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An Analysis of the Melt Casting of Metallic Fuel Pins

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An Analysis of the Melt Casting of Metallic Fuel Pins

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Overview

• Background
  - Casting Volatile Actinides
  - Need to Contain Americium
  - Overview of Project
• Fuel Rod Model
  - Physical System
  - Governing Equations
• Preliminary Modeling Results
  - Mold Materials
  - Injection Casting Velocity
• Summary
Background - Casting Volatile Actinides

- Advantages of Present Technique
  - Alloy uniformity due to intense stirring of the induction
  - Fast (no preheating), consistent, and selective heating
  - Pinpoint accuracy (directional)
  - The induction field and constant stirring of metal maintain a high level of superheat throughout the melt
  - Easily controllable heating

- Casting Process

- Previous ANL Experience
  - Americium Loss During Casting

- Must Develop a Technique to “Contain” Americium
Background - Casting Volatile Actinides

**Heat and Mass Transfer**
- Induction heating of material
- Induced fluid flow
- Mass Transfer of americium

**Fuel Rod Casting**
- Heat transfer
- Fluid flow
- Parametric study
Background - Casting Volatile Actinides

• Three general models will be developed
  • Induction Heating Model
    - Induction heating in system
    - Coupling of mixing and mass transfer
  • Parametric Modeling of Volatile Actinide Transport
    - Examine a range of operating conditions
    - What conditions are feasible?
  • Flow of melt into molds
    - Parametric study of important phenomenon
Fuel Rod Model

- Baseline fuel rod casting model
  - long length-to-diameter ratio
  - heat transfer
  - phase change (solidification – future work)
  - ability analyze a wide range of potential operating conditions
- FIDAP™ used for a preliminary model
  - Finite element technique
  - Volume of Fluid (VOF) method used to model filling (free surface)
  - Free surface approach => significant re-meshing
  - Preliminary results demonstrate capabilities
Fuel Rod Model (Cont.)

- Model - Symmetry Section
- Boundary Conditions (slip vs. no slip)
- Computational Requirements

Parameters:
- Mold preheating
- Mold design
- Melt temperature
- Injection velocity
- Heat transfer

Inlet Flow

"Interface"

Mold

Outlet
Volume of Fluid (VOF)

\[ \frac{\partial F}{\partial t} + \vec{V} \cdot \nabla F = 0 \]

\[ F (\bar{x}, t) = \begin{cases} 
1 & \text{Fluid} \\
0 & \text{Void} 
\end{cases} \]

Pictures used from FIDAP Documentation
Fuel Rod Model (Cont.)

\[
\rho \frac{\partial \tilde{u}}{\partial t} + \rho (\tilde{u} \cdot \nabla) \tilde{u} = -\nabla p + \mu \nabla^2 \tilde{u}
\]

\[
\nabla \cdot \tilde{u} = 0
\]

\[
\rho C_p \frac{\partial T}{\partial t} + \rho C_p \bar{u} \cdot \nabla T = k \nabla^2 T
\]

Interface

\[
\begin{cases}
T_l = T_s \\
k_l \frac{\partial T_l}{\partial n^*} - k_s \frac{\partial T_s}{\partial n^*} = \rho_s L u^*
\end{cases}
\]

\[
H(T) = \int_{T_{ref}}^{T} (C_p(T) + L \eta(T - T_m))dT
\]

\[
\eta(T - T_m) = \begin{cases} 
1 & \text{if } (T - T_m) \geq 0 \\
0 & \text{if } (T - T_m) < 0
\end{cases}
\]

Momentum

Continuity

Energy

Governing Equations

Modeling enthalpy change
Fuel Rod Model (Cont.)

\[ C_{\text{equiv}} \frac{dH}{dT} = C_p(T) + L\delta(T - T_m) \]

\[ C_{\text{equiv}} = C_p(T) + L\delta(T - T_m, \Delta T) \]

Viscosity = \( f(T) \) for flow solution

\[ \rho C_p \frac{\partial T}{\partial t} = k\nabla^2 T \]

Interface Between Liquid and Mold

(Convective)

\[ k_{mt} \frac{\partial T_{mt}}{\partial n} = k_l \frac{\partial T_l}{\partial n} = h(\Delta T) \]
Fuel Rod Model - cont.

- Melt temperature of 1500°C.
- Fill velocities: 0.1 m/sec or 1.6 m/sec.
- Mold thermal properties: Quartz glass or “similar” to copper.
- Dimensions:
  - Pin diameter of 0.008 m.
  - Mold outside diameter of 0.016 m.
  - Mold length of 0.50 m.
- Melt Properties: Dependent on plutonium, americium, and zirconium.
- Heat transfer coefficient between the melt and the mold ranged from 2,000 to 10,000 W/m² K.
- Initial mold temperatures: 1000°C, 800°C, or 600°C.
Preliminary Modeling Results - cont.

Contours of Fill Fraction as Flow Enters the Mold
Preliminary Modeling Results - cont.

Initial mold temperature of 1000 °C. Velocity = 1.6 m/sec

Radial temperature profiles of the melt just behind the melt front as it advances into the mold.
Impact of the mold materials on the cooling of the melt:

$\text{V}_{\text{filling}} = 1.0 \text{m/s}$

$h = 2,000 \text{ W/m}^2\text{K}, T_{\text{mold}} = 800 ^\circ\text{C}$
Comparison of mold materials: Quartz (symbols) and Copper (lines). Model conditions are heat transfer coefficient = 5,000 W/m² K, mold temperature = 800°C, velocity = 0.1 m/sec.

Radial temperature profiles of the melt just behind the melt front as it advances into the mold.
Comparison of mold materials: Quartz (symbols) and Copper (lines). Model conditions are heat transfer coefficient = 2,000 W/m² K, mold temperature = 400°C, velocity = 0.1 m/sec.
Temperature profiles of melt material near the mold interface at 0.30 seconds. Lower to upper curves represent mold temperatures of 600°C, 800°C, and 1000°C. Fill velocity of 1.6 m/sec and heat transfer coefficient = 10,000 W/m² K.
Examination on the impact of assumed heat transfer coefficient on the cooling of the melt. **Mold temperature = 600 °C.** Fill velocity of 1.6 m/sec.
Mold Filling - cont.

![Graph showing radial locations and velocities](image)

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Demonstrates the ability to model complex phenomenon
  - not without limitations (heat transfer: mold/melt)
  - Impact of different process parameters
  - General trends on casting

Remaining issues
  - phase change needs to be included
  - specify known “melt” properties
Summary

- Developed a plan to evaluate the ability to cast high vapor pressure materials (americium)
- Demonstrates the ability to model complex phenomenon
  - not without limitations (heat transfer: mold/melt)
  - Impact of different process parameters
  - Parametric study
  - Ability to determine impact of process parameters
- Remaining issues
  - Phase change needs to be included
  - Specify known “melt” properties
- Future work to enhance capabilities of the models
  - Phase change other process parameters
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