

ULTRASONIC FLOW MEASUREMENT WITH INTEGRATED TEMPERATURE MEASUREMENT COMPENSATION

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ABSTRACT

Compensation for ultrasonic flow measurement has increasingly become the trend for applications that call for higher accuracy and tighter repeatability. Temperature is a variable that tends to have a significant impact on performance. Geometric dimension changes due to thermal expansion and contraction, as well as fluid dynamics, are impacted by temperature and thus have an influence on overall system accuracy. This paper presents a new method for measuring temperature by taking advantage of well characterized material properties that change with temperature and utilizing existing system capability. Integrated temperature measurement can be included as part of the diagnostic support package and used for compensation by using existing capability.

INTRODUCTION

This paper describes an alternate technique for temperature measurement in an ultrasonic flow meter compared to conventional temperature measurement methods.

As metering technologies are being pushed to the limits of their accuracy, compensation needs to be taken into account to be able to achieve high performance over wide operating conditions. There are several factors that need to be considered for compensation, but temperature is one of the more significant ones to consider. This study will focus on a new technique to measure temperature that can be used for this type of compensation.

The analysis and data provided in this study will show that this technique is adequate for the thermal compensation needed in high accuracy ultrasonic flow

meters and discuss the additional benefits of having this method of measurement incorporated into the system.

BACKGROUND

Ultrasound measurement of flow has been widely published and has been a well-known technique for decades [1]. Over the years, many different types of ultrasonic flow meters have been developed—the operating principle varies from transit-time to Doppler and to Transflexion [2]. Among these, transit-time based ultrasonic flow measurement has become the most popular method due to its superior accuracy and robustness.

Transit-time ultrasonic flow meters take advantage of a simple principle, called “time of flight”, as illustrated in Figure 1.

Specifically, the time it takes for an ultrasonic signal to travel against the flow (i.e., upstream), t_{up} , is longer than that it takes following the flow (i.e., downstream), t_{dn} . The difference between upstream and downstream travel times, Δt , is directly proportional to flow velocity as follows [2][3]:

$$V_P = \frac{P}{2\cos\theta} \left(\frac{1}{t_{dn}} - \frac{1}{t_{up}} \right) = \frac{P}{2\cos\theta} \left(\frac{\Delta t}{t_{dn}t_{up}} \right) = \frac{P^2}{2L} \left(\frac{\Delta t}{t_{dn}t_{up}} \right), \quad (1)$$

where V_P is the flow velocity to be measured, P is the ultrasonic path length, θ is the acute angle between the ultrasonic path and the axis of the flow cell or pipe section, and L is the projected length of P along the pipe axis as shown in Figure 1.

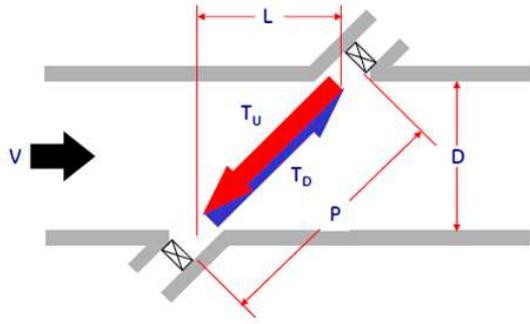


Figure 1 - Transit Time Example

For certain applications, such as where field replaceable transducers are desired or where the process medium is extremely hot or cold, ultrasonic buffers or delay lines are often used to isolate transducers from process fluid (refer to Figure 2).

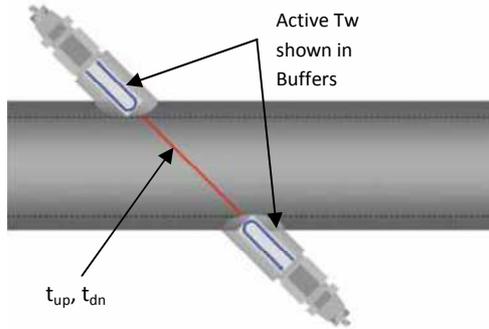


Figure 2 - Schematic showing t_{up} , t_{dn} and Active T_w .

