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RADIATION HARD SENSOR FOR REACTOR APPLICATIONS

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Abstract

A novel method of measuring temperature of the coolant inside a reactor core is presented. The method, which is both standoff and non-invasive, is based on the interaction between an ultrasonic pulse and a delayed light pulse in the coolant. In the interaction, the light pulse, which is scattered backward by Brillouin scattering, is frequency-shifted. The frequency shift is dependent on the temperature and other parameters of the coolant. The light pulses and the ultrasound pulses are generated and detected outside of the core.

INTRODUCTION

Molten salt-cooled reactors and high temperature gas-cooled reactors are actively being developed for the next generation of nuclear power. The interiors of the cores of molten salt reactors and gas-cooled reactors are in excess of 500 °C, and some of the molten salt coolants are corrosive, and all operate in high neutron fluxes and other radiation from radioactive fission products. This presents a challenge to develop monitoring instrumentation that will operate for long times under those conditions. One of the parameters of importance is the temperature inside the core, and its distribution throughout the core. The monitoring system described here is non-invasive and standoff, with no active components inside the core.

Our main intended application is the Mu*STAR accelerator-driven sub-critical, graphite-moderated, molten salt reactor [1], depicted in Fig. 1.

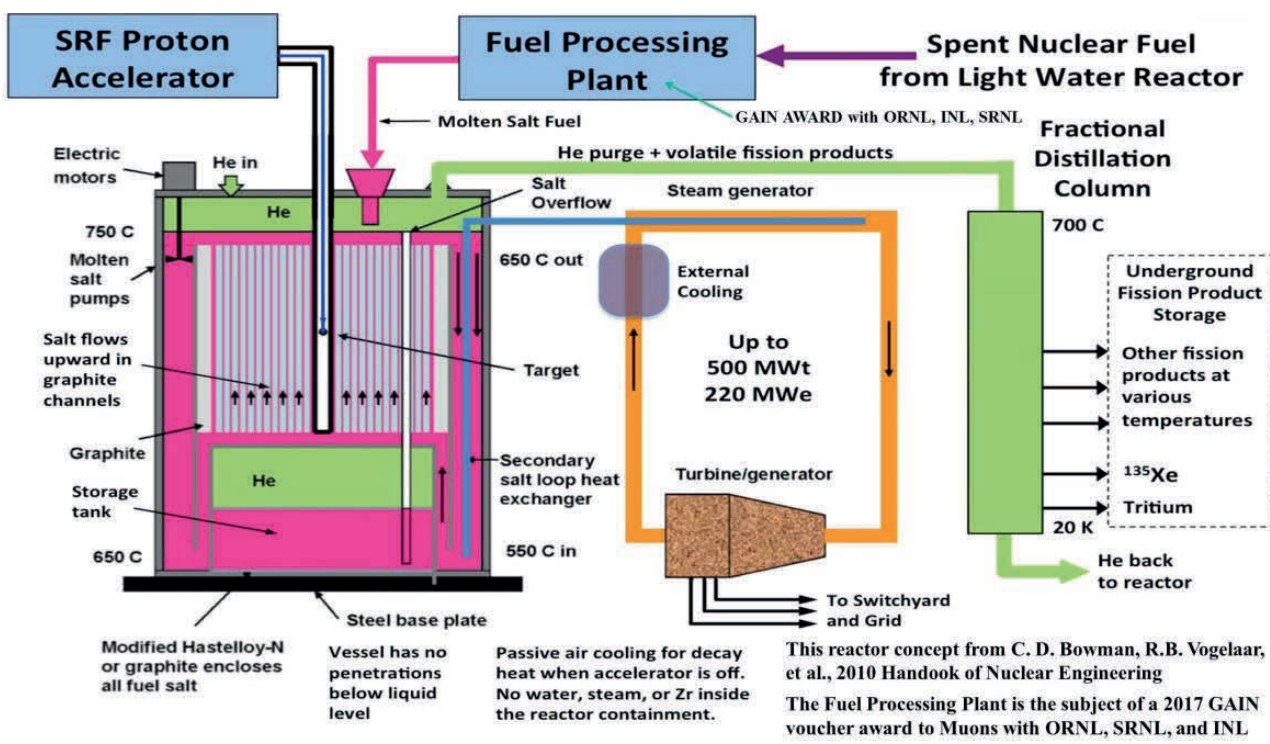

Figure 1: Mu*STAR reactor system. The reactor core, shown at left, is made of graphite cylinders filled with molten salt that circulates upward through the cylinders. Measurement of the temperature distribution in the various cylinders is an intended application of the method presented in this paper.

