Application Report

USS Water Flow Rate Calibration

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ABSTRACT

Accuracy measurements for ultrasonic water flow metering are affected by temperature, particularly at flow rates lower than 100 lph. These errors can be as large as 10-15% for 5-55°C, where as the target specification is approximately ±1% accuracy.

For flow rates greater than 100 lph the temperature sensitivity is lower, presumably since the flow is already turbulent. This application report presents off-line calibration and on-line compensation techniques to meet the ±1% accuracy requirements across all temperatures and flow rates in the 5-55°C range using the MSP430FR604x ultrasonic sensing microntrollers. This accuracy is achieved by a two-dimensional polynomial lookup table across temperature and flow. The coefficients are generated using a bilinear fit to quadrilaterals including measurements across multiple meters. An efficient ray casting algorithm is then presented that is used during runtime for searching the appropriate interpolation coefficients. Measurement results show that the target accuracy can be achieved by these algorithms. The calibration discussed in this document is available in USSLib version 2.30.00.xx or later and can be downloaded from: https://software-dl.ti.com/msp430/msp430_public_sw/mcu/msp430/USSSWLib/USSSWLibWater/latest/index_FDS.html

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Table of Contents

1 Flow Calibration *Without* Temperature Compensation......2
2 Calibration Algorithms......2
3 Calibration Procedure......8
4 Results and Conclusions......8
5 References......11

List of Figures

Figure 2-1. Typical Ultrasonic Water Meter......2
Figure 2-2. Typical Waveform Arrival and Definition of Absolute Time of Flight......2
Figure 2-3. Flow Error Curves for 10°C and 45°C DN20 Meter......3
Figure 2-4. Temperature vs. Sound velocity in water......4
Figure 2-5. Representative Quadrilateral Figure......5
Figure 2-6. 3D View With Several Spools Tested......6
Figure 4-1. Calibration Quadrilaterals......9
Figure 4-2. Calibrated and Uncalibrated Volume Flow Error at 30°C......10

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1 Flow Calibration *Without* Temperature Compensation

In applications where the temperature range is minimal or temperature changes do not affect the flow rate accuracy greatly, a multiple or single point calibration can be implemented without the use of temperature compensation. Details of this implementation can be found in the USS Design Center Users Guide in the calibration section.

2 Calibration Algorithms

Figure 2-1 shows a typical ultrasonic water flow meter.

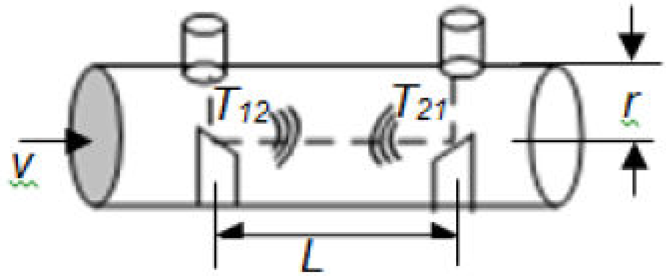


Figure 2-1. Typical Ultrasonic Water Meter

The basic flow meter equation for absolute time of flight is given in Equation 1.

$$T_{12} = \frac{L}{c + v\cos(\theta)} \quad T_{21} = \frac{L}{c - v\cos(\theta)} \tag{1}$$

Where T_{12} is the absolute time of flight in transducer 1->2 direction and T_{21} is the absolute time of flight in the transducer 2 → 1 direction. c is the speed of sound in the medium (water), L is the spacing between the transducers, and v is the flow rate of the medium.

Texas Instruments has developed a solution for water flow metering using the ADC approach of capturing the received waveforms. A typical analog to digital (ADC) captured received waveform for an ultrasonic water flow meter, using 1 MHz transducers and 20 pulses for transmission is shown in Figure 2-2.

