluid with interesting thermal properties, showing higher increases in thermal conductivity and isobaric specific heat.

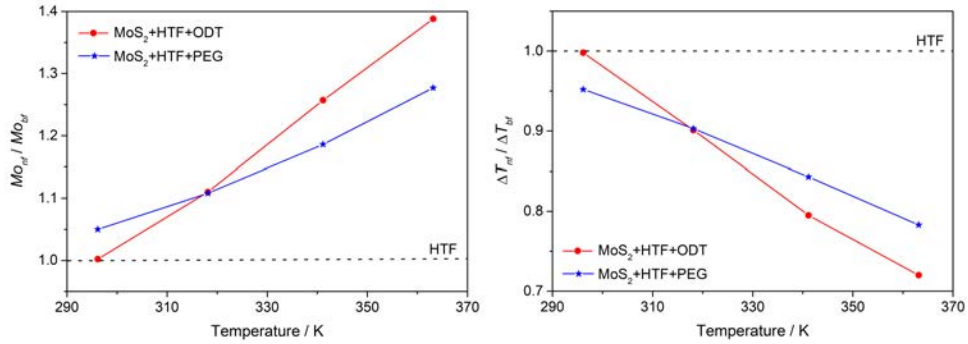
Design rules correlations

Increases ion thermal conductivity about 50%, and in isobaric specific heat up to 7.5% have been reported as the most interesting result for this kind of nanofluids, being these values for 2D-MoS2 based nanofluids.

Photos and plots



Thermal conductivity and thermal conductivity enhancement for nanofluids based on 2D-MoS2 using ODT and PEG as surfactants.



Mouromtseff number ratio of the nanofluids based on MoS2 and the base fluid; and the analysis of the outlet temperature in solar collectors.

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Direct Absorption Solar Collectors (DASC) with nanofluids

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Heat transfer device

Conventional solar thermal collectors normally absorb solar radiation through a solid surface and then the heat is transferred to a working fluid. Direct Absorption Solar Collectors (DASC) systems absorb solar radiation directly and volumetrically through working fluids, enabling more efficient systems. The development of nanofluids (colloidal suspensions with particles < 100 nm) has allowed a suitable working fluid for these DASC systems. To experimentally study the photothermal conversion efficiency of nanofluids in DASC systems, two set-ups (with and without concentration) have been fabricated.

Effects following from employing nanofluids

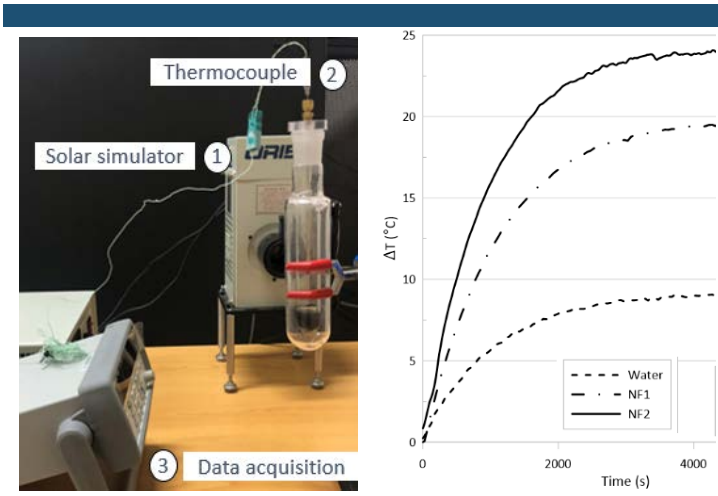
The addition of low concentrations of nanoparticles in a working fluid of a DASC systems:

