DEVELOPMENT OF THERMAL TRANSIT FLOW MEASUREMENT FOR SMALL MODULAR REACTORS

E. T. Riggsbee, A. H. Hashemian, B. D. Shumaker, S. N. Tyler, P. E. Zarb
Analysis and Measurement Services (AMS) Corporation
9119 Cross Park Drive, Knoxville, TN 37923
edwin@ams-corp.com , alex@ams-corp.com, brent@ams-corp.com,
shawn@ams-corp.com, phil@ams-corp.com

ABSTRACT

Safe, reliable, and efficient operation of nuclear reactors requires timely and accurate measurement of primary coolant parameters such as temperature, flow, pressure, and level. These measurements may be challenging in small modular reactors (SMRs) with integral vessel design. For SMRs with the integral design, sensors may be located in confined spaces or embedded within pressure vessels. The absence of primary coolant loops is another fundamental design attribute that will affect the location of sensors, sensor interfaces, and types of sensors suited for process parameter measurements. Further, the number and location of pressure vessel penetrations may be constrained compared to traditional nuclear power plants (NPPs). As a result, conventional NPP temperature, flow, pressure, and level sensors may not be appropriate for use in SMRs.

This paper addresses the development of new sensor technology for hybrid temperature, flow, and level measurement. The authors demonstrate the alternative use of resistance temperature detectors (RTDs) where cross-correlation of process temperature variations between RTDs is used to calculate process flow velocity. The new sensor and measurement technology will also incorporate RTD response time and self-heating chacteristics to provide flow and level measurement in accident conditions. This capability would simplify reactor design and enable optimal placement of reactor pressure vessel penetrations leading to increased operational reliability and safety. The cross-correlation of temperature signals and adaptation for flow measurement in a laboratory setting is presented here.

Key Words: small modular reactor, transit time flow measurement, cross-correlation, response time

1 INTRODUCTION

Measurements of fluid flow in most NPP applications are based on the use of differential pressure (DP) sensors measuring pressure drops across piping elbows or DP sensors connected to Venturi tubes or flow nozzles which are installed in-line with the process flow. However, these traditional types of DP flow measurements are complicated for SMRs with the integral vessel configuration. It is just not feasible to use a conventional Venturi or a flow nozzle in an integral vessel. Likewise, design restrictions on lower vessel penetrations do not favor flow or level measurements that use the difference in pressure between two points. Other physical factors may limit the number and placement of sensors around the reactor vessel. Therefore, new technologies need to be developed or conventional methods adapted to address these SMR I&C measurement needs. This paper represents a brief summary of the collective work performed by the engineers of Analysis and Measurement Services (AMS) Corporation as part of a Small Business Innovation Research (SBIR) Phase II project under the direction of the DOE. In particular, AMS is developing new I&C technologies that can be used for hybrid temperature, flow, and level measurement in SMRs. The technical method presented here takes advantage of existing nuclear qualified temperature instrumentation and cross signal data processing to extract additional information from ordinary process measurements. Cross signal processing has been used by AMS (and others) to diagnose reactor core power and flow anomalies, assess stability of motion of reactor internals using neutron flux signals, and measure primary coolant flow using transit time of Nitrogen-16 (N-16) [1].

2 TEST FACILITIES

The laboratory validation of the method presented here was conducted on the thermal hydraulic test loop at the AMS Corporation headquarters in Knoxville, TN. This test loop allows researchers to independently vary process conditions such as flow rate, temperature, and pressure across a range of operating conditions including forced flow and natural circulation (NC). The flow loop is composed of two major sub-systems: 1) the primary water loop where the majority of research tasks are focused and 2) the secondary cooling loop which serves to provide a constant temperature heat sink for the primary loop. A simplified piping diagram and visual representation of the test loop is shown in Fig. 1.