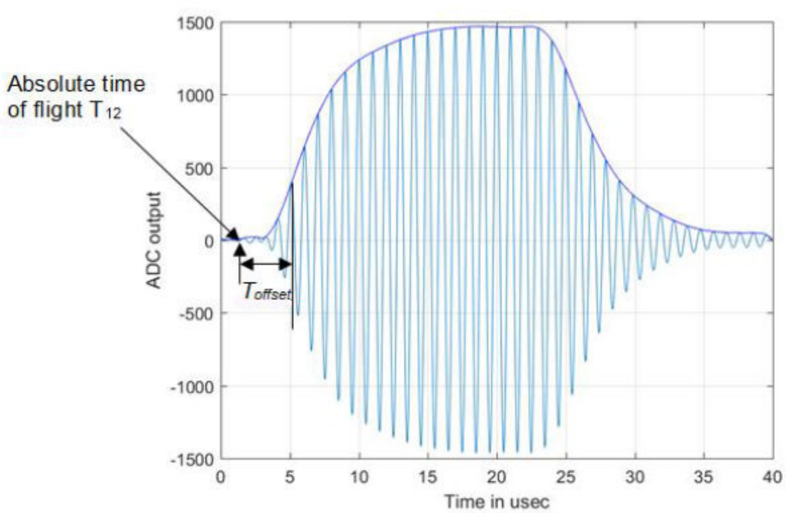


Figure 2-2. Typical Waveform Arrival and Definition of Absolute Time of Flight

The velocity of water flow can be solved with Equation 2.

$$v = \frac{L}{2} \times \left(\frac{1}{T_{12}} - \frac{1}{T_{21}} \right) = \frac{L}{2} \times \left(\frac{T_{21} - T_{12}}{T_{21} T_{12}} \right) = \frac{L}{2} \times \left(\frac{\Delta T}{T_{21} T_{12}} \right) \quad (2)$$

Based on the cross sectional area the volume flow rate (F) is now proportional to the velocity v of fluid. This proportionality constant can be calculated based on the calibration velocity at room temperature (25°C).

Similarly the velocity of sound in water can be solved with Equation 3.

$$C = \frac{L}{2} \times \left(\frac{1}{T_{12}} + \frac{1}{T_{21}} \right) \quad (3)$$

The water flow metering regulations [2] require an error in volume flow calculation of ±5% for low flow rates of approximately 100 lph and ±2% for higher flow rates. However, some applications and standards can have tighter requirements like ±2% for low flow rates and ±1% for higher flow rates. We present the general methodology for improving the final accuracy. In general, the calibration table used here will be larger for tighter requirements.

Measurements of the volume flow for a 20-mm diameter DN20 meter as a function of flow and for different temperatures is given in Figure 2-3.