- Increases the absorption properties of the working fluid
- Allows direct and volumetric absorption of the solar radiation in the nanoparticles, avoiding intermediate thermal steps present in conventional solar collectors
- Permits high flexibility of the working fluids, as can combine different base fluids (water, glycols, thermal oils, molten salts, etc) and different nanoparticles with varying optical and thermal characteristics (carbon based, metals, semiconductors, etc)
- Provides high photothermal conversion efficiency: ratio between the energy power absorbed by the fluid (calculated by fluid temperature) and the incident radiation power that arrives to the fluid
- Avoids possible erosion or clogging problems in pumps and pipes due to the low quantities of extremely small particles used
- Reduces possible problems of stability within the nanofluid, due to the low concentration of nanoparticles required

Design rules correlations

The nanofluid must be optimized, properly selecting the base fluid, the nanoparticle and its concentration. The stability of the selected nanofluid must be checked with time, at the working temperature and also with the expected thermal cycling. The DASC systems must have a) a transparent surface allowing the solar radiation to arrive to the absorbing nanofluid and b) an optimal absorption depth that must be calculated based on the optical absorption properties of the nanofluid.

Photos and plots



DASC system with no concentration and controlled room temperature and solar simulator (left) and increase of measured fluid temperature of water and water based nanofluids in two concentrations (right)

DASC system with concentration and solar tracking system for different fluids at a time

For a carbon water-based nanofluid (33 mg/l) the photothermal conversion efficiency with respect to the base fluid has increased 200% in the DASC system with no concentration and up to 1420% when exposed to direct solar concentrated radiation.

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5. Measurement of Thermophysical Properties

5.1. 3ω device for measuring thermophysical properties of nanofluids

5.2. Ring gap apparatus (RGA) for measuring thermal conductivity

3 ω device for measuring thermophysical properties of nanofluids

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Heat transfer device

The main difference between the employed 3ω hot-wire (3ωHW) method and the traditional transient hot-wire (THW) method relies in the frequency-domain instead of the time-domain modulation. The 3ω signal is generated by a patented double wire probe for compensation of temperature drift. The amplitude and phase signal is exploited to determine simultaneously and independently the sample thermal conductivity and diffusivity, while their time evolution as function of temperature can be monitored continuously. By combining the two quantities, the volumetric heat capacity (product of density and specific heat capacity) is derived. The evolution of phase change materials can be studied in real time, in the two phases.

Effects following from employing nanofluids

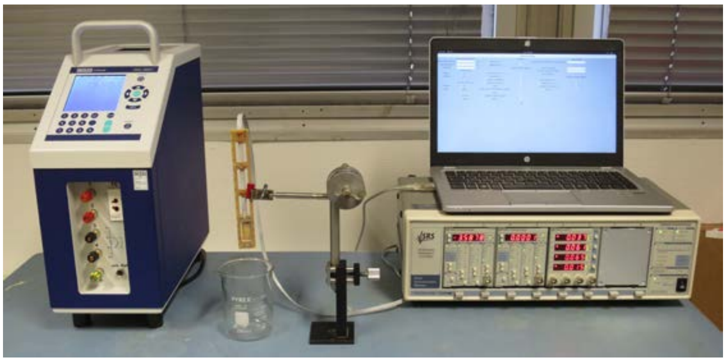
For accurate thermal conductivity measurement of fluids it is necessary to inhibit the heat transfer by convection and to minimize temperature gradients within the sample. Since thermal conductivity enhancement with nanofluids compared to base fluid is relatively low, the measurement devices are challenged by high resolution rather than by high absolute accuracy. The 3ωHW method with low excitation level (below 1 ºC), combined with sensitive lock-in signal processing, satisfies these requirements.

Design rules correlations

Main features of the device:

- Absolute or relative measurements at fixed temperature or during temperature scan in the range -35 ^{o}C to +200 ^{o}C.
- Additionally, the average temperature of the fluid is measured by the same probe, thus minimizing errors due to thermal gradients.
- The resolution of the measurements is 0.1 % in thermal conductivity and 0.3 % in thermal diffusivity.

Photos and plots



Development status: laboratory prototype.

