Project No. 10-959

Development of Thermal Transient Flow Rate Sensors for High Temperature, Irradiation, Corrosive Environment

Reactor Concepts RD&D

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Development of Thermal Transient Flow Rate Sensors for High Temperature, Irradiation, Corrosive Environment

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1 Abstract

In advanced very high temperature reactor (VHTR), the coated particle fuel is burned in a graphite-moderated reactor that is cooled with special coolants. One type of coolant materials that has been actively researched on is liquid fluoride salt, which unfortunately is very corrosive to structure material. As such and also coupled with the extreme operating environment imposed by the reactor, including high radiation level, and high temperature (outlet temperature is up to 1000°C), most existing instruments will fail to function reliably. In order to improve monitoring capability and system reliability in a liquid- or gas-cooled nuclear reactor, research and development of salt-wetted instrumentation for both operations and maintenance is required. This project addresses one such equipment that is used to perform on-line, long term measurement of coolant flow rates, which is essential for determining the maximum power required by plant operation and for monitoring the safety operation of a nuclear power plant.

Coolant flow rate can be measured by various types of sensors, and the technique that measures thermal transient flow rate is by far the most promising one in a harsh environment caused by high irradiation, pressure, temperature and corrosive media. Basically, the transit time of natural random temperature fluctuations in processes or thermal signal generated intentionally, like the coolant flow in a nuclear reactor, can be obtained by the cross-correlation calculation of flow temperatures recorded by two separate temperature sensors. Provided that the cross-sectional area of the pipe through which the liquid flows is known, the flow rate can be readily derived. Although simple in concept, in practice, accuracy of this method is often severely compromised due to the wide peak generated from the cross-correlation calculation and sometimes even additional false peaks. This serious problem has been successfully solved by the PIs' group by introducing a new adaptive signal processing algorithm to better estimate the sensor system's impulse response function. The main peak obtained using the new algorithm is much narrower than that using the classical cross correlation method and the sidelobes (additional peaks) are considerably suppressed.

Besides the development of the new signal detection algorithm, the PIs have completed the following research tasks in this project: (i) calibration strategies based on conventional stainless steel shield thermal couples were developed, (ii) case study of flow meter performance by numerical simulation using commercial computational fluid dynamic (CFD) software (ANSYS-FLUENT), and (iii) investigation of additional thermal sensors (except thermocouple) for this type of flow rate meter, including platinum resistance thermoelectric sensor, and ultrasonic sensor. Due to unavailability of test facility, planned irradiation and corrosive testing using facilities in DoE lab and Ohio State University could not be conducted.

2 Introduction

In a harsh environment of high (>300 ^{o}C – 1000 ^{o}C) with significant level of irradiation and corrosion, as seen in a nuclear reactor, accurate measurement of coolant flowrate is essential for the reactor's safe operation [1]. In such an environment, the non-intrusive flowmeters including the electromagnetic meter and ultrasonic meters can only reliably work for a short period, after which due to accumulated measurement errors caused by device and vessel corrosion/erosion, the measurement readings become quite irrelevant to the actual flow [2 and 3]. As presented in one of our early publications [4], the transit-time-based cross correlation flowmeter using thermocouples with grounded stainless steel sheath is considered one robust and reliable solution to measure the flowrate in a nuclear reactor which imposes an extremely harsh environment to the measurement instrument deployed. Although simple in theory, in practice, we have observed that this type of flowmeter suffers from a few major signal processing problems, such as flat peak plateau or multiple peaks, which can likely lead to wrong readings. To overcome these problems, a few signal processing methods have been proposed and verified by experiments [4]. In addition, the flow measurement is determined to be relevant to the cross-sectional profile of the flow velocity, which dictates the sensor tip locations for better measurements.

We developed a calibration strategy in this project. In light of the approaches presented in [5], where curve fitting using extrapolation approach is utilized for the calibration of an ultrasonic cross correlation flowmeter, we developed a similar approach for calibration of the

thermal cross correlation flowmeter. In addition, we investigated how calibration is impacted by the physical settings such as location of the thermocouple tips across the pipe, the spacing between the two thermocouples (TC), and the pipe diameters.

Case studies of flow meter performance at different geometry set-ups were carried out by numerical simulation using commercial Computational Fluid Dynamics (CFD)software . One benchmark study was carried out to compare our results with other research results, followed by flow meter performance prediction. The numerical simulation model was established at 3-dimension and transient state. Thermal signals acquired by two thermocouples were simulated for different cases to obtain the time delay, linear fluid velocity, and subsequently, flow rate in pipe.

Thermocouple is considered as one reliable thermal sensor at high temperature, corrosive and irradiation condition. However, its slow response time can be a problem for the proposed flowmeter. Therefore, several other thermal sensors were investigated in this project, like platinum resistance thermoelectric sensor.

3 Project Objectives

In liquid- or gas-cooled nuclear reactors, accurate measurement of the coolant flow rate is essential for determining the maximum power required by the plant operation and for monitoring the safety operation of the plant. Coolant flow rate can be measured by various types of sensors, and the technique that measures thermal transient flow rate is by far the most promising one in a harsh environment caused by high irradiation, pressure, temperature and corrosive media. Although simple in concept, in practice, accuracy of this method is often severely compromised due to the wide peak generated from the cross-correlation calculation and sometimes even additional false peaks. The objectives of the research were thus four folds.

1) develop and validate new signal processing algorithm;

2) investigate a few important practical problems related to the flowrate measurement, including the negative delay and the sampling rate of the data acquisition;

3) conduct sensor reliability studies, including development of the calibration strategies;

4) conduct studies of different sensing techniques, and determine how their response times and thus the sensor performance can vary when different shielding materials and geometric dimensions are applied.

4 Work Performed and Results

A. FLOW MEASUREMENT BASED ON THE TRANSIT-TIME OF CORRELATED THERMAL SIGNALS

The flow profile can be obtained through estimation of the time delay (τ) between two correlated thermal signals recorded by two separate thermocouples placed along with the pipe [6-9]. The upstream thermocouple senses a flow signature τ seconds earlier than the downstream one, where L is the distance between the two thermocouples and V is the linear flow velocity in pipe (Fig. 1). As a result, the flow velocity can be found by,

$$\overline{V} = L/\tau \tag{1}$$

Several methods have been proposed in the literature for estimating this time delay [6-10]. By addressing the practical problems with these methods, we proposed an accurate and robust time delay estimation method which was verified in theory and by experiment. This method includes the following major steps:

Step 1) Filter the upstream and downstream signals using a moving average filter. That is,

$$i_{1q}(kT_s) = \frac{1}{q}\sum_{l=0}^{q-1} i_1((k-l)T_s) \tag{2}$$

$$i_{2q}((k-r)T_s) = \frac{1}{q}\sum_{l=0}^{q-1} i_1((k-r-l)T_s) \tag{3}$$

where i_{1q} and i_{2q} are the respective upstream and downstream thermocouple signals, k is the number of sampled-data in signals i_{1q} and i_{2q}, T_s is the sampling period, l is the length of moving average filter, and r is the number of sampled-data that is used in cross-correlation calculation.

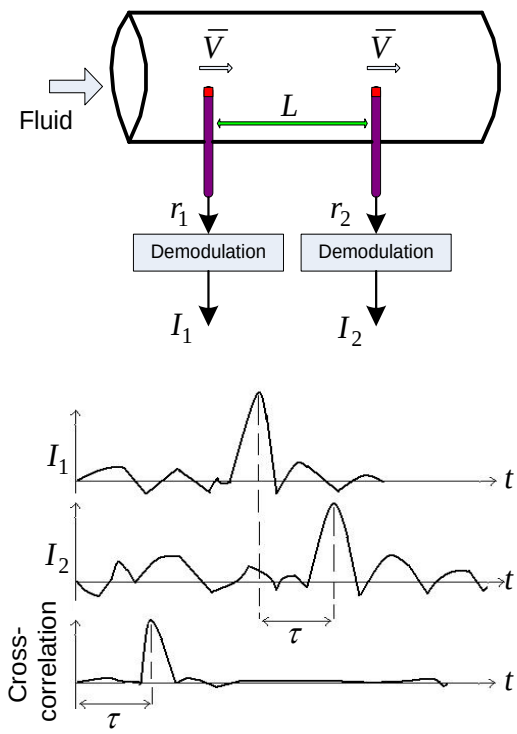


Figure 1 The operating principle of the cross correlation flowmeter.

Step 2) Calculate the autocorrelation of the upstream signal.

$$R_{i_1 i_1}(rT_s) = \frac{1}{T}\sum_{k=1}^{N-1} i_{1q}(kT_s) i_{1q}((k-r)T_s) \tag{4}$$

where T is the window size of i_{1q} and N is sample size of i_{1q}.

Step 3) Calculate the cross correlation of upstream and downstream signals.

$$R_{i_1 i_2}(rT_s) = \frac{1}{T}\sum_{k=1}^{N-1} i_{1q}(kT_s) i_{2q}((k-r)T_s) \tag{5}$$

Step 4) Detect the peak of above cross correlation calculation.

