Simulation of an aerodynamic furnace for high temperature data acquisition using Comsol® Multiphysics

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<table>
<thead>
<tr>
<th>Method</th>
<th>samples</th>
<th>heating</th>
<th>Typical size (mm)</th>
<th>Main limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acoustic</td>
<td>Any</td>
<td>Laser</td>
<td>0.5-3</td>
<td>Limited temperature</td>
</tr>
<tr>
<td>Aerodynamic</td>
<td>Any</td>
<td>Laser</td>
<td>0.7-3</td>
<td>Gas footprint ?</td>
</tr>
<tr>
<td>Electrostatic</td>
<td>Any</td>
<td>Laser</td>
<td>1-4</td>
<td>Require stable electrical charge on sample</td>
</tr>
<tr>
<td>Electromagnetic</td>
<td>Conductor</td>
<td>RF/laser</td>
<td>2-10</td>
<td>conductors</td>
</tr>
<tr>
<td>Optical</td>
<td>Non reflective</td>
<td>Laser</td>
<td>0.0001</td>
<td>Very small samples</td>
</tr>
<tr>
<td>Gas film</td>
<td>Any</td>
<td>Radiative</td>
<td>Up to 30</td>
<td>Limited temperature</td>
</tr>
</tbody>
</table>
Advanced Temperature and Thermodynamic Investigation by Laser Heating Approach

Spherical sample heated by laser up to 3200 K.

Pyrometer for temperature

Infrared Camera for position and volume

Oscillations:
- Surface Tension
- Viscosity

- Laser cut off:
  - Density as function of temperature
  - Specific Heat Capacity

Aerodynamic levitation: access to undercooled liquids – very large temperature range
EVALUATION OF LIQUID ALUMINA DENSITY AS A FUNCTION OF TEMPERATURE – QUICK REVIEW

Apparent **Chemical contamination** for container based technics (pendant drop, archimedian, pressure bubble)

Similar **trends** for containerless (levitation) technics (ESL and ADL)

But **ADL** give **lower values** at fusion point, dependent of sample size and levitation gas type!
Density currently evaluated assuming **spherical shape**

* : C.J. Benmore and Weber aerodynamic levitation, supercooled liquid and glass formation, advances in physics X, 2:3 737-736.
Is the liquid levitated sample really spheric?

Let's have a look using ....

Comsol® Multiphysics
Challenges:
- Temperature gradient (1000 K / 10 µm) close to LG interface
- Sample position in noozle: major impact on gas flow
- Strong Marangoni effect due to temperature gradient (200K) inside sample before laser cut-off

Software:
Heat + Microfluidic Comsol® modules + moving mesh ALE
(first order Winslow smoothing for LG interface temporal evolution)
Convergence strategy:

Preliminary thermomechanical solution:
**Undeformable** spherical sample – **no gravity** – **ramping** viscosity

Controlled temporal iteration until stationary solution:

**Balance internal and external forces at LG interface**

\[ \delta T = 1 \times 10^{-8} \text{ s} \quad \Delta T = 1 \times 10^{-4} \text{ s} \]

Vertical stabilization of sample

\[ \delta T = 1 \times 10^{-5} \text{ s} \quad \Delta T = 1 \times 10^{-2} \text{ s} \]

Convergence of internal liquid flow

\[ \delta T = 0,001 \text{ s} \quad \Delta T = 2 \text{ s} \]
50 mg alumina

The TOP of the sample remains **spherical**

130 mg alumina

The BOTTOM get more and more deformed as its size increases
VOLUME ESTIMATION AFTER LASER CUT-OFF FOR VARIOUS LEVITATION GAS

S : assuming spherical approximation
C : volume calculated by Comsol
Levitation technics give now similar results. Difference at fusion probably due to recalcience of the sample.

$T_{\text{fusion}} = 2323 \ \text{K}$
CONCLUSION:

Using Comsol® multiphysics it seems possible to adjust the density evaluation of aerodynamic levitation.

On going work on other thermodynamical data:
- heat capacity
- viscosity
- surface tension
Thank you for your attention!

Questions and comments are welcome!
Main hypothesis (similar to other levitation technics) only radiative decay after laser cut-off:

\[ \frac{dQ_R}{dt} = \epsilon k_B S (T^4 - T_0^4) \approx \epsilon k_B S T^4 \quad (1) \]

Energy balance on sample

\[ mC_p \, dT + dQ_R = 0 \quad (2) \]

\[ \frac{dT}{dt} = - \frac{\epsilon k_B S T^4}{mC_p} \]

\[ \frac{C_p}{\epsilon} = - \frac{k_B S d(\frac{1}{T^3})/dt}{m} \]

- \( Q_R \): radiative heat
- \( t \): time
- \( \epsilon \): hemispherical total emissivity
- \( k_B \): Stefan Boltzmann constant
- \( S \): surface
- \( T \): sample temperature
- \( T_0 \): ambient temperature
- \( m \): sample mass
- \( C_p \): specific heat capacity
Decay is not purely radiative and depends on gas conductivity.
## Thermodynamic Data at Different Temperatures

### Hypothesis: Air/Oxygen at Thermal Equilibrium

<table>
<thead>
<tr>
<th>Temperature (K)</th>
<th>Air (W/mK)</th>
<th>Xenon (10^{-5} Pas)</th>
<th>Oxygen (W/mK)</th>
<th>Argon (10^{-5} Pas)</th>
<th>Helium (W/mK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T=300 K</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conductivity</td>
<td>0.026</td>
<td>0.0055</td>
<td>0.026</td>
<td>0.018</td>
<td>0.152</td>
</tr>
<tr>
<td>Viscosity</td>
<td>1.82</td>
<td>2.2</td>
<td>1.95</td>
<td>2.1</td>
<td>0.88</td>
</tr>
<tr>
<td>T=3000 K</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conductivity</td>
<td>0.383</td>
<td>0.802</td>
<td>0.09</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Viscosity</td>
<td>8.58</td>
<td>9.49</td>
<td>10</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Hypothesis:** Air/Oxygen at thermal equilibrium
TEMPERATURE EVOLUTION AFTER LASER CUT-OFF

Temperature get homogeneised in a few ms