BASIC CONCEPTS

The theory of the interaction of light and sound is covered in Reference [2]. As shown in Fig. 2 an ultrasonic pulse generator sends a pulse down the column of fluid whose temperature is to be measured. An appropriate time later the laser sends an optical pulse down, which intersects the ultrasonic pulse at the desired depth for the measurement. A fraction of the optical pulse is scattered backward by the ultrasonic pulse, and propagates upward to the Optical Processing unit.

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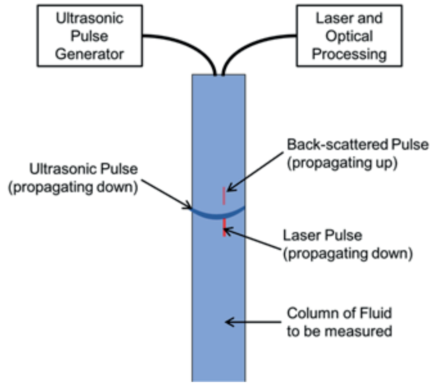

Figure 2: Representation of ultrasonic pulse and delayed laser pulse interacting in fluid column. The laser pulse is scattered upward and shifted in frequency.

Since the ultrasonic pulse is moving downward, the light received by the Optical Processing has been Doppler shifted down in frequency. The Optical Processing heterodynes the received light with a portion of the original laser light, directly measuring the Doppler shift. From the shift in frequency the speed of the ultrasonic pulse can be calculated, which in turn yields the temperature of the fluid in the region where the two pulses overlapped. The actual implementation will use a continuous-wave (CW) laser, as described below.

LASER AND OPTICAL PROCESSING

For a CW laser, a schematic diagram of the laser and optical processing units is shown in Fig. 3. The fiber-coupled laser light is split so 99% goes through the circulator to the collimator. The collimator converts the light from the fiber into a free-space parallel beam down into the fluid column; it also collects the back-scattered light into the fiber (in the other direction). The circulator sends the back-scattered light into the photodetector (PD), where it is combined (heterodyned) with 1% of the laser light. Attenuators (not shown) will be used to equalize the light intensities of the two fibers going into the photodetector. The photodetector is interfaced into the computer such that it measures the frequency of the heterodyne during the timing window.

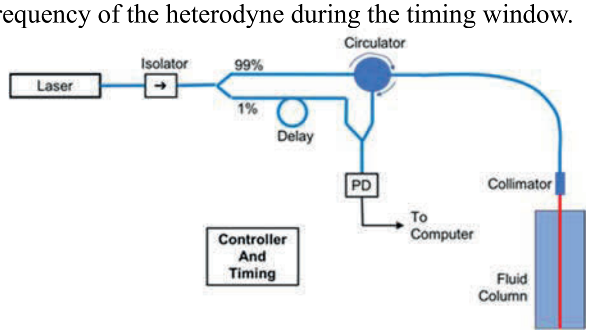

Figure 3: Laser and optical processing elements (not all elements are shown).

The interface between the photodetector and the computer counts the frequency of the heterodyne signal seen by the PD, within each timing window. This design permits a much more stable laser, and generates measurements all along the pulse path in the fluid. The timing determines how large a region of the fluid is used for each measurement; larger regions give averaging over more cycles of the heterodyne, so there is a trade-off between spatial resolution and temperature precision. We expect to arrange the timing to give measurements every 10–20 cm along the pulse path in the fluid. For a fluid with speed of sound 1500 m/s, such measurements would span about 100 microseconds, which is easy to do in the electronics. The frequency of the heterodyne depends on the laser wavelength and the properties of the fluid; it is in the range 500–2000 MHz, which is also easy to handle in the electronics. The repetition rate of the ultrasonic pulses can be 10–20 Hz, so we can average hundreds of pulses and provide several measurements per minute, at ≈15 cm intervals along the pulse path in the fluid.

