Enhanced Nano-fluid Heat Exchange

Reporting

Project Information

NANOHEX
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Final Report Summary - NANOHEX (Enhanced nanofluid heat exchange)
NANOHEX focused on the formulation of nanofluid coolants for application in the data centre cooling and traction power electronic cooling. This included the development of two demonstrator units for the respective application areas and a versatile production pilot. The consortium has filed two patents. The key achievements include:

- The formulation of two nanofluids based on the dispersion of silicon carbide (SiC) and aluminium oxide (Al2O3) in the carrier liquid have been developed and optimised. Thermal testing of the nanofluids indicates the fluid offers thermal enhancement between 10 and 20%. However, further work is required to optimise the thermal performance.
- The development of a new nanofluid assessment model that can be used by industry to rapidly evaluate the thermal performance of the nanofluid in comparison to its base or carrier liquid in convective systems. The model takes into consideration a number of key properties of the base liquid and the nanoparticles dispersed including changes in viscosity, thermal conductivity, specific capacity and concentration of the nanoparticles, density as well as the flow rate, geometry and flow conditions. Hence, the model can be used by industry to optimise the both the formulation of the nanofluid and geometry of the heat transfer unit deployed to harness the benefits.
- The development of two demonstrator units: A server blade cabinet for data centre cooling taking liquid direct to the microprocessor and insulated gate bipolar transistor (IGBT) cooling unit for deployment traction power electronics.
- The consortium has also established a better understanding of the potential adverse impact of nanoparticles on industrial equipment. This has shown that equipment made from stainless steel is not adversely impacted. However, greater care is required for equipment made from copper or aluminium, where pH levels need to be managed to mitigate and prevent corrosion.
- Detailed computer simulations of data centre cooling demonstrated that by taking liquid direct to the microprocessor can both reduce energy consumption required for cooling a server, but also enable data centre operator to more than double computing capacity in comparison to a using air cooling. The use of nanofluids, rather than water, can further enhance the computing capacity by 10%.
- Analysis of nanofluid for power electronics indicated that there deployment in automotive applications may be of greater value than high-speed trains. Harness the benefits of nanofluids is best done under low to moderate flow rate under laminar conditions. These could potentially be realised in cooling of electric barriers in electric vehicles including cars powered by hydrogen fuel cell.
- The consortium established a versatile production pilot line, which can be used for manufacturing nanofluids. The pilot line has the capability to produce nanoparticles using wet chemistry and also disperse commercially acquired nanoparticles into the base or carrier liquid.
- The consortium has also developed a physical model that can be used to better understand the thermal behaviour of dispersed nanoparticles in a carrier liquid. The model takes into consideration the aspect ratio of particles and their rotation in the liquid.

Project context and objectives:

During the first year of the NANOHEX project, the public facing brand name for the project was established as NANOHEX. The new brand name better reflects the purpose and objectives of the project.
The goal of NANOHEX is to advance the state of the art by translating the nanotechnology-based research results into the development of a high-performance coolant for adoption by industry, with enhanced thermal conductivity and heat capabilities not presently accessible. The goals of NANOHEX are:

(a) to translate promising laboratory based nanotechnology research results into pilot lines for the production of nanofluid coolants for industrial heat management applications;
(b) to optimise the formulation of nanofluid coolants through the control of the synthesis process and knowledge of the underlying physicochemical sciences;
(c) to deliver energy savings, and safe and reliable exploitation of nanofluid coolants in cooling of electronics, primarily targeting data centres and power electronics;
(d) to position the European industry ahead of competitors in North America and Asia by capitalising on advances in nanoparticle science and dispersion technology.

The 6 technological aims of the project were:

(1) to translate promising research results into the formulation of highly reliable nanofluid coolants and the development of novel cooling systems harnessing the benefits offered by NANOHEX nanofluids;
(2) to investigate and advance the scientific understanding of the thermal properties and behaviour of nanofluids and develop an accurate analytical model to simulate and predict heat transfer of the formulated NANOHEX nanofluid coolants;
(3) to design, develop and evaluate two small-scale pilot lines for the manufacture of NANOHEX nanofluid coolants, using single-stage wet chemical and two-stage production strategies;
(4) to design, develop and benchmark two demonstrators for data centre and power electronics cooling using NANOHEX nanofluid coolants and novel heat management and cooling systems;
(5) to establish scale-up models for the translation of the two-demonstrator cooling systems and both the single-stage and two-stage nanofluid production pilot lines into large-scale production lines;
(6) to establish the economic viability of NANOHEX nanofluid coolants across the full value chain of production, use, disposal and recycling in both the data centre cooling and the power electronics for traction application.

