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Enhancing Instrumentation for Reactor Materials Experiments

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Summary

Reactor safety experiments for studying the reactions of a molten core (corium) with water and/or concrete involve materials at extremely high temperature. Such high temperature severely restricts the types of sensors that can be employed to measure characteristics of the corium itself. Yet there is great interest in improving instrumentation so that the state of the melt can be established with more precision. In particular, it would be beneficial to increase both the upper range limit and accuracy of temperature measurements. The poor durability of thermocouples at high temperature is also an important issue. For experiments involving a water-quenched melt, direct measurements of the growth rate of the crust separating the melt and water would be of great interest. This is a key element in determining the nature of heat transfer between the melt and coolant. Despite its importance, no one has been able to directly measure the crust thickness during such tests.

This paper considers three specialized sensors that could be introduced to enhance melt characterization:

1) A commercially fabricated, single point infrared temperature measurement with the footprint of a thermowell. A lens assembly and fiber optic cable linked to a receiver and amplifier measures the temperature at the base of a tungsten thermowell. The upper range limit is 3000^{o}C and accuracy is ±0.25% of the reading.
2) In-house development of an ultrasonic temperature sensor that would provide multipoint measurements at temperatures up to ~3000^{o}C. The sensors are constructed from tungsten rods and have a high temperature durability that is superior to that of thermocouples.
3) In-house development of an ultrasonic probe to measure the growth rate of the corium crust. This ultrasonic sensor would include a tungsten waveguide that transmits ultrasonic pulses up through the corium melt towards the crust and detects reflections from the melt/crust interface. A measurement of the echo time delay would provide the location of the interface.

These three sensors would provide a considerable upgrade of the instrumentation used in our reactor materials tests. The infracouple is a commercial product that could provide an immediate improvement in temperature measurements. The sensor could also serve to corroborate thermocouple data by providing a measurement based upon a different physical principle. The ultrasonic temperature sensor would involve a greater investment and longer time frame than the infracouple, but offers all the advantages of the infracouple along with miniaturization and the ability to measure at multiple locations. In addition, the UTS is the platform from which we would begin development of the crust detector. Of the three sensors, the crust detector requires the most effort and entails the greatest uncertainty. However, a real-time crust thickness measurement has never before been made and such data would be unique and of great benefit to reactor materials experiments.

1. Introduction

For reactor safety studies concerned with molten mixtures of uranium dioxide and metals (corium), it is necessary to generate extremely high temperatures to obtain the conditions of interest. These high temperatures limit the types of sensors that can be employed, especially for measuring characteristics of the corium itself. The initial temperature of a corium melt is typically over 2000^{o}C, which is above the melting point of most sensor materials. The temperature may even surpass the 2400^{o}C upper limit for thermocouples.

Nevertheless, there is great interest in improving instrumentation so that the state of the melt can be established with more precision. In particular, it would be beneficial to increase both the upper range limit and accuracy of temperature measurements. Also, the durability of thermocouples is poor at high temperature, often resulting in premature sensor failure. For experiments involving a quenching melt, it would be of great interest to directly measure the growth rate of the crust separating the molten corium from the overlying water layer.

This paper considers three specialized sensors that could be introduced to enhance melt characterization:

1) A commercially fabricated, single point infrared temperature measurement with the footprint of a thermowell. The upper range limit is 3000^{o}C.
2) An ultrasonic temperature sensor, developed in-house, that would provide multipoint measurements at temperatures up to ~3000^{o}C.
3) An ultrasonic probe, also developed in-house, that could measure the growth rate of the corium crust.

2. Infrared Temperature Sensor

Mikron Instrument Co., a firm that manufactures non-contact temperature sensors such as infrared cameras, has developed a point sensor that is similar in form to a thermocouple [1]. This so-called "infracouple" is essentially an infrared pyrometer that uses a fiber optic cable and lens to measure the temperature at the end of a thermowell. The thermowell (in our case, made of tungsten) would be inserted into the corium melt in the same manner as thermowells for thermocouples. A lens assembly is mounted at the far end of the thermowell, which is outside the reaction vessel containing the corium. The maximum ambient temperature for the lens assembly and fiber optic cable is 315^{o}C. The upper range limit for the sensor is 3000^{o}C and accuracy is ±0.25% of the reading. The cost per unit is approximately $5k.