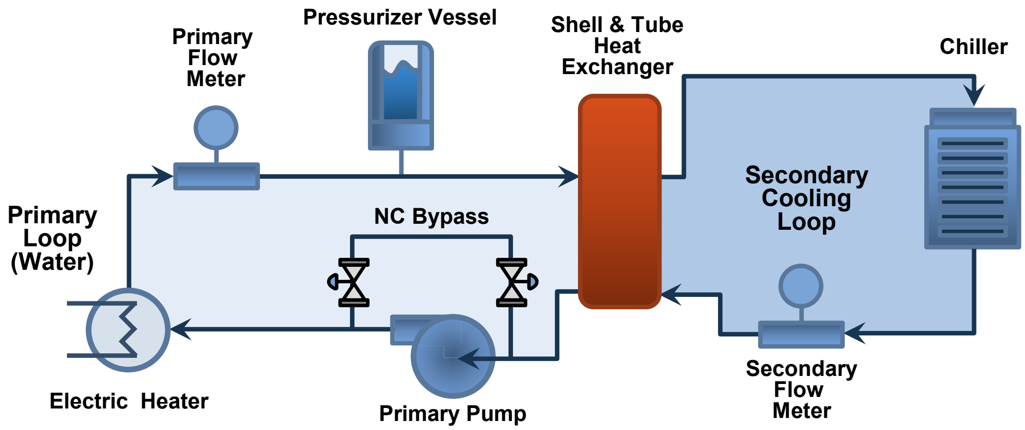

Figure 1. Simple Diagram of the Thermal Hydraulic Test Loop

The flow loop provides over 100 local points of measurement for multiple process parameters. In addition to the local test ports, a multi-manifold sensor test bed is also used to facilitate evaluation of various types of transmitters for use in SMR I&C applications. These transmitters currently consist of 24 nuclear grade pressure and flow sensors such as Rosemount, Weed, Foxboro, Schlumberger, etc. The arrangement of several of these sensors on the test manifolds is shown in Fig. 2. The transmitters were configured to measure differential pressure and pressure associated with major components such as the primary pump and heat exchanger (Fig. 3). Other sensors such as a Pitot tube (Fig. 4), ultrasonic transit time flow meter (USFM), and multiple RTDs were also installed locally on the loop (Fig. 3 and 5). Reference flow measurements were obtained from a calibrated electromagnetic flow meter (EMFM). The measurements obtained from the EMFM, Pitot, USFM, and the RTDs are the focus of this paper.

The Pitot tube is one of the oldest and simplest devices for fluid flow measurement. Fluid velocity can be directly calculated using measured differential pressure (DP) and density of the process media. Some of the advantages of using Pitot tubes are simplicity, low cost, and durability. The main disadvantages are degraded accuracy in the presence of “swirl” or turbulence in the fluid flow, potential for degraded response from clogging of the holes in the tube, and the requirement that the device is installed directly in the flow stream which causes minor obstruction to flow [2].

In contrast to Pitot, ultrasonic flow meters are non-obtrusive and can be used for flow measurements in conventional NPPs. The selected ultrasonic transducers are clamp-on style and the flow measurement is presented on a digital display and with a conventional 4-20 mA loop. The electronics for the transducers are configured to measure how long it takes the pulses to travel in each direction. The upstream and downstream times are different because the ultrasonic path includes a velocity component that is parallel to the flow direction. This will add to the velocity of propagation of the pulse traveling in the same direction as the flow and reduce the velocity of propagation of the pulse traveling against the flow. The time of flight of an acoustic pulse produced by one transducer and received by the other is governed by the distance between the two transducers and the sonic velocity of the pulse.

