Temperature Profiles and Mixing in a Natural Circulation Cooling Facility via Distributed Optical Sensors

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ABSTRACT

The University of Wisconsin has constructed a ¼ scale air-cooled reactor cavity cooling system (ARCCS) as a natural circulation facility based off of a design by General Atomics modular high temperature gas reactor (MHTGR). The ARCCS uses the principle of fluid buoyancy to induce a flow of air through multiple heated risers. This flow is then used to remove decay heat from the reactor pressure vessel and to protect the surrounding reactor cavity in a high temperature gas-cooled reactor. The ARCCS experimental facility is equipped with new temperature sensors designed by LUNA Inc. They are distributed optical fiber sensors that can measure a change in temperature from their initial state every 1.25mm along a 10 meter fiber at a maximum rate of 23.8Hz. This allows for measurements of the temperature distribution of the gas and how it changes with time. The fibers are flexible and can be orientated to collect data in whatever shape the system dictates. 160µm silica fibers with a polyimide coating are used in this system as the sensors due to their ability to reach temperatures of up to 300C without degradation of the coating. The data from the fibers allows for the analysis of the temperature distribution of the air in the ARCCS as it mixes and vents out of the system. The data produced from these fibers can prove to be useful for modeling natural circulation phenomenon and mixing of buoyancy dominated flows.

KEYWORDS
Distributed optical temperature sensors, natural circulation, temperature mixing, CFD validation

1. INTRODUCTION

Natural circulation is of utmost importance for cooling in modern designs of high temperature nuclear power plants due to their ability to work without access to electrical power or operator interaction. Natural circulation is highly dependent on geometry and many of the CFD codes for modeling natural circulation need to be verified to ensure accurate performance. Current designs for reactor cavity cooling systems (RCCS) operating with either air or water are being investigated for stability and their ability to remove decay heat from high temperature reactors and to protect the concrete structures from breaking down due to the large radiative heat loads from the reactor pressure vessel (RPV). Distributed optical temperature sensors (DTS) can measure the temperature distribution of a flow with a single sensor as opposed to hundreds of thermocouples by measuring the movement of defects in the fiber due to temperature and strain on the silica glass. The data can allow for a greater understanding of the flow present under the mixing of buoyancy dominated flows. The fibers also have a very small foot print (ϕ160µm) that can reduce their impact to the flow in the system, which otherwise could later lead to incorrect data for CFD validation. The fibers are able to acquire data at a rate of 100Hz with a maximum fiber length of 10m and a gauge length of 5mm. The RCCS does not undergo thermal gradients at this speed so the system can be adjusted to offer a smaller gauge length (1.2mm) by reducing the sampling rate to 23.8Hz. The limiting factor in the data collection is solely due to processing power of the system. In practical use the fibers require a lot protection to reduce effects from vibration and strain making them hard to work with. Longer fibers also tend to produce more noise due to the higher total number of defects present in them and a higher likely hood of producing strain or vibration in the system that can distort the data. The DTS installed in a natural circulation loop at the University of Wisconsin Madison were used to measure the temperature distribution for possible CFD calculations and to investigate the fibers usefulness under live test conditions.

1.1 Facility

The University of Wisconsin Madison constructed a ¼ scale ARCCS based on designs for General Atomics MHTGR shown below in Figure 1. The system is designed to be an open air loop with natural circulation cooling in order to remove decay heat from the reactor pressure vessel (RPV) and to protect the concrete support structure from the high temperatures radiating from the RPV. The original design as shown in Figure 2 brings in cold air from above the RPV and down the exterior ring of a concentric manifold. The cold air then travels down a set of risers closer to the concrete exterior and then back up a second set of risers nearer to the RPV wall where they can remove heat that is irradiated from the RPV. The hot leg then mixes in an upper cavity before ejecting out through the inner concentric duct of the main air ducts.[1]

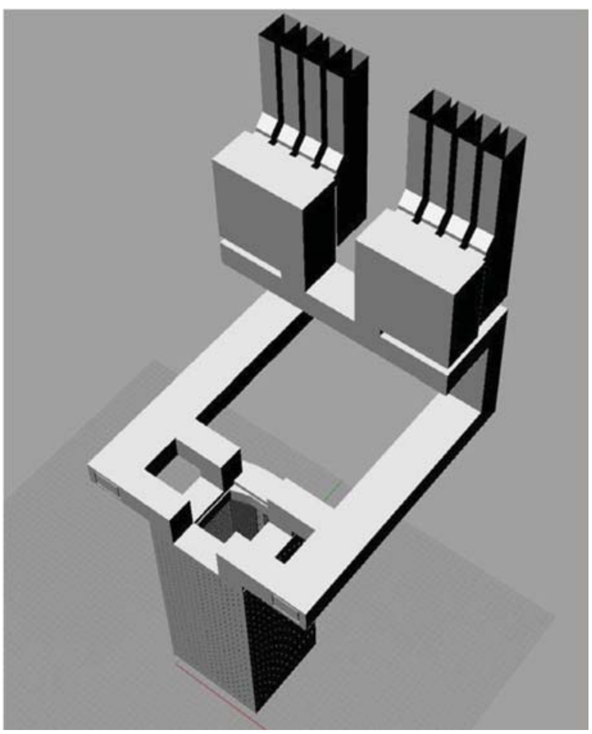

Figure 1: ARCCS isometric view. Show are 8 air inlets and outlets alternating with each

