PRIMARY COOLANT FLOW MEASUREMENT FOR INTEGRAL PRESSURIZED WATER REACTORS USING ULTRASONIC TECHNIQUE

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ABSTRACT

Several pressurized water reactor (PWR) systems under development employ integral primary coolant loop designs, where the primary coolant does not leave the reactor pressure vessel during operation (I^{2}S-LWR, mPower, NuScale). The absence of primary coolant piping inhibits traditional pressurized water reactor primary coolant flow measurement, in which the differential pressure across the steam generator is correlated to flow rate. To address this, a transit time, reflection mode, ultrasonic flow meter is proposed. An experimental flow loop utilizing a test section representative of a thin azimuthal slice of the down-comer region of an integral PWR has been constructed to test the efficacy of the General Electric AT600 ultrasonic flow meter (UFM) in such an application. A Great Plains Industries TM300 turbine flow meter (TFM), reporting volumetric flow rate and installed in-line with the flow loop piping, is used as the reference meter. UFM performance is affected by several factors, including flow development and symmetry. The UFM was installed on three locations along the flow path of water through the test section. The meter performed the best at the downstream end of the test section, where the fluid flow is the most developed. Performance, measured by percent error in UFM average reading with respect to the TFM average reading, generally improved with increasing flow rate at all locations, though absolute difference between meter readings increased with flow rate. This research suggests that ultrasonic approaches hold promise for non-invasive measurement of primary coolant flow in integral PWRs.

Key Words: Integral reactors, ultrasonic flow measurement, GE AT600.

1 INTRODUCTION

Flow rate of primary coolant that carries heat away from the nuclear fuel is an important measurement in pressurized water reactors (PWRs). Insufficient cooling can result in fuel damage, core melt, and radioactive release to the environment, if unmitigated. It is therefore important that the flow rate of primary coolant can be accurately, rapidly, and reliably monitored. Inaccurate monitoring can result in power down-rating and unnecessary downtime. In traditional PWRs the primary coolant flows in pipes between various components of the primary system including the reactor pressure vessel (RPV), which contains the reactor core, the pressurizer, the steam generator, and the primary coolant pumps. This provides straightforward and convenient means of measuring the flow rate of the primary coolant via the differential pressure across the steam generators. This approach is both accurate and fast, as any change in flow rate is reflected in the differential pressure as quickly as the pressure wave travels from the source of flow change back to the transmitter, and the transmitters have sub-second response times. In contrast, temperature measurements made with resistance temperature detectors (RTDs) and thermocouples (TCs) placed inside thermowells have typical response times of several seconds due to the time required for heat transport from the process through the thermowell and to the sensing element of the temperature sensor. Additionally, temperature information about the coolant moves with the coolant, rather than through it, the way pressure waves do.

Advanced PWR designs, such as small modular reactors (SMRs) and medium to large integral reactors, have been proposed which confine the primary coolant, and all the associated equipment, to the RPV. Not only does this present constrained spaces which complicate the instrumentation of these systems, it also removes the normal mechanism for measuring primary coolant flow rate. Several solutions to this issue have been previously proposed including cross-correlation of in-core detectors, energy balance, and of interest to this work, non-invasive ultrasonic techniques [1,2,3,4]. Ultrasonic flow measurement has been used to replace venturi flow meters on steam generator feedwater lines, resulting in power uprates which were unrealizable with venturi meters due to fouling [5]. The proposed application of ultrasound uses pairs of transceivers located around the outside of the RPV surrounding what is commonly referred to as the down-comer region of an integral PWR. This is labeled in Fig. 1. The down-comer is the primary coolant flow region which directs coolant back to the bottom of the core after the coolant has passed through the primary heat exchanger or steam generator. By measuring the velocity of coolant at various locations in this region, and knowing the cross-sectional flow area, the volumetric flow rate may be established.