Figure 2. Test Loop Manifolds with Conventional I&C

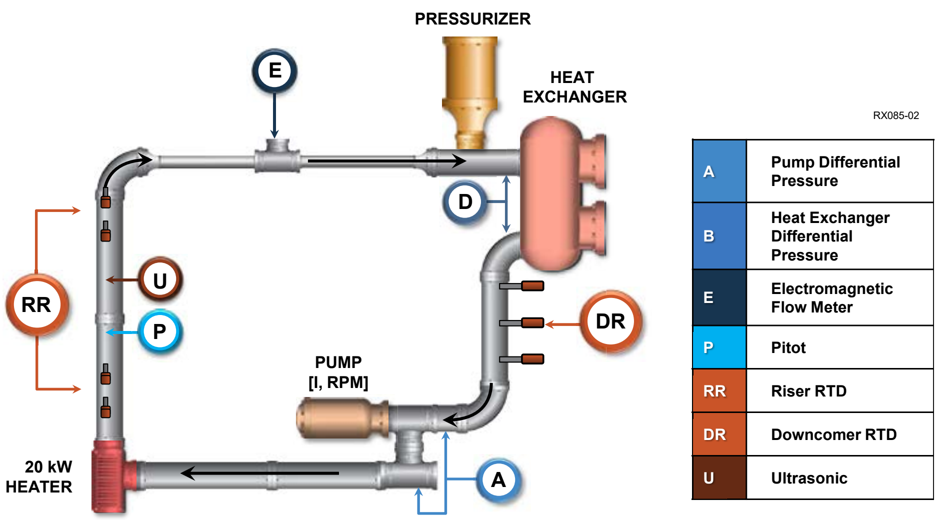

Figure 3. Simple Diagram of Flow Loop Instrumentation

Figure 4. Dwyer Pitot Flow Sensor

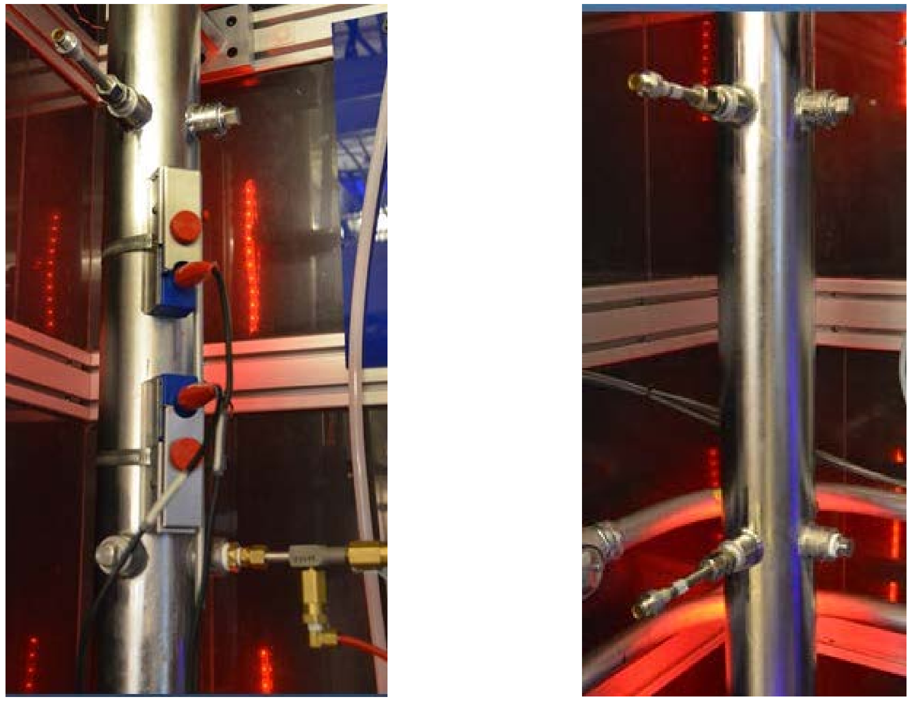

Figure 5. Pitot, Ultrasonic, and RTD Installation on the Test Loop Riser

3 BASELINE FLOW TESTING

Data collection following sensor installation provided a starting point for comparing the Pitot and the ultrasonic sensor flow measurements to the reference flow provided by the EMFM. The test program used a variable speed pump to accurately control flow while simultaneously recording multiple signals from representative sensors. More specifically, baseline measurements were obtained as flow was varied from less than 0.5 feet per second (fps) up to 10.6 fps. These measurements were recorded with high resolution 24-bit sampling at 2000 Hz using an AMS online monitoring system (OLM).

Fig. 6 shows initial baseline flow measurements from the EMFM, Pitot, and ultrasonic plotted versus pump speed. It is apparent that there is a divergence in the ultrasonic compared to the EMFM flow measurement as the pump speed increases. The difference increases to about 10% at full flow. For the Pitot, which provides input to a Rosemount differential pressure transmitter, the difference increases to approximately -4% at full flow. The calibration of the transmitter tethered to the Pitot was checked and verified. The calibration of the EMFM was also checked and certified by an independent test facility. The average accuracy of the EMFM is within 0.4% of NIST reference for flow from 0 to 2000 lbm/min. Additional evaluations of the Pitot and ultrasonic device installation and configuration were performed to resolve the differences. Based on these evaluations, the authors decided to modify the riser section of the test loop to minimize flow disturbances which could affect the accuracy of the USFM as well as the Pitot tube. All previous testing was repeated and new benchmarks established for the test loop flow. At the conclusion of this testing, the accuracy of the Pitot measurements had improved to better than ±1% difference compared to the reference flow. The ultrasonic measurements went from reading 10% high to reading more than 10% low. These tests were repeated several times and no significant improvement could be obtained for the ultrasonic flow measurement. Note that AMS has previously evaluated other ultrasonic technologies and those sensors were found to be accurate when compared to the standards used at the time [2]. The tabular results of the as-left flow characterization measurements (from 0.5 fps to 7 fps) are provided in the following section.