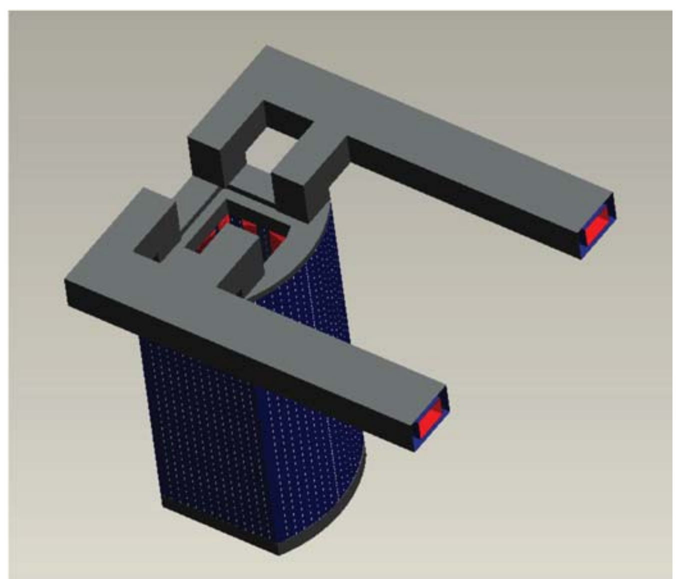

Figure 2: ARCCS hot (red) and cold (blue) legs

Shown below in Figure 3 is the as built ¼ scale RCCS experiment. It consists of a 10º radial slice that includes 6 risers at ¼ height of the full scale design. Some simplifications were made to the original design in order to more easily manufacture, build, and test the system. The concentric inlet/outlet duct was replaced with separate inlet and outlet ducts shown in the bottom right of Figure 3, due to it being easier to construct and to reduce cost on the final system. The inlet also mixes in a lower plenum below the risers as opposed to one above the system next to the hot plenum. The facility was built in a silo as shown so there is no temperature control of the environment and the inlet and outlets are directly affected by the weather at the time of each test just like in the full scale design.

Figure 3: Top Left - as built view of the heated test section. Top Right - exterior of the ARCCS silo. Bottom Left - top view of the upper plenum. Bottom Right - solid works model of the entire system inside the silo.

The ARCCS is scaled according to scaling laws presented in a paper by Argonne National Labs (ANL)[1]. These are the same scaling laws used to produce the ½ scale ARCCS at ANL. They are based on a top-down scaling approach where the heated section of the system is designed to achieve the same temperature rise as in the full scale experiment, this preserves many of the non-dimensional numbers including the Richardson number believed to be of significance to the facilities operation due to the buoyancy driven flow. In order to achieve the same temperature rise the heat-flux to the system must be scaled up by height$^{-0.5}$, where height is the scaled height of the system. For more information on the scaling of all the parameters in the system see the paper previously mentioned.

The ARCCS is equipped with thermocouples, hot wire velocity transducers, a humidity sensor, and distributed optical sensors. 64 thermocouples are distributed throughout the system to measure the temperature rise in the air as well as in the structural components. One heavily instrumented riser contains 6 sets of thermocouples along its axial direction. At every location there are thermocouple on the front riser surface and the center of the air cavity. On the heavily instrumented riser there are thermocouples on the back, left, and right sides of the riser wall as well as the front riser wall and center air cavity at three of the 6 axial locations. The velocity transducer is positioned at the inlet to the lower plenum and the humidity sensor is placed at the entrance to the inlet duct. The distributed optical fibers are arranged in the upper plenum for measurements of the temperature distribution.

1.2 Distributed Optical Sensors

Distributed optical fibers are a relatively new technology that uses Rayleigh scattering in a silica fiber to determine temperature or strain at individual locations. The system installed in the ARCCS was developed by LUNA inc. The system utilizes a Mach-Zehnder interferometer in conjunction with a tunable laser source as shown in Figure 4 [2].