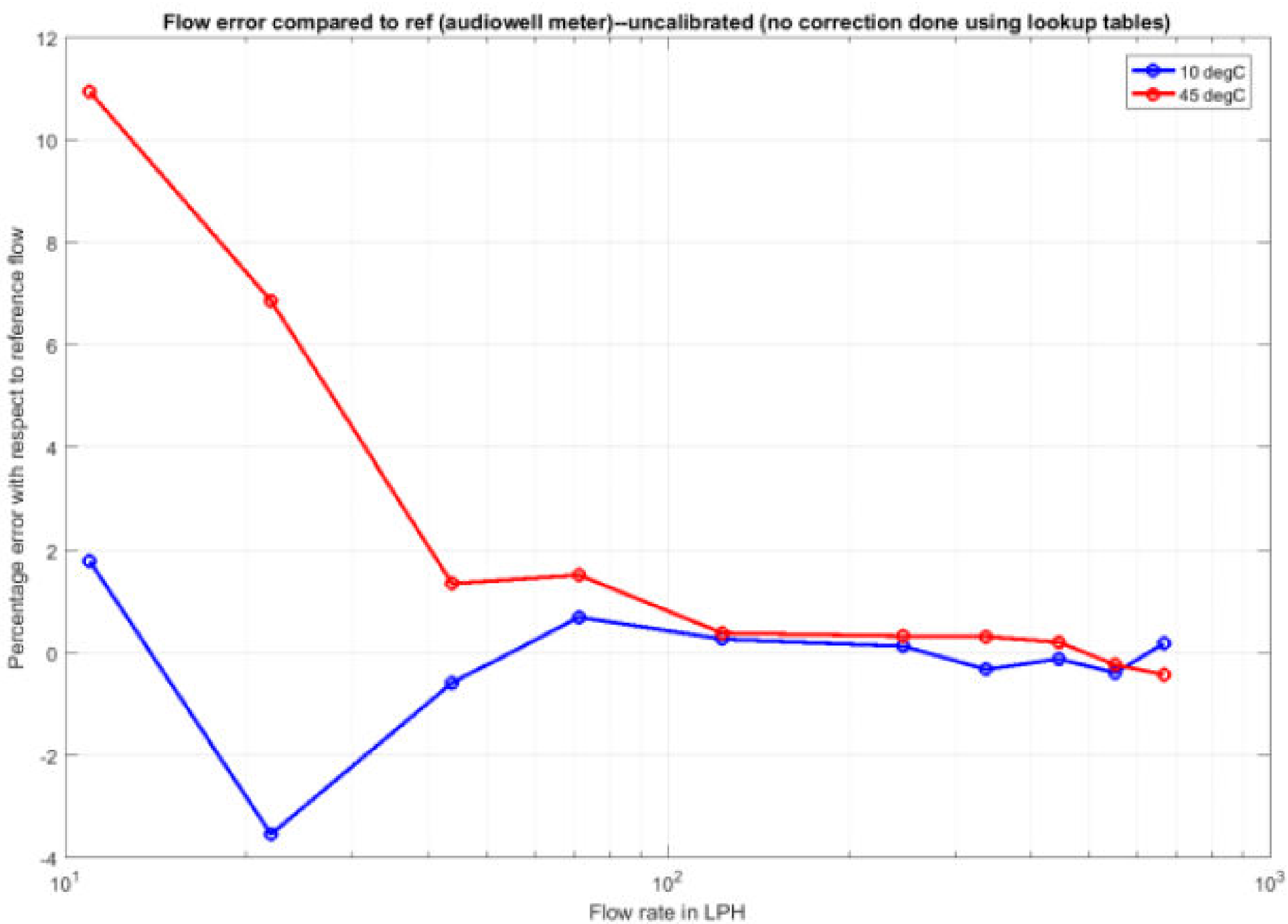


Figure 2-3. Flow Error Curves for 10°C and 45°C DN20 Meter

Note

In general, the error curves are dependent on the specifics of the water meter body design. The error curve is for the specific meter body used in the testing to give a general idea of the dependency of the error curve on the flow rate and temperature and should be used to understand the general steps required for calibration. A different meter can have an error curve that looks different.

As can be seen from Figure 2-3, the errors increase significantly for flow rates under approximately 100 lph, remaining quite tight for higher flow rates. The above effect occurs because the water flow rate turns turbulent higher than 100 lph, depending on the temperature, while remaining laminar for lower flow rates. Due to the large errors as given in Figure 2-3 for low flow rates at different temperatures, a temperature- and flow-based compensation has been implemented. The velocity of water as a function of the temperature is approximated by a Bilaniuk and Wong [3] 5th order polynomial equation given in Figure 2-4. In general, a temperature sensor can be used to obtain the temperature of the medium, but if a temperature sensor is not available, the T12, T21 can be used to estimate the temperature. Using Equation 3, the velocity of sound in water can be calculated and then a lookup table can be used to calculate temperature – for temperatures up to approximately 60°C, given the monotonic nature of the curve in this region. This estimated temperature, along with the estimated flow rate is then used to compensate the measured flow at the measured temperature.