In this case, the time that it takes for ultrasound to travel through the two buffers, T_w , needs to be compensated, and Eq. (1) can be rewritten as:

$$V_p = \frac{P}{2 \cos \theta} \left[\frac{\Delta t}{(t_{dn} - T_w)(t_{up} - T_w)} \right] = \frac{P^2}{2L} \left[\frac{\Delta t}{(t_{dn} - T_w)(t_{up} - T_w)} \right] \quad (2)$$

In cases where volumetric flow measurement, Q , is desired, two more tasks are normally implemented: (1) A K-factor is normally applied to correct the flow profile, converting a line measurement of flow to an area averaged flow across the cross-sections of the pipe depending on the Reynolds number of the flow; (2) Pipe ID needs to be plugged in, converting velocity to volumetric flow. In this case, Eq. (2) can be modified to incorporate both K and ID of the pipe as follows:

$$Q = K \times \frac{ID^2}{4} \times \frac{P^2}{2L} \left[\frac{\Delta t}{(t_{dn} - T_w)(t_{up} - T_w)} \right] \quad (3)$$

For a multi-path flow meter an additional weight and correction factor can be applied as follows:

$$Q_c = K_c \times \sum_{i=1}^n [W_i \times K_i \times V_{Pi}] \quad (4)$$

Where Q_c is the composite volumetric flow rate, W_i is the individual channel weight factor, K_i is the individual channel K-factor, V_{Pi} is the individual channel velocity from Eq. (2), K_c is the composite K-factor and n is the number of channels.

The operation of an ultrasonic flow meter, as seen from Eqs. (1) through (4), relies on the accurate measurements of t_{up} , t_{dn} , T_w , and Δt , while geometrical parameters, such as P and L and ID can be fairly accurately measured using tools such as a CMM machine.

From Eq.(3), we can see that the accurate measurement of volumetric flow becomes complicated, especially because K , ID , P , L , T_w are all temperature dependent; Δt , t_{up} and t_{dn} are excluded here because ultrasonic flow meters can measure these parameters in real time despite the fact that they are also temperature dependent. In order to compensate for these parameters, including K , ID , P , L , T_w , an accurate measurement of temperature is often needed, which is one of the reasons why many of the high accuracy ultrasonic flow meters on the market today have temperature measurement or temperature input capability.

While these geometrical parameters can be accurately measured they can also vary under process conditions. Real-time compensation of these parameters has been shown to have an effect on system accuracy over operating conditions and needs to be compensated due to changes in temperature and pressure. This is especially true for high accuracy flow meters applied in Custody Transfer and Fiscal Metering. The effect of temperature on the inner diameter of the pipe due to thermal expansion is shown in Eq. (5):

$$ID' = ID_o + ID_o \alpha \Delta T, \quad (5)$$

Where ID_o is the original length, ID' is the temperature effected length, α is the coefficient of thermal expansion and ΔT is the change in temperature. In the same respect the change in P and L caused by temperature can be described as follows:

$$P' = P_o + P_o \alpha \Delta T, \quad (6)$$

$$L' = L_o + L_o \alpha \Delta T, \quad (7)$$

Eq.(3) can be rewritten to show the effect of temperature on volumetric flow caused by the geometry changes:

$$Q = K \times \frac{ID'^2}{4} \times \frac{P'^2}{2*L'} \left[\frac{\Delta t}{(t_{dn}-T_w)(t_{up}-T_w)} \right] \quad (7)$$

Where P', L' and ID' are the temperature effected terms as described in Eqs.(5) through (7).

Temperature measurement in industrial applications has been used for decades. This is typically accomplished with the use of a Resistance Temperature Detector (RTD), and in most cases, with the use of a thermowell mounted sensor for measuring process temperatures. In other cases clamp-on sensors are used to determine surface temperatures. Both of these can provide relatively accurate measurement for their respective applications. Careful consideration needs to be taken when locating thermowells since they can disrupt the flow profile. Most ultrasonic flow meter manufacturer's recommend thermowells be placed several diameters downstream of the meter. Fluid temperature is useful for fluid correction factors associated with standards like API MPMS Chapter 11.1 and similar.

For geometrical correction of the flow cell the ideal temperature measurement is of the pipe wall, not necessarily the core fluid temperature. Under certain operating conditions measurement of the process fluid temperature or the pipe wall surface temperature will not provide the most accurate results. Depending on operating conditions the measurement of process fluid temperatures can vary compared to the actual pipe wall temperatures because of ambient conditions as well as flow rate. In addition, there will be a temperature gradient across the pipe wall from fluid to ambient conditions outside the pipe as shown in Figure 3. Other factors to consider are when pipes are insulated which will minimize the gradient in the pipe wall.

One method would be to measure both process fluid temperature and pipe surface temperature and take an average of the two to determine pipe wall temperature. This technique unfortunately requires the measurement of two temperatures which increases the system complexity and cost. Another method would be to provide direct pipe wall measurement that some current products on the market provide.