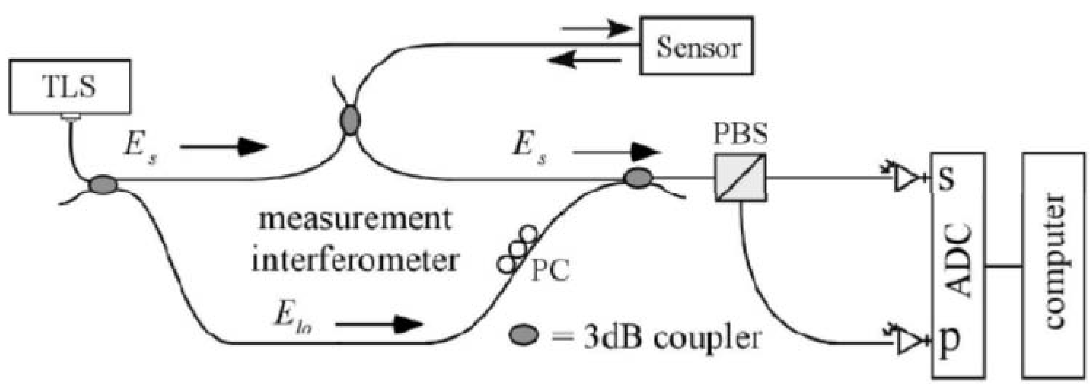

Figure 4: LUNA inc. schematic of the distributed temperature sensor system. The tunable lase source (TLS) sends a swept pulse that is split by a coupler. The Rayleigh backscattering from the sensor is combined with the source laser at a coupler. The interference fringes are split by a polarized beam splitter(PBS) and then read by an analog to digital converter (ADC)[2]

Each fiber (sensor) contains small defects in its construction that lead to localized changes in the index of refraction. These changes create Rayleigh backscattering and the location of these defects are randomly distributed throughout the fibers, but the defects remain in a relatively fixed location for each fiber. When a laser is swept down the fiber over varying wavelengths a Rayleigh backscatter profile is produced and sent through a Mach-Zehnder interferometer along with the original beam. This creates a periodic amplitude based interference spectrum. The spectrum produced with this coherent Optical Frequency Domain Reflectometry(c-OFDR) will remain the same as long as the state (stress, strain, temperature, etc.) of the fiber does not change in any way. The frequency of the each interference fringe from the Mach-Zehnder interferometer in this spectrum is proportional to the distance along the fiber, which gives the capability of distributed measurements. The LUNA system produces this spectrum by averaging all the reflections into discrete frequency bins that correspond to 1.25mm of fiber length. When the fiber changes temperature or is strained in any way the peaks in the spectrum shift and this shift is proportional to the change in the fibers state at that location [3].

Sensors are identified based on a "keyed" profile, when connecting a sensor to the system the first 30cm are interrogated and the produced spectrum is compared to set of stored spectrums. When a match is found the stored spectrum is used as a base set of values to measure the shift in the spectrum along the frequency domain for all tests [4].

2.2.1 Fiber setup

The fibers are extremely sensitive to strain, temperature, humidity, and vibration so utmost care was taken to reduce shifts in the wave spectrum from all but temperature. The fibers in this setup were strung though capillary tubing to protect from strain due to flow across the fibers. Lomperski et al. showed that the ϕ160μm polyimide coated fibers were sensitive to changes in humidity due to the coating absorbing moisture from the environment [5]. During tests the fiber heats up and the moisture is evaporated which can cause an apparent shift in the temperature due to changes in the volume of the polyimide coating. To prevent this, the capillaries were flushed with an inert gas (N_2) and sealed. The flushing of the capillary produced a shift in the fibers temperature spectrum , this is not an actual temperature shift that would occur with the change in pressure from flushing the capillaries because the effect persist long after the capillary has regained temperature equilibrium with its environment. Shown below in Figure 5 is the capillary setup in the ARCCS upper plenum.

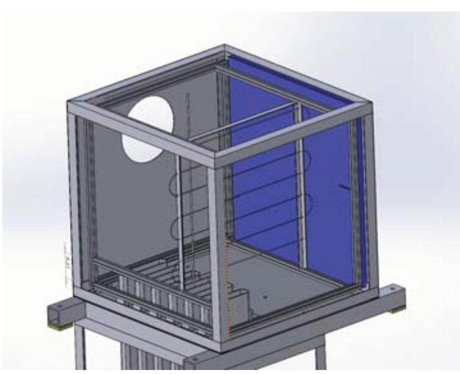

Figure 5: Upper Plenum fibers. Fibers are sealed inside the capillary tubing. Each capillary has a reference thermocouple to validate measurements

The capillaries are strung between a support frame to observe changes in the temperature profile in the upper plenum these observations can be used to verify CFD temperature calculations and give insight to the velocity flow direction in the upper plenum. The support structures contain either 5 or 6 0.7112m runs across the upper plenum in the same plane as the outlet ducts with 0.1m spacing in the vertical direction between the horizontal runs of the capillaries. The limitation in the number of runs is due to limitations in the length capillary lines available. The only sections of the capillaries useful for data collection are the 0.7112m horizontal runs, because the sections of the capillary between horizontal runs experiences too much strain from the thermal expansion of the capillary and are not guaranteed to produce accurate values for the temperature. The horizontal runs are held in tension via springs supplying a force of approximately

Figure 6: capillary in tension via springs and can be adjusted for changes over time

13lbs on either side of the support structure shown in Figure 6. This keeps the capillaries from deforming due to thermal expansion in any direction other than along the capillaries axial direction. The springs also help to keep the spatial position of the fibers the same throughout the test, because movement of the capillary during the test could lead to the fiber being in a different position than the intended starting position making any results invalid. In order to prevent the expansion of the capillary from affecting the fibers position, the fibers were coated in Boron Nitride (BN) which acts as a lubricant so the capillary can slide along the fiber if needed.