As supplementary instrumentation, the infracouple has several advantages: a) it can provide a temperature measurement above the 2400^{o}C thermocouple limit, b) it is expected to be more robust and longer-lasting than tungsten-rhenium thermocouples, and

c) it offers a corium temperature measurement using a completely different physical principle. The latter fact could be used to support the veracity of thermocouple measurements. Disadvantages include the relatively large minimum diameter of the thermowell (12.7 mm) and the fact that each sensor measures temperature at a single location (the end of the thermowell). Also, one cannot rule out the possibility that a breach in the thermowell could occur, which would destroy the lens and fiber optic cable. However, a replacement of these components would cost approximately $700 and so most of the investment, which is in the electronics, would be secure.

Clearly, the addition of one or more infracouples to our set of instrumentation would be of great value. In addition to confirming thermocouple measurements, the sensors could provide data for thermite development tests that has been previously unavailable. There are occasions where experimental thermites prove to be hotter than expected, which can destroy thermocouples within milliseconds of ignition and render tests nearly useless. The data from such tests is, at best, difficult to interpret. However, the infracouple is expected to provide useful data in such instances, which would salvage much of the considerable time and effort expended in conducting a developmental test.

3. Ultrasonic Temperature Sensor

3.1 Background

An ultrasonic sensor relies upon the dependence of the acoustic velocity in a solid medium on the physical properties of the material. A typical sensor consists of a relatively long and narrow piece of metal that acts as a waveguide to propagate either torsional or extensional waves (fig. 1). The acoustic waves are often generated by a magnetostrictive rod and a coil. Magnetostriction is the process by which a material expands and contracts in response to a varying magnetic field. Thus a rapidly varying magnetic field can be used to generate high frequency acoustic waves in the magnetostrictive material, from where they propagate into an attached waveguide.

The velocity of longitudinal waves traveling along a waveguide that is narrow compared with the wavelength is given by [2]:

$$v = \left(\frac{E}{\rho} \right)^{1/2}$$

where both the density ρ and Young's modulus E are functions of temperature. A thin metal rod or wire may be used as the waveguide and discontinuities can be created at selected positions by, e.g., machining notches into the rod. The acoustic waves will then be partially reflected at these notches. Reflections from adjacent notches are separated in time according to the distance l between the notches and the acoustic velocity:

$$\tau = 2l / v$$

Thus the time delay between echoes (τ) serves as an indication of acoustic velocity in the waveguide (v). Variations in sensor temperature can be detected through measurements of the echo delay, and this pulse-echo mode is the basis for most ultrasonic thermometers.

For special classes of research there is a need to measure temperature distributions within solids or liquids at very high temperatures (>2000°C). The objects are often opaque, which precludes the use of an optical pyrometer. Thermocouples may be employed in such cases, but they are restricted to temperatures below about 2400°C and can suffer from decalibration and premature failure even below this limit. This is of particular concern for measurements in radiation fields. Ultrasonic temperature sensors are relatively insensitive to radiation and have the advantage of being able to function near the melting point of the sensor itself. A probe fashioned from tungsten can, in principle, be used at temperatures close to the metal's melting point of 3410°C.

Initial development of high-temperature UTSs took place during the early seventies and was motivated by the unique requirements of nuclear reactor research. Examples include in-pile measurements of fuel centerline temperatures [3,4], coolability experiments for fast reactor core debris [5] and, more recently, corium temperature measurements for vapor explosion experiments [6]. The UTSs used in the in-pile experiments measured average temperatures in five zones along a fuel pin and functioned for hundreds of hours at temperatures as high as 2500°C. In the experiments with corium, UTSs have proven serviceable to nearly 3000°C. In each of these cases UTSs were chosen as the only viable alternative considering the temperature range of interest and the extreme conditions the instrumentation had to endure.

