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Thermal transient flow rate sensor for high temperature liquid metal cooled nuclear reactor

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Project Title: Thermal Transient Flow Rate Sensor for High Temperature Liquid Metal Cooled Nuclear Reactor

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Abstract:

In nuclear power plants and accelerator driven system (ADS) for nuclear waste treatment, it is important to monitor the coolant flow rate in the reactor core and pipe-line. In such a strong irradiation, high pressure and temperature environment, no accurate local flow measurement technique is readily available. Electromagnetic (EM) flow meter is popular in low temperature application as it is a non-intrusive technology. However, additional voltage will be produced due to temperature, flow, pressure, the chemical properties of the liquid metal and surface condition of the steel walls. In addition, the non-definite wetting behavior of liquid lead-bismuth to the electrically conducting structure material can lead to incorrect readings even during one measurement day. As the temperature measurement technique is well developed for high temperature applications, one alternative flow rate measurement technique is proposed here based on correlation velocity measurement using temperature sensors. The impulse response function (IRF) will be used instead of the cross-correlation function in the time delay estimation. The IRF method shows a more accurate estimation of the transit time, which allows extremely low velocities (down to 2 cm/sec) to be detected. In this research work,

the faster thermal diffusion effect in low Prandtl number liquid metal will be considered for the better delay time estimation. The proposed research will be completed in two years, and in specific, the PIs plan to fulfill the research missions by performing the following activities:

1. Review the related literature on correlation velocity measurement technique using temperature noise in the flow field;
2. Design and construct a correlation velocity measurement device with a possibility of changing the distances between the two temperature sensors;
3. Develop a signal processing and data reduction scheme and implement it to a LabVIEW data acquisition system;
4. Perform experiments with different sensor distances and various Reynolds numbers in several different water temperatures in single-phase water flows. Experimental results will be compared to a Pitot tube or hot-wire anemometry;
5. Evaluate the measurement device in the by-pass system of TC-1.
6. Design a circuit board for sensor integration.

Funding Profile:

Two Year Project		
Academic Year:	2007-2008	2008-2009
Total(\$)	95,367	106,265

Background:

In the application of high temperature metal coolant, the flow rate or the velocity is an important parameter for a thermal hydraulic system in nuclear industry.

Available velocity measurement devices include the popular EM flow meter, ultrasonic flow meter, turbine flow meter, hot-wire anemometry, and correlation velocity measurement technique.

The disadvantages of EM flow meter can be found in signal zero drift. The relative position of electrodes to magnet can be seriously displaced with the thermal expansion of a piping system. Thus the calibration results can be varied with the changing temperature conditions. The effects such as contact impedance due to wall oxidation and others will also influence the measurement results of EM flow meter.

Quite a lot of problems arise using hot film anemometers in liquid metal flows. The main question is the chemical compatibility of the liquid metal and the hot wire, in which surface tension and heat transfer aspects have to be considered.

As the turbine flow meter is concerned, there is a temperature limitation of pick-up coil to detect the rotational speed of blade and a corrosion of rotor blades was occurred.

As for the ultrasonic flow meter, there is also a temperature limitation of piezoelectric material due to its Currie point. A waveguide, which is typically used to avoid the

damage of the sensor by high temperature and penetrate ultrasound into liquid metal, is adhered to the wall of flow tube. However, there have been some problems such as sound wettability and inadequate knowledge of sound speed with respect to temperature.

The correlation velocity measurement is based on correlation of random fluctuations naturally existing in the turbulent flow field, such as temperature, pressure, etc. It is a far simpler and more durable sensor, which can be used for the local velocity measurement. In this study, different types of thermocouple temperature sensors will be used to obtain the temperature signals.

This technique is based on the determination of the transient time of a pair of correlative signals from two sensors over a known distance along the flow filed, i.e.,

$$V = \frac{L}{\tau_0} \quad (1)$$

where L and τ_0 are the distance between two sensors and the transient time of signals from upstream sensor to the downstream sensor. The signals can be either pressure or temperature fluctuations inherently existing in turbulent flows. The transit time or time delay can be determined by the well-known cross-correlation technique. If $i_1(t)$ and $i_2(t)$ are the recorded signals obtained from the upstream and downstream sensors, then the cross-correlation between these two signals, defined as:

$$R_{12}(\tau) = \mathit{Lim}_{T \rightarrow \infty} \frac{1}{T} \int_0^T i_1(t-\tau) i_2(t) dt \quad (2)$$

$R_{12}(\tau)$ has its maximum at the time delay τ_0 , which can be considered as the transient time needed for the fluid flowing from the upstream sensor location to the downstream one. This is valid if the signal has a stochastic nature like the fluctuations of the temperature and pressure in the coolant of a nuclear reactor.