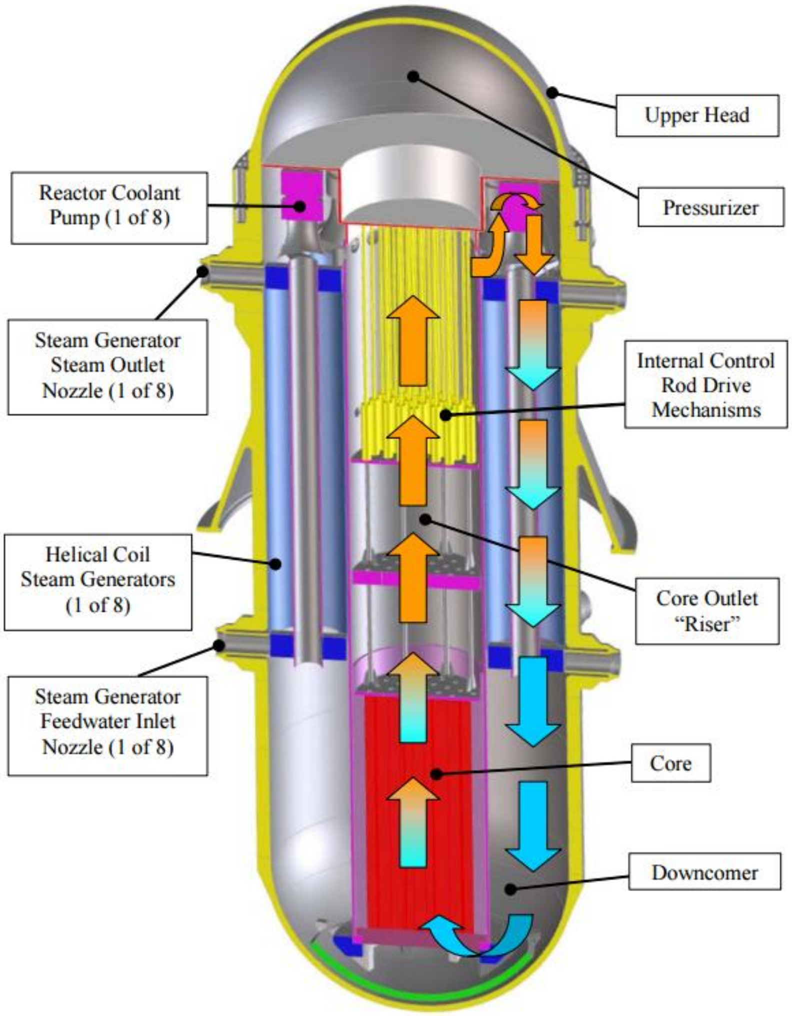

Figure 1. International Reactor Innovative and Secure (IRIS) [6], an integral PWR design.

Ultrasonic flow meters (UFMs) have been widely used in chemical process and wastewater treatment applications, but have generally been applied to circular pipes with fully developed symmetric flows. This study investigated the applicability of a commercially available UFM to fluid conduits of non-circular geometry and uncertain flow characteristics. A water flow loop was constructed for the purpose. The details are discussed in section 2.1 Experimental Setup.

1.1 Ultrasonic Measurement Technique

Sound, being a mechanical wave, requires a medium to travel through. If the medium moves, so too does the wave move. Thus, a sound wave traveling in a moving medium will travel faster or slower, relative to an outside observer, depending upon whether the sound has a component traveling in the same or the opposite direction as the moving medium. Consequently, the speed of a moving medium may be interrogated by passing sound waves both with and against the direction in which the medium is moving. The is the premise used to interrogate the flow in the down-comer region of an integral PWR. Fig. 2 shows a diagram of a possible implementation, where the transceivers are affixed to the outside of the reactor vessel, and the ultrasound pulses are reflected off the core barrel, traversing the flow twice on each path.

