Nanofluids Application as Nanolubricants in Heat Pump Systems

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OUTLINE

- Nanofluids: why nanolubricants?
- Nanolubricant preparation and characterization
- Experimental test rig
- Results and discussion
- Conclusions
WHAT NANOFLOUIDS ARE

Dispersion of solid nanoparticles (metals, oxides, and carbon in several allotropic forms) in common liquids, as water, glycols, oils

Improved thermophysical and/or tribological properties even at low nanoparticle concentrations

Wide range of possible engineering applications

• Heat-transfer
• Tribology
• Electronics
• Environment (pollution cleaning)
• Bio- and Pharmaceutics
• Medical (drug delivery and functional tissue-cell interaction)
WHY NANOLUBRICANTS?

LITERATURE on NANOFLOUIDS
as COMPRESSOR LUBRICANTS in REFRIGERATION

- **Ahamed et al. (2011) and Lee et al. (2006-2007)**
  General reduction in energy losses and in friction coefficient when lubricants added with nanoparticles are employed.

- **Wang et al. (2003)**
  TiO$_2$ nanoparticles in mineral oil in a refrigeration system working with R134a

  TiO$_2$-mineral oil gives a better performance than polyolester (POE) oil, with a larger return of lubricant to the compressor.
WHY NANOLUBRICANTS?

- **Bi et al. (2008)**
  
  TiO$_2$ and Al$_2$O$_3$ nanoparticles added to a mineral oil at 0.1 wt%, in compressors for domestic refrigerators (with R134a)

  ➡️ **Lower energy consumption, till 26%**

- **Subramani and Prakash (2011)**
  
  Al$_2$O$_3$ at 0.06% by weight in mineral oil instead of POE

  ➡️ **Reduction of power consumption of about 25%**
WHY NANOLUBRICANTS?

• **Sabareesh *et al.* (2012)**
  Substitution of a commercial oil with the same oil added with TiO$_2$ nanoparticles at 0.01 wt% as compressor lubricant in a refrigeration plant

  ↓

  **Increase of COP up to 17%**

• **Kumar and Elansezhian (2012)**
  Al$_2$O$_3$ at 0.2% in polyalkylene glycol (PAG) oil in a refrigeration system

  ↓

  **Reduction in energy consumption of about 10%**
WHY NANOLUBRICANTS?

- **Padmanabhan and Palanisamy (2012)**
  0.1 g/L of TiO$_2$ in mineral oil instead of POE in a vapour compression refrigeration system tested with refrigerants R134a, R436A (R290/R600a 56/44 wt%) and R436B (R290/R600a 52/48 wt%)

  Total irreversibility of the vapour compression cycle with R134a, R436A and R436B decreases by 32%, 16% and 17%, respectively

- **Xing et al. (2014)**
  Fullerene (C60) in mineral oil in a domestic refrigerator working with isobutane (R600a)

  COP improvement of about 5-6% with a nanoparticles concentration of 3 g·L$^{-1}$.
• PRELIMINARY STUDY on nano-oils to be used in the experimental test rig was performed.

• NANOLUBRICANTS (all without dispersant):
  - polyolester (POE) oil + TiO$_2$ at 0.05 - 0.1 - 0.5 wt%
  - polyolester (POE) oil + SWCNH at 0.1 wt%
  - mineral oil + TiO$_2$ at 0.1 wt%

• OPTIMIZATION: preparation method parameters were optimized (concentration, sonication time and power, sample temperature).

• PROPERTIES ANALYSIS: stability, thermal conductivity and dynamic viscosity analysis of nano-oils has been performed.
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EXPERIMENTAL TEST RIG

• MAIN COMPONENTS
  - rotary compressor
  - concentric tube condenser
  - expansion valve
  - concentric tube evaporator

• VISUAL INSPECTION ensured by two see-through polycarbonate tubes

• TEMPERATURE MEASUREMENTS:
  - Refrigerant and secondary water: Pt 100Ω thermoresistances (overall uncertainty 0.07 °C)
  - Ambient and compressor base and head: T type thermocouples (±0.3°C).

• PRESSURE MEASUREMENTS:
  - Refrigerant: piezoresistive transmitters (overall uncertainty from 0.036% to 0.75% FS)

• FLOWRATE MEASUREMENTS:
  - Refrigerant: Coriolis mass flow meter (overall uncertainty ± 0.1%).
  - Secondary Water: magnetic flow meters (uncertainty ± 0.35%)
## EXPERIMENTAL CONDITIONS