Bentley and Dawson (1966) and Abeysekera and Beck (1970) were among the earliest who investigated the cross-correlation flow measurement based on the transport of existing temperature fluctuations in a flowing fluid stream. Later, Ong and Beck (1975) developed ultrasonic correlation flow meter for slurry flow. Medlock (1985) provided a review on the technique of cross-correlation flow measurement and pointed out the need of incorporating more sophisticated components into the signal processing and correlator. Recently, based on the same technique, Sun et al. (1996, 1997) developed an on-line digital flow meter and confirmed that the technique is applicable to single-phase turbulent flows. More recently, Karlsson et al. (2003) applied the cross-correlation velocity measurement technique to a natural circulation coolant flow in a boiling capsule used for long-term irradiation of nuclear fuel rods and the results were determined to be reliable. Also, Por et al. (2003) developed a new technique called impulse response function (IRF) estimation to improve the estimation of the transient time. Using the new technique along with the thermocouple signals, Por et al. were able to measure the low natural circulation velocity in a research reactor to a reasonable accuracy.

Research Objectives and Goals:

This project focuses on experimental investigation of a correlation velocity measurement technique by analyzing the temperature fluctuations naturally existing in turbulent flows. Thermocouple temperature sensors are employed in the experiments to obtain local temperature fluctuations. The objectives of the proposed research are as follows:

- To design and construct a correlation velocity measurement device that utilizes the thermocouple temperature sensors to obtain temperature information;
- To develop a data processing scheme and to implement the scheme to build a LabVIEW-based data acquisition system;
- To test the correlation velocity measurement technique in a thermal-hydraulic experimental test facility (water based), which has a round pipe as the test section, and to compare the results with those obtained from other local instruments, such as hot-film anemometry or Pitot tube measurement;
- To test the measurement device in a By-pass system of TC-1 at the University of Nevada, Las Vegas, College of Engineering; and
- To suggest any improvements for the measurement technique based on the experimental results.
- To develop one circuit board for signal conditioning, signal processing, and system integration.

Research Approach:

In this project, the correlation velocity measurement technique will be followed. The stainless steel sheathed thermocouple temperature sensors are advantageous for temperature measurements in the reactor pressure vessels because of their high corrosive resistance to LBE, noticeably at the elevated temperature conditions.

For the determination of the time delay between the temperature signals obtained from two temperature sensors, two approaches will be utilized in the current study. The first one is the conventional cross-correlation approach, as used by most of the researchers referred earlier. The approach can be easily implemented into a LabVIEW data acquisition and processing program and the measurement can be almost simultaneous. The shortcoming of this approach is that the determination of the transient time sometimes can be erroneous when a peak with significant pulse width in the cross-correlation function curve is encountered. Therefore, the second approach, impulse response function, developed by Por et al. (2003) will be employed. The impulse response function approach can give a much sharper peak and hence a more accurate estimation of the transient time. The approach is briefly introduced as follows (Por et al., 2003).

Suppose there is a random relation between the signals obtained from the two sensors and the relation can be expressed as:

$$i_2(t) = \int_{-\infty}^t h(t - \tau) i_1(\tau) d\tau \quad (3)$$

which can be transformed into the frequency domain as:

$$I_2(j\omega) = H(j\omega)I_1(j\omega) \quad (4)$$

where $H_{12}(j\omega)$ is the transfer function in the frequency domain between the two signals, and $I_1(j\omega)$ and $I_2(j\omega)$ are the Fourier transformation of the time signals $i_1(t)$ and $i_2(t)$, respectively. Suppose that there is an impulse at the upstream temperature sensor, i.e., $i_1(t) = \delta(t)$. The downstream sensor will measure the signal as:

$$i_2(t) = \int_{-\infty}^t h(t-\tau) \cdot i_1(\tau) d\tau = \int_{-\infty}^t h(t-\tau) \cdot \delta(\tau) d\tau = h(t) \quad (5)$$

This is an ideal constellation for a time-delay estimation. It is clear from Eq. (5) that in this case the cross-correlation function coincides with the definition of the impulse response function, $h(t)$. Therefore, if one can estimate the transfer function from the temperature fluctuations, it is possible to transfer it back to the impulse response function via inverse Fourier transform and the impulse response function has a narrower peak at the time delay compared to the cross-correlation function. The approach has already been validated by Por et al. (2003) in their measurement in a natural circulation reactor.