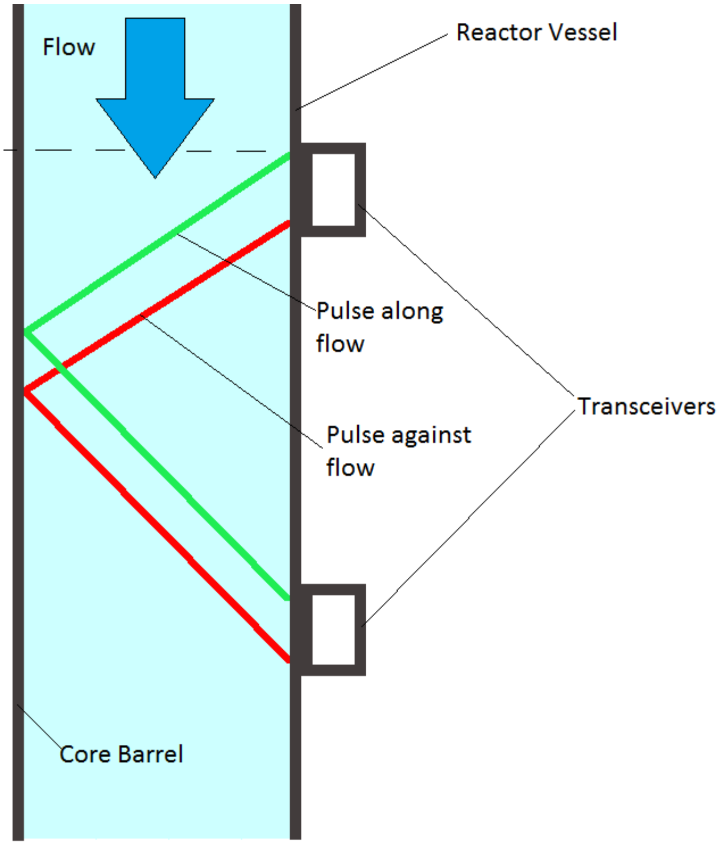

Figure 2. Diagram of ultrasonic transceivers used to measure primary coolant velocity in down-comer region of an integral PWR.

In an application, such as shown in Fig. 2, the velocity of the fluid is calculated based upon the time it takes for the upstream and downstream pulses to travel between transceivers, as shown in Equation (1). In this study, the calculation of velocity is performed by the UFM, which accounts for refraction of the wave when passing between disparate media.

$$V_{flow} = \frac{L*\Delta t}{2\sin(\varphi)*t_{down}*t_{up}} \tag{1}$$

Where: V_{flow} = velocity of fluid flow,

L = ultrasound pulse path length in fluid,

Δt = difference in traverse time between upstream and downstream pulses,

φ = angle of refracted pulse w.r.t. axis perpendicular to flow direction,

t_{down} = transit time of downstream pulse,

t_{up} = transit time of upstream pulse.

In traversing the flow path of the fluid, the sound wave is collecting information about the velocity of the fluid throughout the slice of coolant it passes through, such that the time data represents the average velocity of the flow profile in the conduit. More traverses will yield a better average; however, each traverse attenuates the signal due to refraction of a portion of the wave energy out of the flow. Also, worth noting is that capturing information about a slice of a fluid flow profile does not necessarily inform upon the entire flow unless the flow is fully developed and symmetric. If so, any slice that passes through the center of the flow profile will be the same, allowing one slice to contain all the information of myriad slices. The experimental application in this study employs a non-symmetric conduit with no guarantee of a fully developed flow, which is part of what makes it interesting.

2 METHODS

2.1 Experimental Setup

To probe the usefulness of commercially available UFM technology for integral PWR primary water flow monitoring, a surrogate test section intended to be representative of a thin azimuthal slice of the down-comer region was fabricated from 1/8 in. thick carbon steel. The test section was fabricated at the University of Tennessee. A flow loop was designed and constructed around the test section. A Square D S-Flex variable frequency drive (VFD) manufactured by Schneider Electric connected to a 7.5 horsepower, three-phase, 240V Bell and Gossett pump circulated water around the loop. About 90 feet of schedule 40 PVC piping was used to connect the pump and test section in a loop. In the original construction, only about 10 feet of piping was used, but this resulted in a large fraction of the flow being filled with entrained gas bubbles.