<table>
<thead>
<tr>
<th>TEST A</th>
<th>Refrigerant</th>
<th>Outlet condensation temperature: 60°C</th>
<th>Inlet evaporation temperature: 20°C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Secondary Water</td>
<td>water flow = 105 l/h</td>
<td>Tin = 35°C</td>
</tr>
<tr>
<td></td>
<td>evaporator</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>condenser</td>
<td>water flow = 115 l/h</td>
<td>Tin = 40°C</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TEST B</th>
<th>Refrigerant</th>
<th>Outlet condensation temperature: 48°C</th>
<th>Inlet evaporation temperature: 19°C</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Secondary Water</td>
<td>water flow = 105 l/h</td>
<td>Tin = 35°C</td>
</tr>
<tr>
<td></td>
<td>evaporator</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>condenser</td>
<td>water flow = 115 l/h</td>
<td>Tin = 30°C</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TEST C</th>
<th>Refrigerant</th>
<th>Outlet condensation temperature: 44°C</th>
<th>Inlet evaporation temperature: 10°C</th>
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<tbody>
<tr>
<td></td>
<td>Secondary Water</td>
<td>water flow = 105 l/h</td>
<td>Tin = 25°C</td>
</tr>
<tr>
<td></td>
<td>evaporator</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>condenser</td>
<td>water flow = 115 l/h</td>
<td>Tin = 32°C</td>
</tr>
</tbody>
</table>
The boundary conditions had to be kept constant for the entire length of each test, setting the temperature and the flow rate of the water from the external thermostatic baths surrounding the heat exchangers, fixing, in this way, the evaporation and condensation temperatures. Depending on water temperatures and flow rates at the inlet of the evaporator and the condenser, the following three types of operative conditions were established.

Laura, 6/23/2014
### STUDIED SYSTEMS

<table>
<thead>
<tr>
<th>POE</th>
<th>CHARGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>• POE</td>
<td>• oil</td>
</tr>
<tr>
<td>• POE + TiO₂ 0.1% wt</td>
<td>• R134a</td>
</tr>
<tr>
<td>• POE + TiO₂ 0.05% wt</td>
<td>180 cm³</td>
</tr>
<tr>
<td>• POE + TiO₂ 0.5% wt</td>
<td>500 g</td>
</tr>
<tr>
<td>• POE + SWCNH 0.1% wt</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>MINERAL OIL</th>
<th>CHARGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Mineral oil</td>
<td>• oil</td>
</tr>
<tr>
<td>• Mineral oil + TiO₂ 0.1% wt</td>
<td>• R134a</td>
</tr>
<tr>
<td></td>
<td>180 cm³</td>
</tr>
<tr>
<td></td>
<td>450 g</td>
</tr>
</tbody>
</table>
TEST B

**Nanofluids – why nanolubricants?**

**Nanolubricant preparation and characterization**

**Experimental test rig**

**Results discussion**

**Conclusions**
TEST C

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CONCLUSIONS

• All the tests did not show an increase in COP, within the limits of experimental errors.

• All the results were repeatable.

• Two different types of nanoparticles were tested, excluding the possible influence of the particle material.

• All these results are in contrast with literature.

• POSSIBLE REASONS:
  − nanofluid preparation methodology
  − type of nanoparticles (size, clusters, allotropic forms…)
  − type of compressor (alternative instead of rotative)
  − operative conditions (working temperatures)

• FUTURE PROGRAM
THE END
Pt100 W thermoresistance (1), pressure transducers (2), polycarbonate tube for visual section (3), Coriolis mass flow meter (4).
Different positions (i – vi) for the acquisition of temperature and pressure.
La prima prova, “A”, rappresenta la più classica condizione operativa per una macchina di questa tipologia. \( T_{\text{cond}} \) 60°C e \( T_{\text{evap}} \) 20°C. Le condizioni al contorno per l’acqua, sono \( m_{\text{wevap}} \) 105 l/h e \( m_{\text{wcond}} \) 115 l/h. Il chiller con set point di 40°C e bagno termostatico impostato a 34.5°C.

La seconda prova, “B”, \( T_{\text{cond}} \) 52.5°C e \( T_{\text{evap}} \) 19°C. Le condizioni al contorno per l’acqua, sono \( m_{\text{wevap}} \) 105 l/h e \( m_{\text{wcond}} \) 115 l/h. Il chiller con set point di 30°C e bagno termostatico impostato a 34.5°C.

La terza prova, “C”, è stata pensata per verificare il funzionamento dell’impianto abbassando sia \( T_{\text{cond}} \), a 50°C, che \( T_{\text{evap}} \), a 10°C. Per ottenere queste condizioni di lavoro l’acqua al condensatore doveva essere immessa a 32°C e all’evaporatore a 15°C.

Le misure relative a queste tre modalità di lavoro sono state ripetute tre volte per ogni olio lubrificante caricato nel compressore.
Nanoparticles dispersed in the lubricant by means of \textit{sonicator} (operating at 20 kHz frequency and 130 W maximum power)

Sonication was carried out in different conditions, \textit{i.e.} continuous and pulsed irradiation parameters to be optimized

- sonication time
- sonication power
- sample temperature reached during sonication
In the pulsed method, the sonicator operated for 5 s in ultrasonic emission (tON) and for 5 s in pause (tOFF), in order to limit the temperature increase during the process. Tests with continuous sonication have been carried out, but using low sonication power to avoid large temperature increase. Nevertheless, these tests are not presented in this work, because the resulting nanofluids were evidently unstable.