RELATED METHODS

Some alternative methods of measuring temperature in molten salt have been also been investigated, and their results have substantiated some aspects of our conceptual design.

Purely Acoustical Method

In this method, a bent metallic acoustical waveguide is immersed in the molten salt [3]. An ultrasonic pulse passing down the waveguide is reflected at the end of the waveguide and at bends in the waveguide, as illustrated in Fig. 4.

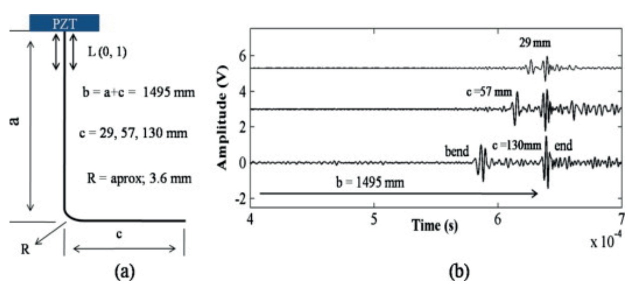

Figure 4: Results from Reference [3] method for sending and receiving an acoustical pulse using a solid waveguide, bent at several places. The time difference between the pulse reflected at the bend and that reflected at the end depends on the temperature along the waveguide.

The signals in Fig. 4 show that timings between incident and reflected ultrasonic pulses can be distinguished. The time differences can be used to determine the temperature at the bend points. However, the speed of sound in the metallic waveguide is altered by radiation damage, particularly, by the accumulated neutron flux exposure over time. Another disadvantage of this method for use in the Mu*STAR design is that the bent sections (indicated by “c” in Fig. 4) are not well suited to measurements inside narrow channels, such as those in the graphite moderator in the embodiment of the Mu*STAR system.

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Compression of Optical Fiber by Acoustical Pulse

In this method an optical fiber is immersed in a liquid and an acoustical pulse is generated in the liquid. The acoustical pulse causes compression of the liquid and in the fiber. The laser pulse in the fiber undergoes Brillouin scattering off the phonons produced in the compressed fiber. The scattered pulse is wavelength-shifted and analyzed by a Fiber Bragg Grating (FBG), which can be engraved in the fiber, or by a Bragg interferometer installed outside of the core of the reactor.

Figure 5 displays results from Reference [4] showing that the wavelength shift is nearly linearly dependent on the temperature difference between the measured temperature and a reference temperature, which substantiates an aspect of our approach.

However, this method has limited longevity due to radiation damage to the optical fiber, deformation of the grating and consequent reduction of its reflectivity, and distortion of the reflected wavelength. These problems are eliminated in our design since the fiber is not inside the core of the reactor. Furthermore, as stated in the following excerpt from Reference [4], the problem has not been overcome: “Although FBGs behavior can be qualitatively explained, the lack of models that accounts [sic] fully for the underlying physics governing the behavior of various types of FBGs in radiation environments remains a problem.”

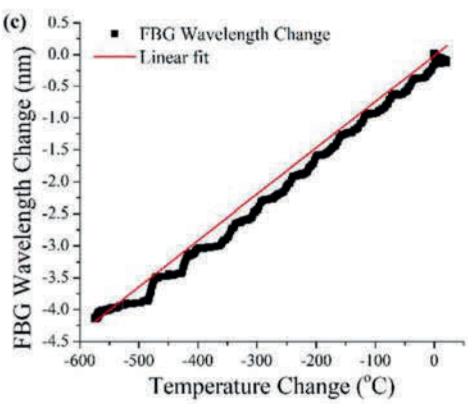

Figure 5: Result from [4] showing nearly linear relation between wavelength shift and temperature change in liquid.

CONCLUSION

In our approach, there are no fibers, metallic waveguides, nor active electronic sensors in the reactor core, thus avoiding problems of radiation damage to them. In addition, there is no contact between the optical or acoustic elements and the (corrosive) molten salt in the reactor.

Our method is not limited to 1-dimensional columns of molten salt. It can readily be extended to 3 dimensions to measure temperature distributions in fast reactors within the volume of molten salt, in which the fuel is dissolved in the molten salt. It can also be applied to water-cooled reactors, and to measure temperatures in non-nuclear hostile liquid or gaseous environments.

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