The developed measurement device will be benchmarked in a thermal-hydraulic experimental apparatus. The results obtained by the correlation technique employing two thermocouple temperature sensors will be compared to the measurements by a Pitot tube and/or a hot-film/wire velocimetry system. The test section of the apparatus is a 2-inch inner diameter round pipe. The apparatus can be operated in the modes of single-phase water flow. In this project, the correlation velocimetry will be examined in the single-phase water and air flows. In the experiments, the fluid temperatures will be varied as well as the Reynolds numbers of the flow, which provides the information concerning the degree of the turbulence. This research thus is to investigate the effects of fluid temperatures and the turbulence level on the measurement accuracy. The distance between the two sensors will also be changed to examine whether there exists an optimal distance corresponding to a certain fluid velocity.

The PIs plan to test the measurement device in the by-pass system of TC-1.

In light of the scheme Por et al. (2003) and also the blind signal processing schemes that have been well known to the telecommunications community, the PIs here suggest a new signal processing algorithm that will be examined and validated early next year after finishing the implementation of the above two signal processing methods. Fig. 1 shows the general structure of the proposed scheme.

This scheme is based on a simple observation that the input signal $I_1(j\omega)$ can be obtained from the output $I_2(j\omega)$ and $H(j\omega)$,

$$I_1(j\omega) = I_2(j\omega) \cdot \frac{1}{H(j\omega)} \quad (6)$$

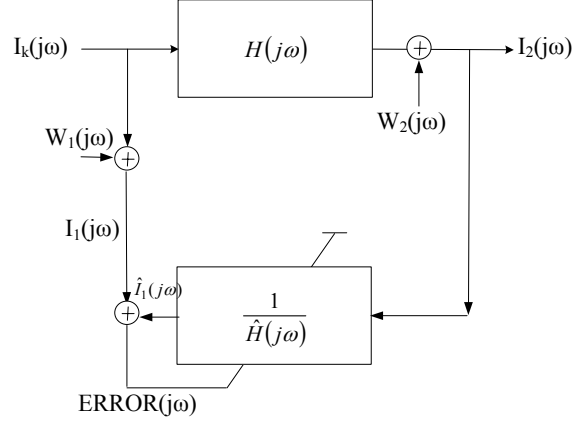


Fig. 1 The proposed signal processing scheme.

Assume the measured signals $i_1(t)$ and $i_2(t)$ have some added white detection noises, $W_1(j\omega)$ and $W_2(j\omega)$. Then the measured signals can be modeled as

$$I_2(j\omega) = I_k(j\omega) + W_2(j\omega) = H(j\omega) \cdot I_b(j\omega) + W_2(j\omega) \quad (7)$$

$$I_1(j\omega) = I_b(j\omega) + W_1(j\omega) \quad (8)$$

Assume that $\hat{H}(j\omega)$ is an estimate of $H(j\omega)$. Then the estimated input signal $\hat{I}_1(j\omega)$ would be given as

$$\hat{I}_1(j\omega) = I_2(j\omega) \cdot \frac{1}{\hat{H}(j\omega)} \quad (9)$$

The error that appears in the form of the difference between the measured signal $I_1(j\omega)$ and the estimated signal $\hat{I}_1(j\omega)$ can be used to tune $\hat{H}(j\omega)$ for a better estimate. That is,

$$ERROR(j\omega) = I_1(j\omega) - \hat{I}_1(j\omega) \quad (10)$$

In the time domain, the error $e(t)$ will be

$$e(t) = i_1(t) - \hat{i}_1(t) \quad (11)$$

Above error function can be used to build a mean square error cost function:

$$E\{e^2(t)\} = E\{[i_1(t) - \hat{i}_1(t)]^2\} \quad (12)$$

At this point, estimate of $H(j\omega)$ boils down to the optimization problem as given below

$$\min \langle E\{e^2(t)\} \rangle \quad (13)$$

Above equation is minimized with respect to $i_1(t)$ to generate the estimates of the unknown $H(j\omega)$ of the system. Ideally, the mean square error cost function is zero when $\hat{H}(j\omega)$ can faithfully track $H(j\omega)$. In practice, the accuracy level is compromised due to the two noise sources, the thermocouple modeling inaccuracy, and violations of the

assumption that the two thermocouples are experiencing identical environmental conditions.