Step 5) Choose a windowed version of the autocorrelation function of i_1 and cross correlation function of i_1 and i_2 around the detected peaks from step 2. These regions can be chosen between two adjacent valley points around the peak. We denote them as $\psi_{11}(t)$ and $\psi_{12}(t)$, respectively.

Step 6) Convert the time domain signals $\psi_{11}(t)$ and $\psi_{12}(t)$ to their frequency representations $\Psi_{11}(j\omega)$ and $\Psi_{12}(j\omega)$.

Step 7) Estimate the transfer function $\hat{H}(j\omega) = \frac{\Psi_{12}(j\omega)}{\Psi_{11}(j\omega)}$.

Step 8) Convert $\hat{H}(j\omega)$ back to $h(t)$ with inverse Fourier transform.

Step 9) Detect the peak of $h(t)$ to obtain the time delay τ.

The flow velocity can be calculated by using this time delay with a known distance *L*.

B. FLOW VELOCITY PROFILE AND FLOWRATE CALCULATION

1) Flow rate profile

The experiment settings with water flows through the pipe have Reynolds numbers in the range of 6.60×10^3 to 6.24×10^4. This indicates that the flow is turbulent, and thus the flow profile across a pipe can be predicted by an approximate curve-fit as given in [11],

$$\frac{V(r)}{\overline{V}} = \frac{(n+1)(2n+1)}{2n^2}(1-2r/D)^{1/n} \tag{6}$$

where $V(r)$ is the flow velocity at radial position r, D is the pipe diameter, $\overline{V}$ is the mean velocity, and n is a constant number which is related to the Reynolds number. In our work, for the corresponding Reynolds number, n is equal to 6.6.To obtain the flow velocity profile in our flow measurement system, we measured the velocity at several radial positions for flowrate range between 0.5 and 3 gallon per minute (GPM) (Fig. 2).

The mean velocity can be derived from the flowrate by,

$$Q = K\overline{V}A \tag{7}$$

where Q is the flowrate, K is the calibration factor, $\overline{V}$ is the mean velocity, and A is the cross-sectional area of the pipe.

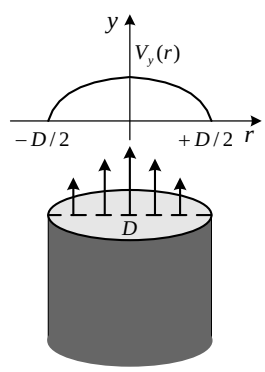


Figure 2 The cross-section view of pipe showing the flow velocity distribution.

2) Flowrate Resolution vs. Response Time of Thermocouple

The time response of the thermocouples imposes a limitation on the flowrate calculation in the transit-time based flow measurement system. This is because the time delay between the thermal signals recorded by the thermocouples is obtained by dividing the detected sample delay by the sampling frequency; the range and resolution of flowrate are influenced by the sampling frequency, and thus the response time of the thermocouples. In our experiments, we have observed that the thermocouples have a response time of 1.4 seconds. This slow response time imposes an upper bound on the frequency component (or Nyquist frequency) of the thermocouple's signal. It has been observed that when sampling frequency is set above 10 Hz,

the thermocouples give 3 repetitive readings, this theoretical limitation agrees well with the experimental observation. Therefore, to avoid over-sampling, we fixed the sampling frequency to 4 Hz.

In this flowrate calculation method, as each detected sample offset delay corresponds to a unique flowrate, all the possible detected time delays will fall into the following set,

$$\tau\ (\mathrm{second}) = \left\{ \frac{n}{f_s} = \frac{n}{4}, n = 1, 2, \ldots \right\} \tag{8}$$

Therefore, the corresponding calculated flowrate for sampling frequency of f_s Hz will be,

$$Q = \frac{\pi D^2 L}{4} \frac{f_s}{n} \tag{9}$$

where L is the thermocouple spacing, D is the internal diameter of the pipe, and f_s is the sampling frequency.

3) Deviation of Calculated Flow Velocity and Flowrate

If the detected peak point n in Eq. (9) deviates for one sample, the difference of calculated flow velocity with respect to n will be,

$$|\Delta V| = |V(n+1) - V(n)| = \frac{L f_s}{n(n+1)} \tag{10}$$

Using $V = \frac{L f_s}{n}$, one may arrive at,

$$\left|\frac{\Delta V}{V}\right| = \frac{V}{V + Lf_s} \tag{11}$$

In a similar way, for the deviation of flow rate, one can get,

$$|\Delta Q| = |Q(n+1) - Q(n)| = \frac{\pi D^2 L f_s}{4n(n+1)} \tag{12}$$

Plugging Eq. (9) into Eq. (12), we shall have

$$|\Delta Q| = \frac{4Q^2}{4Q + \pi D^2 L f_s} \tag{13}$$

Therefore, the relative flowrate deviation can be obtained by,

$$\left|\frac{\Delta Q}{Q}\right| = \frac{4Q}{4Q + \pi D^2 L f_s} \tag{14}$$

Figs. 3-5 show some numerical results for the deviation of the calculated velocity and the actual flowrate.

As far as the thermocouple spacing is concerned, Figs. 3 and 4 show that the rate of deviation in lower flow (< 1 m/s and 1 gpm), due to extending the thermocouple spacing, is quite linearly proportional to the flow range. It is also noticed that a small thermocouple spacing (10 cm) leads to significant change in the deviation of calculated flow.

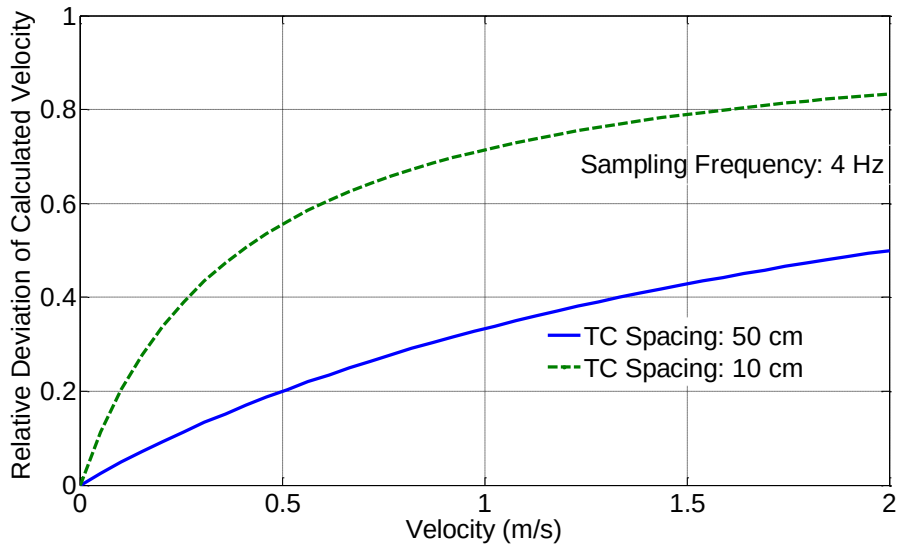


Figure 3 Relative deviation of calculated velocity versus velocity range.

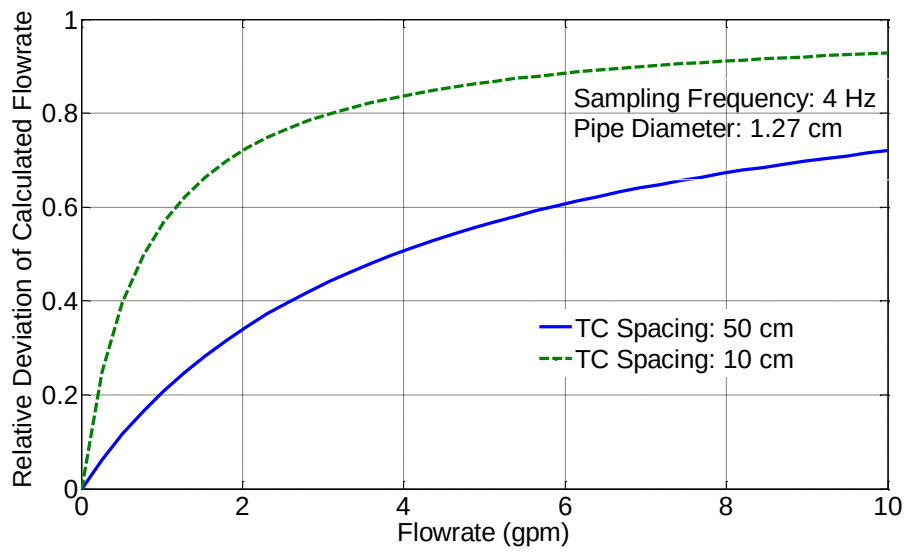


Figure 4 Relative deviation of calculated flow versus flow range

From the pipe size perspective, although the calculated velocity is not influenced by the pipe diameter, as depicted in Fig. 5, the deviation in calculated flowrate for the smaller pipe is noticeably higher than that of the larger one.