Laura, 5/29/2013
### DIFFERENT SAMPLE PREPARATIONS

#### Nanofluids – why nanolubricants?

- **Two-step method preparation**
- **Particle Size Measurements and Stability**
- **Thermal conductivity**
- **Dynamic viscosity**
- **Conclusions**

<table>
<thead>
<tr>
<th>TiO&lt;sub&gt;2&lt;/sub&gt; conc. (wt %)</th>
<th>Time (min)</th>
<th>Power (% P&lt;sub&gt;max&lt;/sub&gt;)</th>
<th>T&lt;sub&gt;max&lt;/sub&gt; during preparation (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>60</td>
<td>30</td>
<td>44</td>
</tr>
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<td></td>
<td></td>
<td>50</td>
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<td>70</td>
<td>34</td>
</tr>
<tr>
<td></td>
<td>120</td>
<td>70</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td></td>
<td>90</td>
<td>70 (set)</td>
</tr>
<tr>
<td></td>
<td>180</td>
<td>90</td>
<td>70 (set)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30</td>
<td>46</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50</td>
<td>73</td>
</tr>
<tr>
<td></td>
<td></td>
<td>70</td>
<td>70 (set)</td>
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<td></td>
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<td>70 (set)</td>
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<td></td>
<td></td>
<td>50</td>
<td>69</td>
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</tbody>
</table>
Particle size measurements

Stability

- Dynamic Light Scattering (DLS) is used to measure the particle size
- DLS measures the diffusion of particles moving under Brownian motion, and converts this to size and size distribution using the Stokes-Einstein equation

<table>
<thead>
<tr>
<th>TiO₂ conc. (wt %)</th>
<th>Time (min)</th>
<th>Power (% Pmax)</th>
<th>T_max during preparation (°C)</th>
<th>Size (1st day) (nm)</th>
<th>Size (sonicated) (nm)</th>
<th>Possible sedimentation (day)</th>
<th>Aggregates</th>
<th>Measuring time (day)</th>
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<tr>
<td>0.1</td>
<td>60</td>
<td>30</td>
<td>175.8</td>
<td>50</td>
<td>258.0</td>
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<tr>
<td></td>
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<td>50</td>
<td>44</td>
<td>121.2</td>
<td>238.0</td>
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<td>no</td>
<td>12</td>
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<td></td>
<td></td>
<td>70</td>
<td>64</td>
<td>270.6</td>
<td>272.6</td>
<td>yes (2)</td>
<td>yes</td>
<td>10</td>
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<td></td>
<td></td>
<td>90</td>
<td>45</td>
<td>307.2</td>
<td>303.7</td>
<td>yes (3)</td>
<td>yes</td>
<td>9</td>
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<td></td>
<td>120</td>
<td>30</td>
<td>70</td>
<td>307.2</td>
<td>303.7</td>
<td>yes (8)</td>
<td>yes</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50</td>
<td>64</td>
<td>307.2</td>
<td>303.7</td>
<td>yes (8)</td>
<td>yes</td>
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<td></td>
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<td>46</td>
<td>275.5</td>
<td>264.3</td>
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<td>10</td>
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<td>50</td>
<td>73</td>
<td>272.2</td>
<td>245.0</td>
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<td>69</td>
<td>288.8</td>
<td>286.8</td>
<td>yes (5)</td>
<td>yes</td>
<td>15</td>
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</tbody>
</table>

Nanofluids – why nanolubricants?
Two-step method preparation
Particle Size Measurements and Stability
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Dynamic viscosity
Conclusions
In order to study the stability of the different nano-oils, all the suspensions were analysed by means of a Zetasizer Nano ZS (Malvern) that measures the average dimension of the nanoparticles in solution basing on the Dynamic Light Scattering (DLS) System technique. The followed procedure was already described in Fedele et al. (2011). Here only few details are given. After each nano-lubricant synthesis, two samples of each fluid were put in two different measurement cuvettes. For few days, each day, the first sample was measured as it is, in order to evaluate the size distribution changes due to natural sedimentation, while the second sample was measured after stirring to evaluate the size distribution changes after mechanically recovering the settled particles. By means of the Zetasizer, each test was repeated three times and the measurement was made at a constant height, at which the average diameter was measured. It was noted that the nanoparticles diameter drops day after day in the unshaken and unstable fluid, because of the precipitation of the bigger particles.

Laura, 5/29/2013
THERMAL CONDUCTIVITY

- Thermal conductivity measured by means of a TPS 2500 S (Hot disk)
- The 2 mm sensor is immersed in the fluid
- A specifically built aluminum box is put in a water thermostatic bath to reach the test temperature
- Declared instrument uncertainty 5%

Preliminary tests were performed on pure water, obtaining a maximum deviation of experimental data from Refprop 9.0 (Lemmon et al., 2010) less than 1%
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Dynamic viscosity measurements of pure water were performed to check the experimental apparatus. The deviations of the experimental measurements from Refprop 9.0 (Lemmon et al., 2010) data are always lower than 1%.
DYNAMIC VISCOSITY

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![Graph showing shear stress vs. shear rate]
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DYNAMIC VISCOSITY

Graph showing dynamic viscosity ($\mu$ in Pa·s) vs. temperature ($T$ in °C) for different concentrations:
- Oil
- 0.05 wt%
- 0.1 wt%
- 0.5 wt%