Technical Development of New Concepts for Operation and Control of Cold Crucible Induction Melters for Vitrification of Radioactive Waste

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ABSTRACT

The Idaho National Laboratory (INL) is performing research to investigate the feasibility of alternative treatment technologies for high-level waste, as part of the DOE-EM clean-up mission. One technology being investigated jointly by INL and the Electrotechnical University (ETU) in St. Petersburg, Russia, is the application of the Cold Crucible Induction Melter (CCIM) technology to vitrify high-level nuclear waste. Previous work at INL resulted in the design, development and initial operational testing of a 60KW prototype CCIM. Using this design as a baseline, current work focuses on developing a new and highly effective method for control of the CCIM providing for real-time non-intrusive quantification and control of the operating regime (i.e. temperature). As part of this effort, the INL has developed and applied for a patent for a closed loop control scheme for CCIM melters utilizing data generated by real-time terminal voltage and current measurements. This paper describes joint development work supporting this approach, and also presents test results obtained recently at ETU using a new class of innovative electrical sensors. In addition, the paper outlines both the results of CCIM calorimetric measurements and empirically obtained in-situ melter temperature profiles. Ongoing work that will be completed during 2006 is also discussed.

INTRODUCTION

INL has developed a new technique for cold crucible induction melter monitoring and automatic control that will enable a higher level of quality control for waste vitrification applications. This technique requires measurements of the primary inductor voltage, current and power factor at megahertz frequencies. ETU has been tasked with developing and implementing these measurements and validating the control model using sensors and data acquisition and processing techniques of their own design, and then providing the results of actual melter tests to INL.

Control of the melting process such that a known melter operating condition is established and maintained over production run time periods of hours, days or weeks will assist in achieving higher and more consistent product quality. The objective of this research is to design and successfully operate a feedback control system that can achieve this. Knowledge of this operating state is important for control because it constrains system throughput as well as governs the functions of melter draining and waste dissolution. Briefly, the operating state is a geometric profile of melt temperature at a given point in time. This is influenced by the varying application of electromagnetic energy and is affected by various factors including the waste input rate and time history of that rate, occurrence of periodic draining, convection and stirring effects in the melter, and the change in melt physical characteristics as a function of temperature. Previous modeling has predicted that the profile consists of multiple convection cells surrounding the central part of the melter, and bordered by cooler zones of melted or semi-molten glass. The extent and thermal profile of these cells and zones must be empirically validated if model results are to believed and used as the basis for automated control.

A necessary prerequisite for the implementation of an automated feedback control system is the ability to measure the melter state. Control electronics can then compare this measured value against a desired set point, applying necessary corrective input to the system to maintain the desired state. Current technology for measurement of melter state involves surface temperature measurements, the use of sacrificial high-temperature thermocouple probes, calorimetric measurements, and various other techniques. None has proved practical for production applications where reliable and accurate automatic control is desired over significant time periods. INL research during the past three years has resulted in the development of a control scheme based on estimating melt power and temperature from measurements of CCIM primary inductor terminal voltage and current, and then using these values to set the induction generator power level as a means of maintaining melter state.[1]

The Electrotechnical University in St. Petersburg, Russia, in collaboration with INL has been conducting in-situ tests during the past year to measure internal melter state at typical operating temperatures of 1000 – 1250^{o}C, and concurrently measuring primary inductor electrical characteristics. This paper summarizes the details of that concept, discusses the innovative control system being developed, reviews a new and innovative technique of in-situ measurements to obtain the model parameters that are enabling for melt power estimation, describes collaborative laboratory test program and setup, and outlines laboratory testing results to date.

RESEARCH OBJECTIVES

The overall objective of the joint research between INL and ETU is to design hardware and empirically quantify state and control parameters with the goal of building and testing a CCIM automatic control system. There are three prerequisites for this automated control of a CCIM melter that have been investigated as part of our research. They are 1) the melter state can be measured accurately, 2) a control signal can be generated by comparing this measured value against a desired set point, and 3) the primary inductor power source can be varied in response to a control input. Each of these prerequisites has been successfully addressed under the current research program.

INL has developed a scheme to represent the melt as a single bulk electrical characteristic. [2] This representation is based on the relationship between the thermal physical characteristics of the melted volume and the interaction between the time-varying applied electromagnetic field and the melt material. The relationship accounts for absolute values and temperature dependence of thermal conductivity, electrical conductivity, and specific heat. Because electrical induction is occurring during time periods that are more than four orders of magnitude faster than thermal changes, the thermodynamic effects and the electro-magnetic effects were modeled separately. The resulting thermodynamic and electrical calculated values were then coupled. The importance of this bulk electrical properties model is that it facilitates the design of a single variant feedback control system to provide demand power to the induction generator power source. Validation of this relationship between melter state and effective melt temperature is one objective of the testing currently underway at ETU.