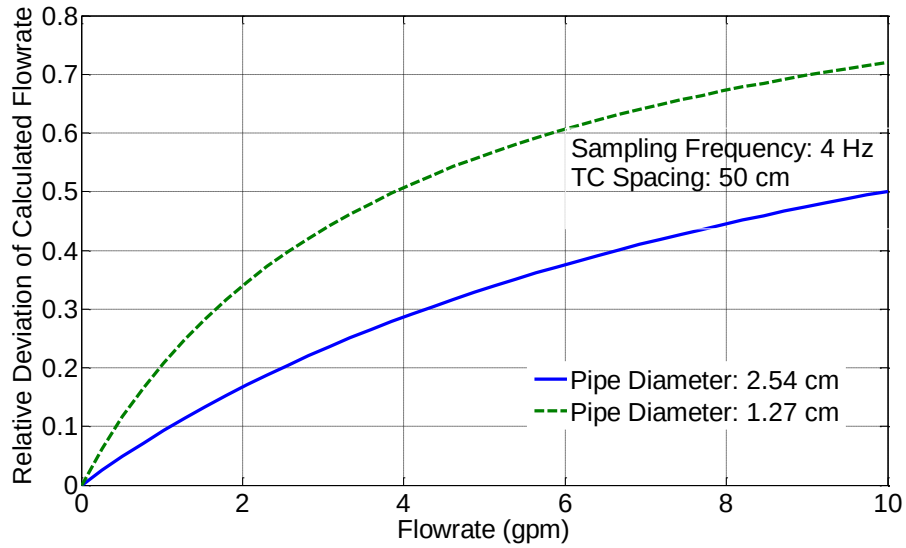


Figure 5 Relative deviation of calculated flow versus flow range

C. CALIBRATION FACTOR ESTIMATION

From Eq. (9), it is noted that the calculated flow is a function of the pipe diameter and the thermocouple spacing. Since the measured flow is based on small temperature fluctuation in the temperature profile, we may assume that this low level fluctuation does not have any influence on these quantities. Moreover, since the roughness of the pipe wall does not affect the temperature profile, the calibration factor shall not be sensitive to roughness. As a result, the single factor that is taken into account for calibration factor estimation is the measurement error due to either background noise or adopted time delay estimation technique. To minimize this error, the linear regression model is applied to observation data and the least square approach is used to fit this model [12 and13].

The instantaneous flow Q is determined as

$$Q_r = k_0 + k_1 Q_m \tag{15}$$

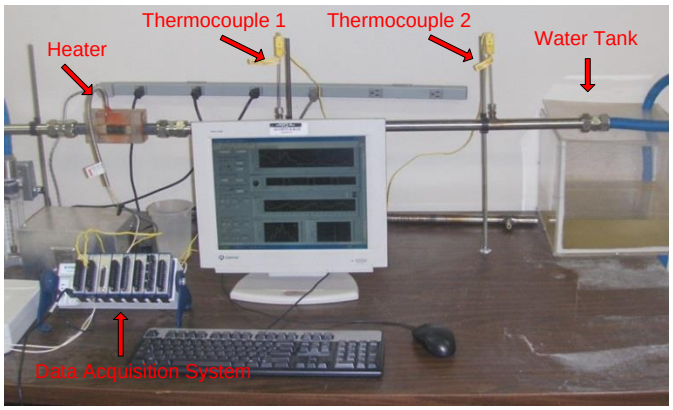
where Q_r and Q_m are the reference and measured flowrates, respectively, and k_0 and k_1 are the calibration coefficients which are estimated by,

$$\widehat{k}_0 = \frac{\overline{Q_r}\left(\sum_{i=1}^{N} Q_{m_i}^2\right) - \overline{Q_m}\sum_{i=1}^{N} Q_{m_i} Q_{r_i}}{\sum_{i=1}^{N} Q_{m_i}^2 - N\overline{Q_m}^2} \tag{16}$$

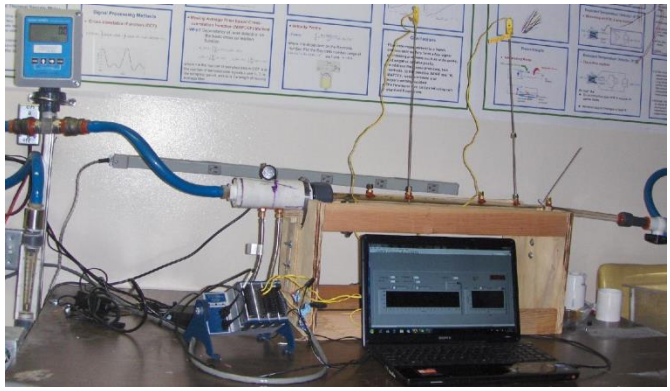
$$\widehat{k}_1 = \frac{\left(\sum_{i=1}^{N} Q_{m_i} Q_{r_i}\right) - N\overline{Q_m}\,\overline{Q_r}}{\sum_{i=1}^{N} Q_{m_i}^2 - N\overline{Q_M}^2} \tag{17}$$

D. EXPERIMENTS AND RESULTS

To estimate the calibration factor, we used experimental data from a water loop testing apparatus (Fig. 6). This apparatus has two configurations: one with pipe diameter of 1 inch (2.54 cm) and TC spacing of 50 cm, and the other with a diameter of 0.5 inch (1.27 cm). We estimated the calibration factor using the first configuration and compared the results using the second system. In specific, the following experiments were performed, and the measurement results were shown in Fig. 6.



(a)



(b)

Figure 6 (a). The water-based test apparatus with pipe diameter of 1 inch.

(b). The water-based test apparatus with pipe diameter of 0.5 inch.

1) Thermocouple location across the pipe

To find the flow velocity profile, we placed the thermocouple tips at different radius points ranging from 0 (the pipe center) to 0.8 (close to the pipe wall). The sample size and sampling frequency are set to 100 and 4 Hz, respectively.

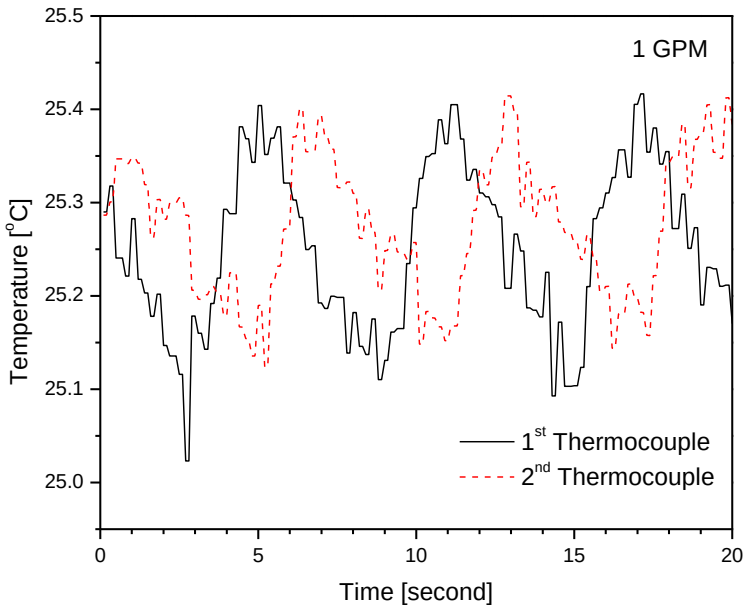


Figure 7. Temperature profiles obtained from experiments at location 1 and 2.

Figs. 8-9 show the flow velocity profile for the reference flow of 0.5 to 4 gpm for a 1-inch pipe system.

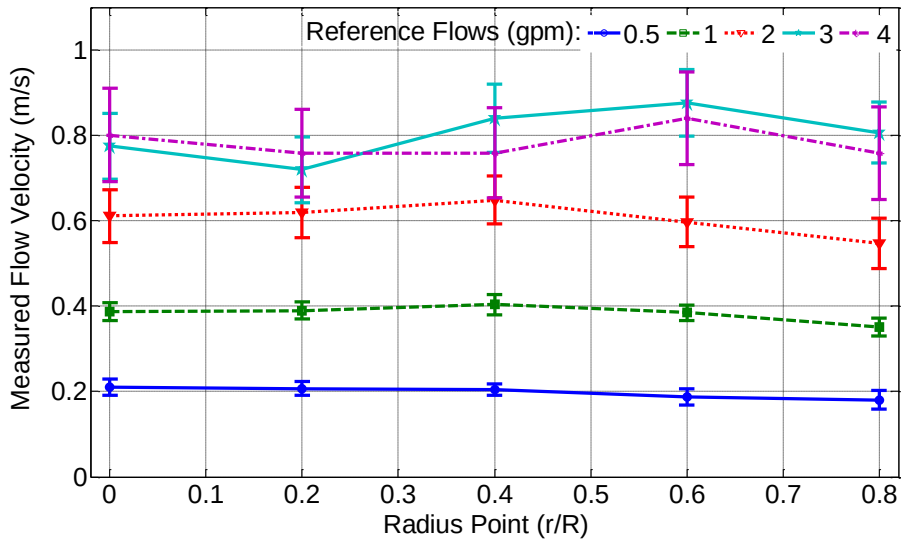


Figure 8 Flow velocity versus radius point for pipe diameter of 1 inch using 10 experiment runs.