2. EXPERIMENTAL DATA

2.1 ARCCS Base System Response

The ¼ scale ARCCS facility can be run under either forced flow or natural circulation; presented below is a standard set of data for a natural circulation test at 19.89 kW input power. The inlet and outlet temperatures shown in Figure 7 show that the system takes approximately 4 to 5 hours to reach a steady state. Steady state can then be maintained indefinitely without any human interaction as long as the environmental conditions are stable. The mass flow rate of the inlet for the system was 0.17kg/s and was evaluated by integrating the velocity profile and assuming that the profile was symmetric in the theta direction. The velocity profile shown in Figure 8 was obtained by varying the position of the hot wire transducer in the duct and taking a time average at each position. The hot wire transducer's measurements can be affected by temperature of the fluid, but by placing the transducer before the heated section of the system and over 10 L/D into the inlet duct the temperature changes of the fluid was limited to just the changes in external temperature and the flow was guaranteed to be fully developed. The acquisition of the velocity profile also only occurs over a short period less than 2 hours over which the temperature of the fluid changed by 0.88C; the maximum temperature change over the entire test period was only 2.77C.

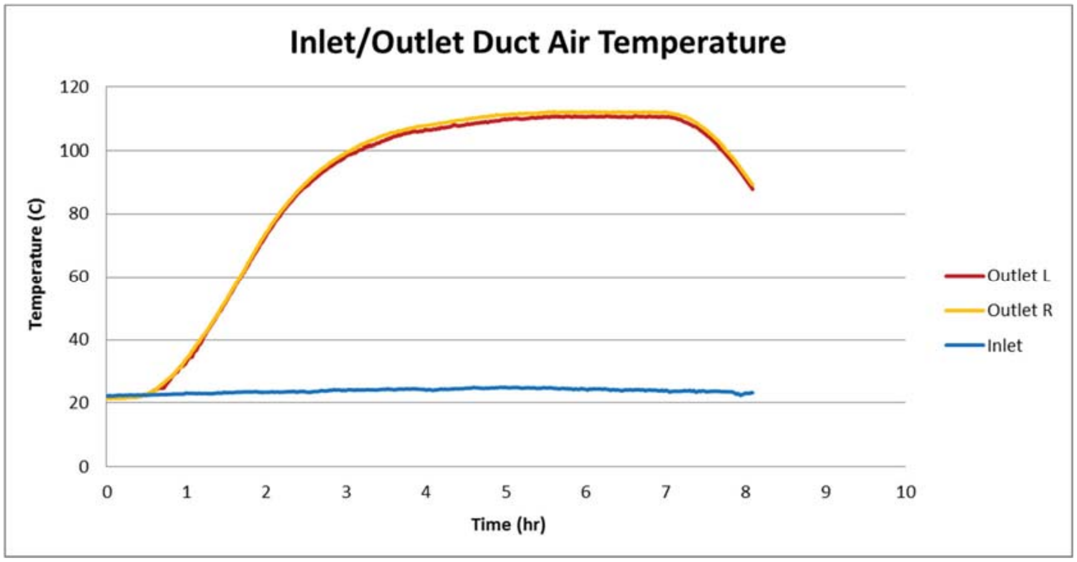

Figure 7: inlet and outlet duct air temperature for a 19.89kW natural circulation test