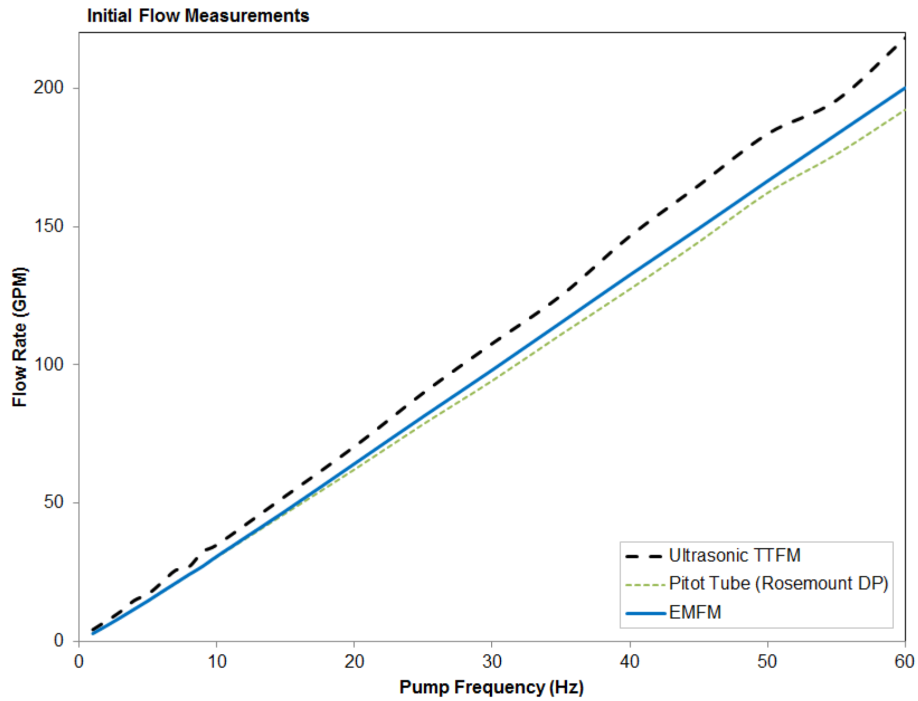

Figure 6. Pitot and Ultrasonic Compared to EMFM – Initial Measurements

4 DEVELOPMENT OF THERMAL TRANSIT TIME FLOW METHOD

Cross-correlation can be used as a technique to measure flow based on the transit time of natural process fluctuations in an operating plant. Fig. 7 shows a section of pipe through which a fluid is flowing. The flow rate can be identified if the fluid is tagged with a tracer which can be detected by sensors at two locations separated by a known distance. The fluid velocity is found by dividing the distance between the two sensors by the time it takes for the fluid to pass from the upstream to the downstream sensor [2]. The plot in Fig. 7 shows the sensors signals, the cross-correlation plot, and the transit time for the fluid tag to pass between the sensors. The cross-correlation function (R_{xy}) can be implemented in the time domain as:

$$R_{xy}(t) = \; . \; x(\tau)y(t+\tau)\; d(\tau) \tag{1}$$

Where:

t = time index of signals x and y
. = time delay of associated components

4.1 Response Time Characterization

Accurate response time characterization is an important consideration for successful cross-correlation transit time flow measurement [3]. If RTD response times are matched, then response time compensation of the data time sequence is not required. However, if RTD response times are not matched, the time sequence for the correlated pair must be corrected as follows:

$$Process\ \Delta T = Signal\ \Delta T + Response\ \Delta T \tag{2}$$

Where:

Process ΔT = actual transit time due to coolant flow velocity
Signal ΔT = time separation of the sensor signals as recorded in the data
Response ΔT = response time upstream sensor – response time downstream sensor

For the response time measurements, a Wheatstone bridge was used along with a current switching network and signal conditioning equipment. The RTD is connected to one arm of the bridge and the bridge current is switched from about 1 or 2 mA to about 35 mA. The bridge circuit and illustration of the loop current step response (LCSR) are shown in Fig. 8. The exponential transient data is sampled by a computer and analyzed to provide the response time of the RTD.

