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Investigations of Advanced Measurement Methods for High-Temperature Heat-Pipe Experiments

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INTRODUCTION

Microreactor systems can provide a stable, continuous supply of abundant energy in a relatively small footprint. For microreactors specific deployment opportunities may include provision of heat and electrical power to remote commercial and industrial applications, such as remote civilian municipalities, or isolated military installations, where typical power needs are in the range from 1 to 10 MWe. In many current applications, power generation at this scale is achieved through the use of diesel generators. However, increasing costs, clean-energy goals, and supply-chain constraints have prompted a desire to examine other options to ensure energy availability and reliability. Microreactors generally produce about 0.1 to 50MWe [1]. They are factory manufacturable, easily transportable and, due to neutronic simplicity, allow for semi- or fully autonomous operation. Ongoing efforts are underway to ensure accelerated deployment, the U.S. Department of Energy (DOE) Microreactor Program (MRP) [2] works closely with vendors, the Nuclear Regulatory Commission (NRC), and other U.S. DOE programs to develop capabilities to demonstrate the concept feasibility through non-nuclear testing.

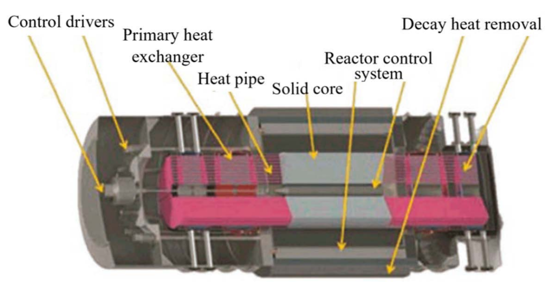

Fig. 1. Heat-pipe-cooled microreactor design concept. Adapted from [3].

Various types of microreactor designs are under consideration, and among those the heat-pipe cooled reactor designs (illustrated in Fig. 1) are currently being actively investigated at Idaho National Laboratory (INL). In order to support non-nuclear testing and demonstration of technology under the MRP, Single Primary Heat Extraction and Removal Emulator (SPHERE) was constructed to perform high-temperature heat pipe (HP) experiments at INL [4].

Meanwhile, software verification and validation (V&V) hold an important role in the safety design and analysis for nuclear facilities, as the codes and models utilized in calculations demonstrate the safety basis as part of DOE authorization must demonstrate an acceptable pedigree. The Nuclear Energy Advanced Modeling and Simulation (NEAMS) program is developing tool for HP applications, currently under development called Sockeye [5], and it is based on the Multiphysics Object-Oriented Simulation Environment (MOOSE) [6] finite element framework. Recently, the MRP technical report published at INL [7] pointed out there were some V&V needs for Sockeye development, and more comprehensive experimental data, preferably the internal measurements during HP operation, is crucial for accurate modeling. Therefore, in order to construct high-quality high-fidelity database, advanced measurement techniques for HP internal physics should be considered and investigated to account for the high-temperature HP experiments.

Heat Pipe: Physics And Measurement

In the past several decades, heat pipes (HPs) are becoming increasingly popular, recognized as one of the most effective passive heat transfer devices available. Therefore, HPs have been employed in a wide variety of thermal applications including micro-electronics cooling, vehicle thermal management, and energy storage/recovery systems [8-10]. Among various types of HPs available, our particular interest to implement for MRP is the liquid-metal heat pipes (LMHPs) which use alkali metals as a working medium. Given the LMHPs can offer a reliable and effective way of thermal management for high-temperature thermal systems, great attention has been paid to them from various industries to build solar collectors [10], advanced nuclear reactors [11, 12], space power systems [13-15], etc.

In general, HPs are passive thermal transfer devices able to transport large amounts of heat over relatively long distances, with no moving parts, using phase-change processes and vapor diffusion. The main structure of a HP consists of an evacuated tube partially filled with a working fluid that exists in both liquid and vapor phases. Fig. 2 represents the basic steps of operation of HPs, and the basic operation is a continuous cycle. When the HP is heating up, the working fluid is allowed to evaporate. The difference in densities between the vapor and liquid, as well as the resultant pressure gradient between the evaporator and condenser parts, allows the vapor to reach the cool condenser section. The difference in wall temperature causes the vapor to condense and release the latent heat, allowing the fluid to return to the liquid pool located in the evaporator by capillary wicking structures [16].

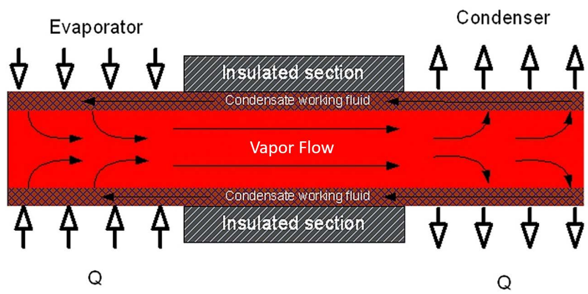

Fig. 2. Heat pipe working cycle. Adapted from [17].