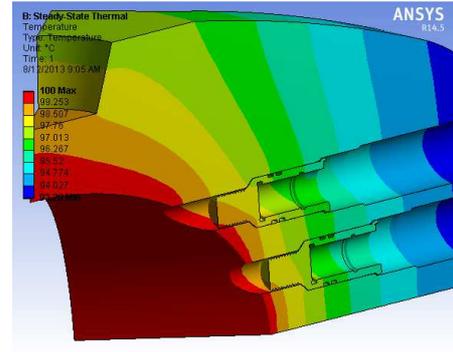


Figure 3 - Finite Element Analysis of Buffer in flow cell

A third option, the new technique proposed in this study, provides an accurate temperature measurement utilizing existing system capability that ultimately streamlines the flow meter design and reduces system cost and complexity [5].

MEASUREMENT TECHNIQUE

Leveraging the Active T_w measurement we are able to accurately measure the time spent in the buffer which can be utilized to get a temperature measurement. Suppose the length of the buffer at temperature T_0 is BL_0 , then we can write T_w as a function of Temperature T , longitudinal speed of sound in the buffer C_L , as follows:

$$T_w = 2 \times \frac{BL_0 + BL_0 \alpha (T - T_0)}{C_L}, \quad (9)$$

Where α is the linear thermal expansion coefficient. Based on Eq. (9), T can be derived:

$$T = \frac{C_L T_w - BL_0}{BL_0 \alpha} + T_0. \quad (10)$$

In Eq. (10), the only unknown is C_L for a given material, which can be generally written as:

$$C_L = \sqrt{\frac{E(1-\sigma)}{\rho(1+\sigma)(1-2\sigma)}}, \quad (11)$$

Where E is the modulus of elasticity, ρ is density, and σ is Poisson's ratio. With the measured T_w and known length of buffer BL_0 the speed of sound can be calculated as:

$$C_L = \frac{BL_0}{T_w}, \quad (12)$$

There are several ways to calculate temperature from the collected data. A few potential methods are described below. Ultimately several factors determine which

technique should be used including electronics system resources and the overall system accuracy requirements.

Algorithm Based

For different materials, E , ρ , and σ as a function of temperature have been investigated and are well known in published literature. For these well studied materials, C_L as a function of temperature can be tabulated or even formulated after some interpolation. Therefore, in order to get the temperature, take Eq. (10) and assume C_L at certain temperature, say room temperature, and get a new T based on Eq. (10); assuming T_w is measured in real time. Then C_L is updated at the new temperature. Based on the new C_L , another updated T is calculated. This process is continued until a temperature is found that is close enough to the previous temperature calculation.

Lookup Table

Another method to calculate the temperature is to have an empirical table, temperature vs. T_w , embedded in the flow meter firmware. T_w can be experimentally measured as a function of temperature. The table can be constructed in firmware and interpolation would be used between values in the table. The table would need to be comprehensive enough to cover the full process fluid temperature range for the product. The downside of doing this would be that many measurements for a given configuration would be needed.

Figure 4 shows the plot of Active T_w measurement alongside temperature. As can be shown the T_w measurement tracks temperature very closely.

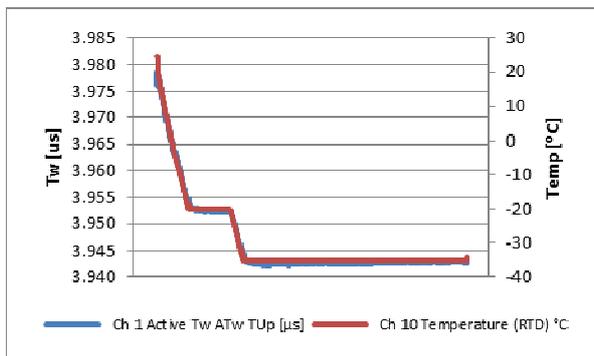


Figure 4 – Active T_w measurement vs Temperature Plot

Regardless of which method is chosen there are advantages of using this new technique above just a single temperature measurement.

ADDITIONAL BENEFITS

With the introduction of the GE Sentinel LCT4 (Figure 5) this measurement is now possible due to the unique features incorporated into the design.



Figure 5 – GE Sentinel™ LCT4 incorporating short buffer design

With the built-in design feature for sensor removability the utilization of a buffer was implemented. As described above the inclusion of the buffer requires the transit time in the buffer T_w to be accurately known to provide an accurate flow measurement as shown in Eq. (2). One of the unique features of this buffer design is that the signal path portion is completely encapsulated in the flow body which allows for a good indicator of pipe wall temperature as shown in Figure 6.