As seen from Fig. 8, when the flow rate increases from 0.5 to 4 gpm, the deviation of the measured flow increases as well. These results are in agreement with the theoretical prediction given in Eq. 14 and shown in Fig. 3.

To choose the best location of the thermocouples tips across the pipe, two considerations are taken in account: (i) the mean square error of measured velocity and (ii) the relationship between the measured flow velocities at each location with respect to the mean flow velocity.

From Fig. 8, it is noted that the mean square errors for radius points less than 0.7 are not remarkably changed. Therefore, from the accuracy point of view, any location within this radial position can be considered as the right location for the thermocouple tips. Also, there is no noticeable change of the flow velocity with radius point interval [0, 0.3] . That is,

$$V(r) \cong \overline{V} \quad , \quad 0 \le r \le 0.3R \tag{18}$$

Therefore, any location within this radial range shall be acceptable for the calculation of flow rate based on the measurement.

2) Small size pipe system

To examine the dependency of flow velocity profile on the pipe diameter and TC spacing, we performed similar experiments with same data acquisition settings described above, but here with a pipe diameter of 0.5 inch. Fig. 9 shows the flow velocity profiles versus radius point for this pipe size. It is noted that, like the previous pipe size setting, the flowmeter is not measureable beyond 3 gpm.

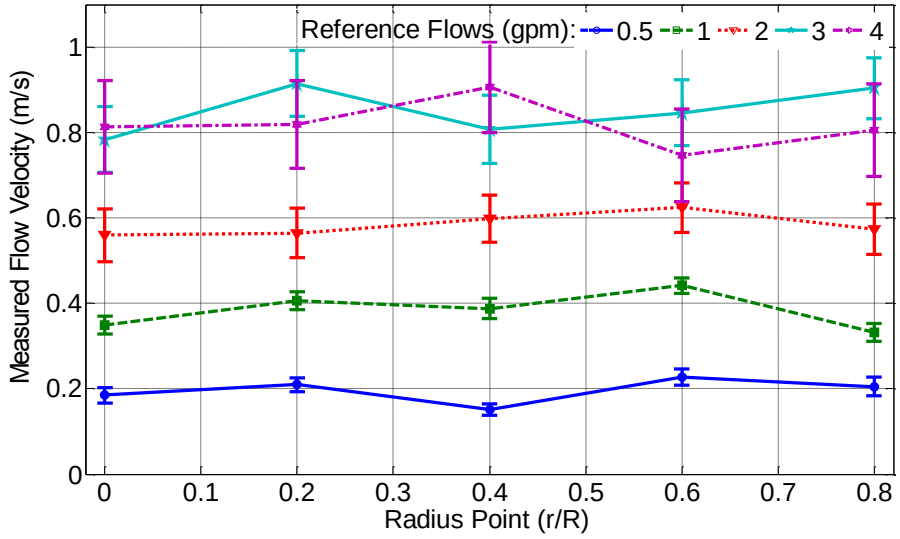


Figure 9 Flow velocity versus radius point for pipe diameter of 0.5 inch using 10 experiment runs.

From Fig. 9, it is noticed that the mean square errors over all radius points are essentially the same. Therefore, any point velocity across the pipe can give a good estimate for the mean velocity.

3) Calculation of the Calibration Factor

The first effort to estimate the calibration factor is to find a constant value for adjusting the measured flow data with respect to the referenced flow readings. Table 1 shows some measured flow rates as opposed to the reference flows. From this Table, one may find that the actual flowrates cannot be found by simply multiplying a constant value within the measured flow rates. Therefore, there may be a bias on the measured flow which is required to apply a linear regression model (Eq. 15) or there is a nonlinear relationship between these quantities which demands a nonlinear model [14].

Table 1 RATIO OF THE REFERENCE FLOW TO MEASURED FLOW

Reference Flow (gpm)	Measured Flow (gpm)	Ratio of the Reference Flow to the Measured Flow
1	1.38	0.72
2	2.98	0.67
3	4.55	0.66

We tried the first approach and found that the linear regression model is really well fitted to the measured data. Table 2 shows the coefficients of the linear function for fitting by this model.

To examine the reliability and repeatability of the model, we used 4 sets of experimental data which were recorded at 4 different times (two times for pipe diameter of 1 inch and two times for a different size). As seen in Table 2, this model presents reasonably consistent results.

Table 2 LINEAR FITTING RESULTS FOR FUNCTION $Q_r = k_0 + k_1 Q_m$

Experiments	k_0	k_1
1	0.13	0.63
2	0.14	0.62
3	0.12	0.64
4	0.13	0.65

Fig. 10 shows that the linear function is well-fitted to the real measurement data. This verifies the linearity of the *K*-factor given in Eq. (7) with an offset compensation factor of about 0.15 gpm to the calibration line.

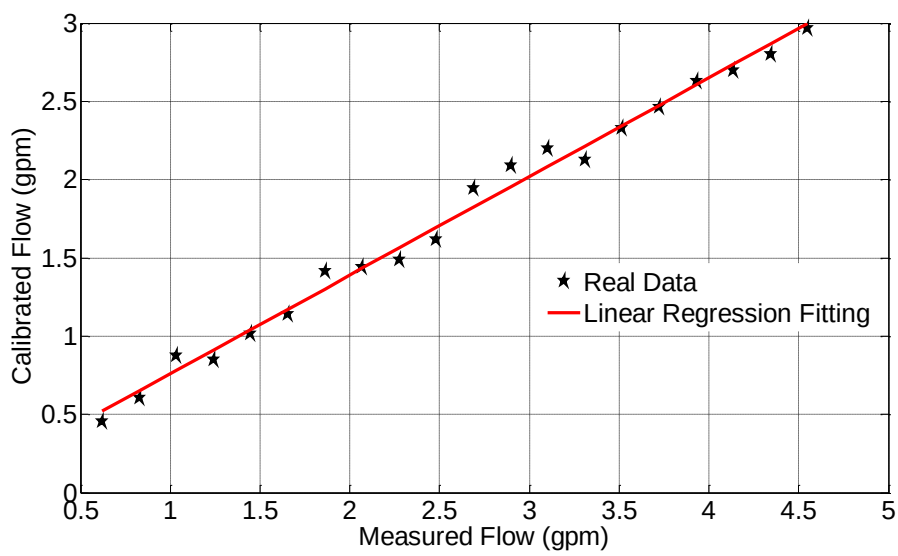


Figure 10 Linear fitting approach.

Finally, we calculated the normalized mean square error of the calibrated flowrate using the following equation,

$$NMSE = \frac{1}{M}\sum_{i=1}^{M}\left(\frac{\hat{Q}_{r_i} - Q_{r_i}}{Q_{r_i}}\right)^2 \tag{19}$$

where $\hat{Q}_r$ is the calibrated flowrate using Eq. (15), Q_r is the reference flow, and M is the number of experiment runs. The results are shown in Fig.11. One may see that the experiment results are in sound agreement with the theoretical prediction given in Eq. (14) and shown in Figs. (4) and (5).

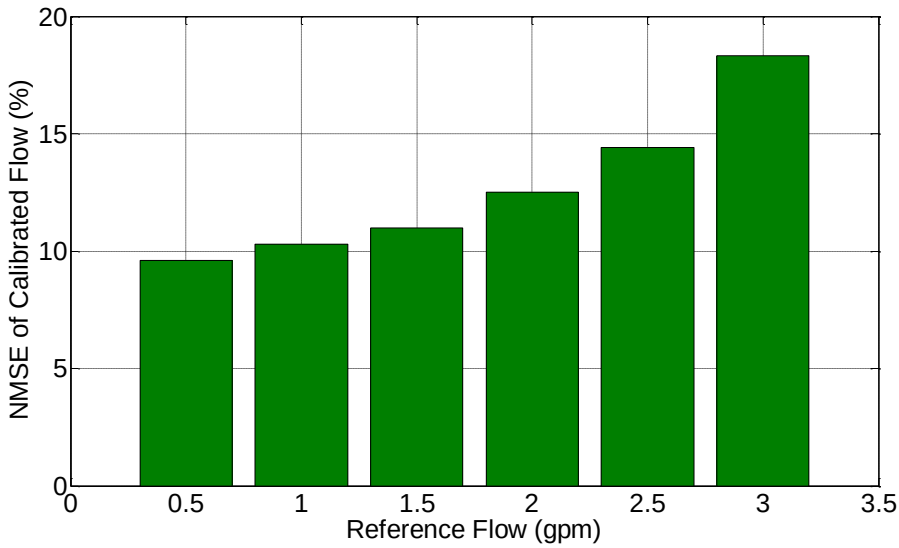


Figure 11 Normalized mean square error of calibrated flow using 10 experiment runs.