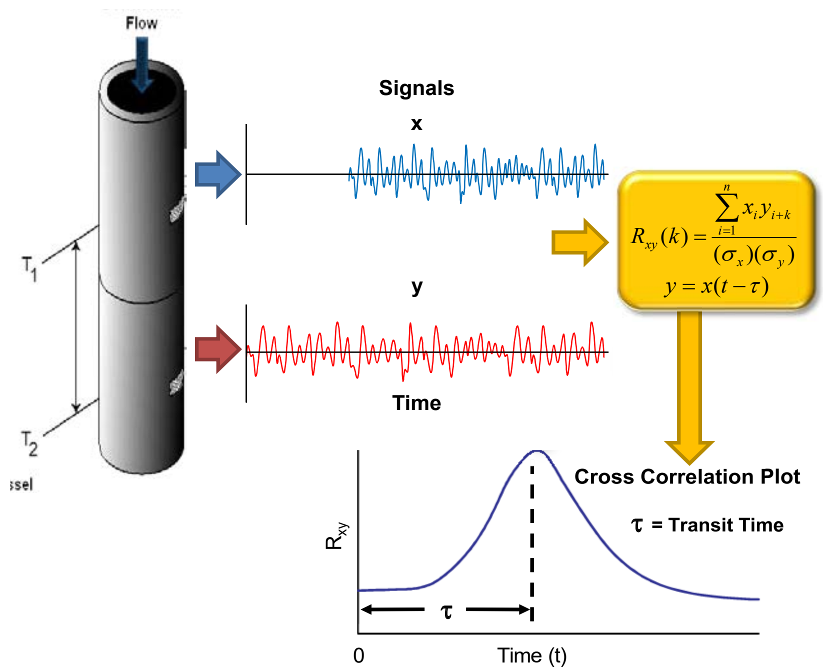

Figure 7. Flow Measurement by Transit Time Technique

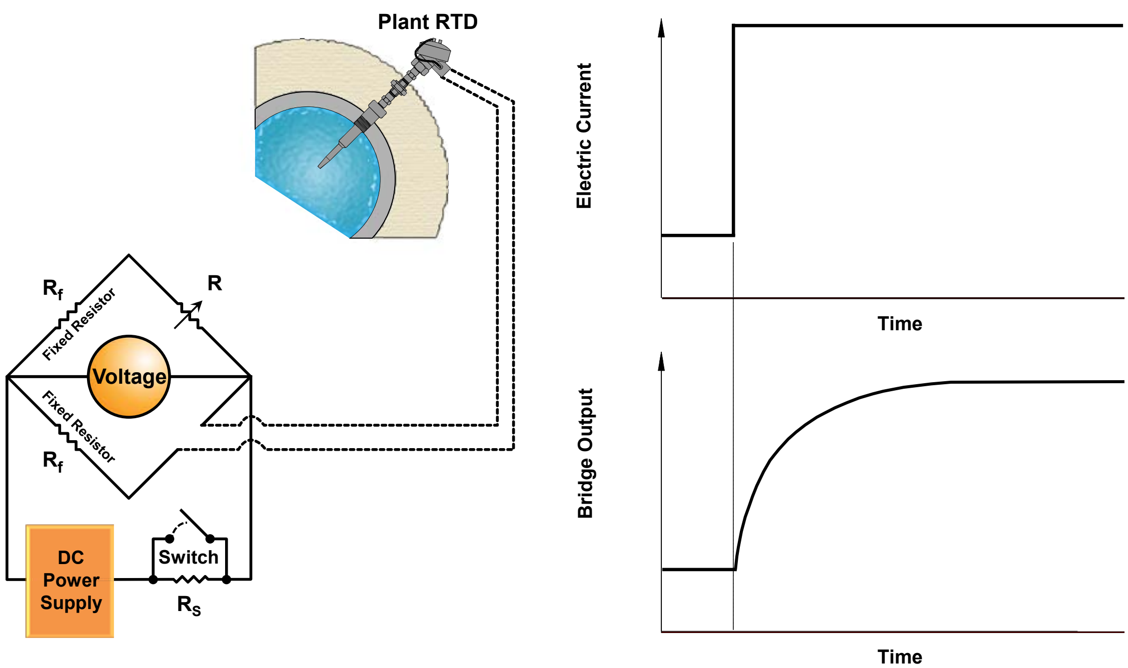

Figure 8. Wheatstone Bridge (Left) and Step Change in Current with Exponential Voltage Transient (Right)

LCSR response time is typically referenced to the laboratory standard plunge test at a fluid flow velocity of 3 fps. However, depending on the heat transfer characteristics of the RTD and the medium in which it is immersed, actual response time is somewhat dependent on the flow velocity of the process. In general, heated element response is more sensitive to flow rate at low flow velocity compared to low sensitivity at higher flow rates. The opposite is true for most conventional differential pressure flow sensors which are generally less sensitive at low flow rates [4]. The sensitivity of temperature sensor response time to fluid flow velocity and fluid type could potentially prove useful in determining the amount of flow present in accident conditions and whether the sensing element is immersed in liquid coolant, steam, or void. This methodology could be a means of obtaining information on the state of cooling flow and coolant level if traditional I&C methods are not available such as in a severe accident coupled with station blackout.

The authors performed comprehensive LCSR testing of RTDs installed on the test loop as flow was varied from about 0.5 fps up to 10 fps. A detailed response time evaluation was used to optimize the placement of RTDs on the riser and downcomer of the test loop. The LCSR testing was then repeated to verify sensor response times versus flow in the new locations. These response time results were used to compensate the time sequences of RTD signals in subsequent thermal transit flow measurement tests.

The average response times of five RTDs on the loop riser versus flow are presented in Fig. 9. As shown in the graphic, the response times of four of the RTDs were less sensitive to flow and these RTDs correlated accurately in subsequent tests. There were biases in response times between these four RTDs, but these biases were relatively uniform across the range of measured flow. The fifth RTD was more sensitive to flow velocity and did not correlate accurately regardless of compensation. A similar response time characterization was performed for the downcomer RTDs and used to match three RTDs for subsequent cross-correlation tests. We found that matching similar RTD response time sensitivity to flow seems to be critical to obtaining accurate thermal transit time results.

