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**ENGINEERING TECHNIQUES TO OBTAIN
UNIFORM HEATING OF SPHERICAL METAL
OBJECTS IN AN INDUCTION FURNACE**

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Engineering Techniques to Obtain Uniform Heating of Spherical Metal Objects in an Induction Furnace

Abstract

We have designed, constructed, and are presently operating a unique induction furnace for the purpose of uniformly heating spherical metal test objects to temperatures near 1200° C. This is accomplished while maintaining overall object temperature uniformity of <10° C.

Introduction

Material Sciences Division, in support of the Pit Reuse, Enhanced Safety and Security (PRESS) Program, Fire Resistant Pit (FRP) Project, expressed a need to construct, document and test an induction furnace capable of raising the temperature of spheroids, constructed of various metals and alloys, to approximately 1200° C maximum. During these tests the overall object temperature uniformity must remain within 10° C.

We also accomplished some limited experimental analysis which investigated portions of the complex computer model findings undertaken by R.W. Martin¹ on the properties of magnetic fields and their lack of penetration into molten metals while housed in a graphite susceptor.

This furnace has been constructed and is undergoing evaluation at LLNL. It will then be shipped and installed in the neutron containment hot cells, numbers 6 and 8, located in the Chemistry and Materials Research (CMR) facility at LANL. A complete, detailed mechanical, electrical, and software documentation package is available for the LANL engineering staff.

MASTER

EP

Engineering Design, Furnace Interior Configuration

The airtight chamber

The airtight chamber is temporary and will be replaced with the LANL alpha glove box design when the apparatus is deployed to LANL. The temporary chamber is constructed with an extruded aluminum frame supporting the 1/8 in. (3.18 mm) sheet aluminum wall pieces which are sealed with rubber gaskets during operation. This chamber is designed in a cubical shape and is 4 feet (1.22 m) on each side. Aluminum was selected because aluminum has low electrical resistance and will not become too hot due to eddy current flow generated by close proximity to the induction heating transmission components. The size was determined to closely approximate the LANL alpha glove box and to reduce the radiant heat transfer in the chamber walls. The chamber is evacuated and refilled with argon during operation (Figure 1A).

Figure 1A. Furnace interior displaying gas inlet and outlet valves, view port, thermocouple and transmission line feedthrough flanges and the graphite susceptor arrangement.

This chamber has feedthrough penetrations for the transmission lines, the thermocouple diagnostics, and a viewing window port. The thermocouple feedthrough is a commercially available product. The transmission line feedthrough is machined from Dupont Delrin. The desired coolants can be introduced into the coil and transmission lines at the individual connections illustrated in Figure 1B.

Figure 1B. RF feedthrough port.

The Graphite Susceptor

The susceptor is machined from certified ATJ grade Union Carbide graphite. Its overall shape is cylindrical with a cavity machined in the center to house the test sphere positioned on the alumina standoff studs. The susceptor opens and closes around the test sphere when its two halves are overlapped in a telescopic fashion. There is a circular hole centered at the top to allow penetration of the several diagnostic thermocouple probes. There are also additional openings at the midpoint and the bottom for molten metal to drain out if required. The lower half has an

additional area machined to accommodate a tube appendix to the test sphere. The susceptor will be mounted in either of two configurations. This versatility is necessary for the study of welds and other material and metallurgical areas of interest. Configuration number one, tube down, is illustrated in Figure 2A; and configuration number two, waist down, is illustrated in Figure 2B.

Figure 2A. Tube down.

Figure 2B. Waist down.

The Insulating Blankets and Coil Sheath

The susceptor described above requires appropriate insulation to prevent heat loss and ensure high temperature efficiency during tests. To this end customized blankets were fabricated using 3M Nextel insulating materials wrapped around the susceptor. Next, the susceptor's upper hole was plugged with Nextel after the thermocouple probe harness was installed. This was followed by sliding a sheath of Nextel material over the entire length of the copper coil. Finally, the whole assembly was covered with one last Nextel custom fabricated blanket.