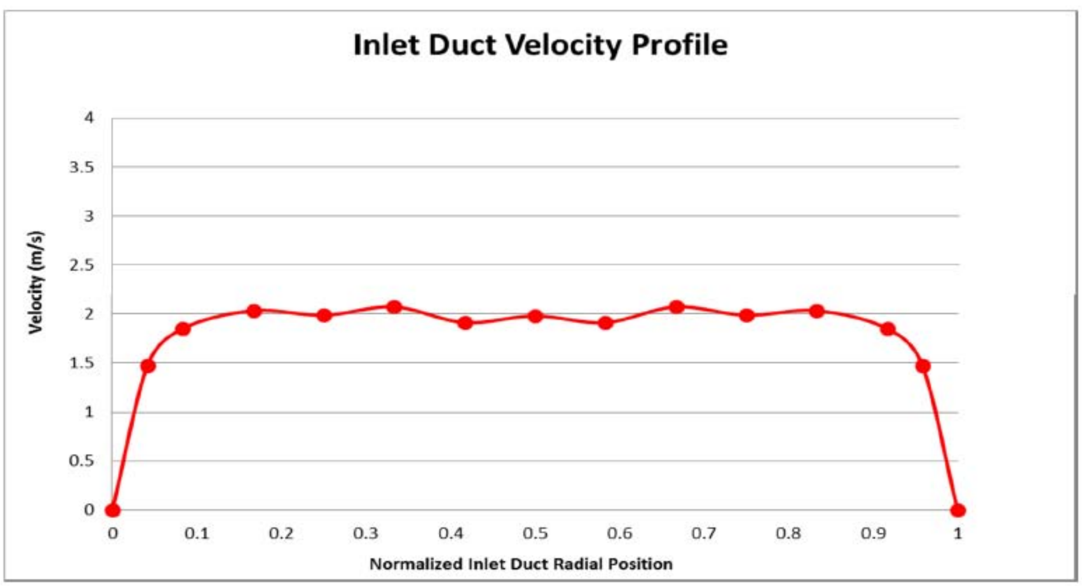

Figure 8: Velocity profile for the 12" inlet duct

2.2 Fiber Data

2.2.1 Fiber calibration

Early work with the fibers showed that LUNA Inc.'s built in coefficients that relate the wave shift data to temperature are only good for low temperatures (~sub 70C) before the offset causes large inaccuracies in the temperature reading. Small heated tests were performed where the capillary was directly heated to a known temperature to determine if the temperature rise that the fibers recorded was repeatable and if a simple calibration curve could be used to correlate the temperature reading of the fiber to the temperature reading from the thermocouples. One stretch of a capillary was wrapped with nichrome wire and insulated to examine the fibers behavior in a controlled environment temperature ramp. Shown in Figure 9 the capillary and fiber temperature were cycled to verify that the temperature of the fiber responds the same every time. The nichrome wire was ramped up to 45W over 13.25min and then held there for 20 minutes to allow the system to stabilize. After stabilizing the nichrome was ramped down over 5min and then held at 0 W for 20 minutes. This was performed three times in series.

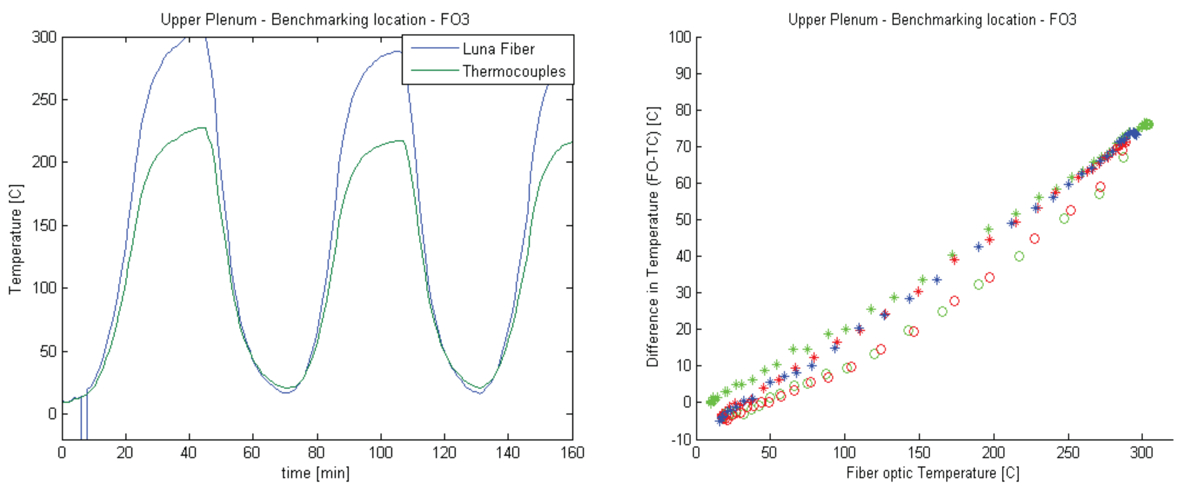

Figure 9: Left - cycled temperature, the luna data is averaged from all data within 0.25" of the thermocouple. Right - the difference between the thermocouple measurement and the fiber temperature measurement. The asterisks represent the ramp up and circles are the down ramp.

The difference in temperature between the fiber and the thermocouple is very linear with the exception of the lower temperatures. The difference between the first cycle and subsequent ones is attributed to moisture that was absorbed in the fiber's polyimide coating prior to the test being baked off and thereby causing a release of built up stresses in the fiber. Under humid conditions polyimide is known to swell and has also been used as a humidity sensor due to its change of properties with a change in relative humidity in the environment [6-7]. In order to combat this phenomenon the capillaries were flushed with nitrogen and sealed to remove as much moisture from the air as possible and to leach some of the moisture out of the fibers coating.

