CHARACTERIZATION OF HEAT AND MASS TRANSFER PROPERTIES OF NANOFLUIDS

EDEN MAMUT

“Ovidius” University of Constanta, 124 Mamaia Av. 8700 Constanta, Romania
Email: emamut@univ-ovidius.ro

Received December 21, 2004

The paper presents the results of a research project regarding the characterization of the thermal conductivity of nanofluids like water + Cu nanoparticles. The experimental results are compared with theoretical simulations based on the assumptions regarding the heat and mass transfer.

OVERVIEW

The thermal conductivity of heating or cooling fluids is a very important property in the development of energy-efficient heat transfer systems. At the same time, in all processes involving heat transfer, the thermal conductivity of the fluids is one of the basic properties taken into account in designing and controlling the process.

Fig. 1 – Thermal conductivity coefficients available for current engineering solutions [9].


Thermal conductivity coefficient is determined by experimental measurements. An overview of the values of the thermal conductivity coefficients available for current engineering solutions is presented in Figure 1. Also in Table 1 there are presented the values for heat transfer coefficient for some bulk materials:

Table 1

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal conductivity [W mK⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water [2]</td>
<td>0.613</td>
</tr>
<tr>
<td>Ethylene Glycol [2]</td>
<td>0.252</td>
</tr>
<tr>
<td>Glycerol [6]</td>
<td>0.289</td>
</tr>
<tr>
<td>Engine Oil [2]</td>
<td>0.145</td>
</tr>
<tr>
<td>Pump Oil [6]</td>
<td>0.141</td>
</tr>
<tr>
<td>Aluminum Oxide [2]</td>
<td>40.0</td>
</tr>
<tr>
<td>Silicon [2]</td>
<td>148.0</td>
</tr>
<tr>
<td>Aluminum [2]</td>
<td>237.0</td>
</tr>
<tr>
<td>Copper [2]</td>
<td>401.0</td>
</tr>
<tr>
<td>Gold [10]</td>
<td>317.0</td>
</tr>
<tr>
<td>Silver [2]</td>
<td>429.0</td>
</tr>
</tbody>
</table>

The concept of nanofluids is an old concept [1] but it was possible to be put into practice particularly after the tremendous development of nanotechnologies in the last decade. A nanofluid could be defined as a nanocomposite where the matrix is a liquid or as a colloid where the suspensions consist of nanoparticles. There are two fundamental methods to obtain nanofluids [1]:

1. Single-step direct evaporation method – the dispersion of nanoparticles is obtained by direct evaporation of the nanoparticle metal and condensation of the nanoparticles in the base liquid;
2. Two-step method – first the nanoparticles are obtained by different methods and then are dispersed into the base liquid.

The suspensions obtained by either case should be well mixed, uniformly dispersed and stable in time. A literature survey including the reported experimental results is listed in Table 2.
### Table 2