INL has also developed a technique to measure this bulk electrical characteristic in real time during melter operation using non-invasive techniques. [3] This development precludes the need for real-time in situ measurements of melt state, which have proven problematic. The measurement technique, however, has required the development and testing of special high-accuracy current, voltage and power factor sensors. This is a challenge because measurements to the stringent requirements driven by the INL-developed technique must be performed at induction generator radio frequencies in the megahertz range.

The last prerequisite does not represent a research challenge. An investigation into the design and theory of operation of radio frequency inductor power generators indicated that varying output power in response to a control input is a common design feature in these units, and does not require development.

DESCRIPTION OF LABORATORY TESTS

During the past year ETU has designed and prototyped sensors, and performed the associated and necessary modeling and simulation to measure cold crucible primary inductor voltage, current and phase, and designed and constructed a thermocouple dip system to profile temperature distribution. A research prototype melter was designed, fabricated and tested. During summer 2005 a complete electrical and thermal profile of a cold crucible induction melter was performed by INL and ETU staff for the first time in history. In addition, for the first time, detailed electrical characteristics of the primary induction coil were performed during full power operation.

Four tests have been conducted to date. These are designated as Department of Energy-1 (DE-1), DE-2, DE-3 and DE-4. These test set-ups and operational conditions are described below.

DE-1 Test

The DE-1 test was conducted on May 11, 2005. This is best described as a preliminary operational test and its purpose was to define melt power modes appropriate for test operation, test the thermocouples and thermocouple deployment system and determine startup heating parameters. The melter itself was configured with a charmotte brick ceramic bottom and a removable, water cooled copper lid. The CCIM furnace contained a non-magnetic stainless steel crucible with internal diameter of 300 mm. The crucible sections are made from round tubes with external diameters of 16 mm and are assembled on an insulating plate. To conduct calorimetric measurements, a removable water-cooled copper lid insulated with mineral cotton wool was placed on top of the crucible, providing a measurement of the thermal losses from the melt surface. The crucible was covered with an aluminum silicate coating where it joined the ceramic bottom and fiberglass tape was wound on the outside. The primary inductor for this test was a 3-turn spiral inductor with a height of 250 mm. The induction generator operates at a nominal frequency of 1.76 MHz with a maximum power of 60 kW. Internal melt temperature measurements during the DE-1 test were made using a single thermocouple. Surface melt temperature was measured using an optical pyrometer.

During the test the melt depth was measured to be 15 cm. Inside melt temperature was 1190^{o}C and maximum surface temperature was measured at 1200^{o}C. Using thermal measurements (calorimetry), the power factor was estimated under these conditions to be 0.1148. After cooling, a large crystallized layer was observed at the bottom of the melted volume. This is attributed to the periphery field of the primary inductor due to its spiral configuration. Also contributing to this may be the fact that the test glass had a substantial fraction of iron oxide in its composition. Approximately 5 mm of un-melted frit was observed at the bottom of the crucible also.

DE-2 Test

The DE-2 test was conducted on June 22, 2005. The primary inductor for this test was a two turn co-planar inductor approximately 95 mm high. This new inductor was intended to heat the ground layer of the crucible and avoid the crystallization observed following the DE-1 test. There were four purposes of this test. The first was to observe performance of the electric sensors. Other purposes were to take calorimetric measurements under different temperature regimes, to test the thermocouple array deployment system with four thermocouples, and to verify improvements in the parameter measurement system. The test was designed so that maximum melt temperature did not exceed 1350°C.

Results were satisfactory, and systems worked as designed. There were no problems experienced with the deployment of the thermocouple array, and radial and vertical temperature profiles were successfully taken. The cold cap did not deflect the thermocouples. Although the system was configured for five thermocouples, measurements were only taken using four thermocouples because the electronics provides four channels only. Four radial temperature readings were taken at each of ten melt depths, resulting in a 40-point data set. Temperature measurements were taken between 0.2 cm and 9.2 cm in a 10 cm deep melt. Some spreading/bending of thermocouple shafts was observed. A maximum temperature of 1410°C was observed near the wall of the melter at a depth of 2.2 cm. Melt temperature was found to be most constant radially at depths of 4-8 cm, which was expected as this is the zone of most efficient energy transfer. Temperature was observed to decrease near the walls at the bottom, with 850-900°C measured in this region. Note the bottom of the inductor is approximately 5-6 mm above the bottom of the melter. There was concern about grain growth within the thermocouple sheath following exposure to high temperatures, but no change was observed in output following the test at ambient temperature. Post test examination found that the bottom layer had heated properly. In fact, some bonding between the glass and the ceramic bottom was observed. Fig. 1 shows the melt temperature profile that resulted from the thermocouple data. The molten zone extends up to the 10 cm mark, and the 0 cm line denotes the centerline of the melter.

