UNOOSA Webinar Series on Hypergravity/Microgravity

*Physical Science  Part 1. Materials Science*

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Crystal Growth in Materials Science

Why and how are these beautiful patterns formed in nature?

Snow crystals
Mineral crystals
Metal crystals
Synthetic crystals
Protein crystals

Next, Watanabe

Crystal growth mechanism is a key concept for the material science researches.
Crystal growth and materials processing under microgravity

1G conditions on ground

Liquid (or Vapor) → Convection → Interface → Crystal

No convection

We can pick up pure interfacial phenomena.
Interfacial phenomena in immiscible liquids process
- Refining, smelting and welding processes -

We can pick up pure interfacial phenomena using microgravity conditions.
Interfacial phenomena and thermophysical properties of high temperature liquids

-INTERFACIAL ENERGY PROJECT-

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High Temperature liquids in Material Processing

Crystal growth

Density, Thermal expansion

Unidirectional solidification

Welding

Surface tension

Viscosity, Thermal conductivity

Thermophysical properties need for process control of production engineering

V.V. Kalaev et al.

G.G. Roy & DebRoy

P. Thevoz et al.

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Thermophysical Properties for Materials Processing

- \( \mu(T) \) Electrical resistivity
- \( \varepsilon(T) \) Emmissivity
- \( \sigma(T) \) Surface tension
- \( \eta(T) \) Viscosity
- \( \beta(T) \) Thermal expansion
- \( \rho(T) \) Density
- \( \kappa(T) \) Thermal conductivity
- \( \alpha(T) \) Thermal diffusivity
- \( C_P(T) \) Specific heat

Electronic Property

Mechanical Property
Advantage of Microgravity for High Temperature Liquids Handling

High-Temperature Liquids Sample Handling on Ground

- Refractory Materials Crucible
- Refractory Materials Substrate

Temperature limits by crucible or substrate materials

High-Temperature Liquids Sample Handling under Microgravity

- High-Temp. Liquids
- Heating Power

No Temperature limits, if we have heat sources
Containerless Sample Handling Levitation Techniques

Electromagnetic Levitation (EML)

MSL-EML Facility of COLUMBUS in ISS

Electrostatic Levitation (ESL)

ELF of KIBO in ISS

Aerodynamic Levitation (ADL)

On ground
Interfacial Tension Measurement by Electrostatic Levitation Furnace (ELF) in International Space Station (ISS)

Electrostatic Levitation Furnace (ELF) in ISS “KIBO”

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Electrostatic levitation of molten SiO₂-CaO-Mn₃O₄-TiO₂-Fe₂O₃ in ISS

SiO₂:CaO:Mn₃O₄:TiO₂ = 22:12:16:50 (wt%)
Electrostatic Levitation of Molten SiO$_2$-CaO-Mn$_3$O$_4$-TiO$_2$-Fe$_2$O$_3$ in ISS

SiO$_2$-CaO-Mn$_3$O$_4$-TiO$_2$-Fe$_2$O$_3$ = 25:7:23:18:27 (wt%)
Surface oscillation of levitated molten SiO₂-CaO-Mn₃O₄-TiO₂ system droplet in ELF

**Surface tension –Rayleigh–**

\[ \sigma = \frac{\rho R^3}{l(l-1)(l+2)} \omega^2 \]

- **Drop Oscillation frequency** \( \omega = 168 \text{ Hz} \)
- **Surface tension** \( \sigma = 419 \text{ mN/m} \)

**Time variation of diameter**

**Input 194Hz**

**Side view of droplet**

**Fast Fourier Transform result**

FFT

**Intensity [a.u.]**

**Diameter amplitude**

**Time [sec]**  
1.32 1.34 1.36 1.38 1.40 1.42 1.44
Surface oscillation of levitated molten SiO₂-CaO-Mn₃O₄-TiO₂ system droplet in ELF

Time variation of diameter

Decay rate $\tau$

Side view of droplet

Diameter

Time [sec]

Decay rate fitting

Diameter amplitude

Viscosity –Lamb–

$$\eta = \frac{\rho R^2}{(l - 1)(2l + 1)^\tau}$$

Sine dump function fitting

$$a(t) = A_0 + A \exp\left(-\frac{t}{\tau}\right)\sin(\omega t)$$

$\omega$: Drop oscillation Frequency
$t$: time
$A_0$: Radius
$A$: Constant

Decay rate $\tau=168$ s

Viscosity $\eta=24.7$ mPa·sec

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Interfacial Tension Measurement by Core/Shell Droplets with Containerless Technique

Container-less approach for understanding interfacial phenomena between steel melts and molten slag system using core/shell droplet technique.