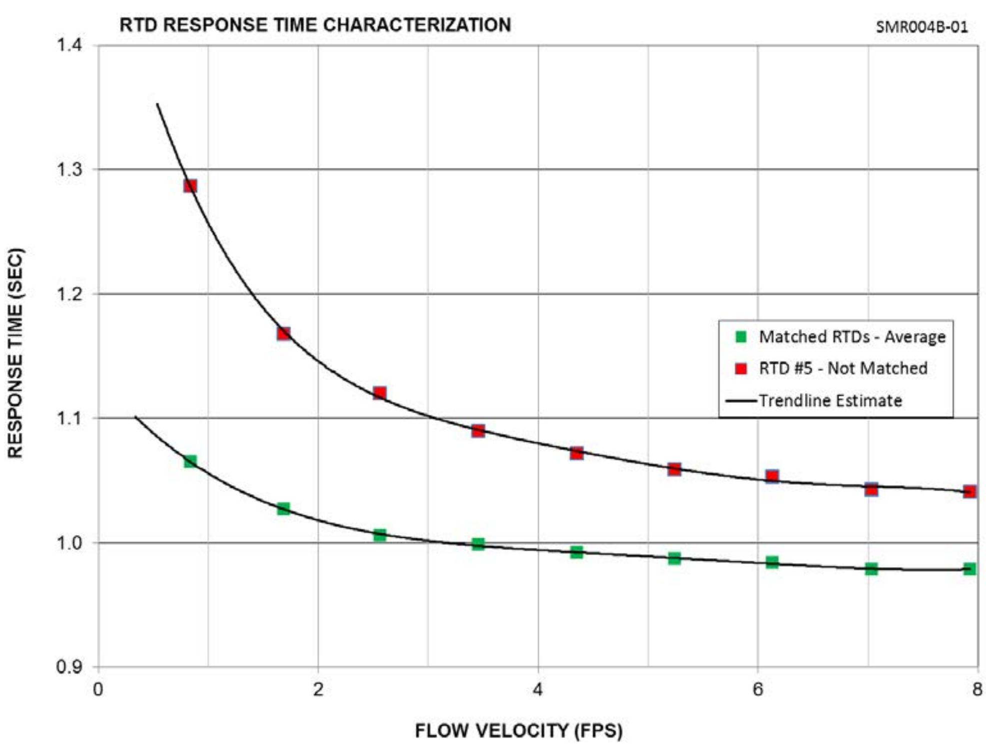

Figure 9. Characterization of RTD Response Time versus Flow Velocity

4.2 Thermal Transit Flow Test Results

Nine RTDs were installed on the test loop primary circuit for thermal transit time testing. Five RTDs were installed on the hot riser and four RTDs were installed on the heat exchanger cold outlet. The response times of all RTDs as a function of flow were well-defined by previous LCSR testing. Four of the five RTDs on the riser and three of the four RTDs on the downcomer had similar response time sensitivity to flow.

Each RTD was configured for measurement by connecting the RTD as one leg of a multi-channel Wheatstone bridge circuit. The bridge current was set to 2 mA for normal measurement and the bridge output was sampled at 2000 Hz for approximately 2 minutes per test run while the primary loop temperature was cycled around a set point. Multiple data collections and cross-signal processing were performed as loop flow was varied from 0.5 to 8 fps. Actual loop flow was benchmarked to the output of the EMFM flow meter which has a reference accuracy of ±1%. Data from the Pitot and ultrasonic flow sensors were also recorded simultaneously with the RTDs output signals. The cross-signal transit time results for four of the RTD pairs, with two pair from the riser and two pair from the downcomer, were found to provide flow velocity with accuracy better than the ultrasonic and similar to the Pitot. The test results are shown in Fig. 10 and tabulated in Table I.

The identification of thermal transit time based on the RTD signals, implementation of response time compensation (as previously described by equation 2), and calculations of flow velocity and flow rate (either in feet per second or gallons per minute) were accomplished by new "temperature wave analysis" software (TWA10) developed by AMS. An example of the RTD signal data processing from the testing described here is provided in Fig. 11. The next stage of development is to incorporate the TWA software as a real-time add-on to AMS OLM data acquisition hardware and software. Further, the hardware for data acquisition will integrate the RTD bridge circuitry, signal conditioning with gain and filtering, and customized fast sampling capability for multiple signals.