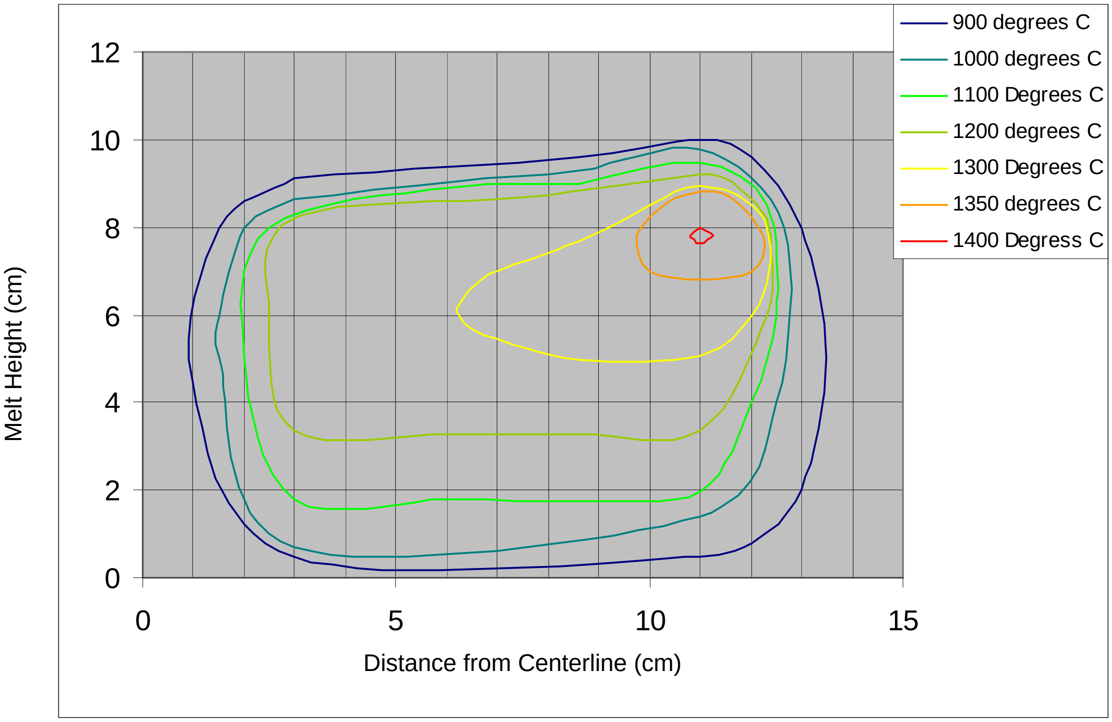

Fig. 1. Radial temperature profile within melt

DE-3 Test

On July 20, 2005 the DE-3 test was conducted at the cold crucible induction melter laboratory at ETU, with INL representatives in attendance. The test melter was operated at a radio frequency tube plate voltage typical of full melt operation. During the test the primary induction coil current and voltage sensors were observed on a Tektronix 3054B digital phosphor oscilloscope. Additionally, the sensor outputs were observed, on analog d'Arsenval true RMS meters. The relative phase between the low voltage current and voltage sensor outputs was observed, as well as the RMS values of sensor outputs at various oscilloscope sweep values. Also deployed was an eight thermocouple array whose purpose was to develop a detailed internal melt profile. Fig. 2 shows the thermocouple arrangement during melter operation.

