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Design and Analysis for Melt Casting Metallic Fuel Pins Incorporating Volatile Actinides: Quarterly Progress Report 5/16/03- 8/15/03

Yitung Chen  
*University of Nevada, Las Vegas*

Randy Clarksean  
*University of Nevada, Las Vegas*

Darrell Pepper  
*University of Nevada Las Vegas, pepperu@nye.nscee.edu*

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Design and Analysis for Melt Casting Metallic Fuel Pins Incorporating Volatile Actinides

Quarterly Progress Report
5/16/03- 8/15/03

UNLV-AAA University Participation Program

Principal Investigator: Yitung Chen
Co-Principal Investigators: Randy Clarksean and Darrell Pepper

Purpose and Problem Statement

An important aspect of the Advanced Fuel Cycle Initiative program is the development of a casting process by which volatile actinide element (i.e., americium) can be incorporated into metallic alloy fuel pins. The traditional metal fuel casting process uses an inductively heated crucible. The process involves evacuation of the furnace. The evacuation of the furnace also evacuates quartz rods used as fuel pin molds. Once evacuated the open ends of the molds are lowered into the melt; the casting furnace is then rapidly pressurized, forcing the molten metal up into the evacuated molds where solidification occurs.

This process works well for the fabrication of metal fuel pins traditionally composed of alloys of uranium and plutonium, but does not work well when highly volatile actinides are included in the melt. The problem occurs both during the extended time period required to superheat the alloy melt as well as when the chamber must be evacuated. The low vapor-pressure actinides, particularly americium, are susceptible to rapid vaporization and transport throughout the casting furnace, resulting in only a fraction of the charge being incorporated into the fuel pins as desired. This is undesirable both from a materials accountability standpoint as well as from the failure to achieve the objective of including these actinides in the fuel for transmutation.

Candidate design concepts are being evaluated for their potential to successfully cast alloys containing volatile actinides. The selection of design concepts has been conducted in close cooperation with ANL staff. The research centers on the development of advanced numerical models to assess conditions that significantly impact the transport of volatile actinides during the melt casting process. The work will include the collection and documentation of volatile actinide properties, development of several conceptual designs for melt casting furnaces, modeling and analysis of these concepts, development of sophisticated numerical models to assess furnace operations, and analysis of these operations to determine which furnace concept has the greatest potential of success. Research efforts will focus on the development of complex heat transfer, mass transfer, and inductive heating models.
Personnel

Principal Investigator:
- Dr. Yitung Chen (Mechanical Engineering)

Co-Principal Investigators:
- Dr. Randy Clarksean (Mechanical Engineering)
- Dr. Darrell Pepper (Mechanical Engineering)

Graduate Students:
- Mr. Taide Tan, M.S. Graduate Student, (Mechanical Engineering)

National Laboratory Collaborators:
- Dr. Mitch Meyer, Leader of Fabrication Development Group, ANL-West
- Dr. Steve Hayes, Manager of Fuels & Reactor Materials Section, Nuclear Technology Division, ANL-West

Management Progress

Budget Issues:
- N/A

Student Issues:
- N/A

Management Problems

No management problem issues at this time.

Technical Progress

The analysis of mold filling and solidification continues with progress being made for the consideration of these two features within one model. Analysis of the induction heating process of an Induction Skull Melter (ISM) is under study. Efforts are underway to validate the modeling procedure and specific comparisons are being made to previously published work. Few detailed modeling results have been reported by other researchers, making the validations an important part of the overall modeling process. Skin heating depths, power deposition rates, and other process parameters are being evaluated for use in upcoming furnace design simulations. Efforts are beginning on the development of a numerical model that assesses the impact of americium transport from a heated melt. Figure 1 shows the temperature contours of induction furnace.
The mold filling process and the solidification modeling have been combined and simulated together using the VOF-solidification algorithm. The solidification could take place during the filling process. Since the casting process is very difficult and complicated, the software FIDAP alone is not enough for this kind of numerical simulation. Thus, two FORTRAN subroutines have been developed to link with FIDAP in the calculation. The results of casting process FIDAP are shown schematically in Figure 2.