The Thermocouple Probes

The thermocouple probes are type K (chromel-alumel) contained in stainless steel sheaths 1/16 in. D (1.6 mm) x 30 in. L (0.76 m). The maximum temperature permitted during experimentation is 1200° C, which is very near the upper boundary of type K thermocouple sensors (1250° C). Nevertheless, experience reveals that type K thermocouples operate efficiently in this upper temperature region. Therefore, the very expensive type S (platinum/platinum-rhodium) probes are not necessary. The diagnostic thermocouple probes are attached to the test sphere at all areas of interest. These thermocouple probes are fastened to the test sphere by welding stainless steel clamps over them; then the leads are routed out of the susceptor in a neat bundle. There are also similar type K thermocouple diagnostic probes inserted into the outside of the susceptor to monitor these regions (Figures 3A, 3B, and 3C).

Figure 3A. Thermocouple probe with clamp.

Figure 3B. Test sphere thermocouple harness.

Figure 3C. Susceptor thermocouple holes.

Two other thermocouples are used as feedback to the cascade controls of the induction power supply. Additional thermocouples monitor the coolant temperatures for interlocking purposes.

Copper Coil And Ceramic Mounting Assembly

A liquid-cooled copper coil is used as the induction field source inside the furnace. It is configured to optimize the introduction of magnetic fields into the graphite susceptor which will radiantly heat the test sphere. The coil is a 1/2 in. (12.7 mm) copper tubing constructed to have 15 turns spaced about a 12 in. (30.5 cm) diameter over the 24 in. (61 cm) height of the susceptor. The coil arrangement consists of turn concentrations both top and bottom with fewer turns at the center. It has a measured inductance of 14.7 μ h. Calculations, using the formula $X_L = 2\pi fL$, indicate this value would result in an inductive reactance acceptable for the power factor correction requirements of the Tocco power supply unit. This induction heating coil is supported by a machined Coors Macor ceramic assembly which will allow simple coil adjustment and reconfiguration if necessary (Figures 4A & 4B).

Figure 4A. Coil assembly.

Figure 4B. Macor support bracket.

Mounting Hardware

All nuts, bolts, brackets, etc., are detailed on the parts lists in the drawing package. It should be noted that wherever possible this hardware is made of non-ferrous metals to minimize interaction with the magnetic field. The high temperatures and magnetic properties of the furnace are carefully considered prior to installation of the hardware.

Engineering Design, Induction Furnace System Furnace Exterior Configuration

Ten capacitors impregnated with polychlorinated-biphenyl (PCB) as a dielectric were removed, disposed of, and replaced with non-PCB type capacitors in a vintage 1960-era 50 kw, 9.6 kHz Tocco motor-generator type induction power supply. This power supply was then modified with a Yokogawa power meter and an Opto-22 analog/digital computer interface chassis. These modifications were made for remote control and regulation with a Macintosh computer running National Instruments' LabVIEW software. The Tocco power supply and associated sub-systems are described below.

The Tocco motor-generator power supply system requires a 480 VAC, 3 ϕ , 225 ampere electrical service. This is connected to the control/regulator portion of the power supply called the "Meltmaster" via a motor starter contactor assembly and routed to the motor-generator. It is important to keep ferrous metals away from the power transmission system. Therefore, a twisted pair of 4/0AWG welding cable, housed in an aluminum conduit (not extruded metal tube—EMT), comprises the 9.6 Khz high-frequency output conductor extending from the motor-generator back to the Meltmaster controller. This circuit component can be as long as 200 ft. (61m) if necessary (Figures 5A and 5B).

Figure 5A. Furnace exterior.

Figure 5B. Furnace electrical service.

In the Meltmaster controller the proper capacitance and inductance are selected to assure that the induction heating circuit power factor correction (pf) matches the load efficiently. E.K. Greenwald² states that current should neither lead nor lag voltage significantly and the phase difference between the two should be as near to zero degrees as possible. This is demonstrated by the $\cos\phi$ parameter in the formula $P=VI\cos\phi$.