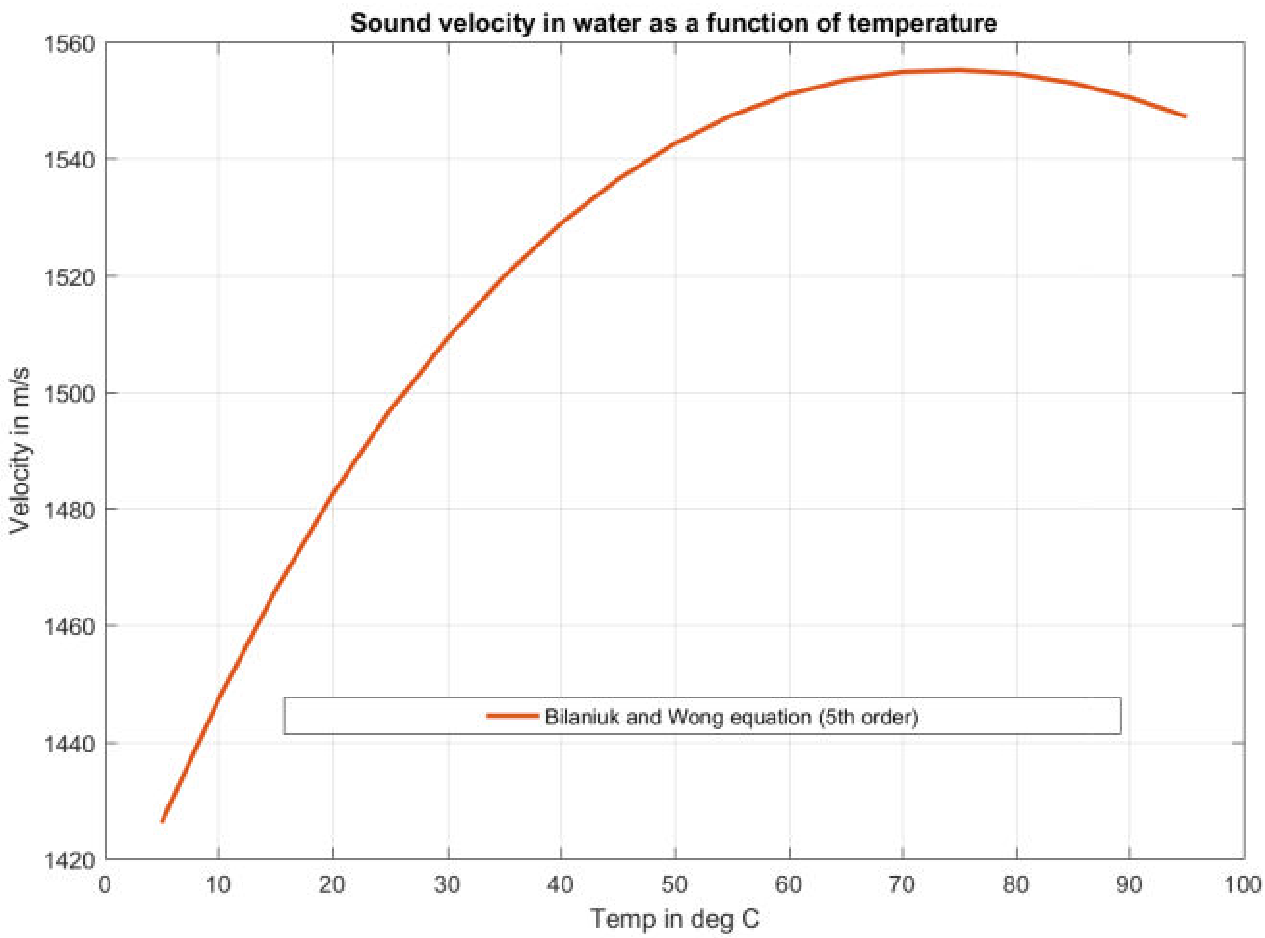


Figure 2-4. Temperature vs. Sound velocity in water

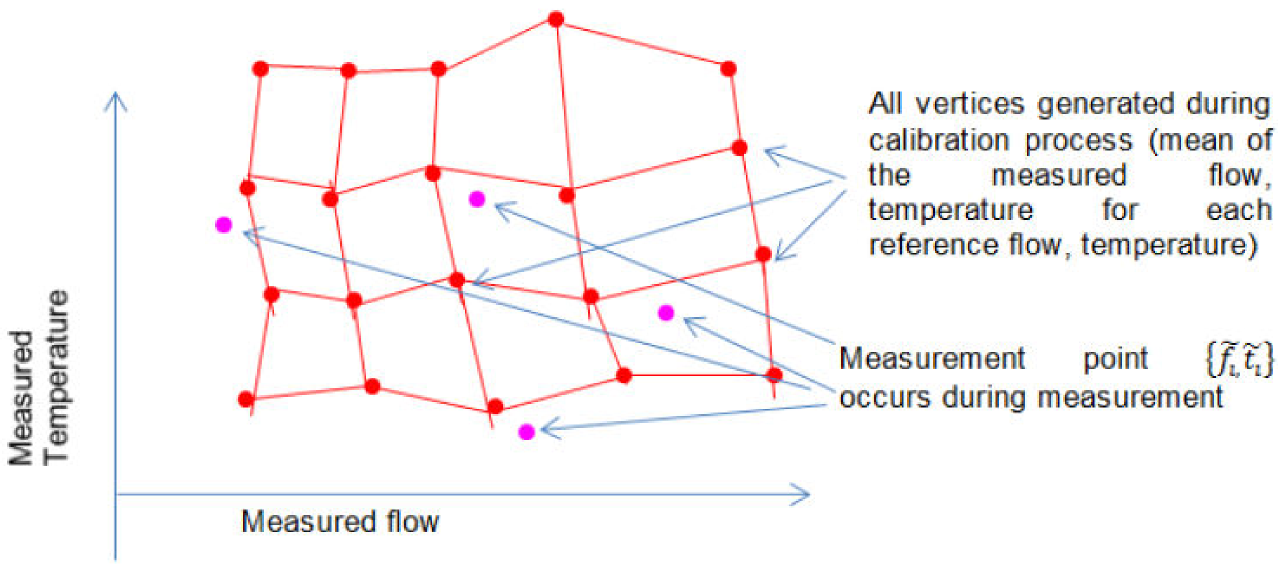
The sections below describe the temperature, flow based calibration table generation, and compensation algorithm to reduce the volume calculation error given in Figure 2-3.

A. Calibration table for water flow metering

To generate the two dimensional calibration table, the reference flow measurement is done at multiple flow rates, at different temperatures and across multiple spools for a given meter design. The two dimensional error (see Figure 2-5) for a given calibration spool would then look as follows, the measured temperatures(on MSP430FR60xx) T_0, .., T_N and the measured flow volume (on MSP430FR60xx) f_0, f_1, .., f_M (the reference flow at which these measurements are done is on the Z axis). The maximum temperature in the table T_N is expected to be less than 60degC because of the limitation of identifying the temperature beyond this value because of the shape of the velocity of temperature curve as shown in Figure 2-4.

Note

A water meter body is also called a spool and the terms are used interchangeably in this document.



Note

This figure is generated during calibration for measured flow versus measured temperature (reference flow is on the Z axis).

Figure 2-5. Representative Quadrilateral Figure

For M reference flow measurements and L reference temperature measurements there will be (L-1)*(M-1) such quadrilaterals. There could be several spools used for calibration (for example 20). Even for a given water meter body design, each individual body or spool can have small variations and it is important to get sufficient measurements across a few spools to get a good calibration table that works across a large number of spools of the same meter body design. A 3-D pictorial view of this is given in Figure 2-6.

