Containerless Measurements on Liquids at High Temperatures

Richard Weber
Intersonics, Incorporated
3453 Commercial Avenue
Northbrook, IL 60062

Abstract

The application of containerless techniques for measurements of the thermophysical properties of high temperature liquids is reviewed. Recent results obtained in the materials research laboratories at Intersonics are also presented.

Work to measure high temperature liquid properties is motivated by both the need for reliable property data for modeling of industrial processes involving molten materials and generation of data form basic modeling of materials behavior. The first two figures indicate the motivation for this work and present examples of variations in thermophysical property values from the literature. The variations may be attributed to changes in the specimen properties caused by chemical changes in the specimen or to and/or measurement errors.

The two methods used to achieve containerless conditions were aeroacoustic levitation and electromagnetic levitation [1]. Their qualities are presented. The accompanying slides show the layout of levitation equipment and present examples of levitated metallic and ceramic specimens.

Containerless techniques provide a high degree of control over specimen chemistry, nucleation and allow precise control of liquid composition to be achieved. Effects of minor additions can thus be measured in a systematic way. Operation in reduced gravity enables enhanced control of liquid motion which can allow measurement of liquid transport properties. Examples of nucleation control, the thermodynamics of oxide contamination removal, and control of the chromium content of liquid aluminum oxide by high temperature containerless processes are presented.

The feasibility of measuring temperature, emissivity, liquidus temperature, enthalpy, surface tension, density, viscosity, and thermal diffusivity are discussed in the final section of the paper. Temperature measurement is achieved by conventional pyrometry. Emissivity measurement presents an important issue in many processing applications, particularly when temperature-dependent properties are to be measured. The polarimetric technique is illustrated with an example of the relatively large change in emissivity which occurs during melting of niobium. The spectral emissivity of liquid inconel is shown to be almost constant over the temperature range from 1650 to 1950 K.

The proposed method for enthalpy measurements is drop calorimetry. This compliments
the contained techniques such as differential thermal analysis. The analysis of the effects of specimen emissivity are presented. Surface tension and density can be measured from the oscillation frequency of levitated drops [2] and by imaging the drop and determining its volume respectively.

Low gravity experiments to determine liquid viscosities and thermal diffusivities are described. A diagram of the apparatus used for ground-based experiment to evaluate a new method for measurements of thermal diffusivity are also shown.

In conclusion, containerless techniques combined with non-contact diagnostic techniques enable high temperature liquid property measurements under controlled conditions. Extensions of the techniques to low gravity will provide for more accurate measurements of transport properties.

The work presented here was supported by the Air Force, Los Alamos National Laboratory, NASA, and NSF.

References:

MOTIVATION

♦ Many manufacturing methods involve HT liquid-phase processing.

♦ Improved understanding of processes = more cost effective manufacturing.

♦ Lack of HT data for liquids.

♦ Conflicting values in data.

♦ Containerless techniques have advanced greatly in the last decade and offer unique opportunities for HT measurement.


### METHODS FOR CONTAINERLESS PROCESSING

#### TABLE I
Comparison of Qualities of Electromagnetic and Aero-Acoustic Levitation

<table>
<thead>
<tr>
<th>Electromagnetic Levitation</th>
<th>Aero-Acoustic Levitation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metals and alloys</td>
<td>Metals, alloys, semiconductors and ceramics</td>
</tr>
<tr>
<td>Simultaneous positioning and heating</td>
<td>Separate positioning and heating</td>
</tr>
<tr>
<td>Operation in gas or vacuum</td>
<td>Requires gaseous atmosphere</td>
</tr>
<tr>
<td>Induction stirring</td>
<td>Aerodynamic stirring on ground</td>
</tr>
<tr>
<td>Field coils occlude specimen</td>
<td>Wide access to specimen</td>
</tr>
</tbody>
</table>
QUALITIES OF CONTAINERLESS PROCESSING

♦ Eliminates contamination
♦ Eliminates nucleation
♦ Enables equilibration and purification

Low Gravity Processing

♦ Transport property measurements, D., α, η
♦ Control of segregation
♦ Control of gas evolution

---

Critical cooling rates, R*, for Calcia-Gallia-Silica Compositions

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>CGS</td>
<td>300-350</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CGS-Pt1</td>
<td>450-550</td>
<td>&lt; 10</td>
<td>1.8%</td>
</tr>
<tr>
<td>CGS-Pt5</td>
<td>&gt; 700</td>
<td>40-80</td>
<td>0.7%</td>
</tr>
<tr>
<td>CG</td>
<td>&gt; 700</td>
<td>50-60</td>
<td>0.6%</td>
</tr>
</tbody>
</table>

\[ R = \frac{(O/M)_{\text{vapor}}}{(O/M)_{\text{metal}}} \]

