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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

DOE's Quarterly Review meeting in Albuquerque, NM
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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*

Argonne Furnace

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
- *FIDAPTM 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

Fuel Rod Model (Cont.)

Volume of Fluid (VOF)

$$\frac{\partial F}{\partial t} + \bar{V} \cdot \bar{\nabla} F = 0$$

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

Pictures used from FIDAP Documentation

Fuel Rod Model (Cont.)

$$\rho \frac{\partial \vec{u}}{\partial t} + \rho (\vec{u} \cdot \nabla) \vec{u} = -\nabla p + \mu \nabla^2 \vec{u}$$

Momentum

$$\nabla \cdot \vec{u} = 0$$

Continuity

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \vec{u} \cdot \nabla T = k \nabla^2 T$$

Energy

Interface $\left\{ \begin{array}{l} T_l = T_s \\ k_l \frac{\partial T_l}{\partial n^*} - k_s \frac{\partial T_s}{\partial n^*} = \rho_s L u^* \end{array} \right.$

Governing Equations

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

Modeling enthalpy change

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

Fuel Rod Model (Cont.)

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

$$C_{equiv} = C_p(T) + L\delta^*(T - T_m, \Delta T)$$

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.

Radial temperature profiles of the melt just behind the melt front as it advances into the mold.

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

Preliminary Modeling Results – cont.

Impact of the mold materials on the cooling of the melt:

$$h = 2,000 \text{ W/m}^2\text{K}, T_{\text{mold}} = 800 \text{ }^{\circ}\text{C}$$

Preliminary Modeling Results – cont.

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 $\text{heat transfer coefficient} = 5,000 \text{ W/m}^2 \text{ K}$, mold temperature = 800°C , velocity = 0.1 m/sec .

Preliminary Modeling Results – cont.

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.

Preliminary Modeling Results – cont.

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**.

Preliminary Modeling Results – cont.

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.

Preliminary Modeling Results – cont.

- *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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