In the casting process, the velocity profiles are found increasing rapidly and then dropping off as solidification occurs. The following figure shows the velocity profiles for the different time steps in the VOF-solidification process. Average inlet velocity is 1 m/s. The parabolic velocity profile has been used. The mold material is copper. Inlet
temperature is 1,500 °C. Heat transfer coefficient is 2,000 W/m²°C and mold preheated temperature is 800 °C. Figure 3 shows the axial velocity profile for constant inlet pressure of 20 kPa.

![Axial velocity profile](image)

Figure 3. Axial velocity profile for constant inlet pressure of 20 kPa (mold preheated temperature=800 °C, inlet melt temperature=1,500 °C, interfacial heat transfer coefficient =2,000 W/m²°C).

A new system design using a plug at the end of the mold which can control the backward pressure inside the mold has been suggested by ANL-West. Hence, two fluids VOF method will be used to include air and melt during the casting process. The Figure 4 shows two different casting scenarios.

![Casting scenarios](image)

Figure 4. Two different casting scenarios for single and two fluids.

Skin heating depths, power deposition rates, and other process parameters have been continuously evaluated for use in upcoming furnace design simulations. The computation geometry is shown in Figure 5.
Efforts are beginning on the development of a numerical model that assesses the impact of americium transport from a heated melt. The heating rates with temperature profiles with the different power deposition to the crucible have been studied. One of example is shown in Figure 6.

Figure 5. The computational geometry of induction heating furnace

Figure 6. The temperature contours of induction furnace using specific power deposition.
We continue to work on the induction heating system of crucible modeling. The differences of the required heating time to reach the melting temperature by increasing the coil numbers have been studied. Figure 7 shows the geometry of crucible and heating coils.

![Figure 7. The geometry of crucible and heating coils](image)

Two different coil numbers $n=5$ and $n=6$ have been used. The heating time is about 450 seconds when $n=5$ and 200 seconds when $n=6$ to reach the melting temperature of 1,400 °C based on $d=3$ mm and $b=10$ mm. The dimensions of $b$ and $d$ are also the important factors in the induction heating system modeling. The modified design of $d=2$ mm, $b=5$ mm, and $n=6$ instead of $d=3$ mm, $b=10$ mm, and $n=5$ has been studied. The modified design of induction heating system shows about 3 times faster than the original design for temperature to reach the melting point 1,400 °C. Figure 8 shows the induction heating system influenced by using the different coil numbers. Figure 9 shows the time requirement for reaching the melting point using the different coil numbers.
The influence of coils' number

Figure 8. The induction heating system influenced by using the different coil numbers.

Figure 9. The time requirements for reaching the melting point using the different coil numbers.
As in most materials, especially in the oxides, the electrical conductivity is strongly dependent on temperature. From the former work we know electrical conductivity has great impact on the calculation of the two complex components of power deposition $Q$, i.e. $C$ and $S$. A subroutine has been developed in the simulation of induction heating problem when the electrical conductivity is a variable value. It is shown in Figure 10. From this developed subroutine we can use a loop to calculate the temperature distribution in the system.

It will have a difficulty to use the low electrical conductivity materials on the induction heating system. It will be necessary to add the pure material such Zr which has the high electrical conductivity to ZrO$_2$ powder. Zr is acted as a “conductor” during the induction heating process. The location of the “conductor” material, shape, and volume are important factors during the numerical modeling. We have assumed the “conductor” material has a loop shape. We have revised our computational domain according to the added “conductor” which is shown in Figure 11.
Figure 11. A “conductor” is added into the crucible for the low electrical conductivity materials in the induction heating system

Graduate student Mr. Taide Tan, Dr. Clarksean and I visited ANL-West in Idaho Falls on July 10 and 11. We have updated our research progress to them. We had very good technical discussions during meeting. Dr. Mitch Meyer at ANL-West has also provided us a few suggestions such as adding plug at the end of mold in our numerical modeling which will be implemented in August.


The poster of “Simulation and Analysis for Melt Casting a Metallic Fuel Pin Incorporating Volatile Actinides” has been presented to the AFCI semi-annual meeting in Santa Fe, NM, August 25-28, 2003.

The paper of “Simulation and Analysis for Melt Casting a Metallic Fuel Pin Incorporating Volatile Actinides,” IMECE2003-42092, has been peer reviewed and accepted by 2003 International Mechanical Engineering Congress and Exposition Conference which will be held in Washington, D. C., November 16-21, 2003.