The difference between the curves in the up ramp and down ramp is due to the thermocouple cooling down faster than the center of the capillary where the fiber is located. In all subsequent tests in the ARCCS the heat up of the system to steady state (first ~200min) shown previously in Figure 7 is used to formulate the calibration curve for the fiber and then fitted with a power fit. The fit is then applied to the entire fiber to produce the temperature distribution in the upper plenum.

2.2.2 Fiber test data

Presented below is fiber data from the same natural circulation test shown above with an input power of 19.82kW. The inlet mass flow was 0.17 kg/s and the temperature rise of the air in the risers was 73.1C. The fiber in this test was located in the center of the upper plenum between risers 3 and 4. The calibration of the fiber is shown below in Figure 10 and corresponds to a RMSE of ±3.67C.

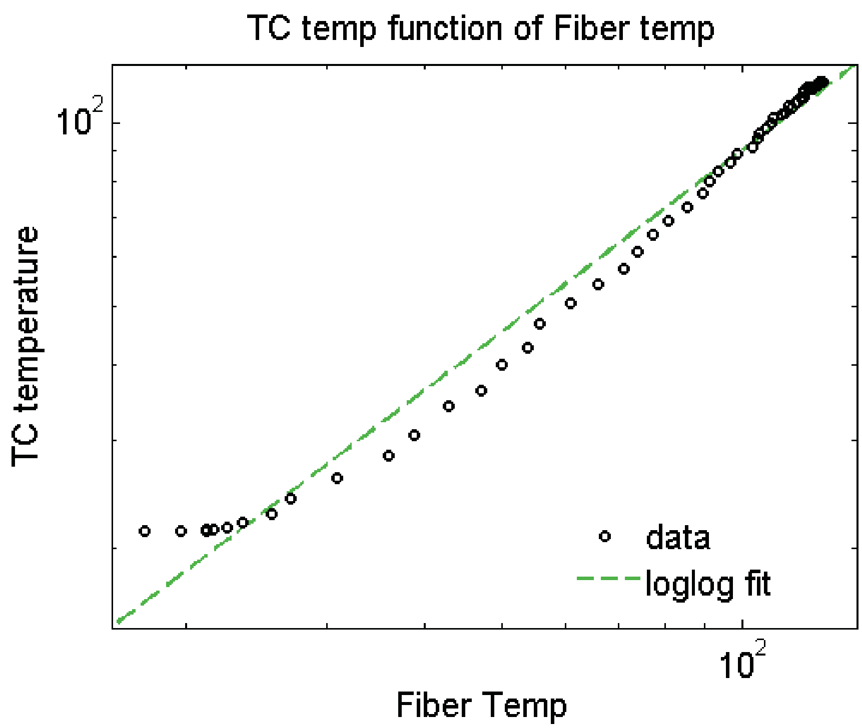

Figure 10: Power fit for the fibers actual temperature vs. measured temperature

This fit was then applied to the fiber data which is presented below in Figure 11 as a line at 5.63hrs into the test. The line gives information as to the noise in the sensor due to vibration in the systems standoff cable, which is essentially a large extension cable for the fiber. The noise was dampened as much as possible by protecting the cable in PVC piping and foam tubing for its run from the LUNA electronics box to sensor, but further dampening requires movement of the electronics to the outside environment which could damage it in the cold Wisconsin winters. The median fit seen was performed by taking a moving median. This consisted of 5 points in the time direction and then 30 points in the spatial direction. This was used to eliminate any outliers in the data that occur from vibration. The error in the data is classified by the error of the electronics and the error in the sensor. The electronics are guaranteed to give an error of ±0.2°C, while the sensor error is dependent on the temperature calibration and vibrational error. The total error in the fiber data presented amounts to the square root of the errors squared which is ±6.21C