Power Supply Modifications

To facilitate total remote control of the Meltmaster matching/control unit, several modifications were made to the system, including the addition of an in-house designed remote-control interface chassis. Also added was a Tocco voltage-controlled, regulated field current supply. These modifications are detailed below.

Power Supply Computer Control System

Because the Meltmaster will be inaccessible to the operator while in operation, the unit needs to be controlled remotely. However, the unit was built long before modern computer control methods were available. The only provision for remote control is an upgrade available from the manufacturer for controlling the field current with a 0-10 VDC signal, which in turn controls the power output. We have developed and installed our own control system which allows the operator to have access to the same indicators and controls as those on the front panel of the Meltmaster and has the capability of closed loop control.

The basis for the remote control system is a Macintosh personal computer running LabVIEW. LabVIEW is a graphical programming language developed for data acquisition and process control applications. A control panel on the computer screen allows the operator to see the same information that is displayed by the Meltmaster's front panel meters and indicator lights (Figures 6A and 6B).

Figure 6A. Meltmaster local controls.

Figure 6B. Computer screen depicting Meltmaster controls.

LabVIEW allows the operator to control the Meltmaster output manually or let it automatically control the output to a temperature set-point or ramp using a Proportional-Integral-Derivative (PID) control algorithm. There are two ways the Macintosh receives data from the Meltmaster. The first is through a Yokogawa digital power meter communicating with the Macintosh over a general purpose interface bus (GPIB IEEE-488), communications bus. The Yokogawa unit is used to acquire the same analog information displayed on the Meltmaster's front panel meters: voltage, current, power, and KVA_r (reactive power). It does this by monitoring the voltage and current and using the magnitudes and phase difference to calculate power and KVA_r. Because of the digital power meter's capabilities, other parameters, such as frequency, can also be measured. The data is constantly updated by requests to LabVIEW at regular intervals. The Yokogawa 2534 digital power meter measures four power parameters used in the control of the Meltmaster matching and control unit. These parameters are: output voltage, current, power, and power factor. The Yokogawa 2534 is connected with existing Meltmaster power measuring devices.

Sequence of events for reading Power Measurements:

- 1) Operator requests voltage, current, power, and power factor from the Macintosh (running a LabVIEW driver) to the Yokogawa 2534 via GPIB.
- 2) Yokogawa 2534 reads the selected power measurements
- 3) Yokogawa 2534 sends the results of its readings in string form to the Macintosh via the GPIB.
- 4) Power measurement data is parsed and displayed within LabVIEW and saved to memory.

The second method of communicating with the Meltmaster is through the Opto-22 input and output modules. Analog and digital Opto-22 modules plug into their own 16-channel backplane controlled by a microprocessor based "brain board". The brain boards communicate with the Macintosh through the computer's RS-422 serial port. The digital Opto-22 inputs read voltage across the Meltmaster's front panel indicator lights to determine when they are being lit. The status of these lights is displayed on the computer screen. Digital outputs are used to mimic the control switches on the front panel. The outputs activate relays whose contacts are placed in parallel or

series with the manual control switches, as required. A selector switch on the front panel of the chassis which houses the Opto-22 backplane allows the Meltmaster to be controlled in manual mode or remote control mode, but *not both simultaneously*. Indicator Light Emitting Diodes (LEDs) on the front panel of the chassis also display the status of the digital outputs (Figure 6C).

Figure 6C. Furnace automation block diagram showing the relationship between the Meltmaster, the computer, and the three computer interfaces. The Opto-22 chassis receives status indications from the Meltmaster and delivers control commands; the Yokogawa makes voltage current and power; and the HP3852A acquires temperature data for storage and closed loop control.

The single analog channel output controls the field current of the motor generator. The manufacturer's upgrade equipment requires 0-10 VDC input and controls the field current proportionally. An analog Opto-22 output module provides this signal.

Example of remote operations combined with LabVIEW Virtual Instrument:

Run to 600° C.

- 1) All temperatures are read via the HP 3852A.
- 2) Temperatures are recorded to disk as needed.
- 3) Control temperature values from susceptor and test sphere are read into the cascade PID loops.

