Demonstrating Distributed Fiber-Optic Temperature Sensors in a Simulated Gas-Cooled Reactor Outlet[1]

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INTRODUCTION

Gas-cooled reactors operate with a large temperature variation across the core due to the low heat capacity of gaseous coolants such as helium. There are also significant variations in local power generation and coolant flow rates through many parallel flow channels that ultimately combine and mix at the core outlet. These complexities make it difficult to identify and/or predict the hot channel within the core, which ultimately limits the total reactor power. In addition, the complex mixing that occurs at the core outlet can make it difficult to accurately monitor the mixed mean core outlet temperature, which is used for calorimetry and periodic calibration of the reactor power. Finally, large core outlet temperatures could potentially damage downstream components due to alternating thermal loads.

Even though gas-cooled reactors have been operated in many countries such as the United States [1], United Kingdom [2], and China [3] for many years, their reliability has been low. The aforementioned issues with mixing at the core outlet have contributed to these reliability issues. For example, in the Fort Saint Vrain high temperature gas-cooled reactor, temperature measurements made at the coolant outlet were observed to be as high as 22°C, over an 8–20 min period with no obvious pattern [1]. The limited instrumentation led to a three year experimental study to determine the cause of the fluctuations [1].

The Transformation Challenge Reactor (TCR), shown in Figure 1(a), sought to leverage recent advances in materials, manufacturing, and modeling and simulation to demonstrate a gas-cooled nuclear microreactor core that would be fabricated using advanced manufacturing [4]. One novel aspect of the core design is that it included sensors that were to be embedded within the fuel [5] and throughout the outlet plenum region [6] to improve the understand of power generation, heat transfer, and thermal hydraulics.

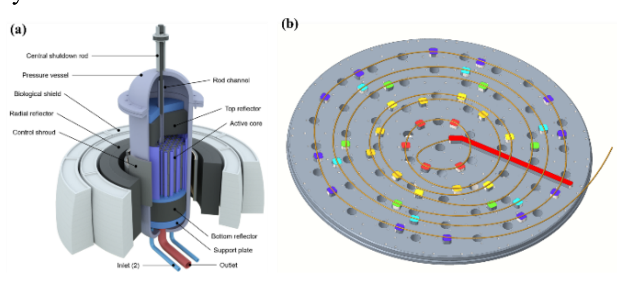

Figure 1. Drawings of (a) the TCR and (b) an example of routing a single fiber around all the outlets of the support plate beneath the core [4, 6].

Figure 1(b) shows a conceptual rendering of one potential routing of a single optical fiber to measure the local outlet temperature of every individual coolant channel. Alternatively, instrumenting every coolant channel with conventional thermocouples is not ideal considering that there could be hundreds of flow channels, and each thermocouple lead would need to be routed through penetrations in the pressure vessel. In addition, thick-walled thermowells are used to route the thermocouples through the pressure vessel wall. Additional thermowells could potentially lead to obstructions in coolant flow due to the larger diameter of the thermowells.

Fiber-optic sensors could offer a superior alternative to conventional sensors such as thermocouples since they are immune to electromagnetic interference, and are resistant to ionizing radiation [7], and high temperatures (up to approximately 1,000°C) [8]. For example, fiber optics have been used to measure distributed measurements of temperature [6, 9] and strain [10], in other industries, such as measuring strain and cracking in pipe lines and bridges, temperature and pressure monitoring in oil and gas wells, and around cables and transformers in the energy sector [11].

Although additional work is needed to understand fiber optics performance in a reactor environment, they offer the ability to map environmental parameters such as temperature with only a single sensor. In this work, a testbed was designed to test the ability of fiber optic sensors to resolve individual coolant channels prior to downstream mixing. Cold and hot air streams were mixed at different ratios through multiple channels and directed through an orifice plate to simulate a scaled version of the gas-cooled reactor outlet, as demonstrated in Figure 1(b) for the TCR. An appropriate support structure was needed to properly mount and route the fiber around each flow channel. The mounted fiber was subjected to various thermal transients in the test bed that included exposures to temperatures ranging from approximately 25 to 450°C. Discussion will include fiber's performance and potential application in gas-cooled reactors. A detailed discussion of the fiber's performance and implications for gas-cooled reactor applications is provided elsewhere [6].