<table>
<thead>
<tr>
<th>Base fluid</th>
<th>Nanoparticles / average diameter / concentration</th>
<th>Method</th>
<th>Dispersant</th>
<th>Peak thermal conductivity ratio</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>Al₂O₃ &lt;50 nm; up to 4.3 vol%</td>
<td>Two-step</td>
<td>Not specified</td>
<td>1.08</td>
<td>[1]</td>
</tr>
<tr>
<td>Water</td>
<td>Al₂O₃; s = 25 m²g⁻¹; 5.0 vol%</td>
<td>Two-step</td>
<td>No dispersant</td>
<td>1.22</td>
<td>[6]</td>
</tr>
<tr>
<td>Water</td>
<td>CuO &lt; 50 nm; up to 3.4 vol%</td>
<td>Two-step</td>
<td>Not specified</td>
<td>1.1</td>
<td>[1]</td>
</tr>
<tr>
<td>Water</td>
<td>Cu 18 nm; up to 5.0 vol%</td>
<td>One-step</td>
<td>No dispersant</td>
<td>1.6</td>
<td>[2], [5]</td>
</tr>
<tr>
<td>Water</td>
<td>Cu up to 100 nm; up to 7.6 vol%</td>
<td>Two-step</td>
<td>Laurate salt 9 wt% via particles</td>
<td>1.76</td>
<td>[5]</td>
</tr>
<tr>
<td>Water</td>
<td>C-MWNT 50 µm, 5 µm 3 µm; 0.6 vol%</td>
<td>Two-step</td>
<td>Sodium Dodecyl Sulfate</td>
<td>1.38</td>
<td>[7]</td>
</tr>
<tr>
<td>Ethylene Glycol EG</td>
<td>Al₂O₃ &lt;50 nm; up to 5.0 vol%</td>
<td>Two-step</td>
<td>Not specified</td>
<td>1.18</td>
<td>[1], [3]</td>
</tr>
<tr>
<td>Ethylene Glycol EG</td>
<td>Al₂O₃; s = 25 m²g⁻¹; 5.0 vol%</td>
<td>Two-step</td>
<td>No dispersant</td>
<td>1.29</td>
<td>[6]</td>
</tr>
<tr>
<td>Ethylene Glycol EG</td>
<td>CuO 35 nm; up to 4 vol%</td>
<td>Two-step</td>
<td>Not specified</td>
<td>1.21</td>
<td>[1], [2], [3], [4]</td>
</tr>
<tr>
<td>Ethylene Glycol EG</td>
<td>Cu 10 nm; up to 0.5 vol%</td>
<td>One-step</td>
<td>No dispersant</td>
<td>1.14</td>
<td>[2], [3], [4]</td>
</tr>
<tr>
<td>Ethylene Glycol EG</td>
<td>Cu 10 nm; up to 0.5 vol%</td>
<td>One-step</td>
<td>Thioglycolic acid &lt; 1 vol%</td>
<td>1.41</td>
<td>[2], [3], [4]</td>
</tr>
<tr>
<td>Glycerol Gly</td>
<td>Al₂O₃; s = 25 m²g⁻¹; 5.0 vol%</td>
<td>Two-step</td>
<td>No dispersant</td>
<td>1.27</td>
<td>[6]</td>
</tr>
<tr>
<td>Oil (Pump oil)</td>
<td>Al₂O₃; s = 25 m²g⁻¹; 5.0 vol%</td>
<td>Two-step</td>
<td>No dispersant</td>
<td>1.38</td>
<td>[6]</td>
</tr>
<tr>
<td>Oil (Trans.oil)</td>
<td>Cu up to 100 nm; up to 7.6 vol%</td>
<td>Two-step</td>
<td>Oleic acid 22 wt% via particles</td>
<td>1.43</td>
<td>[5]</td>
</tr>
<tr>
<td>Water + (up to 100 vol%) Ethylene Glycol EG</td>
<td>Al₂O₃; s = 25 m²g⁻¹; 5.0 vol%</td>
<td>Two-step</td>
<td>No dispersant</td>
<td>1.29</td>
<td>[6]</td>
</tr>
<tr>
<td>Water + (up to 100 vol%) Glycerol Gly</td>
<td>Al₂O₃; s = 25 m²g⁻¹; 5.0 vol%</td>
<td>Two-step</td>
<td>No dispersant</td>
<td>1.27</td>
<td>[6]</td>
</tr>
<tr>
<td>Oil (500 SN)</td>
<td>TiO₂; 20 nm; 0.757 wt %; 0.84 wt %; 0.92 wt %</td>
<td>Two-step</td>
<td>Sorbitol monostearat of 1.00 wt %</td>
<td>1.14</td>
<td>[8]</td>
</tr>
</tbody>
</table>
THE VERL DEVICE

The device, uses single-step direct evaporation method to prepare nanoscale metal particles dispersed in liquid matrix, has been built and the advantage of this device is that the preparation and dispersion of nanoscale metal particles can be successfully done in the vacuum condition at the same time.

A view of the VERL device is included in Figure 2.

![Fig. 2 – View of the VERL device.](image)

When the metal species comes from the heater by heating, they can impact each other in the vacuum chamber and become the cluster or nanoscale particle. When the nanoscale particle comes to the surface of the running liquid matrix, it will be wrapped by the liquid matrix. It means the liquid matrix restrains the other particles to impact with this particle, so the growth of nanoscale particle will be limited. In our device, the vacuum in the chamber is better than $2.5 \times 10^{-5}$ torr.

The appropriate preparation condition has been investigated and nanoscale Ag and Cu particles dispersed in silicon oil and liquid paraffin respectively have been successfully prepared.
Figure 3 includes the TEM micrograph of nanoscale Ag and Cu particles observed with JEOL-200CX TEM. It can be found that the nanoscale metal particles have a good dispersion in liquid matrix and aggregate could hardly be found. Assistance with X-ray diffraction line profile analysis, it can be pointed out that the bigger particles consist of a number of grains, but the smaller one only consists of one grain.