According to the Sockeye development manual [18] and the computational modeling needs to support the microreactor development and demonstration program [19, 20], advanced measurement techniques are needed to obtain the following properties with high accuracy and repeatability:

- Temperature on internal and external side of the HP during the full operation cycle;
- Stress and displacement measurement for the containment holding the HP;
- Internal measurement of void fraction and film thickness for operating HPs;
- Gas velocity in the vapor core of the HP in operation;
- Sodium vapor pressure inside the HPs at different operating stages.

These quantities mentioned above are extremely arduous to measure due to the high operating temperature of LMHPs. What's more, the HPs' stainless steel sheath makes it impossible to visualize the internal part with the traditional optic measurement techniques. Based on these measurement needs as well as challenges, an extensive literature review is presented with the available and possible advanced measurements techniques.

SPHERE Facility

The major benefits to performing electrically heated experiments - besides not having to work with criticality challenges, reactor constraints, and activated materials - are the ability to incorporate more-detailed instrumentation during the tests. Non-nuclear experiments, which will be performed with SPHERE facility using a single HP, will provide some insights into thermomechanical parameters and quantify fundamental limitations of heat-pipe-cooled microreactor components and systems [21].

The SPHERE facility is equipped with a test chamber that allows for either vacuum (10^{-4} torr) or inert gas operation. As shown in Fig. 3, the test chamber is an 8-ft long, 6-inch diameter quartz tube with flanges for gas flow connections, instrumentation feedthrough ports, and several internal Macor ceramic supports. The central HP is heated utilizing 6 surrounding cartridge heaters, which have a maximum heat-flux value of 3.8 W/cm^2 to mimic the expected microreactor core power densities. Cooling water is recirculated using a 2.5 kW circulating chiller unit. The water-flow loop includes a precision turbine flow meter and a delta-T meter that will allow for accurate determination of the heat-removal rate from the HP to the cooling water. The test article was equipped with a thermowell that allowed for a type-K multipoint thermocouple with ten points to be used to get internal temperature measurements along the axis of the HP. External thermocouples, also type-K, were spot welded to the outside of the HP as well as on the outside of the hex block using stainless steel straps to get a better temperature distribution of both the HP, and the hex block.

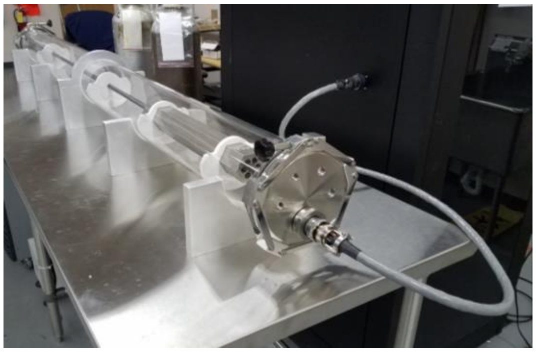

Fig. 3. Single heat-pipe experiment quartz tube with core block, end flange, and Macor ceramic supports.

OVERVIEW OF ADVANCED MEASUREMENT TECHNIQUES

This section provides the potential advanced measurement techniques that can be utilized for the high-temperature HP experiments and visualizations.

Temperature Measurement

To determine the HPs thermal performance, temperature measurement is a key parameter to investigate. For the alkali metal charged HPs, the resultant high-temperature and corrosive environment limit the available component and instrument material options.

As a relatively new technique, distributed temperature sensing using fiber optic is based on Rayleigh scattering and swept-wavelength interferometry; thousands of temperature measurements can be acquired using a single optical fiber [22]. Given the mentioned advantage, a distributed temperature sensor (DTS) can span large flow fields and function in environments that are unsuitable for image-based techniques [23]. With the improved coating formula and protection, the distributed temperature sensors (DTSs) have been shown to function well at temperatures up to 600 °C [24]. As a recent progress, Gerardi et al. [25] immersed their improved DTSs in liquid sodium pool and obtained high-resolution liquid-sodium temperature measurements.

Stress/Strain Measurement

In order to assure the accuracy of the stress measurements, the traditional strain gauges will usually need to be welded onto the test article. As an intrusive method, this will affect the structural integrity of the test article, especially for high-temperature test conditions. For example, for an ASME stamped pressure vessel, it is not allowed to spot weld any strain gauges to it after receipt. Therefore, the ability to embed sensors with ultrasonic additive manufacturing (UAM), which can provide spatially distributed strain measurements for real-time health monitoring, will be particularly advantageous. Hyer et al. [26] proposed a novel method to investigate the processing and microstructure of UAM-fabricated SS304 foils to SS304 base while simultaneously embedding fiber-optic sensors in the metal matrix. Fiber-optic sensors were then successfully embedded within SS304 test articles, including a pipe and a hexagonal component that represents a section of a heat pipe–based microreactor core block.