Project results:

The NANOHEX project was segmented into three reporting periods for the European Commission (EC):

- Period 1 - 12 months in duration
- Period 2 - 12 months in duration
- Period 3 - 18 months in duration.

During period 1, after establishing and standardising thermal test rigs, the consortium successfully started to demonstrate obtain and observe some thermal enhancement for both static thermal conductivity and more importantly for cooling systems under convective heat transfer conditions.

During the start of period 2 a videocast 'Discovering Nanofluids' was completed for the NANOHEX project
During the first year a campaign of testing was started that finished on April 2010 in period 2. The campaign of thermal testing was comprised of measuring a number of properties including:

(a) effective thermal conductivity of the nanofluid;
(b) heat transfer coefficient in straight pipes and micro-channel cold plates;
(c) viscosity of the resulting nanofluid;
(d) particle size, both primary and hydrodynamic particle size;
(e) erosion and corrosion testing to assess any adverse physical damage that dispersed nanoparticles may impart on the heat management equipment.

Tests were performed on a range of nanofluids prepared by the consortium and a number sourced from suppliers. The nanofluids tested included TiO2, Al2O3, ZrO2, Ag, CeO2, carbon nanotubes (CNTs), SiC, SiO2, Fe2O3 and industrial diamond. The consortium has narrowed the nanofluids down to those comprised of TiO2, Al2O3, CeO2, Ag and SiC. In addition, a thermal testing rig has been established for rapidly screening nanofluids prepared from other nanomaterials.

During Period 2 work commenced on more detailed testing and characterisation of nanofluids based on TiO2, Al2O3, CeO2, Ag, Clays and SiC in order to establish the thermal performance of nanofluids their dependency on parameters that can be controlled such as particle size, concentration, flow regime, mass flow rate and particle shape.

Through the consortium’s research work and interaction with other researchers in the field a number of technological challenges have been identified and confirmed. These require addressing to enable adoption of thermal nanofluid. On summary they are:

(a) primary particle size, particle size distribution, hydrodynamic particle size and temperature influence thermal performance;
(b) increase in viscosity on the addition of nanoparticles, hence the increase in associated pressure drop and pumping power;
(c) surface modifiers capping nanoparticles may be increasing the heat transfer resistance at the particle / liquid interface and hence impeding thermal performance;
(d) thermal nanofluids need to comprise of well dispersed nanoparticles as dispersion instability adversely impacts thermal performance;
(e) nanoparticles have a specific heat capacity that is less than water and hence the resulting nanofluid has a slightly reduced specific heat capacity compared to the base carrier liquid;
(f) the distribution of nanoparticles in a tube cross section may not be even due to particle migration.

During period 3, the consortium narrowed down the selection of nanoparticles to two species: Al2O3 and SiC nanofluids. Through the activities of period 3 and the completion of the NANOHEX project the consortium has achieved:
- Database of comprehensive results showing a characterisation of nanofluid systems and their thermal performance. In the first step the standardisation of the measurements have been undertaken for each of the rigs and characterisation tests by partners. This is probably the world's largest compilation of nanofluid thermal performance test data, comprising results and comparisons from three leading European research facilities at Royal Institute of Technology (KTH), University of Twente and Birmingham University. This is a very valuable resource for understanding the parameters determining thermal properties of nanofluids.

- Optimisation of the nanofluid included composition, concentration of the nanoparticles, type and concentration of the surfactants as well as the method of preparation of the nanofluid. The optimisation was done for water and water-Ethylene Glycol mixtures as base fluids.

(i) For the Al2O3 -water system it was found that the best formulation was, at 9 wt % (2.4% by volume), gamma type, octysilane as surfactant with a pH of 7.5 to 8. For this system, the increase in thermal conductivity was 10 %.

(ii) For the Al2O3 - water / ethylene glycol system the best formulation was, at 9 wt % (2.6 % by volume): gamma type, octysilane as surfactant. For this system, the increase in thermal conductivity was 10 - 11 %

- For the SiC- water system, it was found that for the nanofluid at 9 wt % (3 % by volume), alpha type and no surface modifiers the solution was too viscous to be used as a heat transfer fluid.