METHODS

A custom experimental testbed was designed to vary temperature by mixing hot and cold air streams at different ratios, as shown in Figure 2(a) [6]. The cold (i.e., room temperature) air intake was provided by a regenerative air blower, and the hot air intake was sourced by a heat gun. Six different piping stems were connected to a manifold on both the cold and hot air legs to divert flow (Figure 2(c)), with mixing occurring at a Y-junction downstream from each manifold.

Controller valves were installed on each pipe stem on the cold leg as a method for regulating the temperature of the flowing air. Each outlet pipe was leveled to ensure that the support plate would sit flat. On the orifice plate, the outlets were numbered clockwise 1 through 5, and the center channel was labelled 6, as shown in Figure 2(b). As shown in Figure 2(c), the ordering of the pipe stems into the manifold was not sequential because the piping was routed to minimize bends, which affected the ordering [6].

An orifice plate was scaled from the TCR support plate and had an outer diameter of 152 mm, a thickness of 15 mm, and six holes to direct the outlet flows, each 25 mm in diameter [6]. A 10 mm tall star-shaped support structure was printed on top of the orifice plate with holes and open channels, as shown in Figure 2(b) [6]. The orifice plate was fabricated via binder-jet printing from a SS316 feedstock (Desktop Metal, MA). A SS316 metal sheath, ~1.6 mm in diameter, used to house the fiber and hold it in place during the testing. The sheath was spot welded to at the entrances to the holes as it was routed around the orifice plate. Additional holes were machined into the side of the channels as a port for inserting Type-K thermocouples for comparison on temperature with the fiber.

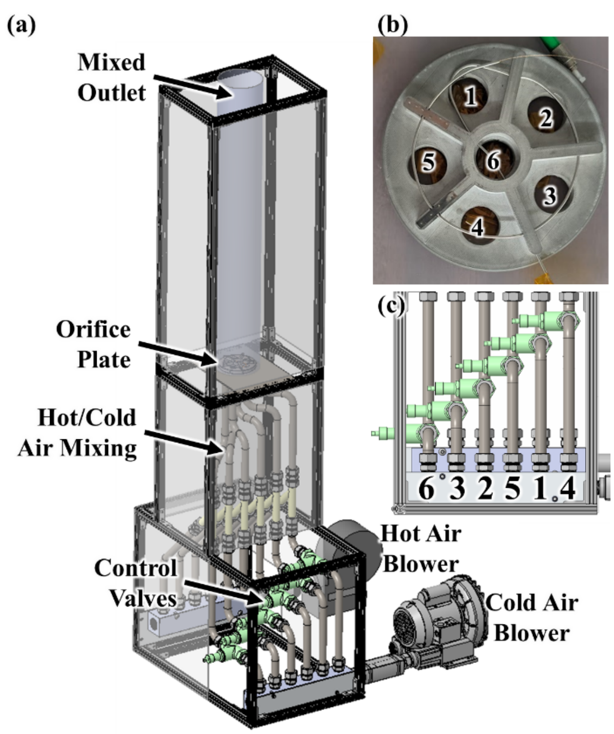

Figure 2. (a) Testbed designed with six legs, each with the ability to mix hot and cold air [6]. (a) Orifice plate scaled from the TCR support plate to be used in the testbed [6]. (c) Cold-air manifold for the testbed in which the corresponding leg to orifice hole is labeled [6].

Distributed measurements were made by inserting a polyimide coated, SMF28, fiber-optic into the SS316 sheath [6]. The diameter of the fiber core, cladding, and polyimide coating were ~9, 125, and 155 µm, respectively. During testing, the fiber was continuously interrogated using a Luna Innovations Optical Distributed Sensor Interrogator (ODiSI) 6108, which relies on the Rayleigh backscatter of light from the optical fiber during interrogation by a tunable laser source [6]. The backscatter signal can be discretized into spatial regions using optical frequency domain reflectometry. The beat frequencies of the measured interference pattern are Fourier transformed to isolate discrete reflections and then transformed back into the spectral domain to determine the relative spectral shifts. A temperature can then related to the spectral shift using calibration data published by Jones et al. [6, 9].

RESULTS AND DISCUSSION

The system was allowed to reach steady state by flowing hot air for approximately 90 min. Once the maximum temperature of the system was achieved, cold air was introduced into the flow stream. The control valves were partially opened, ~15–20% from their fully closed position, set based on the user's discretion to set each channel at a different temperature. The lower bound of the setpoint temperatures (275°C) is generally representative of typical inlet coolant temperatures for gas-cooled reactors, and the maximum setpoint temperature (400°C) was selected to provide a 50°C margin to the maximum allowable temperature of the system (450°C).