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Ring gap apparatus (RGA) for measuring thermal conductivity

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Heat transfer device

The physically correct determination of the thermal conductivity of nanofluids is a key feature in qualifying nanofluids. ILK Dresden has built end employs a ring-gap apparatus (RGA) for this task. The apparatus consists mostly of high grade silver to ensure an excellent heat conduction. A sophisticated measurement strategy including four times repeated measurements, extraordinary exact determination of temperature differences between inner and outer corpus allow a measurement accuracy of ± 3 %.

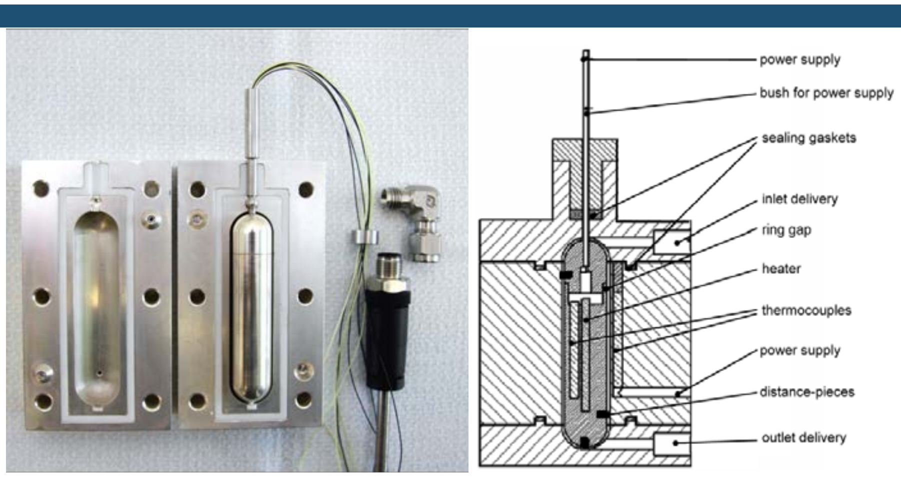
Effects following from employing nanofluids

The RGA belongs to the steady-state methods for measuring thermal conductivity of liquids and gases. The physical operation principle is equal to coaxial-cylinder cell apparatuses. The liquid under investigation is filled in a gap of 1 mm with which is formed by an inner and an outer body of the device. The inner part is weakly heated. Temperature difference is measured between inner and outer body of the device. Thermal conductivity of the liquid is predicted assuming it is not moved by free convection. The latter is confirmed by numerical simulations at least for watery suspensions and solutions [1].

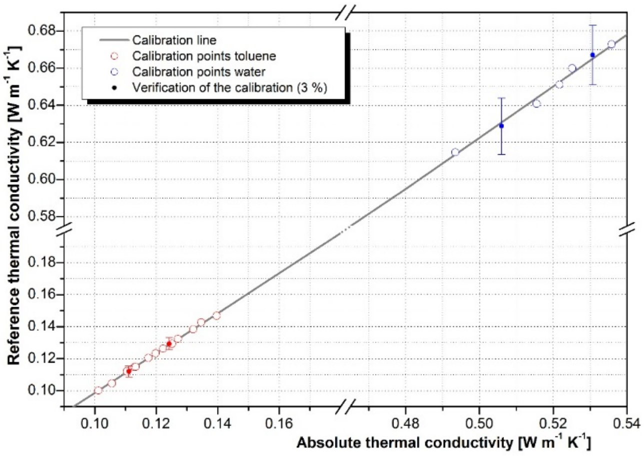
Design rules correlations

- About 8 ml of the fluid to be measured are needed
- Temperature range for water based liquids ranges between 5 and 95 °C
- Pressure ranges between 0 – 5 bar (higher pressure possible)

Photos and plots



Ring gap apparatus made of silver (left) and main parts of device [1]



Calibration / verification of the measurement device

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