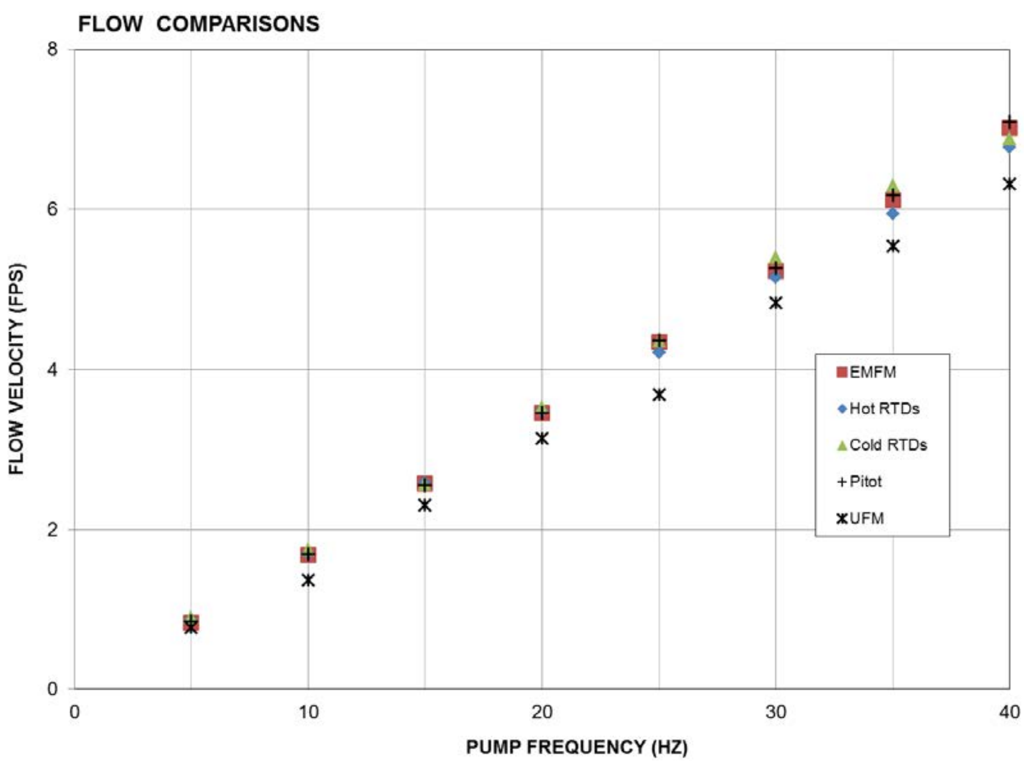

Figure 10. Flow Comparisons: Thermal Transit, Pitot, and Ultrasonic

Table I. Comparison of Flow Measurements					
Frequency (Hz)	**Reference (FPS)**	**Pitot % Diff**	**USFM % Diff**	**Hot RTDs % Diff**	**Cold RTDs % Diff**
5	0.83	0.1	-0.6	0.4	0.6
10	1.68	0.2	-3.0	0.2	0.6
15	2.57	-0.1	-2.5	0.1	-0.1
20	3.45	0.0	-3.0	0.3	0.6
25	4.35	0.2	-6.3	-1.3	0.1
30	5.23	0.3	-3.7	-0.8	1.6
35	6.12	0.5	-5.4	-1.6	1.7
40	7.02	0.7	-6.6	-2.2	-1.3