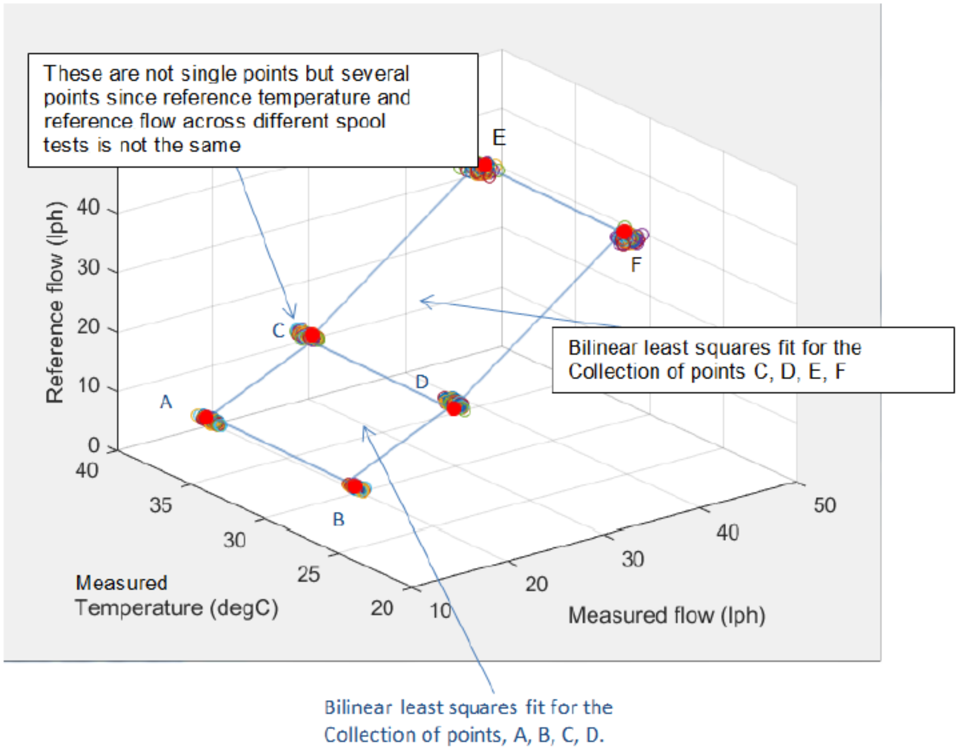


Figure 2-6. 3D View With Several Spools Tested

For each such quadrilateral (an example shown by A, B, C, D or C, D, E, F), for a given reference flow and temperature measurement let $\{f_1^{\,1}, f_2^{\,1}, .., f_N^{\,1}, f_1^{\,2}, f_2^{\,2}, .., f_N^{\,2}, f_1^{\,3}, f_2^{\,3}, .., f_N^{\,3}, f_1^{\,4}, f_2^{\,4}, .., f_N^{\,4}\}$ be the flow measurements.

Let $\{t_1^{\,1}, t_2^{\,1}, .., t_N^{\,1}, t_1^{\,2}, t_2^{\,2}, .., t_N^{\,2}, t_1^{\,3}, t_2^{\,3}, .., t_N^{\,3}, t_1^{\,4}, t_2^{\,4}, .., t_N^{\,4}\}$ be the measured temperatures.

Let $z=\{z_1^{\,1}, z_2^{\,1}, .., z_N^{\,1}, z_1^{\,2}, z_2^{\,2}, .., z_N^{\,2}, z_1^{\,3}, z_2^{\,3}, .., z_N^{\,3}, z_1^{\,4}, z_2^{\,4}, .., z_N^{\,4}\}$ be the corresponding actual (reference) values of the flow, the notation used is $f_i^{\,j}$ where i is the spool number and j is vertex number on the quadrilateral. (N is the total number of spools -- we assume the measurements for a given spool at a given flow rate and temperature is averaged. Thus N, is the number of measurement points corresponding to a particular quadrilateral). The coefficients m_0, m_1, m_2, m_3 are computed by the generalized form of standard bi-linear fit [4] using least square equation:

$$\sum_{i=1}^{N}\sum_{j=1}^{4}\left(\left(z_i^j-\left(m_0+m_1 f_i^j+m_2 t_i^j+m_3 f_i^j t_i^j\right)\right)^2\right) \tag{4}$$

This equation can be solved by equating the derivatives with respect to the constants m_0, m_1, m_2, m_3 to zero and is given by Equation 5.

