NanoHex
Enhanced Nano-Fluid Heat Exchange

Final Publishable Summary

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/was 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/were to:

- Translate promising laboratory based nanotechnology research results into pilot-lines for the production of nanofluid coolants for industrial heat management applications
- Optimise the formulation of nanofluid coolants through the control of the synthesis process and knowledge of the underlying physico-chemical sciences
- Deliver energy savings, and safe and reliable exploitation of nanofluid coolants in cooling of electronics, primarily targeting Data Centres & Power Electronics
- Position European industry ahead of competitors in North America and Asia by capitalising on advances in nanoparticle science and dispersion technology

The six technological aims of the project comprised:

Aim 1	Translation of 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
Aim 2	Investigate and significantly advance the scientific understanding of the thermal properties and behavior of nanofluids and develop an accurate analytical model to simulate and predict heat transfer of the formulated NanoHex nanofluid coolants
Aim 3	Design, development and evaluation of two small-scale pilot-lines for the manufacture of NanoHex nanofluid coolants, using single-stage wet chemical and two-stage production strategies
Aim 4	Design, development and benchmarking of two demonstrators for Data Centre and Power Electronics cooling using NanoHex nanofluid coolants and novel heat management and cooling systems
Aim 5	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
Aim 6	Establish the economic viability of NanoHex nanofluid coolants across the full value-chain of production, use, disposal and recycling in both Data Centre cooling and Power Electronics for traction application.

The NanoHex project was segmented into three reporting Periods for the European Commission:

- 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, 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 NanoHex project and published by the consortium. It is accessible on project website and YouTube: http://www.youtube.com/watch?v=mJRl6eCMabw

During the first year a campaign of testing was started that finished in April 2010 in Period 2. The campaign of thermal testing was comprised of measuring a number of properties including:

- Effective thermal conductivity of the nanofluid
- Heat transfer coefficient in straight pipes and micro-channel cold plates
- Viscosity of the resulting nanofluid
- Particle size, both primary and hydrodynamic particle size
- Erosion and corrosion testing to assess any adverse physical damage that dispersed nanoparticles may impart on heat management equipment

Tests were performed on a range of nanofluids prepared by the consortium and a number sourced from suppliers. Nanofluids tested included TiO2, Al2O3, ZrO2, Ag, CeO2, Carbon Nanotubes (CNT), 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:

- Primary particle size, particle size distribution, hydrodynamic particle size and temperature influence thermal performance
- Increase in viscosity on the addition of nanoparticles, hence the increase in associated pressure drop and pumping power
- Surface modifiers capping nanoparticles may be increasing the heat transfer resistance at the particle/liquid interface and hence impeding thermal performance
- Thermal nanofluids need to comprise of well dispersed nanoparticles as dispersion instability adversely impacts thermal performance
- 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.
- 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: Al_2O_3 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 standardization 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.

- Optimization 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 optimization was done for water and water-Ethylene Glycol mixtures as base fluids.

    - For the Al_2O_3 -water system it was found that the best formulation was, at 9wt% (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%.

    - For the Al_2O_3 -water/Ethylene Glycol system the best formulation was, at 9wt% (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 9wt% (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:
  - **SE1000924-9:** The use of a suspension comprising mesoporous silica particles as heat exchange fluids. This patent has been granted.
  - **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 predication 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 Life Cycle Analysis and Economic Viability for the deployment of nanofluids for 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 the 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.

The consortium has investigated potential application areas for thermal nanofluid through literature research and interaction with industrial stakeholders. Potential application areas include:

a. Cooling of electronics
b. Power electronics in traction
c. Power electronics in renewable power plants and smart grids arena
d. Geothermal and ground heat extraction fluids
e. Hydrogen production processes
f. Cooling of fuel cells in applications such as hydrogen fuel cell electric cars and off-grid power
g. Steel quenching & annealing
h. Solar water heating
i. Electric Engines in vehicles
j. Transformers
k. Nuclear reactors
l. Heat pipes
m. Industrial heat exchangers
n. Cooling and heating in buildings
o. Cameras and displays
p. Industrial chillers
q. Domestic refrigerators
r. Coolant in machining
s. Diesel electric generators
t. Diesel combustion
u. Boiler flue gas temperature reduction
v. Medical applications
w. Transportation sector, including duty vehicles