3.2 Probe Development

The development of UTSs would begin from scratch since there is no previous experience in RAE with high temperature ultrasonic temperature sensors. However, the author has worked with such sensors at JRC Ispra and also developed an ultrasonic

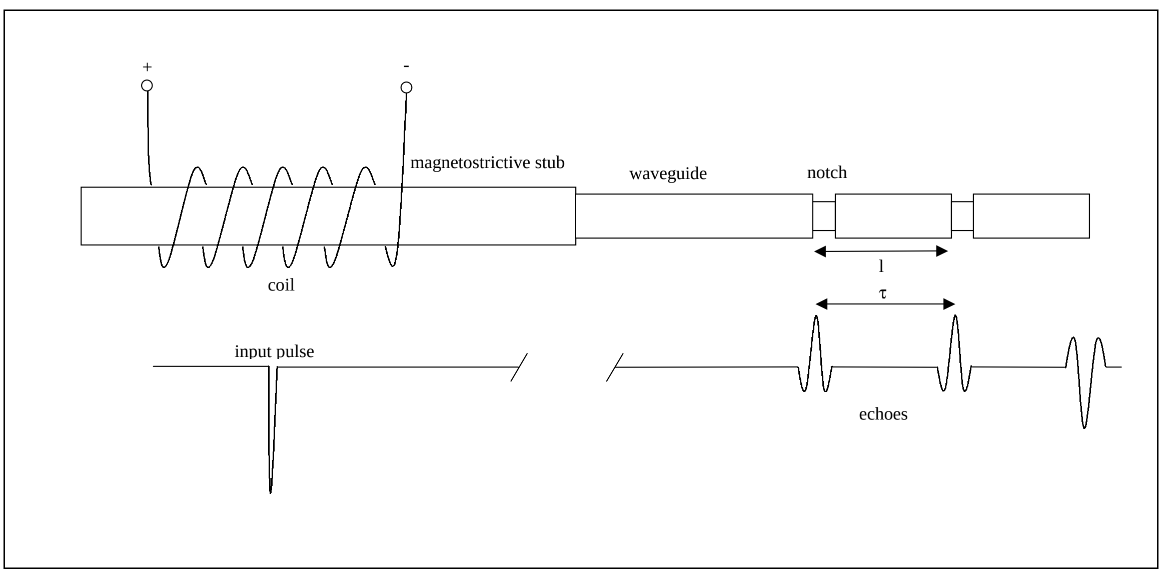

Figure 1. Schematic of ultrasonic sensor and echo pattern.

hydrogen sensor [7]. It is estimated that roughly a year would be required to produce the first successful prototype for temperatures above 2000^{o}C (measuring lower temperatures is less technically challenging and could be accomplished more quickly). Equipment and staff costs associated with the development in the first year are estimated to be $240k.

A typical probe would consist of a thoriated tungsten rod, 1 mm in diameter, with 3-5 measurement zones, each approximately 10 mm long. Thorium-doped tungsten has historically been the material of choice for high temperature because thorium stabilizes the tungsten grain boundaries and largely eliminates calibration shifts after temperature cycling. Other candidate materials, such as rhenium, suffer from excessive attenuation at high temperature.

For sensor excitation and signal processing, suitable off-the-shelf electronics are available from the nondestructive testing industry. Pulser/receiver electronics can be purchased as all-in-one PC cards with 100 MHz analog to digital converters. Such systems would offer a time resolution of 10 ns, which translates into temperature resolution of roughly 10^{o}C for a 10 mm long measurement zone (the change in sound speed for tungsten at high temperature is ~ 0.9 ns/^{o}C cm).

The UTS can provide all the benefits of the infracouple: a) measurements above the 2400^{o}C thermocouple limit, b) a sensor that is more robust and longer-lasting than tungsten-rhenium thermocouples, and c) a corium temperature measurement based upon a completely different physical principle. In addition, however, the UTS offers the ability to measure multiple zones with a single sensor. And probes can be made rather small, down to at least a 5 mm diameter (less than 1/6 the footprint of the infracouple).

Finally, it is noted that nearly all the hardware purchases and development work associated with the UTS are necessary to pursue the more challenging task of developing a sensor to measure corium crust growth rate. Such a sensor is discussed in the next section.

4. Crust Detector

For experiments involving a corium melt quenched with water, one of the chief quantities of interest is the thickness of the crust as it forms over the melt. The crust insulates the melt from the overlying water layer and inhibits heat transfer between the two. However, water is able percolate down through cracks in the crust to enhance heat transfer above what one would expect if the crust were impervious. Both the nature and extent of such enhanced heat transfer is not known and the subject of continuing studies. Having a history of the crust thickness would be of great benefit to understanding the heat transfer mechanisms involved in quenching the melt.

Melt quench tests occur under such severe conditions that, to date, no direct measurement of the crust thickness has ever been made. It is difficult to gauge the chances of producing a sensor with such a capability because the physical properties of the molten corium and the precise nature of the crust/melt interface are not well known. Also, the extremely high melt temperature greatly limits the number of materials that are suitable for the sensor. Nevertheless, some recent developments associated with die casting suggest that a "crust sensor" is possible.