Above signal processing algorithm requires an initial estimate of $H(j\omega)$, which is achieved following the procedure described in Por et al. (2003) and summarized in the following.

Of the two measured signals $I_1(j\omega)$ and $I_2(j\omega)$, one can see that

$$\frac{I_2(j\omega)}{I_1(j\omega)} = \frac{H(j\omega) + \frac{W_2(j\omega)}{I_k(j\omega)}}{1 + \frac{W_1(j\omega)}{I_b(j\omega)}} \quad (14)$$

The cross power spectral density ($CPSD_{12}$) of the two signals can be calculated as

$$\begin{aligned} & \text{cross power spectral density (CPSD}_{12}) \\ &= E[I_2(j\omega) \cdot I_1^*(j\omega)] \\ &= E\{[I_k(j\omega) + W_2(j\omega)] \cdot I_1^*(j\omega)\} \\ &= E\{[H(j\omega) \cdot I_b(j\omega) + W_2(j\omega)] \cdot I_1^*(j\omega)\} \\ &= E[H(j\omega) \cdot I_b(j\omega) \cdot I_1^*(j\omega)] \end{aligned}$$

where $I_1^*(j\omega)$ is the complex conjugate of $I_1(j\omega)$.

The auto power spectral density ($APSD_1$) of $I_1(j\omega)$ is given as

$$\begin{aligned} & \text{auto power spectral density (APSD}_1) \\ &= E[I_1(j\omega) \cdot I_1^*(j\omega)] \\ &= E\{[I_b(j\omega) + W_1(j\omega)] \cdot I_1^*(j\omega)\} \\ &= E[I_b(j\omega) \cdot I_1^*(j\omega) + W_1(j\omega) \cdot I_1^*(j\omega)] \end{aligned}$$

By taking into account of the fact that the noise noises are not correlated with $I_1(j\omega)$ (i.e., the mathematical expectation value from their multiplications will be zero), one can finally arrive at

$$\frac{CPSD_{12}}{APSD_1} = \frac{E[H(j\omega) \cdot I_b(j\omega) \cdot I_1^*(j\omega)]}{E[I_b(j\omega) \cdot I_1^*(j\omega) + W_1(j\omega) \cdot I_1^*(j\omega)]} = \frac{H(j\omega)}{1 + \frac{|W_1(j\omega)|^2}{|I_b(j\omega)|^2}} \quad (15)$$

Above equation provides a venue for the initial estimation of $H(j\omega)$ as needed for the scheme shown in Fig. 1.

Expected Technical Results and Deliverables:

The proposed research will be completed in two years, from Oct. 01, 2007 to July 31, 2009. Detailed activities for this research period were proposed as follows:

7. Review the related literature on correlation velocity measurement technique using temperature noise in the flow field;

8. Design and construct a correlation velocity measurement device with a possibility of changing the distances between the two temperature sensors;
9. Develop a signal processing and data reduction scheme and implement it to a LabVIEW data acquisition system;
10. Perform experiments with different sensor distances and various Reynolds numbers in several different water temperatures in single-phase water flows. Experimental results will be compared to a Pitot tube or hot-wire anemometry;
11. Evaluate the measurement device in by-pass system of TC-1.
12. Design a circuit board for sensor system integration.

Capabilities at UNLV:

- **Target Circuit Loop (TC-1)**

The Target Circuit Loop (TC-1) is a prototype lead-bismuth eutectic accelerator target, which was designed by the International Science and Technology Center and was employed to support of the international efforts to develop accelerator-driven spallation systems for nuclear transmutation and other applications. Now is modified to the material testing, thermal hydraulic fundamental research especially for molten metal. One by-pass system is equipped with material testing section for different temperature conditions.

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