E. Numerical Simulation

With the aid of Computational Fluid Dynamics (CFD) coupled with energy solution, our flow meter can be simulated using a commercial software package, Fluent (ANSYS). The case study of analysis and design of flow meter can be accomplished in a cost effective way by changing parameter values in software. Based on the initial benchmark study in comparing our results with other results from other research groups, our model is reliable to predict the performance of our flow meter that includes an electric heater for the generation of thermal signals.

Our numerical simulation CFD model is a 3-dimensional model at transient state to predict two thermal signals acquired by two thermocouples along the flow stream (Fig. 12) at time-domain. The time delay can be obtained and the linear velocity is able to be derived, which is employed to find out the flow rate. Fluid (water) passes though the heating zone from the left, where the heater is located (Fig. 12), at a flow rate of 1 GPM. In our experiment, we use a heating pattern that creates square-like thermal signals spanning several periods; these patterned thermal signals can be carried along with the fluid flow and picked up by the thermocouple at locations 1 and 2. In numerical simulation, we only use one heating impulse at duration of 1 second to simplify the time-dependent flow; here the heater is turned on for one second and off for all other time.

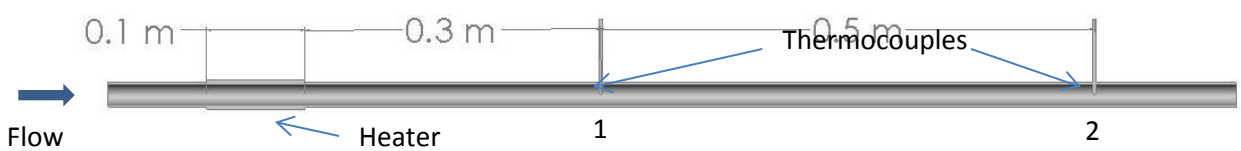


Figure 12. Flow meter design.

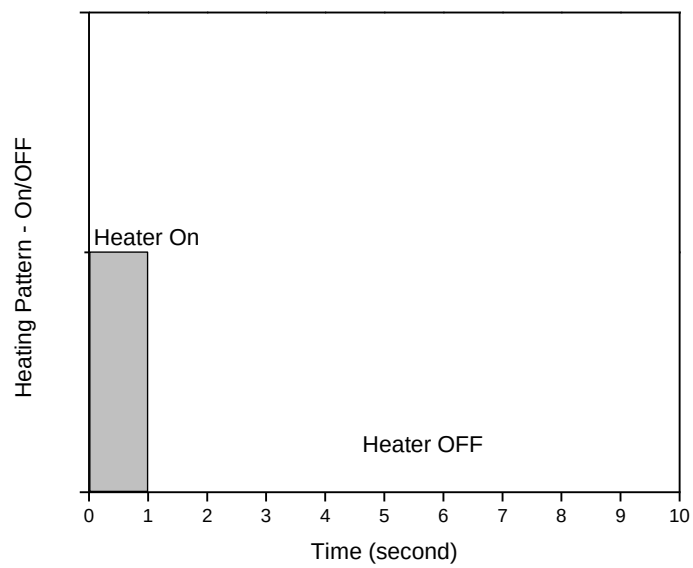
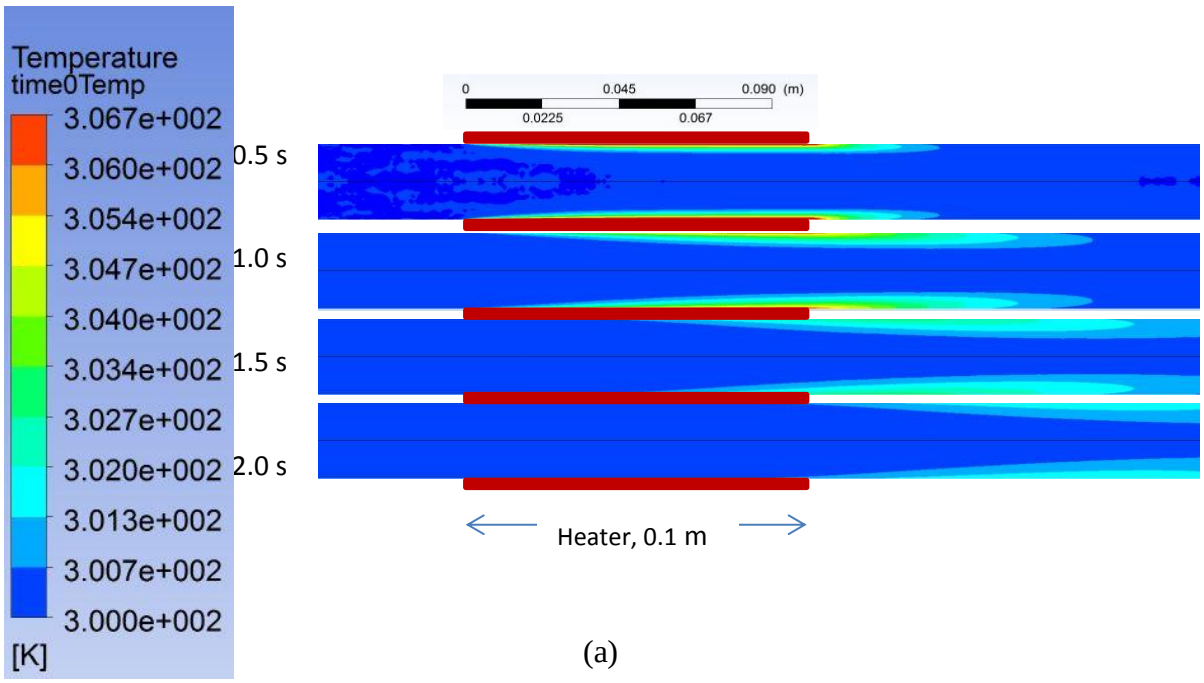
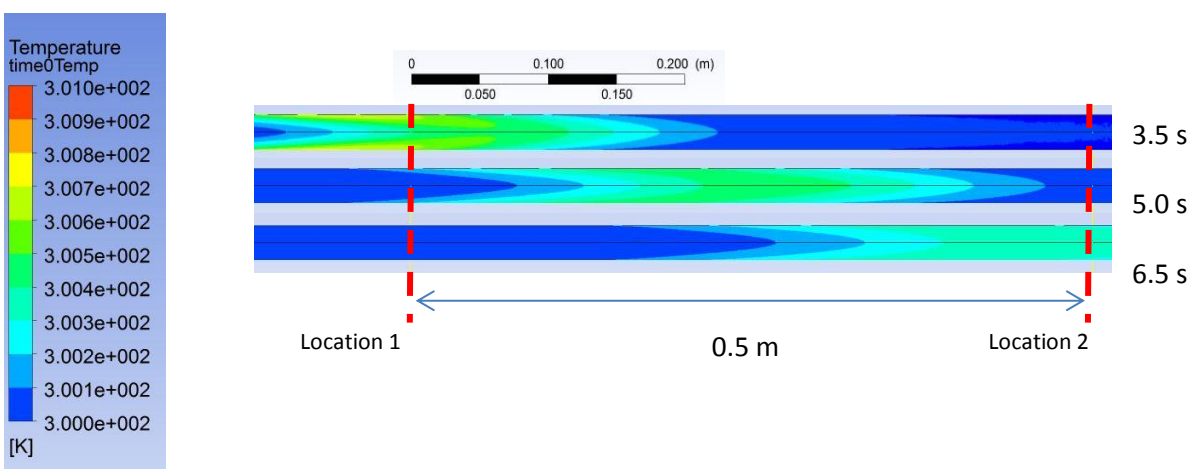


Figure 13. Heating pattern.

The temperature contour plot shows the heating process developed by the heater at different time instances, 0.5, 1.0, 1.5 and 2.0 second. Fluid (water) was heated by the heater near the boundary of the heater and carried with fluid flow to the downstream zone during the heating process within the first second, as shown in Fig. 14 (a). Since the heater was turned off right after 1 second, heating process was stopped and no higher temperature zone could be found near the heater.



(a)



(b)

Figure 14. Temperature contour varied at different time, t=0.5 second, 1.0s, 1.5s, 2.0s, 3.5s, 5.0s and 6.5s.

The turbulence flow inside the 1-inch tube helps the mixing of hot fluid with cold fluid. After a couple of seconds, hot fluid approaches the first thermal detector and then proceeds to the second thermal detector. These two thermal detectors (thermocouples) acquire the temperature variation with time. The temperature profiles are presented at Fig. 15. Two dominant signal peaks are apparent, which corresponds to the variation of temperature at locations 1 and 2. The time delay between the two thermal signals can be easily determined and this number is used to derive the fluid flow rate. At location 2, the peak temperature drops from 300.48 K down to 300.39 K, which verifies the mixing process of hot and cold water in the tube.