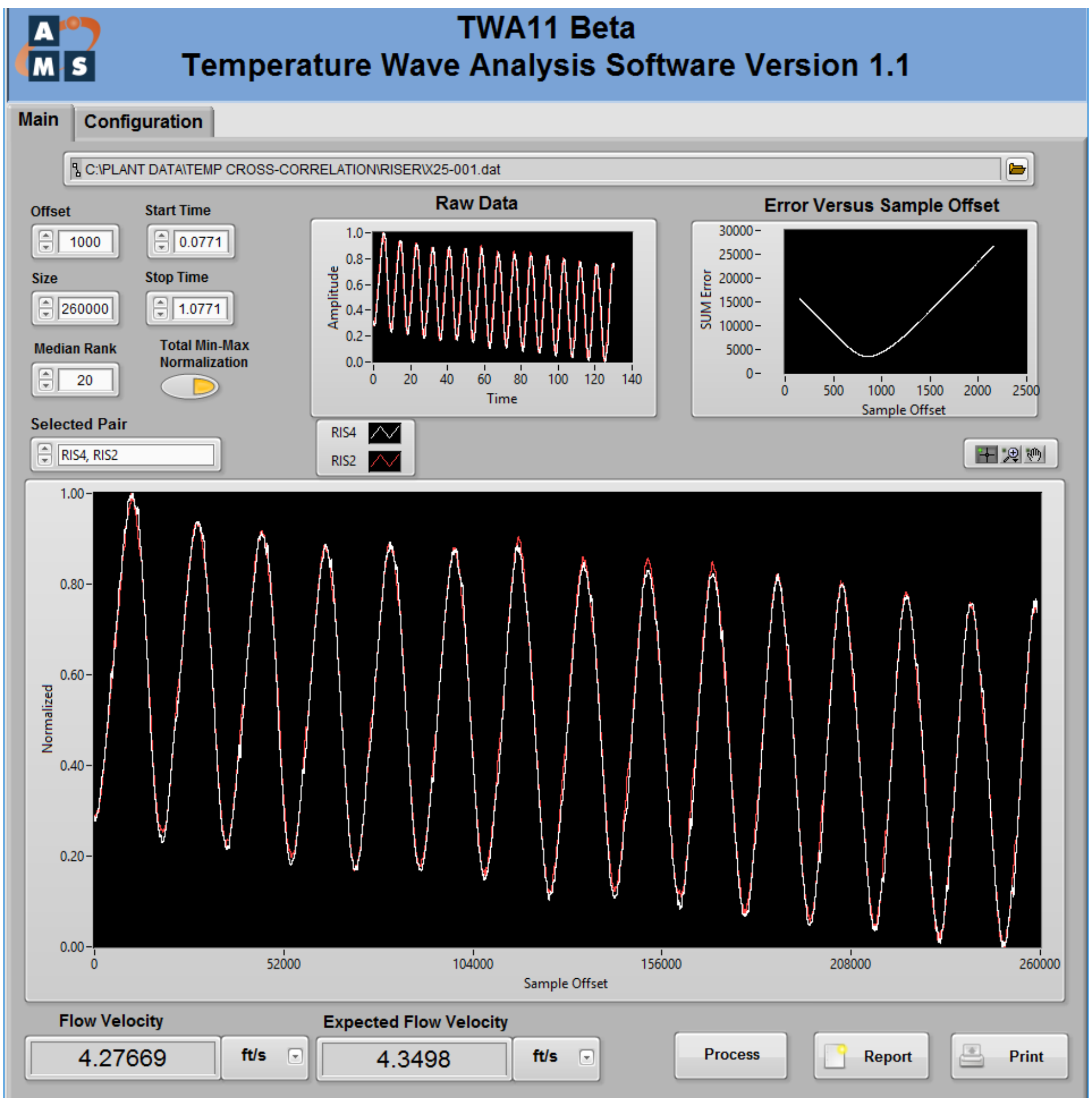

Figure 11. Example of Temperature Wave Analysis with Pump Speed at 25 Hz

5 CONCLUSIONS

The research and development associated with this DOE-sponsored project has shown that RTD temperature signals can be successfully used for thermal transit time flow measurements. Cross signal processing of temperature signals has been used to provide flow measurement with an accuracy of ±2% in a laboratory setting for flow rates between 0.5 to 7 fps. The accuracy of the temperature transit method was obtained by comparison to an electromagnetic flow meter with a certified calibration accuracy of better than 0.5% over the range of measurements. RTD response times and response time sensitivity to flow must be accounted for to obtain accurate results using the temperature transit method. Further, the response time characterization performed in conjunction with these developments have shown that sensor response time and self-heating characteristics can be used to infer fluid flow rate at low flow velocity.

The follow-up to this work is to integrate the hardware and software for RTD signal conditioning and the high speed, high resolution OLM data sampling with real-time cross signal processing including response time compensation of the signals. The authors will also investigate the reliability and repeatability of the test methods over the current range of flow measurements including evaluation of extending the transit time method to higher flow rates up to 50 fps. AMS is also assessing the potential for incorporating the thermal transit time methods with multi-point temperature sensors as opposed to separate discrete RTD elements. The authors anticipate cross-correlation technology can be used to address some of the I&C measurement challenges for light water integral vessel SMRs.

6 ACKNOWLEDGMENTS

This material herein is based upon work supported by the Department of Energy, Office of Nuclear Energy, under the Small Business Innovation Research program Award Number DE-SC0011859. AMS would like to acknowledge Brian Robinson, the DOE project manager, for his oversight and assistance on this project. This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

7 REFERENCES

1. Hashemian, H.M. “Listening in Real Time” *Nuclear Engineering International,* pp. 13–20 (April 2010).

2. Hashemian, H.M., et.al, “Advanced Instrumentation and Maintenance Technologies for Nuclear Power Plants.” U.S. Nuclear Regulatory Commission, NUREG/CR-5501 (August 1998).

3. Riggsbee, E., *Thermal Transit Flow Measurement for Small Modular Reactors*, 59th Annual ISA POWID, Charlotte, North Carolina, June 2016.

4. Hashemian, H.M., et.al, “New Sensor for Measurement of Low Air Flow Velocity.” U.S. Nuclear Regulatory Commission, NUREG/CR-6334 (August 1995).