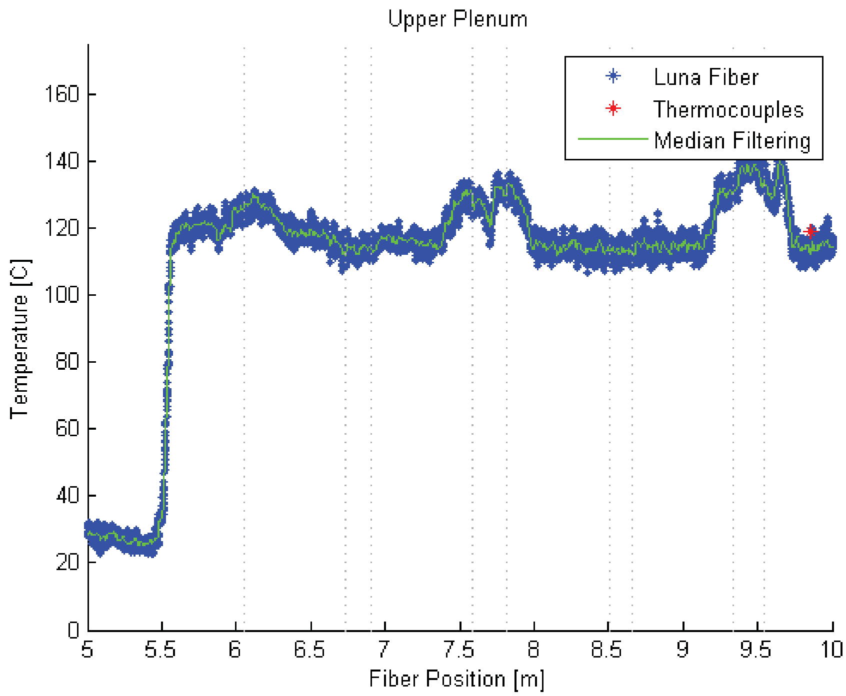

Figure 11: Fiber data adjusted by the power fit. Also shown is the median filter used to remove any outliers.

This form of the data is only useful to determine nose in the fiber and to verify that any filtering processes are working correctly. For use in CFD validation all data points from the fiber need to be placed spatially. By pin pointing locations of the thermocouples and edges of each horizontal run through the use of a hot soldering iron the data can be presented spatially as shown below in Figure 12. The data shown here was produced by using the median filtered data from above to remove spikes that distort the data and then using MATLAB's natural neighbor scattered interpolation algorithms. The 3D plot is dimensionally accurate to the actual dimensions of the ARCCS' upper plenum. Shown in a top view of the plenum is the fiber's location in respect to the risers.