The simulation result also indicates that a 500-watt heater is sufficient to generate a thermal signal strong enough that it can be picked up at the second location; the lower bound of the signal strength needs to be higher than the measurement error (about 0.2 K) of the thermocouple.

The effect of thermocouple itself on the accuracy of the measurement was also studied by numerical simulation. Our flow rate detection technology is intrusive by nature. As so, thermocouple will have an interfering impact when using this flow meter to predict flow rate. With the help of numerical simulation, temperature variation at locations 1 and 2 can still be obtained without actual insertion of thermocouples. Two cases were studied; one is a straight tube with insertion of thermocouples (mesh was generated as shown in Fig 15 for simulation); another is a simple straight tube. The temperature profiles with respect to time, without insertion of thermocouple, were illustrated in Fig. 16. When comparing the two cases that thermocouple does and does not get inserted, it has been noticed that there is no substantial difference between the two. Only a slight peak temperature drop at the second location could be found, but this does not introduce any error in the calculation of the time-delay. It can be concluded from the numeric simulations that the small size of thermocouple will not cause measurement errors.

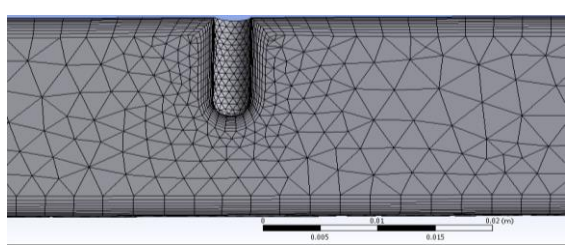


Figure 15. Geometric mesh for numerical simulation with insertion of a thermocouple (1/8 inch diameter).

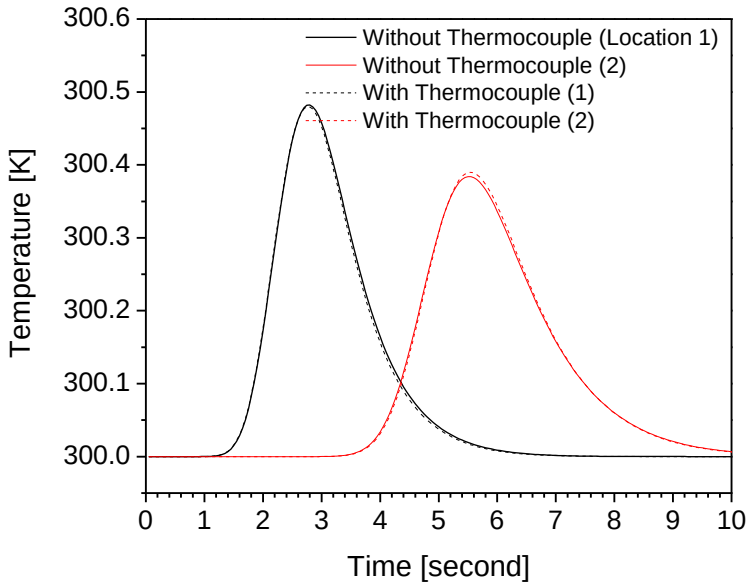


Figure 16. The temperature profile detected from locations 1 and 2.

Besides flow rate of 1 GPM, numerical simulations also were performed for other flow conditions, like 2, 3 and 4 GPM. The flow rate derived from the thermal signal time delays at locations 1 and 2 are very close to the set points. The diagonal line in Fig. 17 is the theoretical predication at y=x. It is noted that simulation has a very close prediction of flow rate as compared with the set-point value. The experiment data are distributed along the theoretical diagonal line within a 4% deviation.

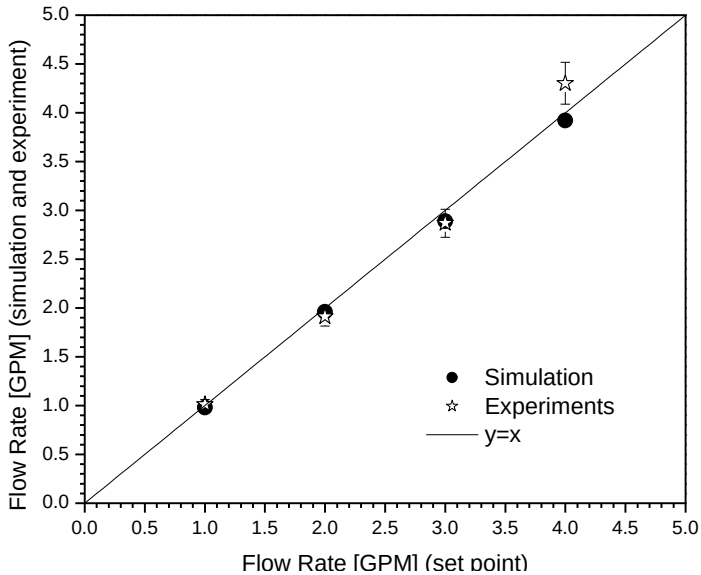


Figure 17. Flow rate predictions by simulation and experiment.

F. Extended Research on By-pass Design

As described above, the measurement errors will be considerably large at high flow rate range. Furthermore, since the functionality of this flowmeter is strongly dependent on the strength of generated thermal signal by the heater, this technique is not economic for larger pipe as it requires high heater power. These two limitations motivate us to design a new flow meter using a bypass configuration, which can extend the measurement range to cover a higher flow rate. Instead of measuring the flow directly from the main pipe, all the system components, including the thermocouples and the heater, are mounted on the by-pass route, as shown in Fig. 18. The flow velocity vector is shown in Fig. 19. The flow rate in by-pass route is smaller than that in main pipe.

The numerical simulation results showed that the slow flow rate in the bypass route is linearly proportional to the main flow over a large range of flows. Therefore, the flow of interest can be accurately deduced from the measured flow of the bypass route.

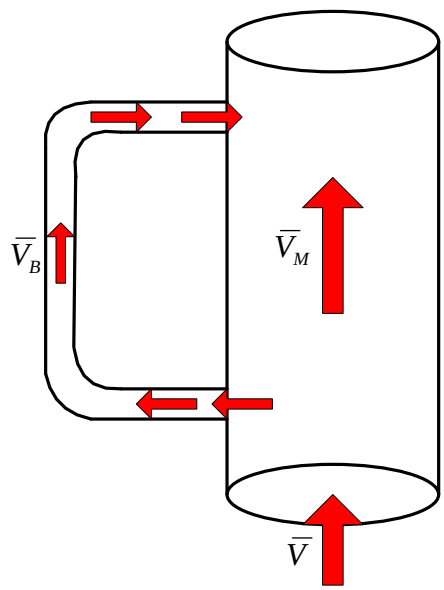


Figure 18. Bypass system configuration.

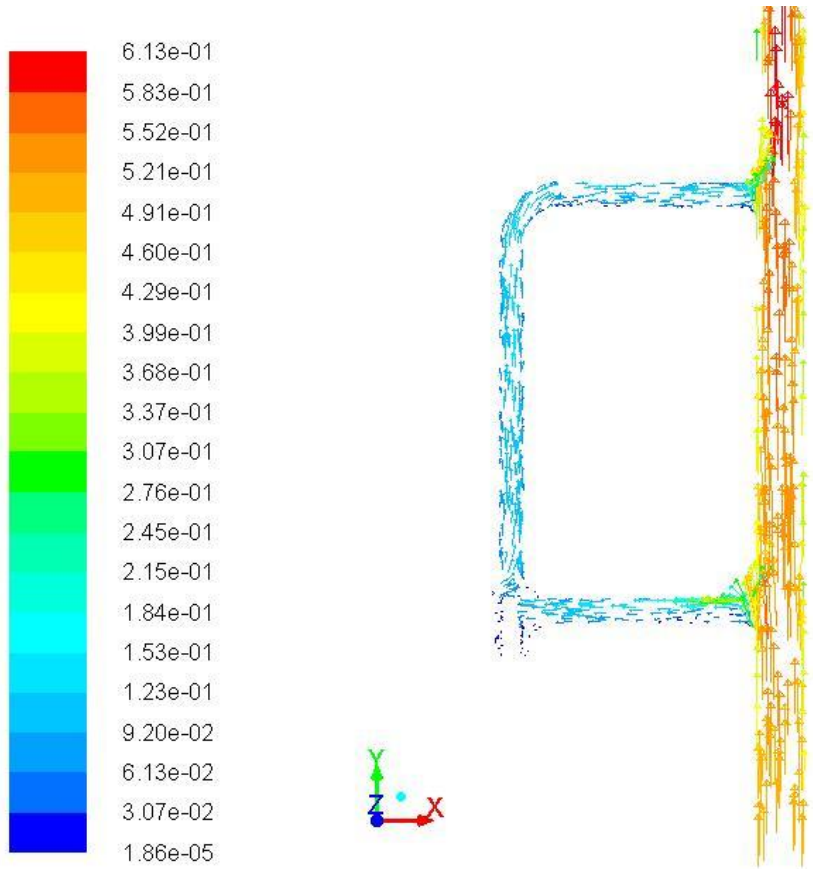


Figure 19. Velocity vector plot of by-pass flowmeter design.