As a reference meter for evaluating the UFM, a Great Plains Industries TM300 turbine flow meter (TFM) was installed on the flow loop. The bubbles present in the originally constructed design interfered with TFM performance, artificially inflating it, and made it impossible for the UFM to collect sufficient signal to operate. This is due to the changes in speed and direction of the ultrasonic pulses when passing through bubbles. Many changes in media between water and bubbles result in many reflections and refractions, diluting the signal until it is meaningless. A significant weakness of UFMs is they are easily befuddled by bubbly flow. Adding length to the connecting loop, and thus water mass to be moved by the pump, resolved the issue of bubbles in the flow. This was confirmed using a medical ultrasound device to evaluate flow quality before and after lengthening the loop. The test section and complete flow loop are shown in Fig. 3 and Fig. 4, respectively.

The UFM evaluated was a General Electric AquaTrans 600 using CRS-10 transducers operating at one MHz [7]. The AT600's transceivers have a fixed angle at which they produce ultrasound waves, which fixes the separation distance between installed transceivers based upon the dimension of the fluid conduit and the number of traverses. The AT600 can calculate and report volume flow rate, but assumes a circular flow cross section, as in a pipe, which is not useful in this study.

To evaluate the UFM performance under varying flow conditions within the test section, the transceivers were installed at the bottom of the test section, where it was hypothesized that the flow would be the most developed, as well as in the middle, and near the top of the test section. To ensure agreement between the UFM and TFM for the same conditions of measuring the flow through the piping, the UFM was installed on the PVC piping and 25 readings were taken from both meters, approximately one second apart, at six different applied frequencies of power applied to the pump motor. Frequencies ranged from 15 Hz to 60 Hz yielding flow rates ranging from about 70 gallons per minute (GPM) to about 300 GPM. The average percent difference between the UFM and TFM was calculated and the TFM calibration was adjusted. This ensured that the TFM and UFM were producing the same results when installed in-line with one another.

Figure 3. Test section with UFM on bottom region.

Figure 4. Complete flow loop.

2.2 Data Collection and Analysis

For each of the three transceiver locations, top, middle, and bottom of the test section, 25 readings were taken from each sensor, at each of six different applied pump motor frequencies from 15 Hz to 60 Hz, producing flow rates between approximately 70 GPM and 300 GPM. Measurements were taken approximately one second apart and five minutes were allowed for the system to come to steady state at each new flow rate.

The average of 25 readings for each meter under each condition was calculated, along with percent error in UFM calculated volume flow rate with respect to the TFM and is reported in section 3 Results. The standard deviation of the meter readings for each meter and condition is also reported. Data sheets for the UFM [7] and TFM [8] report meter accuracy to within 1% and 3% of reading, respectively. These uncertainty values were used for error bars in plot comparisons of volume flow rates from the two meters. The UFM outputs meters per second while the TFM outputs GPM, so both were converted to cubic meters per second, propagating these uncertainties with the conversions. Uncertainty in the cross-section area of the test section is unknown, must be assumed to be large, but cannot be incorporated in the calculations or error bars on plots. Data was analyzed in Microsoft Excel and imported to Mathworks Matlab for plotting.

3 RESULTS

The results of data collection and analysis are summarized in Table I. Fig. 5, Fig. 6, and Fig. 7 show the average reading of each meter as a function of pump motor applied frequency for the top, middle, and bottom regions of the test section respectively.