- For the SiC- water / ethylene glycol system, it was found that the best formulation (at 9 wt % (3.2 % by volume)), was alpha type. For this system, the increase in thermal conductivity was 19 %, with only a small rise in viscosity.

- Development of a versatile production pilot line for nanofluid coolants that has the capability for both single-stage and two-stage production capabilities. The single-stage process enable in one process stream the manufacture of the targeted nanoparticles and their dispersion to yield an optimised nanofluid formulation. The two-stage stream allows the production of nanofluids using nanoparticles supplied by a third party. This versatile approach has equipped the consortium with a pilot-line that will aid the development of more application specific thermal nanofluids.

- Development of an assessment model that can be used to determine the likely thermal performance of nanofluids relative to their basefluid using experimental data on the viscosity and thermal conductivity.

- Two patents during the duration of the project. These patents have been applied for by KTH and cover the production of nanofluids and a method to determine the stability of nanofluids:
  (a) SE1000924-9: The use of a suspension comprising mesoporous silica particles as heat exchange fluids. This patent has been granted.
  (b) SE1100961-0: New method and apparatus for a simple determination of the shelf lifetime, or stability of nanofluids. In this method, the weight of solid content inside the sample, which accumulates on a tray submerged in the colloid, is measured by an accurate scale.

- Development of a new physical model for the prediction of the thermal performance of nanofluids based on oblong particles (particles will an aspect ratio different from 1) dispersed in a carrier fluid.

- Development of two demonstrator units for data centre and power electronics cooling.
Completion of a lifecycle analysis and Economic Viability for the deployment of nanofluids for the data centre cooling and traction power electronics. The analysis showed that significant environmental benefits can be gained from liquid cooled data centre. It also suggested that nanofluid cooling does not offer significant environmental benefits in traction power electronics applications, but could potentially offer significant increase in operating life of inverters.

Further, a simulation of a typical Data Centre using water and nanofluid cooling, showed that the server capacity, or the computing capacity, of a data centre using liquid cooling by taking water and/or nanofluids direct on the processor could be more than doubled. Thermacore, the lead industrial partner, will be looking to enter the emerging liquid cooling data centre market based on the outcome of the NANOHEX.

Potential impact:

1.1 Introduction

Over the period of the NANOHEX project the consortium has progressed, the state of nanofluid coolant formulation and its industrial application. Prior to the start of the project, the consortium anticipated a thermal enhancement of over 40% plus in static and convective heat transfer systems. These promising results were also in alignment with experimental results published in many peer reviewed research papers. Some papers also indicated that thermal enhancement using CNTs to be over 300%.

Such level of thermal enhancement would create new opportunities for innovation in process and heat management for industry. This level of thermal performance could also not be explained by current physical theory.

During the course of the project, the NANOHEX consortium prepared a variety of nanofluids using a range of nanoparticle species. On summary it was found that thermal performance could be improved by around 10 - 20% using SiC and Al2O3 nanoparticles dispersed in a water / EG carrier fluid. Whilst this level of enhancement is not as high as anticipated by industrial partners, it is of a level were value could potentially be realised.

During the course of the NANOHEX project, the consortium discovered that the addition of nanoparticles caused a significant increase in viscosity, which needed to be taken into consideration in formulating nanofluids for different industrial application. Viscosity is influenced by a number of factors including the additives used in preparing nanofluids. Hence, the formulation of a thermal nanofluid needs to look at not just the rise in thermal conductivity or effective convective heat transfer co-efficient, but also the use of additive or dispersion strategies that minimise any increase in viscosity following the addition and dispersion of nanoparticles.

Contrary to some published literature, NANOHEX determined that the observed thermal enhancement does not deviate significantly from classical heat transfer correlations. Deviations observed from classical correlations remained in most cases within 10%. Furthermore, the consortium found that nanofluids could impact the different materials used in industrial equipment, with regards to corrosion and erosion, but this
could be prevented or minimised by careful control of pH levels.