![TEM Micrographs of (a) as-prepared silver particles and (b) as-prepared copper particles.](image)

**HEAT TRANSFER ENHANCEMENT**

At the macroscopic level the heat transfer processes are modeled based on the 1st and 2nd Laws of Thermodynamics. Applying the 1st Law to a control volume of a homogeneous general continuous, non-isotropic, with non-uniform distribution of the internal heat sources it will be obtained the **general form of the differential equation of thermal conduction** as follows:

$$
\left[ \frac{\partial}{\partial x}\left( \lambda_x \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y}\left( \lambda_y \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z}\left( \lambda_z \frac{\partial T}{\partial z} \right) + \sum_{i=1}^{n} \frac{Q_i(x,y,z,t)}{dV} \right] + \frac{1}{\rho(T)p_c(T)} \frac{\partial T}{\partial t} = \rho(T)c_p(T) \frac{\partial T}{\partial t}
$$

where:

- \((\lambda_x,\lambda_y,\lambda_z)\) - thermal conductivity coefficient tensor;
- \(T(x,y,z,t)\) - temperature field;
- \(Q_i(x,y,z,t)\) - heat flux of distributed internal sources;
- \(\rho(T)\) - temperature dependent density;
\[ c_p(T) \] - specific heat at constant pressure;
\[ x, y, z \] - space variables;
\[ V \] - volume;
\[ t \] - time variable.

For the estimation of the thermal conductivity of heterogeneous mixtures there are recommended in the literature, the following formulas:

- **Maxwell – Eucken (Maxwell 1892) formula [11]:**

\[
\lambda_M = \lambda_c \left[ 1 + 2 \nu_D \frac{1 - \frac{\lambda_c}{\lambda_D}}{2 \frac{\lambda_c}{\lambda_D} + 1} \right]
\]

- **Landauer (1952) Effective Media Percolation Theory (EMPT) formula [12] used mainly for solid compounds:**

\[
\lambda_M = \frac{1}{4} \left[ \lambda_D (3\nu_D - 1) + \lambda_c (3\nu_C - 1) + \left[ \lambda_D (3\nu_D - 1) + \lambda_c (3\nu_C - 1) \right]^2 + 8\nu_D \lambda_c \right]^{\frac{1}{2}}
\]

- **Hamilton – Crosser (1962) formula [5] for liquid-solid mixtures when the ratio of conductivity is larger than 100:**

\[
\lambda_M = \lambda_c \left( \frac{\lambda_D + \nu_D (n-1)(\lambda_c - \lambda_D)}{\lambda_D + (n-1)\lambda_c + \nu_D (\lambda_c - \lambda_D)} \right)
\]

- **Wasp (1977) formula [5]:**

\[
\lambda_M = \frac{\lambda_c \frac{\lambda_D + 2\lambda_c - 2\nu_D (\lambda_c - \lambda_D)}{\lambda_D + 2\lambda_c + \nu_D (\lambda_c - \lambda_D)}}
\]

Where:
\[ \lambda_D, \lambda_C, \lambda_M \] - thermal conductivity coefficients for dispersed phase, continuous phase and mixture;
\[ \nu_D = \frac{V_D}{V_C + V_D} \] - volume fraction of the dispersed phase;
\[ n = \frac{3}{\varphi} \quad - \text{shape factor}; \]

\[ \varphi = \frac{\text{surface area of a sphere with a volume equal to that of the average particle}}{\text{surface area of the average particle}} \]

- sphericity.

In should be noted that Wasp formula is a particular case of Hamilton – Crosser formula when the dispersed phase consists of perfect spherical particles.

In Figure 4 there are plotted the theoretical estimations and the experimental results for water + Cu, nanofluids. The value of the thermal conductivity for water is: \( \lambda_C = 0.613 \frac{W}{mK} \) and for Copper (bulk): \( \lambda_D = 401 \frac{W}{mK} \)

![Graph showing thermal conductivity ratio vs. volume fraction](image)

Fig. 4 – Theoretical estimations (continuous lines) and experimental results (isolated dots) for thermal conductivity ratio for nanofluids over the volume fraction of the dispersed Copper particles.

In the case of Hamilton – Crosser formula the sphericity has been considered in two cases as \( \varphi = 0.5 \) and \( \varphi = 0.3 \). The results are plotted with continuous lines for the theoretical estimations and isolated dots for the experimental reported data [2] – Eastman and [8] – Xuan.

**CONCLUSIONS**

The heat transfer properties of nanofluids could be controlled by the concentration of the nanoparticle and also by the shape of nanoparticles.
Further research is under development in order to validate these conclusions and also study the influence of the size of nanoparticles.

Acknowledgements. Financial support from Ministry of Science and Technology No. 2003AA333110 Nature Science Foundation of China (No. 19974052, 51072048 and 10274085), Nature Science Foundation of Anhui Province, P.R. China (No. 01044906) and Talent Foundation of Anhui Province are gratefully acknowledged.

REFERENCES
11. http://dmxwww.epfl.ch/ltp/Cours/