Table I. Summary of UFM and TFM data collected from three regions of test section at various flow rates

VFD	**UFM@Top**			**UFM@Mid**			**UFM@Bot**		
(Hz)	**UM m^3/s**	**TM m^3/s**	**% E**	**UM m^3/s**	**TM m^3/s**	**%E**	**UM m^3/s**	**TM m^3/s**	**%E**
15	0.00579	0.00450	28.8	0.00631	0.00443	42.4	0.00502	0.00447	12.3
25	0.00901	0.00754	19.5	0.01020	0.00752	35.5	0.00808	0.00755	6.9
35	0.01286	0.01069	20.3	0.01449	0.01066	35.8	0.01123	0.01068	5.1
45	0.01650	0.01387	19.0	0.01850	0.01388	33.3	0.01473	0.01385	6.3
55	0.02005	0.01711	17.2	0.02296	0.01708	34.4	0.01805	0.01706	5.8
60	0.02209	0.01868	18.3	0.02427	0.01865	30.2	0.01906	0.01860	2.5

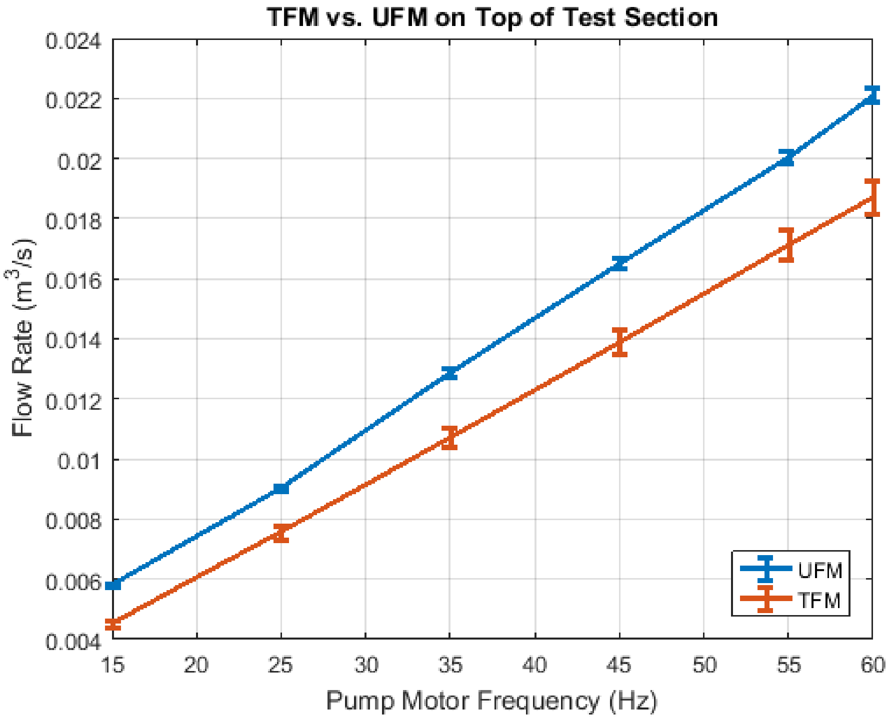

Figure 5. Volume flow rates from TFM and UFM installed on upper region of test section as a function of pump motor applied frequency.