Molten Oxide (Slag)

Steel melt

(Slag: SiO$_2$-CaO-Al$_2$O$_3$+other oxides)
Interface in Materials Processing

Continuous casting processes

Mold flux
(Molten oxides)

Nozzle

Solid flux

Liquid Fe

Prevent pulling down of flux particle

Cast steel

Welding processes

Mold

Molten Slag
(Liquid Metals)

Weld Pool

http://www.steelconstruction.info
Surface Oscillation Frequencies of Core/Shell Droplets with molten oxide viscosities

SiO$_2$:CaO:Mn$_3$O$_4$:TiO$_2$ = 22:12:16:50 (wt%)

![Graph showing surface oscillation frequencies for two temperatures: 1536°C and 1900°C. The graph plots frequency against strength, with peaks at 250 Hz for 1536°C and a broader peak at 300 Hz for 1900°C.](image-url)
Microgravity Experiments by Parabolic Flight of Airplane

Start levitation

Sample melting

End of experiments

ALTIMETRY (Feet)

Heating

Measurements

250KIAS

-5~10° Shallow Dive

367KIAS

170KIAS

260KIAS Push over

36~240KIAS Recovery

22,000

24,000

26,000

28,000

0.6~1.2G

1.5G

0~0.03G

1.5G

1G

-60

-30

-25

0

25

50

TIME (Sec)

“1Min Before”

“30Sec Before”

“NOW”

Start to Preparation for Next Experiment

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Fe/Oxide Droplet under Microgravity Conditions

Fe/Welding Flux
(CaO-SiO$_2$-TiO$_2$-FeO)

Fe/BF Slag
(CaO-SiO$_2$-Al$_2$O$_3$)

Core/Shell Droplet
Janus Drop
Surface Oscillation of Fe/Welding Flux

Analytical solutions of core/shell droplet oscillation

\[
\omega_{\pm}^2 = \omega_0^2 K \pm \frac{\tau^8}{\sigma (1 + \Delta \tilde{\rho})} \frac{1}{\tau^1} + \frac{2}{3} \Delta \tilde{\rho}_i
\]

\[
K \pm = \frac{1}{2} \left( \frac{\frac{\sigma m_i}{\tau^3}}{\sigma} + \frac{m_o \tau^3}{\sigma} \right)
\pm \sqrt{\frac{1}{4} \left( \frac{\sigma m_i}{\tau^3} - \frac{m_o \tau^3}{\sigma} \right)^2 + 1}
\]

Frequency of Fe/Welding flux

- \( \omega_- = 26.2 \text{Hz} \)
- \( \omega_+ = 41.1 \text{Hz} \)

Interfacial tension

700~1000mN/m(@Iron M.P.)
Non Core-Shell (Janus) Drop Case for Fe/CaO-SiO$_2$-Al$_2$O$_3$ Slag

Fe/ BF slag (SiO$_2$:CaO:Al$_2$O$_3$=20:30:40 )

0s  1.2s  2.4s  3.6s  4.8s  6.0s

Interfacial tension from contact angle

\[ \sigma_{12} = \cos \theta_{\text{slag}} + \sigma_{\text{metal}} \cos(\theta_{\text{slag}} + \theta_{\text{metal}}) + \sigma_{\text{slag}} \]

Contact angle between Fe melt and molten slag

\[ \theta_A + \theta_B = 222^\circ \]

\[ \sigma_{\text{slag}} = 570 \text{mN/m} \]

\[ \sigma_{\text{Fe}} = 1590 \text{mN/m} \]

Interfacial tension

\[ 1.22 \times 10^{-3} \text{N/m ( @1953K) } \]

S. Taguchi et al, Poster No.3

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Change of surface and interface free energy as a function of $h$

$(-1 \leq h \leq 1, \ h=1 \text{ is } h=R_{fe})$

$$G_S = \gamma_{Fe} S_{Fe} + \gamma_{slag} S_{slag} + \gamma_{AB} S_{int}$$

$S$: Area, $\gamma$: Surface tension, $\gamma_{int}$: Interfacial tension
Drop Shape Prediction from Energy Balance Between Total Surface and Interface for Fe/Oxide

These values were obtained by aerodynamic levitation.
I introduced levitation techniques under microgravity conditions for high-temperature liquids studies in materials sciences.

For understanding interfacial phenomena in materials processing, microgravity conditions combined with levitation techniques have big advantages.

Near future, we hope clarify the interfacial phenomena between Fe melts and molten oxides by our INTERFACIAL ENERGY projects.

International Project Member

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