Internal Void Fraction Measurement

To model the HP with computational tools and predict its thermal behavior, the phase change physics with the alkali metal charged in the HP is one of the most essential and crucial pieces, especially during the HP transient scenarios (the starting and cooling phases). One of the key features to obtain is the void fraction at the HP vapor core region. Radiation-based tomography is, therefore, the most attractive method to penetrate the metal wall of the high-temperature HPs. A state-of-the-art sodium-filled heat pipe experimental facility at the University of Michigan (UM) was designed and constructed to generate high-fidelity experimental data using a high-speed X-ray radiography system [27]. They successfully investigated HP's start-up process and its performance under various operation conditions, including effects of heat transfer rate, cooling condition of condenser section, and heat pipe orientation.

Advanced Laser Diagnostics for Velocimetry, Pressure and Temperature

Based on recent investigations, unique and novel measurement technique has been proposed by Professor Philippe Bardet from the George Washington University, which utilizes lasers to measure temperature, pressure, and velocity of the vapor region within a sodium-charged HP. In order to apply the laser technique and visualize the internal part of the HP, small through ports (estimated to be less than 5mm in diameter) can be created on the HP walls with visualization windows. As shown in Fig. 4, there are two schemes to setup the diagnostic experiments. The straight on approach shown in Fig. 4(a) will introduce the laser beam perpendicular with respect to the HP wall. From the opposite side, the laser signal receiver will examine and plot the laser spectrum after it passes through the HP internal vapor core region. Theoretically, we will see one characteristic peak for the laser spectrum, with the height of the peak which correlates to pressure and the width correlates to temperature. On the other hand, another more sophisticated way to setup the experiment is having an angled approach shown in Fig. 4(b). The two visual ports on the opposite side of the HP wall will allow the incoming laser beam to have an angle with the HP wall. Then, instead of one peak, there will be two peaks showing up on the laser spectrum illustrated in Fig. 5. By applying the proper calibration and cross-correlation algorithm for the two peaks, we will be able to obtain the vapor speed during the HP operation.

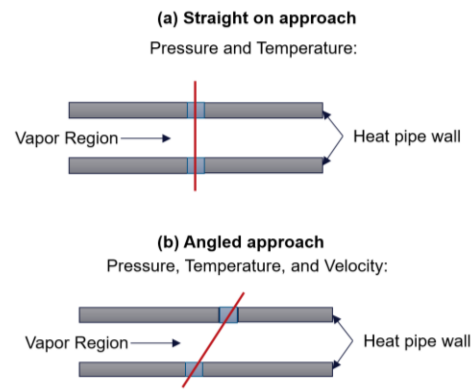

Fig. 4. Two difference schemes for the advanced laser diagnostics that can be applied to high-temperature HP experiments: (a) Straight on approach with laser perpendicular to the HP wall; (b) Angled laser orientation with a certain angle to the HP wall.

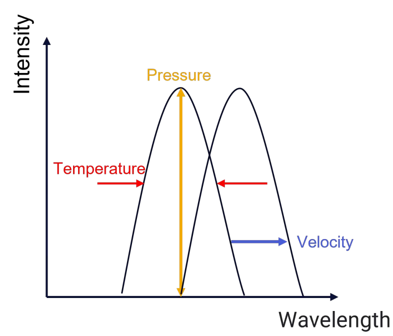

Fig. 5. With the angled laser orientation setup, the laser spectrum can be used for post-processing to measure the velocity, pressure, and temperature in the vapor core region.

Overall, this is a quite promising method to utilize limited resources while achieving the HP internal measurement for velocity, pressure, and temperature at the same time. However, it does have certain challenges and limitations given the high operating temperature as well as the potential leakage issues around the visual ports. Given the balance of its associated benefits and challenges, it is worthwhile to investigate this further based on the potential of possible measurements and fidelity.

CONCLUSION

This paper summarizes the preliminary investigations of advanced measurement techniques for high-temperature HP experiments, which can be implemented to support the microreactor research and development. Innovative techniques are being explored to measure various parameters to support validation needs for high fidelity tools that are being developed under DOE NEAMS program.

Future collaborations with additional research institutes and universities are considered to examine the feasibility of some advanced techniques. The resultant database can be utilized to support the development and demonstration needs of the microreactor and advanced energy systems.

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