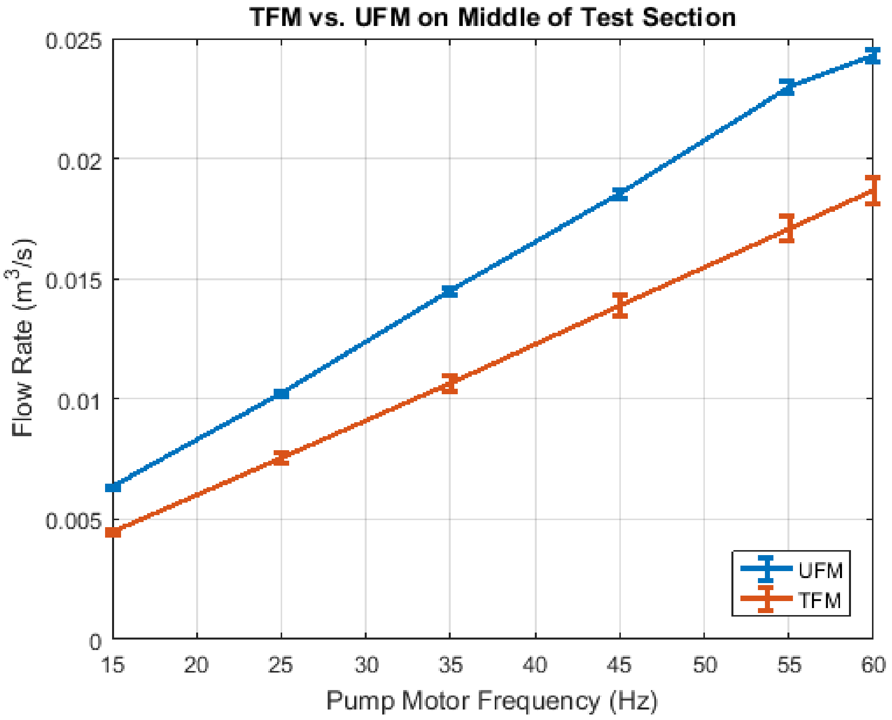

Figure 6. Volume flow rates from TFM and UFM installed on middle region of test section as a function of pump motor applied frequency.

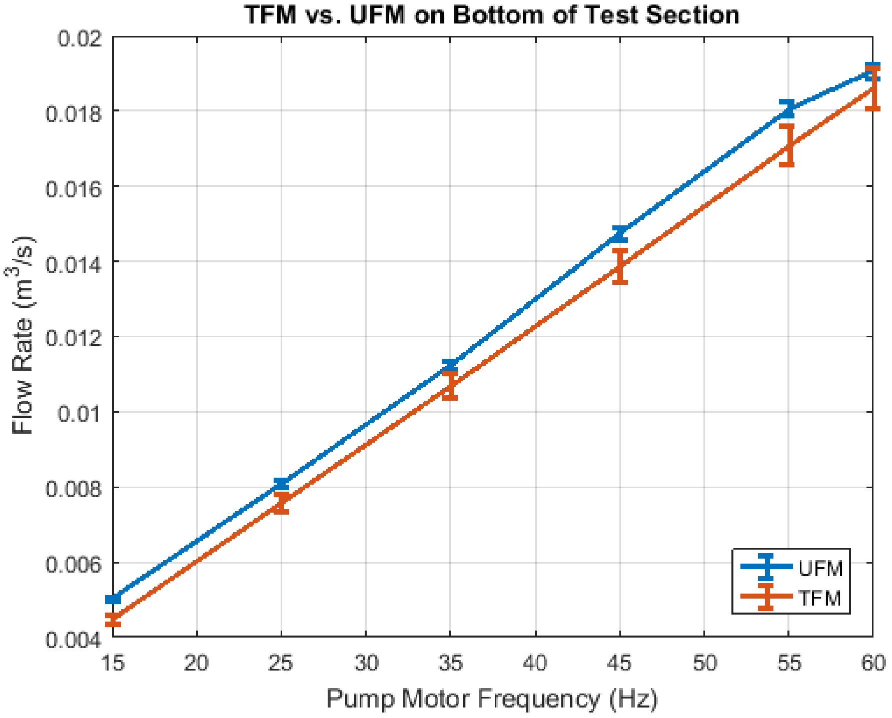

Figure 7. Volume flow rates from TFM and UFM installed on lower region of test section as a function of pump motor applied frequency.

Fig. 8 and Fig. 9 show the standard deviation of UFM and TFM readings at each location and pump speed. These plots do not show any discernable trend. The high standard deviation of TFM reading when

UFM measurements were taken at the top of the test section may indicate some problem with the experiment during that time, as it is highly inconsistent with the data taken during the other trials.