Where \( R = \text{Total oxygen in gas} \)
\( \text{Total metal in gas} \)

Brewer and Rosenblatt
Containerless Measurements and Feasibility Studies

1 Temperature - pyrometry
2 Emissivity - polarimetry
3 Liquidus temperature
4 Enthalpy - drop calorimetry
5 Surface tension - drop oscillation
6 Density/expansivity - drop imaging
7 Viscosity - drop oscillation
8 Thermal diffusivity/conductivity

\[ \frac{1}{T} - \frac{1}{T_a} = \frac{\lambda \ln \epsilon_\lambda}{c_2} \]

Illustration of Rotating Analyzer Ellipsometry

The normal spectral emissivity of Niobium as a function of temperature at 0.6328 µm.

Normal Spectral Emissivity of Inconel 718 at 633 nm

Data Acquisition

Waterbath Heater

Photodetectors

Calorimeter Cup

Radiation Gate

Temperature-Controlled Water Bath

Analysis of preliminary Niobium Results

Solid:
\[ \varepsilon_{\lambda}(T) = 0.3620 - 0.000017 \times T \]

Liquid:
\[ \varepsilon_{\lambda}(T) = 0.7443 - 0.000154 \times T \]

\[ \frac{\delta \ln \varepsilon}{dT} \text{ at } T_m = -4.78 \times 10^{-4} \]

\[ \frac{C_p}{C_{ps}} = 0.83 \]

Calorimeter design. The instrument would be positioned beneath the electromagnetic levitation chamber with a thermostatically controlled water bath surrounding the calorimeter block.

Corrected Values

Hultgren Est. (33.5)

<table>
<thead>
<tr>
<th>Measurements</th>
<th>Bonnell</th>
<th>Cazazbilyan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurements</td>
<td>40.6</td>
<td>40.8</td>
</tr>
<tr>
<td>Corrected Values</td>
<td>33.7</td>
<td>33.8</td>
</tr>
<tr>
<td>Hultgren Est.</td>
<td>(33.5)</td>
<td>(33.5)</td>
</tr>
</tbody>
</table>
SURFACE TENSION - RAYLEIGH EQUATION

\[ \gamma = \frac{3}{8} \pi m \omega^2 \]

DENSITY & THERMAL EXPANSIVITY

\[ \rho = \frac{m}{v} \]

LOW GRAVITY EXPERIMENTS

MARANGONI CONVECTION

Marangoni number \( M \) is derived from the surface tension/temperature coefficient, \( \frac{dy}{dT} \); temperature gradient, \( \Delta T \); specimen radius, \( r \); dynamic viscosity, \( \nu \); thermal diffusivity, \( \alpha \); and density, \( \rho \).

\[ M_a = \frac{dy}{dT} \frac{\Delta T}{r} \frac{r}{\rho} \alpha \nu \]

VISCOSITY

Lamb's relationship equates the time constant, \( r \), for damping of oscillations to viscosity, \( \nu \), via the specimen radius, \( a \), used to calculate kinematic viscosity, \( \nu \), from the time dependence of liquid oscillation.

\[ \nu = \frac{a^2}{5r} \]

THERMAL DIFFUSIVITY

Laser-acoustic levitation and auxiliary equipment. Side view shows acoustic transducer, laser beam path and levitation needle. Lower view shows plan in the optical plane with relationships between instruments.
Conclusions

Containerless melting combined with accurate NCTM provide the basis advancing TPMs on high temperature liquids.

Several properties could be measured in ground-based experiments with a well integrated facility.

Transport properties in liquids require minimal liquid motion and can best be conducted in reduced gravity.

A focussed program to advance key measurement techniques could provide much of the data required for industrial process modelling.

Acknowledgements

Financial support for work presented here:

Air Force, Auburn CCDS, National Aeronautics and Space Administration, Los Alamos National Laboratory, National Science Foundation, Private Industry.

Helpful Discussions:

David Bonnell, NIST
Stan David, ORNL
Bob Hauge, Rice University
Bill Hofmeister, Vanderbilt University
Bill Jellison, Panoptix
Jay Khodadadi, Auburn University
Ken Mills, NPL
Tony Overfelt, Auburn CCDS
Ivan Egry, DLR
Members of the AFS Heat Transfer Committee