Figure 3(a) maps the temperature profile that the optical fiber measured as a function of position and time during the thermal testing [6]. The fiber was first routed through the center outlet (channel 6) before it passed radially outward and through channels 2, 3, 4, 5, and 1, as shown in Figure 2(b) [6]. The local temperature maxima with respect to position corresponding to each channel location are indicated in Figure 3(a) [6]. Channel 4 exhibited the coldest temperatures since it is the first leg on the manifold, shown in Figure 2(c) [6]. Air entering the manifold would have to make an immediate 90° turn to enter the channel, making the impact on temperature the smallest. Channel 6 shows the highest temperatures since it is last on the manifold, making it more susceptible to higher hot air flow.

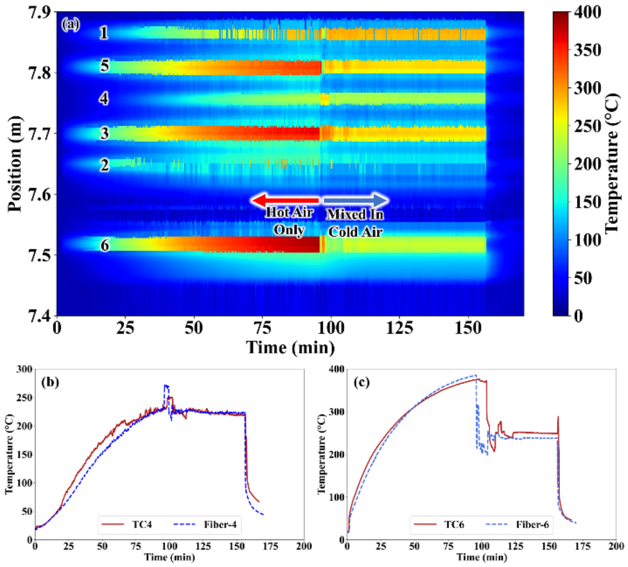

Figure 3. (a) Spatially mapped temperature along the region of the fiber routed around the orifice plate [6]. Temperature comparison as read by the thermocouple and corresponding position along the fiber, for (b) channel 2 and (c) channel 4 [6].

Type-K thermocouples were also placed at the center of each outlet to compare with the fiber. For this experiment, placing thermocouples into each outlet was easy, but scaling that up to a gas-cooled reactor with hundreds of flow streams would be impractical. Comparison of the thermocouple with a position along the fiber near the center of the channel is shown for channel 4 in Figure 3(b) and channel 6 in Figure 3(c) [6].

The temperatures recorded by the thermocouples and fiber generally showed good agreement. Some of the discrepancies could be explained by differences in the precise position of the sensors over the small 25 mm diameter flow area at the outlet of each channel [6]. There may have also been physical movement as temperatures increased, due to the differences in thermal expansion between the various materials [6]. Even though the discrepancies between the thermocouples and fiber were small, future studies are warranted to fully understand the differences between using the two types of sensors. Improvements on the current design would include limiting effects of vibrations from the system by properly securing the fiber and/or embedding the fiber in the component during fabrication via advanced manufacturing techniques [6, 10].

SUMMARY

Fiber-optic sensors offer the potential for distributed sensing in harsh environments and could be used for mapping individual core outlet temperatures in advanced nuclear reactor designs such as TCR. This study designed an experimental testbed with the capability to vary temperatures in six different channels using mixed hot and cold air to simulate the mixing that occurs in the outlet of a gas-cooled reactor. Maximum temperatures of 450 °C were achieved, which are within the range of some gas-cooled reactor designs. The mixed air stream was discharged through an orifice plate in which the temperatures of each channel were measured with a single fiber optic and six thermocouples, placed at the center of each outlet. The system was allowed to heat to a maximum temperature, and then user-controlled amounts of cold air were mixed into the hot air stream. The temperature of each channel was set to a different value to induce a variation across each outlet. Overall, the fiber accurately measured the temperature of all six outlets, as compared with the thermocouples located at the center of each outlet. Minor differences in temperature magnitudes were observed between the fiber and thermocouple but were attributed to differences in the placement of the fiber and thermocouple.

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