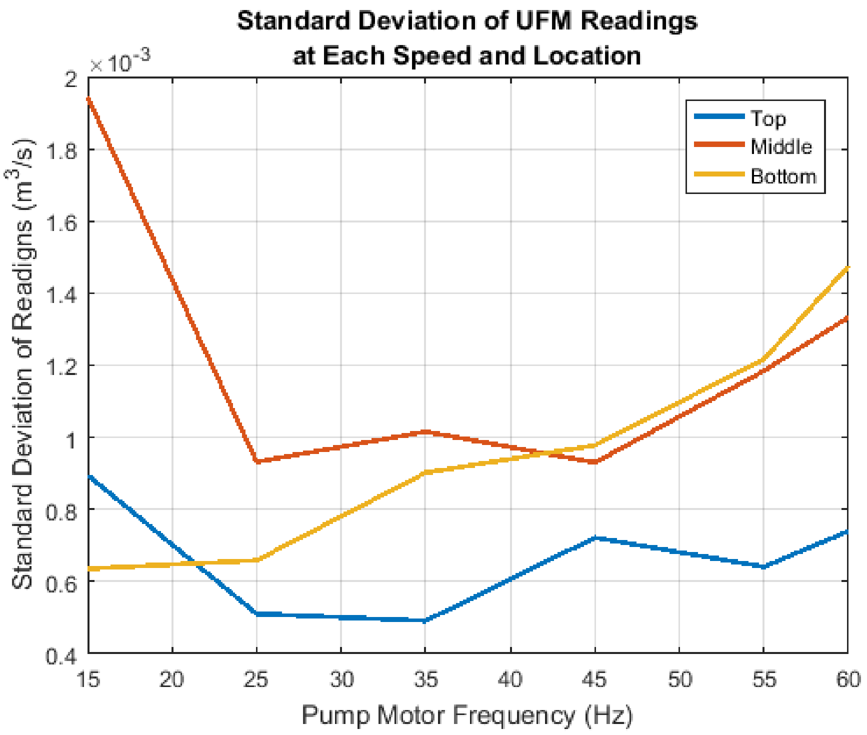

Figure 8. Standard deviation of UFM readings by transceiver location and pump speed. No general trend.

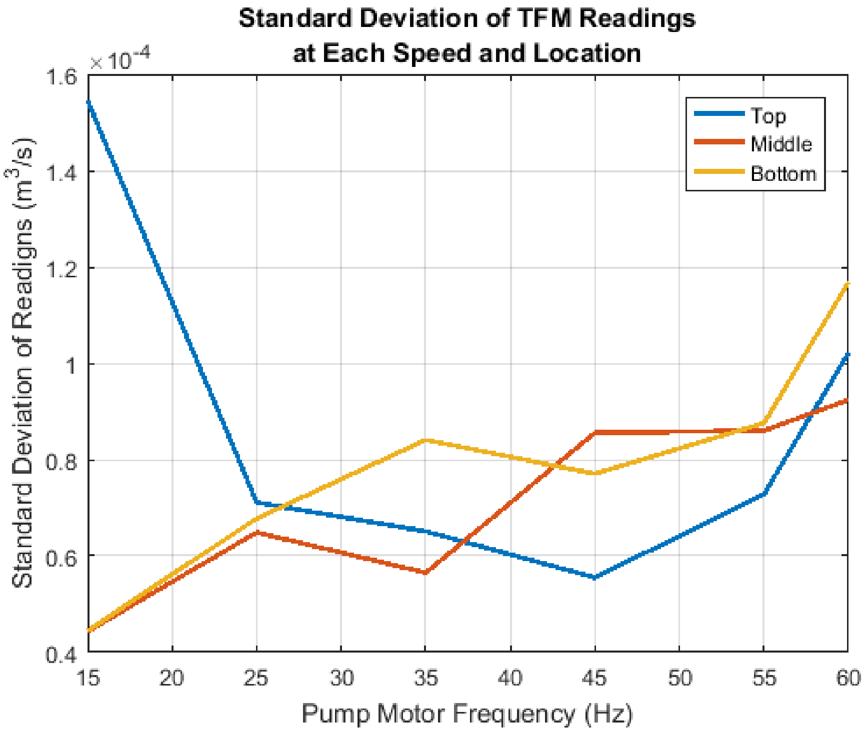

Figure 9. Standard deviation of TFM readings by transceiver location and pump speed. Slight general upward trend. Highly divergent data at 15 Hz for the top of the test section may indicate errors.