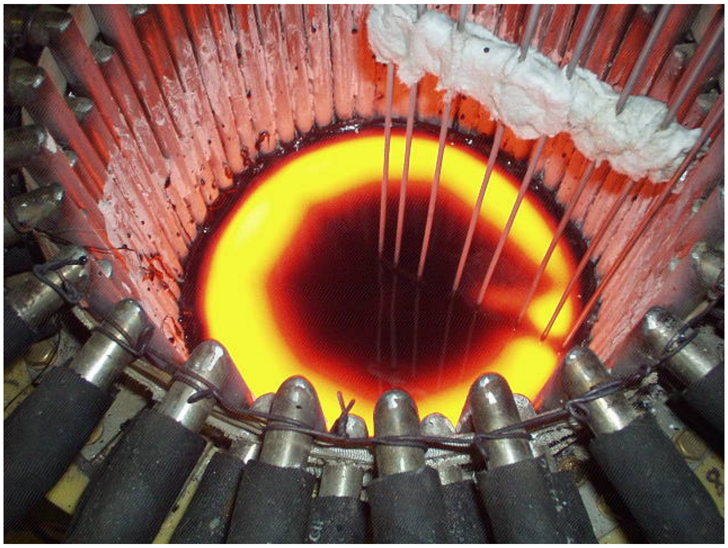

Fig. 2. Temperature profile measurement using 8-point thermocouple array inside glass melt.

Initially, inductor voltage and current true RMS values were recorded, and waveforms were recorded to compute the phase. Next, an insulated lid was placed on the top of the melter and head temperature was recorded, as were cooling water temperatures and flow rates. Following this, three sets of measurements were planned to characterize temperature profiles of different operating modes. Each of three modes was defined as an equilibrium state of the melter with stirred surface temperatures of 1000^{o}C, 1050^{o}C and 1100^{o}C. During each mode, the power was to be adjusted so that the melt surface temperature, as measured with an optical pyrometer, was constant and the melt was presumed to be at equilibrium. An array of eight thermocouples was lowered into the melt in 1 cm steps, beginning just below the surface and continuing toward the bottom of the 10 cm melt as far as practicable. Prior to temperature measurement at each vertical level, the generator was turned off. Following each measurement, the generator was turned on again, with ample time allotted for the melter to reach equilibrium again.

Initial measurements were made with a surface temperature of 1000^{o}C at vertical intervals of 1 cm. As the array approached the bottom of the melt it was noted that the thermocouple nearest the outer wall was indicating a much lower temperature. This was explained by noting that the thermocouple had entered the "marsh" volume near the bottom of the crucible. The outer thermocouple was removed, and measurements continued. Toward the end of the mode 1 test, one thermocouple failed catastrophically and approximately 10 cm of sheathed thermocouple detached from the remaining thermocouple shaft. Following thermocouple insertion and steps to the bottom of the melt, the thermocouple assembly was withdrawn in steps and the measurements repeated. All thermocouple measurements were recorded on a multi-channel strip chart recorder and results were noted in a table.

Thermocouple measurements were repeated for the melt in a second mode, with observed stirred surface temperature of 1050°C. Profile measurements were repeated and measurement data recorded in the same manner. Test measurements were taken at 2 cm intervals to limit cumulative thermocouple immersion time and hopefully preclude further thermocouple failures. However, during the course of this second mode test three more thermocouples failed catastrophically. Following completion of the second mode test, the number of remaining thermocouples was deemed inadequate for meaningful profiling, and testing was concluded.

DE-4 Test

The DE-4 test was conducted on November 24th, but the results were not available in time to specifically include in this report. However, the preliminary results support the trends observed in the earlier tests, which are discussed in more detail below.

TEST RESULTS

As noted earlier, inductor voltage, current and the phase relating these two signals were recorded in various steady-state melter conditions. All three of these are necessary to compute melt power and equivalent melt temperature. Fig. 3 shows a representative measurement of primary inductor current and voltage waveforms taken during DE-2, and an illustration of the phase measurement.[4] These waveforms have periods on the order of 0.5 microseconds, and the time resolution of the measurement is approximately 3 nanoseconds (3E-9 seconds).