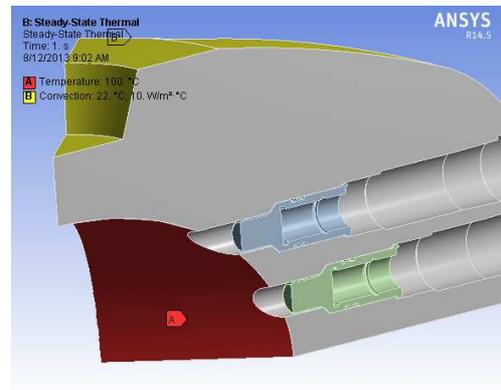


Figure 6 - Fully encapsulated buffer representing pipe wall thickness

Other designs that incorporate buffers have disadvantages. Some are so short that a measurement of T_w cannot be made. Others are too long such that the gradient across the buffer does not provide an accurate indication of pipe wall temperature.

The methodology described in this paper focuses on the details of an accurate temperature measurement made through ultrasonic time measurement in a buffer. Consider, at a system level, the advantages of this type of measurement.

Active T_w Diagnostics

Ultrasonic signals inherently provide significantly more information about the health of an application through diagnostics than most other types of flow meters. Diagnostic variables such as gain, signal-to-noise and criteria related to signal shape can provide information regarding the health of the application and system. The active measurement of T_w provides an additional layer or diagnostic information that the through transmission may not. Diagnostics provided by the active T_w measurement can provide information specifically about the health of the sensors without the need of taking into account fluid operating conditions. In fact, these diagnostics would be available even with an empty pipe. Combining the standard set of diagnostics with this additional layer can give a more clear indication if failures are sensor or application related.

Multiple Temperature Measurements

A typical high accuracy ultrasonic flow meter will provide multiple paths of ultrasonic measurement. A custody transfer system would contain somewhere between 4 and 8 paths or measurement spread throughout the pipe. Considering each path contains a pair of sensors and buffers this would result in providing 8 to 16 integrated temperature measurements per system (Figure 7). These measurements are spread out circumferentially around the flow cell and would provide an indication of temperature across the entire sensor section of the pipe.

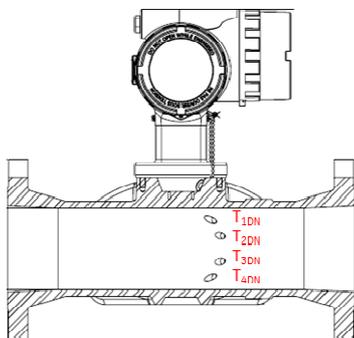


Figure 7 – Cross-section of 4-path LCT4 with labels

There are several ways this data can be interpreted. A simple approach would be to take all of the measurements and provide an average temperature for the

Another approach would be to consider the system broken into quadrants as shown in Figure 8. By considering the values measured and their relative location, it may be possible to understand more about the application and installation. Comparison of temperature at the top vs. the bottom of the meter body can be attained, as shown in Figure 8. This effectively provides temperature compensation that is independent of stratification in the pipe.

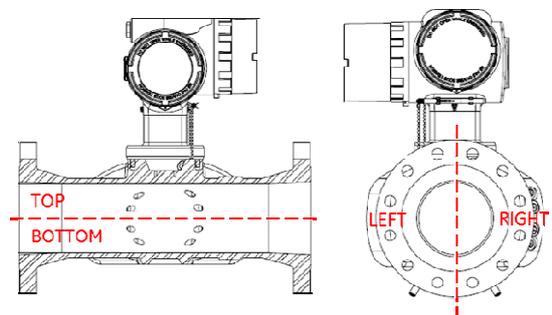


Figure 8 – Temperature mapping quadrants shown on 8-path LCT4

Consider a practical example of the impact of the sun beating down on the top or side of a pipe. These integrated temperature measurements may be able to provide information on how much effect this has on flow profile. Ultimately this information may be able to be used to provide a correction or compensation for the flow measurement.

You can also consider the case for an 8-path system where 16 temperature measurements are available. In addition to the wealth of information and diagnostics with all of these measurements you can also consider redundancy built into the system. Typically a single RTD would be installed for traditional temperature measurement. If any failures were to occur with the RTD or electronics associated with making the measurement there would be no available temperature measurement until a repair is made. With the proposed integrated temperature measurement there are always multiple temperatures being measured which can be checked against each other.

Reduced System Cost

Typically with the introduction of new features and capability come additional cost associated with sensors, electronics and other components such as wiring, etc. Considering that active T_w measurements are already incorporated into the GE Sentinel LCT4 and already used for real-time transit time compensation, the integrated temperature measurement comes at no additional system cost or complexity. Only the functionality needs to be incorporated into the firmware.

CONCLUSIONS

The method described in this paper provides an alternative to traditional temperature measurement techniques for ultrasonic flow meters. In addition to the reduced system cost and complexity the benefits of this technique include an enhanced set of diagnostics as well as multiple measurements taken across the entire circumference of the spool, providing redundancy and validation of each measurement.

Ultimately the temperature measurement method selected for a particular application needs to meet the system requirements for the intended purpose.

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