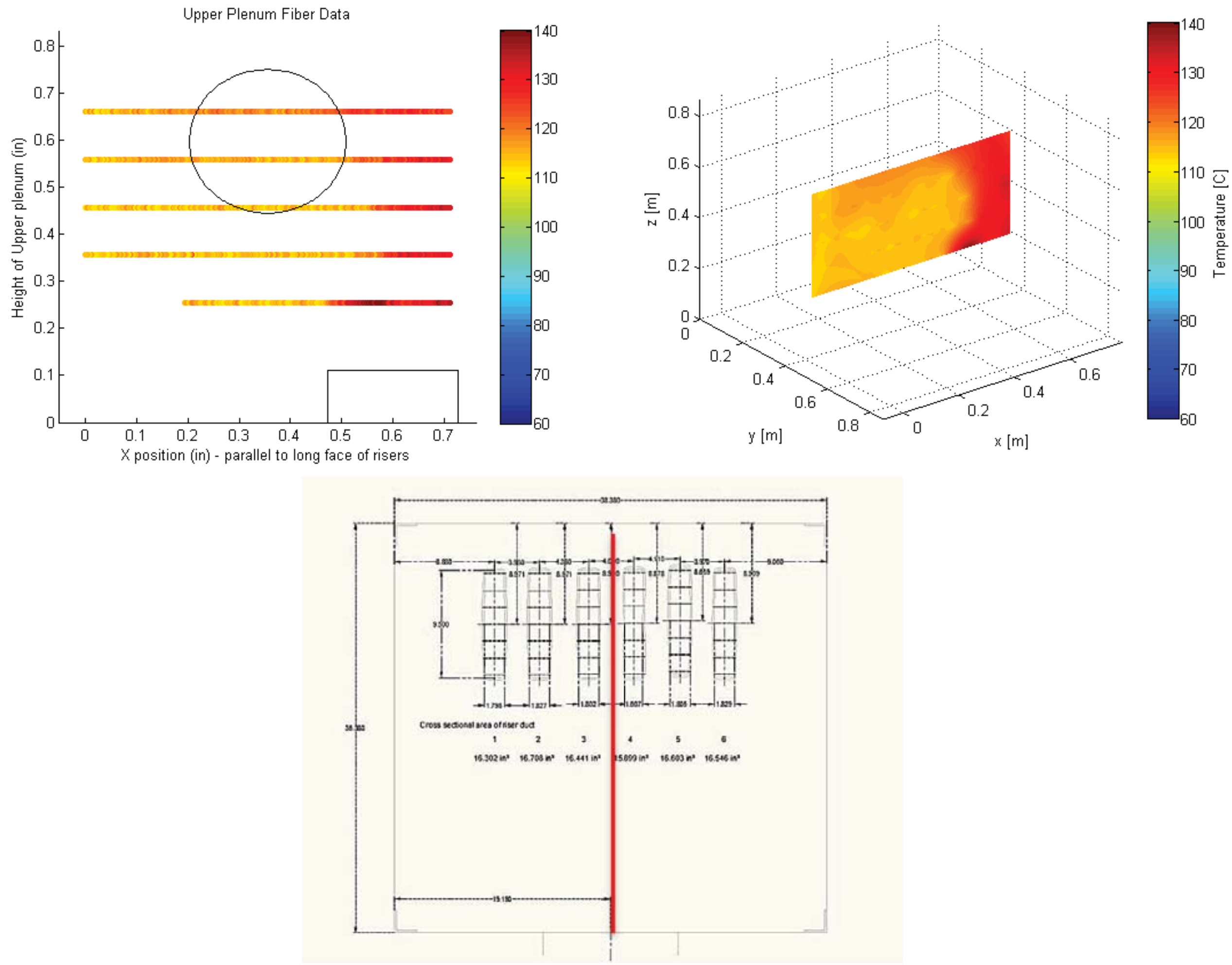

Figure 12: Top Left - fiber in position, the circle represents in the outlet duct location and the rectangle represents the riser duct. Top Right - a 3D representation of the data in the upper plenum using a natural neighbor interpolation. Bottom Left - positon of the fiber relative to the risers in the upper plenum.

3. CURRENT OBSERVATIONS

Distributed fiber optic sensors present a large amount of data to process and utilize for CFD validation, but setting up the fibers in a vibration and strain free environment is difficult and presents a great challenge to reduce noise in the data. The fibers have a high data acquisition rate and a small dimensional foot print that could be nice for industrial use when the technology improves to a point that makes it more reliable in the field and where it is burdensome to use a large amount of thermocouples. The fibers presented were enclosed in stainless steel capillaries and coated with boron nitride to prevent strain and vibration within the test section. Outside of the test section vibration on the standoff caused an increase in the error of the data. Filtered data from the fibers presented above can be used as a good base line for CFD codes to work with, but the unknown localized errors that could be due to strain in the fiber keep the data from being 100% accurate. Large strains in the presented data are unlikely though due to the fibers being enclosed in stainless steel capillary lines and there being no unexplainable qualitative shifts in the data. Changing the coating or finding protective sleeves for the fibers could be examined to eliminate or reduce the strain on the fiber. Another interest is in reducing the noise in the data. This is mostly attributed to vibration of the fiber and a softer or possibly thicker coating could help to prevent the vibrations from adding noise to the data.

Current plans include expanding the amount of operational fibers in the ARCCS in order to fully characterize the flow in the upper plenum of the ARCCS. With the increase in dimensional temperature data there are plans to evaluate unstable conditions that arise in the system when the weather changes. Currently, flow reversal has occurred on one of the outlet ducts numerous times due to changes in wind speed and direction at the outlet ducts exits. Temperature data in the upper plenum from this phenomenon could prove useful for CFD analyst and for studying the stability of air based natural circulation. Data for temperature mixing under forced flow tests will also be collected as a bench mark for all other data sets due to the increased stability that forced flow provides under all weather conditions.

ACKNOWLEDGMENTS

The authors would like to thank Moses Muci for construction of the UW-Madison ARCCS facility and initial benchmarks of the systems performance. Additional thanks from D. Lisowski, S. Lomperski et al. at Argonne National Labs for their help in comparing and presenting data for the ARCCS and joint work on the LUNA fibers.

REFERENCES

1. S. Lomperski, W.D. Pointer, et al. "Generation IV Nuclear System Initiative. Air-Cooled Option RCCS Studies and NSTF Preperation" http://www.ipd.anl.gov/anlpubs/2012/11/71292.pdf (2011)
2. Soller, B.J.; Gifford, D.K.; Wolfe, M.S.; Froggatt, M.E.; Yu, M.H.; Wysocki, P.F., "Measurement of localized heating in fiber optic components with millimeter spatial resolution," *Optical Fiber Communication Conference, 2006 and the 2006 National Fiber Optic Engineers Conference. OFC 2006* , vol., no., pp.3 pp.,, 5-10 March 2006
3. D. Samiec, "Distributed fibre-optic temperature and strain measurement with extremely high spatial resolution," *Photonik,* Wladbronn Germany, 6/2011, pp. 10-13(2012)
4. Froggatt, M.; Soller, B.; Gifford, D.; Wolfe, M., "Correlation and keying of Rayleigh scatter for loss and temperature sensing in parallel optical networks," *Optical Fiber Communication Conference, 2004. OFC 2004* , vol.2, no., pp.3 pp. vol.2,, 23-27 Feb. 2004
5. Lomperski, S.;Gerardi, C.;Pointer, W.D.,"Fiber optic distributed temperature sensor mapping of jet-mixed flow field" *Experiments in Fluids* **56**(3) (2015)
6. Bhargava P, Chuang CK, Chen K, Zehnder A (2006) Moisture diffusion properties of HFPE-II-52 polyimide. J Appl Polymer Sci 102(4):3471–3479
7. Ding F, Wang L, Fang N, Huang Z (2011) Experimental study on humidity sensing using a FBG sensor with polyimide coating. SPIE-Int Soc. Opt Eng. 7990 Optical Sensors Biophotonics II 79900C