Due to longer pipe at by-pass route and additional friction hydraulic head added by the two elbows and tees pipe joint, flow rate in by-pass route is much slower than in the main pipe. Even under the condition that both by-pass and main pipe assume the same diameter, flow rate is only about 0.35 GPM as the overall main pipe flow rate is at 2.3 GPM (See Figure 20). The linear relationship of flow rates of the by-pass pipe and overall flow rate allows this flow meter to measure the main pipe flow rate at ease.

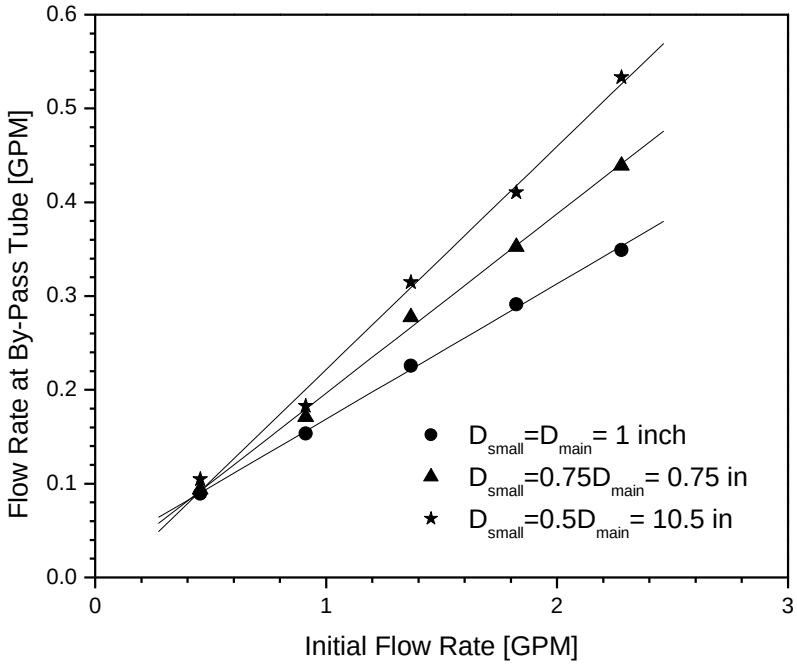


Figure 20. Relationship of flow rate between by-pass and overall flow rate.

G. Other Thermal Sensors

Different types of thermal sensors were considered to compare their accuracy, resolution, as well as their compatibility with coolant etc., including (i) fiber optic thermal senor, (ii) platinum resistance thermoelectric sensor, (iii) SiC (Silicion Carbide) temperature sensors. Only platinum resistance thermoelectric sensor was selected for further investigation, due to the limitation of specifications and availability of the devices/materials.

One experiment was conducted to compare with thermocouple and platinum based resistance temperature detector (RTD). Platinum temperature sensors are an alternative to be considered for its applicability for flow rate measurement. Platinum thermal resistance sensor (e.g., PS08 from AcamMess-electronic) has two distinguishable features as compared to other thermal sensors: (i) its minimum total current can be as low as 2 μA, and (ii) the resolution (~1mK) is much higher than most competing technologies. Pt-based temperature sensors, however, are highly nonlinear, and thus significant research effort has to be devoted to the development of the calibration strategies if they are deemed useful in the flow rate measurements in a reactor environment.

However, the critical parameter of thermal sensor used for our thermal transient flow meter is response time. Quick sensor response time ensures the capture of thermal signal fluctuation characteristics, which is needed for signal correlation calculation. In order to increase the flow rate measurement range, a short response time is preferred. Our experiments show that the response time of RTD is longer than that of thermocouple, which makes it unsuitable for measuring large flow rate (Figure 21). Therefore, the RTD thermal sensor was decided not be further pursued in our project.

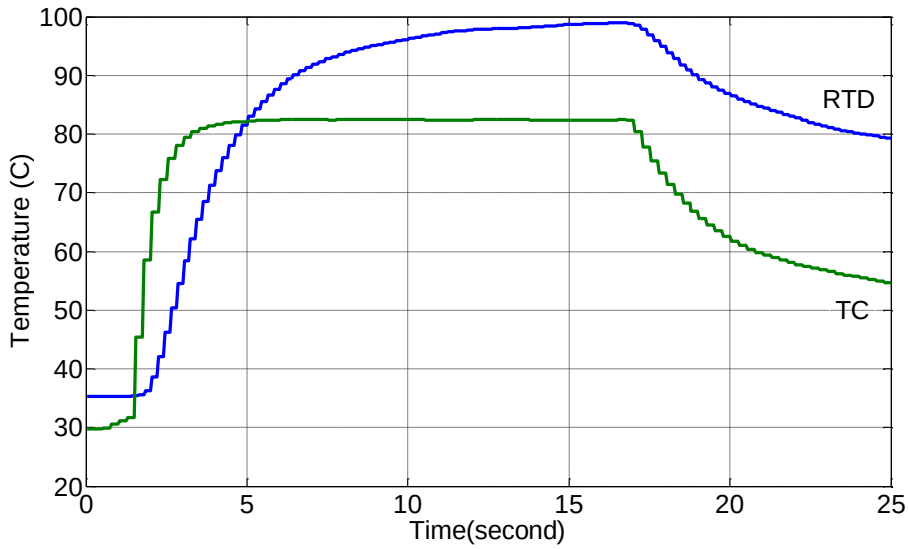


Figure 21. Temperature measurement by thermocouple and Platinum based resistance temperature detector.

H. Corrosion and Irradiation Test

After waiting for nearly one year for programmatic funding support for the modification of our heavy liquid metal coolant loop (TC1 loop) that is needed for our experimental work, we were finally advised at the end of 2010 that the funding was cancelled. This funding was part of a bigger commitment from DOE that it would provide $2 million to UNLV in FY11 to help maintain the major investment in infrastructure and capabilities including radiochemistry and materials research as well as new programs related to accelerator technology.

Corrosion test of our flow rate measurement device in substantive corrosive coolant (like Lead bismuth eutectic-LBE) will help to showcase the superiority for other less corrosive

coolants. We had to seek other available facilities, as our TC1, in this case, was not ready to be used for corrosion test. Except TC1, there is another available U.S. LBE material test facility (DELTA Loop) located in Los Alamos National Laboratory (LANL). That facility is now at stand-by status, also suffering from the lack of funding to support any research. Although we explored other venues, like use of some other international facilities, unfortunately, we encountered a policy barrier that any work done in any foreign country cannot be financially supported by NEUP.

Even encountered so many technical, financial, and infrastructure difficulties, we did manage to conduct some measurements at the Ohio State University Nuclear Reactor Lab, and we planned to use these results as a preparation step for the irradiation testing for our flowrate meter. The Ohio State University Nuclear Reactor Lab (OSU-NRL) is utilized for a variety of instructional, research, and service activities. It is a pool-type reactor and has been in operation since 1961. The reactor is immersed in a pool of light water that provides moderation and cooling by natural convection flow. It includes start-up and shut-down processes, allowing researchers to observe the reactor dynamics associated with these processes. It was licensed to operate at continuously variable thermal power up to the nominal value of 500 kilowatts. The other operating specifications and physical settings are:

The average thermal neutron flux in the core: $5X10^{12}$ $n/cm^2/s$;

The maximum temperature at the inlet and outlet of the core: 100 °C;

The maximum reading voltage from the thermocouples: 10 V;

The nominal flow rate flows in the pool: 80 gpm;

The distance between the inlet and outlet thermocouples: 34 inches. We obtained temperature data from two existing thermocouples in the light water reactor. These data include the inlet and outlet temperatures in the reactor pool as well as the voltage signal corresponding to the reactor power. In this experiment, different operation points were set while the reactor was operational. The analysis of data of thermal fluctuation level acquired by thermocouples helped to provide the information for flow rate meter design.

The output voltage data from the thermocouples (inlet and outlet of the core) were acquired during our experiments at OSU-NRL. A linear relationship was provided to obtain the temperature corresponding voltage reading. Several set of experiments were conducted under different flow rates (0, 40 and 80 gpm), at reactor power of 0 100 and 450 kw.

It was conclude that even at high power, like 450 kw, the thermal signal fluctuation is not strong enough to be picked up by the thermocouples. In addition, there is no obvious correlation between the two signals from thermocouples placed at the inlet and outlet of the core. The compacted space, where fluid passes through, is only about 2 inch in diameter, which is not sufficient to place the prototype of flow rate meter. The new design of immersed type flow meter using the same principle needs more complicated machining and fabrication process, which is far beyond the scope of the task proposed in this project.