- 4) Scan of operational settings (switch positions, etc.) is made via the Opto-22 equipment to ensure operational readiness.
- 5) Scan of power measurements (voltage, amperes, power, and power factor) is made via the Yokogawa 2534 to ensure that measurements are within acceptable limits.
- 6) Power measurements are recorded to disk as needed.
- 7) Change voltage to the Regulated Field Current Power Supply via the Opto-22 analog module based on the amount of change requested by the PID loops to achieve the desired temperatures.

Transmission Lines

The most important consideration when designing induction heating equipment is to electrically match the power supply equipment to the load and thus magnetically couple into the load at optimum efficiency. In this design the heating coil is a fixed parameter. Therefore, there is great need to have the lowest impedance and inductance present in the transmission line assembly. The transmission line assembly described here is installed at the LLNL test facility and will not be transferred to LANL. Nevertheless, the basic design style and theory are the same. Twin parallel copper pipes and the necessary G-10 fiberglass insulating support assemblies comprise the transmission line design. The 3/4 in. (19.05 mm) parallel pipes reduce the impedance by increasing the surface area. Also, the close proximity of the conductors cancels the magnetic fields, thus reducing coupling problems even more. It is also very important to assure that all joints are silver-soldered with great care. These steps reduce the skin-effect component which would be very high if customary wire-type conductors had been selected or less rigorous joining techniques were undertaken (Figure 7).

Figure 7. Typical transmission line section shown with twin parallel copper pipes extending through the Lexan insulators.

Coolant Heat Exchanger System

For safety reasons, it is mandatory that the amount of coolant available within the glove box system be minimal. If a failure occurred, such as a leak in the induction coil circuit, it is required that only a small amount of liquid coolant be available. With this parameter as a design criteria, a pump and reservoir system with a heat exchanger is utilized for coil cooling. The heat exchanger system reservoir has a 10 gal. (37.85 liters) capacity and is a nonrefrigerated stand-alone unit manufactured by Lepel. It has 18 square feet (1.7 m²) of cooling surface in the heat exchanger unit. It utilizes a 3 ϕ , 208 VAC, 30A motor in the pumping circuit: this can circulate coolant through the coil circuit at approximately 2 gpm (7.57 lpm). Heat transfer from the coil circuit has been excellent during tests with the reservoir filled to only 5 gal. (18.93 liters). Even with these favorable experiences, the inlet and outlet temperatures will be sensed and interlocked. This interlocking is described later in this paper. The heat exchanger is illustrated in Figure 8.

Figure 8. Coolant heat exchange.

Diagnostics and Data Acquisition

Data generated during a test will consist of temperature, pressure, and neutron output as a function of time.

Temperature Diagnostics

The temperature data acquisition system is comprised of three major units. The Hewlett Packard HP 3852A data acquisition and control unit, the Macintosh Quadra 950, and sensors. Most of the data consists of temperature measurements. The Hewlett Packard 3852A measures all system thermocouple temperatures. The HP 3852A mainframe is equipped with an HP 44708A thermocouple analog relay multiplexer plug-in accessory module capable of reading twenty thermocouples. Multiplexed thermocouple values are measured by another plug-in accessory the HP 44701A integrating voltmeter. Thermocouple extensions are wired directly into the 44708A. The mainframe is also equipped with a General Purpose Interface Bus (GPIB) interface, which allows excellent data communication between the HP 3852A and the Macintosh (Figure 9). The LabVIEW screen which displays the various temperatures and thermocouple locations is shown in Figure 10.

Figure 9. Data acquisition system.

Figure 10. Macintosh Quadra 950 computer screen with LabVIEW presentation of thermocouple locations for temperature data analysis.

Sequence of events for reading Thermocouple Values:

A request for the desired thermocouple channels to be read is sent from the Macintosh (running a LabVIEW driver) to the HP 3852A via GPIB.

- 1) HP 3852A reads the selected thermocouple channels.
- 2) HP 3852A sends the results of its readings in string form to the Macintosh via the GPIB.
- 3) Thermocouple data is parsed, displayed, and saved to disk within LabVIEW.