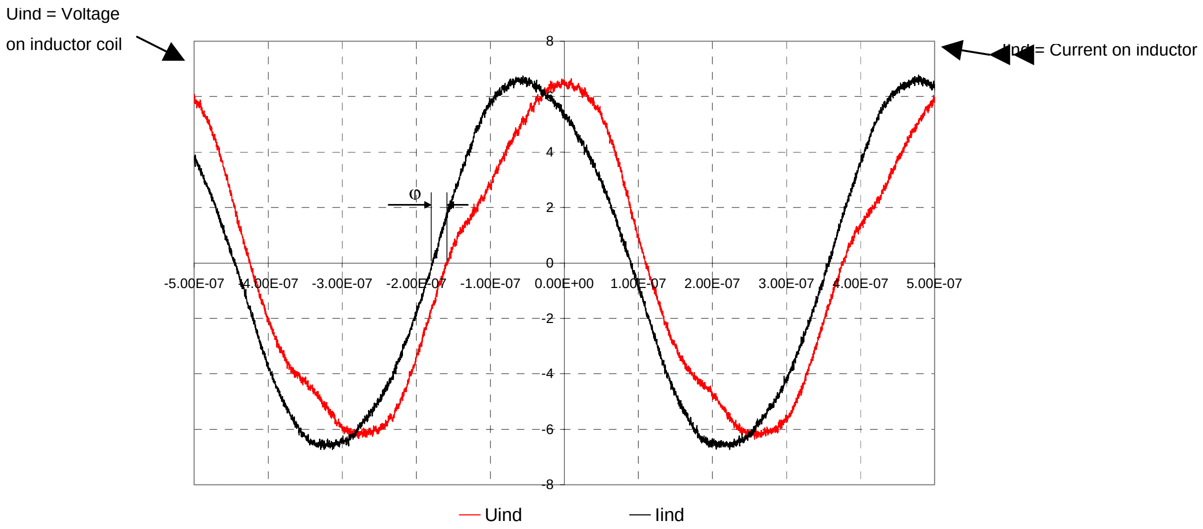

Fig. 3. Primary Inductor Voltage and Current Waveforms during DE-2 Test

The cosine of the phase angle is called the electrical power factor, which relates to melt state. This electrical measurement of phase Φ was independently computed using the results of the calorimetric measurements in which

$$\cos(\Phi) = P/(V^2\omega C) \qquad \text{(Eq. 1)}$$

where P is power as measured calorimetrically, V is inductor voltage, and C is capacitance across primary inductor.

Data assessment is ongoing, but both INL and ETU have observed the expected correlation between measured temperature and computed power factors based on the data obtained to date. Table 1 summarizes these results showing a clear relation between phase angle, power factor and temperature regime. Results must still be viewed as preliminary as there is work yet to be done improving the design of the calorimetric measurement. This will include the installation of additional temperature sensors in the melter base, which is planned within the anticipated 2006 work scope.

Table I. Test Results Illustrating Correlation between Power Factor and Melt Temperature

Time (minutes)	*Melt Temperature Regime*	*Primary Inductor Phase (degrees)*	*Primary Inductor Power Factor*
196	960°C-970°C	82.876	0.1240
214		82.952	0.1227
221		82.953	0.1227
230		83.160	0.1191
242		83.305	0.1166
252		83.265	0.1173
261		83.281	0.1170
270	1060°C – 1070°C	83.168	0.1190
294		82.190	0.1359
305		82.001	0.1392
310		81.934	0.1403

SUMMARY AND CONCLUSIONS

The results of these first tests are very promising, in that a measurable correlation between a specific melt state and key electrical parameters was clearly demonstrated. Further testing is needed, as discussed before; however, initial laboratory work has shown that the approach is feasible. This will be a highly useful tool in validation, implementation, and operation of alternative processing technologies, not only for existing legacy waste inventories, but also for support of next generation reactors and advanced fuel cycles that will constitute the renaissance of nuclear power in the United States. A secondary benefit of this research has been to enhance our understanding of the melt state, particularly in regards to temperature profiles. The 1400°C hot spot corresponding to a 1000°C nominal surface temperature clearly demonstrates the need for supplemental mixing in an induction melter for overall homogeneity and waste form quality. This will be particularly important as higher temperature waste forms (e.g.. liquidus temperatures of 1300°C) are developed as enhancements to existing and future waste processing scenarios.

During FY 2006, we anticipate additional and continuing work supporting the development and operation of this CCIM feedback control system. Reliable information must be obtained on the relationship between melt resistivity and temperature, as this is a key component of the melt state model. The prototype current, voltage, and phase sensors will be redesigned for reliability and manufacturability. Specifically, the new designs shall ensure that additional sensors can be manufactured that exhibit the same response to input parameters with minimal calibration required, be compatible with commercial standards of production, and incorporate a mechanical design that is compatible with an industrial/commercial application environment. Three controlled temperature profile tests are planned in FY 2006 to establish reproducibility of results. This will include construction of a new 8-thermocouple array extending from a location adjacent to the wall to the centerline of the test melter. Temperature measurements will to be taken at 1 cm intervals beginning at the surface and extending to the bottom inside of the melter crucible. The melter to be used is the existing 30 cm test melter at ETU operated for the initial INL profile tests during 2005. Each profile test will be conducted in three or more modes, as defined by three distinct stirred surface temperature values between 1000°C and 1200°C. We also plan to develop and test a method of automatically measuring melt level during cold crucible induction melter operation.

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