Future work beyond NANOHEX should focus on the following activities:

- Formulation of a nanofluid that is not only stable with respect to dispersion, but in which the percentage increase in its viscosity is significantly less than the percentage increase in its thermal conductivity. This is necessary for both power electronics and the data centre cooling. In such a fluid, engineers will be able harness the thermal performance of nanofluids deployed within convective systems.
- The use of the NANOHEX assessment model should be further extended to evaluate the relative performance of nanofluids in convective heat transfer systems. The model requires measurements to be taken of the relative increase in thermal conductivity and viscosity providing a simple tool for industry wide use. The model can also be deployed to compare the likely performance within different geometries and hence be used by engineers to design heat transfer devices.
- The formulation of nanofluids for deployment in convective systems should focus on applications where low flow rates under laminar conditions within the cooling devices provide benefits. For example data centre cooling and electric vehicles.
- Further optimisation work on the formulations developed by NANOHEX should be continued to further reduce viscosity levels whilst maintaining or increasing thermal conductivity.
- The consortium will be taking to market the data centre cooling system developed by NANOHEX initially using water and then subsequently offering nanofluids. The consortium will also be investigating the use of nanofluids in electric vehicles that require lower flow rates for cooling power electronic components than high-speed trains.
- Adoption of nanofluids in thermal systems where both the increase in viscosity and thermal conductivity could be of benefit. Applications here could include metal processing such as quenching and cutting metal.
- Health and safety data / information on nanoparticles and their toxicology to human health and the environment. There was insufficient published data available to fully assess the actual risks and hence a risk management approach was concluded in the handling and processing of nanoparticles.

1.2 Optimisation of thermal nanofluid

At the start of the NANOHEX project it was anticipated that thermal performance would be greater than 40% and well beyond that predicted by classical heat transfer theory would be observed. In order to optimise the fluid for industrial adoption it was anticipated the key challenge would be the formulation of a nanofluid that exhibited dispersion stability over a long duration.

In the first half of period 1 the consortium mainly focused upon building and calibrating thermal test rigs and associated characterisation instruments. The convective heat transfer tests were started from the second half of period 1 and were continued until the end of the project. In period 2 a wide range of nanofluids were tested including. Based on the results the consortium selected some of the nanofluids for further detailed investigation. These nanofluids were TiO2, Al2O3, CeO2, Ag and SiC.Whilst thermal enhancement was observed of around 10%-20%, the viscosity increase of the resulting nanofluid was
often over 80 %. This made harnessing the thermal benefits very difficult, even if the dispersion could be stabilised.

Midway through period 3 the consortium narrowed down the candidate nanofluids into Al2O3 and SiC. Emphasis was then placed upon optimisation activities to reduce the viscosity of the nanofluid and at the same time increase the thermal conductivity and stability of the nanofluid.

As a result the NANOHEX consortium formulated two nanofluid using SiC and Al2O3 nanoparticles dispersed in a water / EG basefluid. In the case of SiC, the NANOHEX consortium yielded a nanofluid that showed a thermal conductivity increase of 19 %, with only a 15 % increase in viscosity. For Al2O3, the consortium formulated a nanofluid that showed an increase in Thermal Conductivity of around 10% and viscosity increase of only 12 %. These are strong candidate nanofluids for potential adoption by industry. In particular, SiC water / EG nanofluids shows the strongest potential as the percentage increase in viscosity was less than the percentage increase in thermal conductivity.

Based on the NANOHEX Assessment Model, future work should focus on further reducing the viscosity increase to as low as 8 % and maintaining or increasing the percentage increase in its thermal conductivity. This will yield a nanofluid, which will consistently offer a higher thermal performance than its base fluid in convective systems.

1.3 Erosion and corrosion impacts of nanofluids

At the start of the NANOHEX project, the consortium anticipated that nanofluids, comprising a low concentration of nanoparticles would have little, if any, impact on industrial equipment with regards to erosion and corrosion. This was based on the assumption that the nano-scale of the particles would not cause equipment to wear. No published literature was available and hence the consortium included in the project tasks to carefully assess the adverse mechanical impact of nanofluids on industrial equipment made from different materials.

As part of the project the consortium assembled the hydraulic experiments on thermo-mechanical of nanofluids (HETNA) Rig for assessing the adverse erosion and corrosion impacts of nanofluids.

For stainless steel this has been proven to be true. No adverse impact was observed in comparison to water. However, for aluminium and copper the situation was found to be different. Adverse impact was observed, however it was found that by controlling pH levels this could be prevented. As pH can be used to control the corrosion, the issue is related to the additives and surface modifiers used rather than the mechanical impact of the nanoparticles alone. NANOHEX found that the pH of the nanofluid changes during use in industrial applications. Applications using thermal nanofluids hence need to take into consideration the potential requirement to monitor / control pH.