There are two variations of the proposed crust sensor, both of which rely upon ultrasonic transmissions similar to that of the UTS. The first version would be a sensor that protrudes through the bottom of a reaction vessel containing corium, extending a small distance into the melt itself. The sensor would send ultrasonic pulses up towards the crust where they are reflected back and detected by the sensor. The time delay would be used to determine the distance of the crust from the sensor tip. This technique has been used with molten steel to monitor the die casting process [8]. The authors used a waveguide to transmit ultrasonic pulses through the wall of a die and into the molten metal. The pulses traveled through 5 mm of melt to the other side of the die, reflected off the wall, and returned to the sensor. The delay time gave an indication of metal temperature while changes in signal attenuation were used for monitoring the die filling process and detecting defects. At the same laboratory, other sensors were developed to detect interfaces at the bottom of pools of molten magnesium (700^{o}C) and aluminum (960^{o}C) [9]. These sensors were made of various combinations of steel, aluminum, and bronze, and could detect interfaces through tens of centimeters of melt.

A key element to both of the sensors described above is the use of a clad "buffer rod" that serves as an acoustic waveguide between the transducer and the molten material. The purpose of the cladding is analogous to that of a fiber optic cable: it confines the energy of the propagating wave to the waveguide and isolates it from the environment. The waveguide increases the signal to noise ratio and enables one to pass the sensor through a vessel wall without disturbing the signal.

Even with the demonstrated success of the sensors described above, it would be challenging to develop a similar sensor for corium melts. The following issues would have to be addressed:

1) Our high melt temperatures preclude the use of *all* of the materials used as waveguides in the cited studies. We will be limited to refractory metals, which may prove difficult to fashion into the clad buffer rods.
2) How well will ultrasonic pulses travel through the corium melt? Of particular concern are the acoustic properties of the melt while it is between the liquidus and solidus temperatures.
3) How well is the sound speed of the melt between the probe and crust known? This quantity is necessary to convert the sensor signal into a crust interface location.
4) The nature of the corium melt/crust interface is not well defined. Will signals reflecting off the crust be sufficiently strong to detect the location of the interface with acceptable accuracy?

The second version of the sensor is simpler than the first and may circumvent the difficulties created by having a melt with ill-defined acoustic properties. This sensor would again be made of refractory metal, but it would be long enough to penetrate through the crust. This sensor would use the fact that echoes are produced by discontinuities along the waveguide. In general, solid objects should not come in contact with the waveguide because false echoes may be generated, which can then affect sensor operation and/or calibration. For this reason, the waveguide is often enclosed within a sheath for protection, and the two are separated by a gas-filled gap. This is how a UTS would be constructed to ensure that only the machined notches produce echoes.

However, if a sensor has no sheath and a portion of the tip is embedded in the crust, an ultrasonic pulse will be partially reflected back along the sensor at the location of the melt/crust interface. A second reflection would occur at the next density change (at the water layer if the sensor is mounted from below, or the melt/crust interface if the sensor is mounted from above). Again, there are some unanswered questions regarding the feasibility of such a sensor:

1) Could the sensor, once fixed on one end by the crust, buckle and break during the freezing process?
2) Would the signal to noise ratio be high enough to obtain a useful measurement?
3) Is it better to detect the melt/crust interface directly from below (better S/N ratio, but significant technical development for a high temperature clad buffer rod) or to insert the probe from above (the second echo at the melt/crust interface will be very weak, but probe construction and mounting is straightforward and would require little special development)?

5. Conclusion

This report has identified three sensors that would provide a considerable upgrade of the instrumentation used in our reactor materials tests. The infracouple is a commercial product that could provide an immediate improvement in temperature measurements. The sensor could also serve to corroborate thermocouple data by providing a measurement based upon a different physical principle.

An ultrasonic temperature sensor would involve a greater investment and longer time frame than the infracouple, but offers all the advantages of the infracouple along with miniaturization and the ability to measure at multiple locations. In addition, the UTS is the platform from which we would begin development of the crust detector.

Of the three sensors, the crust detector requires the most effort and entails the greatest uncertainty. However, a real-time crust thickness measurement has never been made before and such data would be unique and of great benefit to reactor materials experiments.

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