Fig. 10 shows the average percent error between the UFM readings and the TFM readings, where the TFM average reading is the accepted value in the percent error calculation.

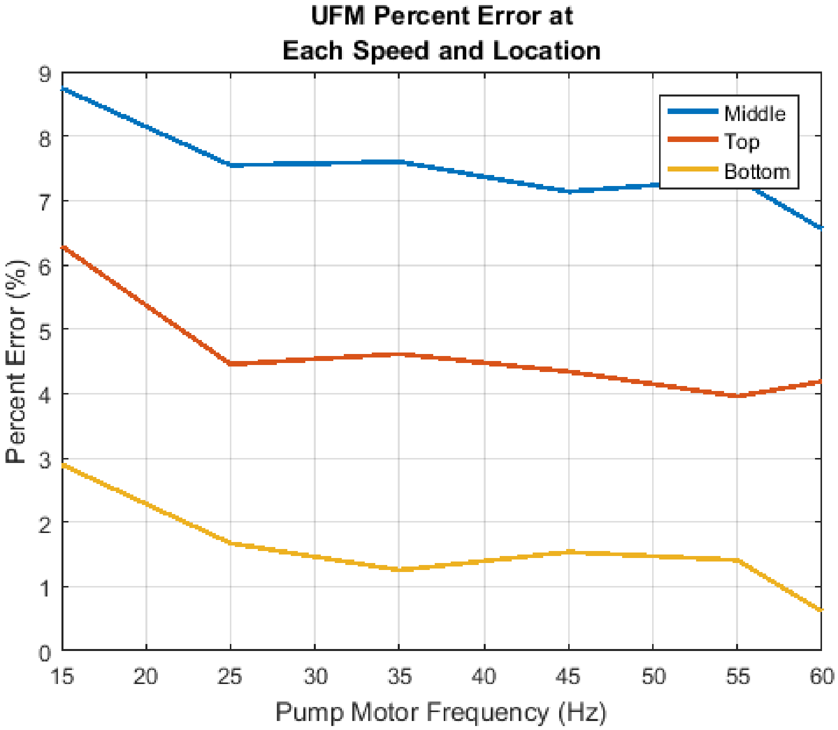

Figure 10. Average UFM percent error with respect to TFM average reading for each pump speed and transceiver location.

Absolute error between meter readings generally rises with pump speed, but percent error generally falls for all transceiver locations. The bottom installation position performed the best, as hypothesized, while the middle performed the worst. This would tend to indicate that the middle of the test section has the least developed flow of the three regions.

4 CONCLUSIONS

This study has examined the viability of transit time ultrasonic flow measurement for primary coolant monitoring in integral PWRs using a test section representative of an azimuthal slice of the down-comer region of an integral PWR, where it is proposed that this type of flow meter could be utilized.

This research fails to reject transit time ultrasonic flow measurement as a candidate for primary coolant flow rate monitoring in integral PWRs. It can be generally concluded that this technique, which is well demonstrated on circular pipes, is also applicable to non-circular geometries, though with greater difficulty and less assured accuracy.

With potentially varying flow profiles throughout the down-comer, a series of UFMs installed around the reactor vessel might struggle to capture the total average downward velocity of primary coolant, allowing the direct assessment of flow rate via flow cross-sectional area. However, it is likely that clever placement of the meter would allow the output to be *calibrated* to the total flow rate under known conditions, providing rapid and sensitive information about changes in the flow rate that would be important to human and automated operators.

It should be noted that the 1/8 in. thick steel of the test section is a poor analogue of the several inches of steel that comprise nuclear RPVs, and the thickness of the steel attenuates the ultrasonic wave considerably. However, it stands to reason that this can be overcome with more powerful transceivers. High temperature and irradiated environment applications present additional challenges that will need to be overcome to realize this approach.

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