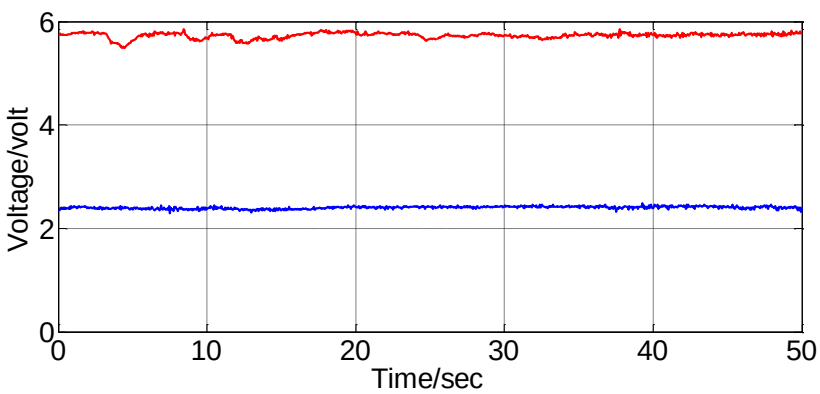


Figure 22. The voltage variation (from thermocouples) for flow rate: 80 *gpm*, reactor power: 450 kw, blue: inlet TC, red: outlet TC.

I. Education and Collaboration

This project funded two graduate students and several undergraduate students to perform project related research. This project has led to two dissertations. As part of dissemination efforts, students shared with other researchers of their research results at ASME (American Society of Mechanical Engineering) and IEEE conferences.

Design of thermal transient flow meter is truly interdisciplinary, crossing the traditional boundaries between fluid mechanical and electrical engineering. As such, the participating students had unique research opportunities to prevail in interdisciplinary research. In addition, this project enables faculty at their early career to create a successful interdisciplinary training program, which will meet the current and future workforce needs of the industry.

Collaboration with DOE national laboratory, other leading research university (Ohio State University), helps students gain experience of learning and communicating with other researchers to achieve shared goals by working together. In this project, we built valuable relationship with minority-serving institutions (Northern New Mexico College-NNMC) by creating a four-week training program for a student from NNMC. Student came to PI's university and participated in research work side by sidewith our graduate students. This student was exposed to knowledge of fluid dynamics, signal processing and instrumentation in nuclear engineering, and learnt the importance of flow rate monitoring in nuclear industry under harsh conditions of high temperature, corrosive and irradiative environments.

J. CONCLUSIONS

The concept of using thermal cross correlated signal flow meter was verified by experimental and numerical simulation investigations during the three-year period. It demonstrated the possibility of using this technology for nuclear industry under high temperature, corrosive and irradiation environments. A flow measurement and calibration approach for thermal cross correlation flowmeter were developed. It was observed that in the linear regression calibration the deviation from linearity is small. The model was verified using experimental data recorded in the lab calibration facility and through numerical simulations. The dependency of the calibration factor on the system size and the parameters which are used in signal processing algorithms were investigated and verified with computational fluid dynamic simulations. While experimental data for a limited flow range (0.5-3 gpm) were used for the calibration, the model serves as a foundation that can extrapolate lab measurements to measure the higher flow in real applications.

5 Publications and Presentations

1. T. Moazzeni, J. Ma, and Y. Jiang, “Measurement and Calibration of Thermal Cross-correlation-based Flowmeter Operating in Harsh Environment,” *IEEE Trans. Instrumentation and Measurement*, vol. 62, no. 8, pp. 2280-2285, Aug. 2013.

2. E. Alidoosti, J. Ma, Y. Jiang, and T. Moazzeni, "Numerical Simulation of Thermal Transit-Time Flow Meter for High Temperature, Corrosive and Irradiation Environment", Presented at ASME 2013 Summer Heat Transfer Conference, HT2013-17309, Minneapolis, MN, USA, July 2013.

3. E. Alidoosti, J. Ma, Y. Jiang, and T. Moazzeni, "Design of a New Thermal Transit-time Flow Meter for High Temperature, Corrosive and Irradiation Environment", Presented at ASME 2013 Verification And Validation Symposium, V&V2013-2233, Las Vegas, Nevada, USA, May 2013.

4. Moazzeni, T.; Amei, A.; Ma, J.; Jiang, Y., "Statistical model based SNR estimation method for speech signals," *Electronics Letters* , vol.48, no.12, pp.727,729, June 7 2012.

5. T. Moazzeni, J. Ma, and Y. Jiang, “Calibration of Thermal Cross correlation Flowmeter in a Harsh Environment, *In Proc.* “*The American Nuclear Society (ANS) Annual Meeting*,” Hollywood, Florida, Jun. 2011.

6. T. Moazzeni, J. Ma, Y. Jiang, and Ning Li, “Flow Rate Measurement in a High Temperature, Radioactive, and Corrosive Environment,” *IEEE Trans. Instrumentation and Measurement*, vol. 60, no. 6, pp. 2062-2069, Jun. 2011.

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7 Final Quad Chart

U.S. DEPARTMENT OF ENERGY

Nuclear Energy

Development of Thermal Transient Flow Rate Sensors for High Temperature, Irradiation, Corrosive Environment

OVERVIEW

Purpose: Summary statement of project purpose

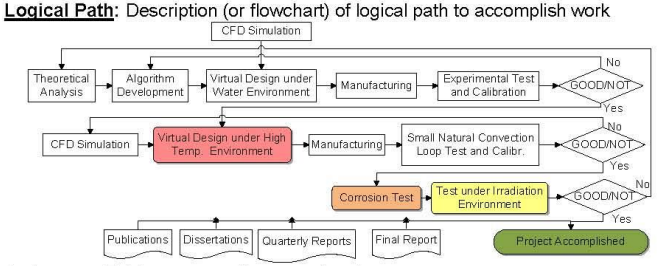
Develop a thermal transient flow rate measurement technology, which is by far the most promising one applicable in a harsh environment caused by high irradiation, pressure, temperature and corrosive media.

Objectives: Bulleted list of summarized objectives

1. The measurement range, device dimensions (i.e., length, diameter, thickness, etc), sampling interval, processing response time, will be studied to find out how they are related to the flow meter's resolution, stability, and accuracy. This study will be carried out through experiments and simulation, including system modeling, fluid dynamics modeling, and so on.
2. Calibration is an important step to verify the simulation results by experiments. The accuracy, resolution will be further quantified after a calibration process is completed. Several calibration procedures thus will be examined to determine the one that is applicable to industry.
3. Irradiation test will be carried out by using a Material Test facility located in a DoE lab that the PIs have been collaborating with for years.
4. Different types of thermal sensors will be investigated to compare their accuracy, resolution, as well as their compatibility with coolant etc, including (i) fiber optic thermal senor, (ii) platinum resistance thermoelectric sensor, (iii) SiC (Silicion Carbide) temperature sensors.

IMPACT

Logical Path: Description (or flowchart) of logical path to accomplish work



Outcomes: Brief summary of expected project outcomes

The PIs plan to present the findings in two technical conferences. At least three peer-reviewed journal articles are expected to be generated during the course of the project. Other deliverables will include, final products of flow meter, undergraduate and graduate student training, and progress report.

DETAILS

Principal Investigator: Prof. Yingtao Jiang, and Jian Ma

Institution: University of Nevada, Las Vegas

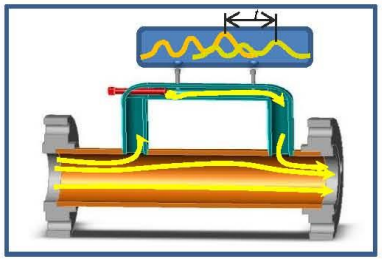
Collaborators: LANL and N. New Mexico College

Duration: Three Years **Total Funding Level:** $451,269.00

TPOC: Stefanie Johnston
Federal Manager: Kurt Davis

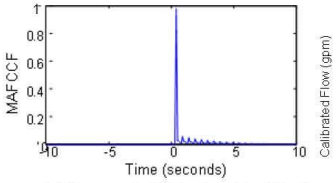
Workscope: (G4B-4)

PICSNE Workpackage #:
10-313

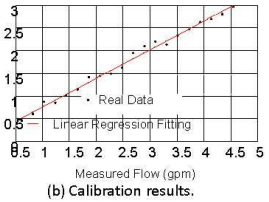


RESULTS

Results: Statement of preliminary results and/or graphs, pictures, etc. if available



(a) Sharp peak of delay time identification with the new algorithm



(b) Calibration results.

Accomplishments: Summary of deliverables already met

There are three journal paper published in 2011, 2012 and 2013, respectively. In addition, we presented our researches at three conferences during the past three years.

We accomplished simulation of flow meter with the aid of Fluent CFD software. Almost all tasks and subtasks were accomplished, like signal algorithm development and improvement, flow meter calibration, several flow meter prototypes fabrications, and investigation of different types of thermal-sensors for our flow meter.