Neutron Counter Instrumentation

As described in a memorandum, Hankins³ states that several types of neutron instruments were considered for use with this furnace. Because of the possible high gamma-ray component, detectors utilizing scintillators were eliminated—they would have a problem with gamma discrimination. Moreover, the commercially available instruments using boron tri-fluoride can become neutron-energy-dependent if the polyethylene surrounding the detector is too thin. Therefore, a standard neutron remmeter, Model ESP-1/NRD-1 manufactured by Eberline, was selected; it fulfills the requirements.

Macintosh Quadra 950

Lengthy discussion of the Macintosh Quadra 950 hardware will not be attempted in this paper. However, it is important to note that the Macintosh running LabVIEW and associated Virtual Instruments is integral to this data acquisition and control system design. Without major changes to the basic design, this furnace cannot operate without it.

Interlocks Safety Systems

The safety and interlock philosophy has to be sound and flexible. This is required because the hardware will be operated at LLNL and then be consolidated into the LANL CMR Facility Safety Plan.

At the heart of the interlock system is a Siemens Simatic 305 Programmable Logic Controller (PLC). This comprises a central processing unit (CPU) and the analog and digital input and output modules. The field input devices are composed of micro-switches, relay closures, temperature measurements, and linear analog signals. After appropriate handling of these inputs within the PLC, the field output devices are activated. These devices consist of light-emitting diodes located on an operator's annunciator chassis and closure signals which inhibit the operation of the Tocco power supply.

The exact arrangement of the field input and output devices will be determined when the furnace is deployed to LANL. Moreover, the programming of the PLC will become a part of the CMR Facility Software Quality Assurance Plan.

Operational Tests

The furnace has been operated and tested to discover any weak points or problem areas and to identify any necessary changes. This followed a natural evolutionary process described below.

Phase I: (low temperature operations 600-800° C)

- These tests were conducted to "shake-out" the engineering bugs in hardware and software design and to refine the operations procedures.

Phase II: (magnetic field analysis)

- Magnetic fields were measured using a Bell gauss meter. Comparison was accomplished distinguishing the magnetic field strength produced by the coil circuit alone, and then re-measured when shielded by the graphite susceptor. The data is illustrated on Figures 11A, 11B, and 11C.

Phase III: (intermediate temperature operations 800-1100° C)

- During these operations, the ramp-up and hold time times were carefully evaluated as a function of object temperature uniformity (Figure 12).

Phase IV: (high temperature operations 1200° C)

- These tests studied the object temperature gradient with emphasis on the data points during the period where the test object was held at 1200° C (Figure 13).

Test Setup:

Figure 11A. Magnetic field analysis test equipment arrangement.

Test 1

Probe inserted into the center of the coil with the susceptor removed:

Results: 10% Power,

NORM: < 1 Gauss

REV: < 1 Gauss

AC: 785 Gauss

Figure 11B. No susceptor; power supply operating at 10% efficiency measured an AC magnetic field 785 gauss.

Test 2

Probe inserted into the susceptor, with the ball removed. Probe location is ball center.

Results: 100% Power,

NORM: < 1 Gauss

REV: < 1 Gauss

AC: 365 Gauss

Figure 11C. With susceptor and power supply at 100% efficiency measured an AC magnetic field of only 365 gauss.

Figure 12. Operation times evaluated as a function of object temperature uniformity during ramp-up and hold periods.

Table 13. High temperature (1200° C) held for 40 min. without significant variation across test object.

Problem Areas

Two problems were encountered during the test operations. It was discovered that the thermocouple probes were very fragile. These probes are small, and after they have been heated, they become somewhat embrittled. Once this occurs, any manipulation or adjustment must be done with extreme care. Another area of concern is the Nextel blanket insulation. It requires constant attention and re-adjustment each time it is removed and replaced around the susceptor and coil system.

Conclusions

The furnace engineering design is sound and should afford the client scientific community many successful operations over the next several years. It has heated test objects to the required temperature (1200°C) while maintaining the temperature constraints prescribed. A computer controls the induction heating equipment and acquires the temperature diagnostic data as well as the required neutron information required.

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