In the future, work needs to be conducted to investigate ways to reduce the mechanical effects by improving surface properties of the components in conjunction with controlling / monitoring pH and/or using additives that help maintain pH level to remain stable during use.
1.4 Data centre cooling

At the onset of the project, the consortium anticipated that commercialisation of nanofluids would become possible as the data centre operators shifted from air to liquid cooling systems driven by the adoption of water. This would open the path for the data centre operators to adopt rack using nanofluid coolants to cool directly microprocessors on each individual server.

The consortium has explored the needs of the data centre operators and designed a heat transfer device (cold plate) that can be deployed using water or nanofluids to directly remove the heat from the microprocessor into the liquid. The consortium has also designed a server rack that incorporates a nanofluid cooling circuit and drip-less connectors - it is first of its kind in the world. The nanofluid is chilled using water and hence remains enclosed within the rack. The design of the rack hence offers the data centre operators a plug and play solution. The rack can be easily deployed in any data centre that has an available water infrastructure for cooling.

The commercialisation strategy that Thermacore Europe will be deploying will be taking water cooling to market and then subsequently nanofluids. Water offers the benefits to double the computing capacity of data centres and the use of nanofluids will further boost this capacity. The data centre simulation analysis showed that a nanofluid having a thermal performance enhancement of 10% greater than water would provide around a 10% reduction in the energy that is required to cool the servers. The data centre operators are likely to translate this energy saving into boosting computing capacity to increase overall performance, productivity and revenues. This will equate approximately to a 10% increase in compute capacity.

The consortium established that lifecycle analysis of data centres requires the use of sophisticated and specialist tools designed specifically for data centre builders and operators to simulate accurately the energy usage in a given data centre based on its topology. Without these tools the lifecycle analysis for a data centre is unlikely to offer realistic predictions of different cooling scenarios and strategies.

Further research and development for the deployment of nanofluids in data centres should focus on long-term stability of the nanofluids of up to 5 - 10 years. The data centre operators are unlikely to adopt solutions where the coolant has to be replaced prior to the rack itself. Even if a server experiences difficulty and fails, a data centre operator will not immediately replace the server until its replacement time comes - even if this is a year or two away. Today’s data centres use virtual servers. A given virtual server can operate any server and indeed can operate across more than one server. Operators also tend to have agreements in place with server suppliers to provide a free server in the future at the allocated time to replace any failed servers. This requirement and sector 'mindset' is likely to apply to the rack and hence the nanofluid itself.

1.5 Traction power electronics cooling

At the onset of the project the consortium anticipated that nanofluid would both reduce the energy utilisation for cooling IGBT units in traction applications such as high-speed electric trains and enhance the reliability of the components by maintaining a lower operating junction temperature in order to reduce
thermal stresses.

The consortium designed, developed and tested an interchangeable cold plate that can be deployed in existing traction cooling systems. This was used for the development of a demonstrator unit. Testing of the optimised SiC water / EG nanofluid indicated that significant thermal performance under low flow rates and laminar flow conditions could be realised. At a flow rate of around 4 l / min the IGBT junction temperature was found to be 6 K lower using nanofluids than that using water / EG. At higher flow rates of 10 l / min the temperature difference dropped to 2 K. Note a 3-K reduction in the junction temperature equates to a thermal performance improvement of about 10 %.

Traction applications in high-speed trains operate at higher flow rates in the range of 10 - 25 l / min. Harnessing this benefit is likely to difficult in trains. A more likely application could be electric vehicles where flow rates are in the range of 5 - 10 l / min. Hence for future work, the automotive sector is likely to be a better alternative market for cooling lower power IGBT modules. It also offers a larger market opportunity than traction, to scale nanofluid production.

1.6 Thermal assessment model

At the onset of the project the consortium adopted the strategy to use fixed mass flow rate, Reynolds number and the Nusselt number as methods for assessing the thermal performance of nanofluids in convective systems by calculating the heat transfer co-efficient. This approached was also reflected in many published literature on nanofluids. However, through thermal testing NANOHEX established that this approach did not give a complete picture to assess nanofluids. It does not take into consideration a number of parameters such as viscosity and pumping power that are vital for industrial adoption in closed loop convective heat transfer systems.

The NANOHEX consortium established a new assessment model that has now been published. The model takes into consideration thermal conductivity, specific heat capacity, density, viscosity, pumping power, Nusselt number and velocity of the base fluid as well as the geometry of the cooling device. A new parameter, called thermal resistances, which has been detailed in this report, has been established and can be used to effectively evaluate the thermal performance of nanofluids. Based on measurements of viscosity and thermal conductivity the thermal resistance can be calculated. A negative value of the thermal resistance indicates that the nanofluid will lower the wall temperature of the surface been cooled more than the base fluid alone would using the same pumping power.

Future work on nanofluids should utilise the published NANOHEX assessment model to evaluate nanofluids and design heat transfer devices using nanofluid coolants. Details of the model have been published in the International Journal of Heat and Mass Transfer: ‘Assessment of thermal conductivity, viscosity and specific heat of nanofluids in single phase laminar internal forced convection,' 64 (2013) 689-693, S. Vanapalli, H.J.M. ter Brake.

1.7 Production pilot line

The consortium has established versatile production pilot-line for manufacturing small-scale volume of
nanofluid coolants. The pilot-line comprises the capabilities of both a single-stage and two-stage production route enabling the consortium to formulate bespoke thermal nanofluids for different applications. The single-stage capability enables the production of thermal nanofluids by dispersing commercially acquired nanoparticles into the carrier liquid and addition of additives, whilst the two-stage capability enables the production of nanoparticles using wet chemistry and then the subsequent dispersion into the carrier liquid. The pilot line has been established in facilities at ItN Nanovation and can be used by the consortium to formulate new nanofluids for alternative applications as well as manufacture nanofluids at a small-scale for demonstration.

1.8 Alternative applications

At the onset of the project the consortium targeted two application areas based on the needs of its industrial partners: data centre cooling and IGBT cooling for train applications. Through the course of the project the consortium has explored alternative applications. Through the NANOHEX assessment model developed it has become possible to gain insight into different attributes of nanofluids and hence their likely potential applications. This is driven by the relative increase in viscosity and thermal conductivity.

We can segment these applications into three groups:

(1) Percentage increase in viscosity is slightly or moderately higher than the percentage increase in thermal conductivity (initial market entry for thermal nanofluids):
(a) This includes applications where both the increase in thermal conductivity and viscosity could be exploited.
(b) This includes metal processing such as quenching and cutting. Here the rise in thermal conductivity reduces the overall quenching time by increasing the rate of cooling, whilst the rise in viscosity increases the residence time of the liquid on the metal during cooling. This can be also used to control physical properties of the metal being cooled. Furthermore, as the fluids are used once before recycling the dispersion stability issues are minor.
(c) These applications also represent the initial market deployment for thermal nanofluids. As a result of the dissemination activities of NANOHEX a number of EU companies have initiated nanofluid projects for applications in metal cutting and quenching.

(2) Percentage increase in viscosity is similar to the percentage increase in thermal conductivity:
(a) Systems adopting these fluids are likely to require significant fine tooling, especially if they are closed loop cooling circuits in order to harness the thermal benefits.
(b) These fluids will be difficult to commercialise into closed loop convective heat transfer system, but can be used as outlined above in point (1).

(3) Percentage Increase in viscosity is significantly less the percentage increase in thermal conductivity:
(a) All applications and ideal for closed loop cooling circuits for managing heat transfer and heat management.
(b) The NANOHEX assessment model can be used to identify rise in viscosity that can be tolerated.

Alternative application markets include:
- cooling of electronics,
- power electronics in traction,
- power electronics in renewable power plants and smart grids arena,
- geothermal and ground heat extraction fluids,
- hydrogen production processes,
- cooling of fuel cells in applications such as hydrogen fuel cell electric cars and off-grid power,
- steel quenching and annealing,
- solar water heating,
- electric engines in vehicles,
- transformers,
- nuclear reactors,
- heat pipes,
- industrial heat exchangers,
- cooling and heating in buildings,
- cameras and displays,
- industrial chillers,
- domestic refrigerators,
- coolant in machining,
- diesel electric generators,
- diesel combustion,
- boiler flue gas temperature reduction,
- medical applications,
- transportation sector, including duty vehicles.

List of websites: http://www.NANOHEX.org/

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