$$\begin{bmatrix} m_0 \\ m_1 \\ m_2 \\ m_3 \end{bmatrix} = M^{-1} V \tag{5}$$

Where,

$$M = \begin{bmatrix} 4N & \sum_{i=1,j=1}^{i=N,j=4} f_i^j & \sum_{i=1,j=1}^{i=N,j=4} t_i^j & \sum_{i=1,j=1}^{i=N,j=4} f_i^j t_i^j \\ \sum_{i=1,j=1}^{i=N,j=4} f_i^j & \sum_{i=1,j=1}^{i=N,j=4} f_i^{j^2} & \sum_{i=1,j=1}^{i=N,j=4} f_i^j t_i^j & \sum_{i=1,j=1}^{i=N,j=4} f_i^{j^2} t_i^j \\ \sum_{i=1,j=1}^{i=N,j=4} t_i & \sum_{i=1,j=1}^{i=N,j=4} f_i^j t_i^j & \sum_{i=1,j=1}^{i=N,j=4} t_i^{j^2} & \sum_{i=1,j=1}^{i=N,j=4} t_i^{j^2} f_i^j \\ \sum_{i=1,j=1}^{i=N,j=4} f_i^j t_i^j & \sum_{i=1,j=1}^{i=N,j=4} f_i^{j^2} t_i^j & \sum_{i=1,j=1}^{i=N,j=4} t_i^{j^2} f_i & \sum_{i=1,j=1}^{i=N,j=4} f_i^{j^2} t_i^{j^2} \end{bmatrix}$$

$$V = \begin{bmatrix} \sum_{i=1,j=1}^{i=N,j=4} z_i^j \\ \sum_{i=1,j=1}^{i=N,j=4} f_i^j z_i^j \\ \sum_{i=1,j=1}^{i=N,j=4} t_i z_i^j \\ \sum_{i=1,j=1}^{i=N,j=4} f_i^j t_i^j z_i^j \end{bmatrix}$$

B. Flow calculation based on measurements during real time operation

For a given flow measurement the estimated flow calculation can now be calculated by the following steps:

(1) Using Equation 1, Equation 2, calculate the flow velocity v_i, sound velocity C_i and the volume Fi for the given measurement. The i is to indicate the individual measurement.

(2) Then using the Figure 2-4 calculate the temperature $\tilde{t}_i$ corresponding to the sound velocity C_i.

(3) We now have the temperature $\tilde{t}_i$ and the volume flow $\tilde{f}_i$. Please note that if an external temperature sensor is available, steps (1) and (2) can be skipped and just use the temperature estimate/value from the sensor directly.

(4) Each measurement of the measured flow and measured temperature is binned in the appropriate quadrilateral in the Figure 2-5 and then the corrected flow for measurement point { $\tilde{f}_i$, $\tilde{t}_i$} is given by Equation 6.

$$m_0 + m_1 \tilde{f}_i + m_2 \tilde{t}_i + m_3 \tilde{f}_i \tilde{t}_i \tag{6}$$

C. Algorithm for binning, finding the quadrilateral for a given measurement point

We now consider the algorithm that will be used to find out for a given flow and temperature measurement {$\tilde{f}_i$, $\tilde{t}_i$} (see Figure 2-5 for such example points) which quadrilateral the point lies in. If the point falls outside of all the quadrilaterals then the closest one is to be found. At the heart of the algorithm is the key problem to solve that for a given point and the vertices of the quadrilateral, how to find whether the point is in the quadrilateral or not. This problem can be solved with a ray casting algorithm [5]. The basic idea of a ray casting algorithm is to determine if a ray from a given point in a given direction intersects the polynomial in even or odd points to determine if the point is outside or inside the polynomial respectively. A normal ray casting algorithm however has the drawback that a point on the edge and the vertices of a quadrilateral will be declared as outside it. Hence we modify the algorithm to first check this condition. The algorithm works as follows by searching for the closest topmost and leftmost quadrilateral to the given point. Refer to Figure 4-1, where the leftmost quadrilateral point represents the smallest flow and the topmost quadrilateral points represent the highest temperature.

Assumptions:

- Measurement point is ($\tilde{f}_i$, $\tilde{t}_i$)
- M flow and L temperature measurements
- row=0 and col=0
- Let FT[NxL] includes (flow, temperature) point.
- F(row,col) = FT[row*N+col]
- F(row,col)[0] = flow and F(row,col)[1] = temp
- An API rcMethod(meas_point, 4 corner points) returns true or false

Then the algorithm is:

1. Find column based on quad top side, where one of the following statement is true:

   Fp < F(0,0)[0] then col' = 0, is row 0 the top side row?
   Fp > F(0,N-1) then col' = N-2
   Col' where F(row,col')[0] <= Fp < F(row,col+1)[0]
2. Find row based on quad left side, where one of the following statement is true:

   Tp > F(0,row)[1] then row' = 0
   Tp > F(L-1,row) then row' = L-2
   row where F(row',col')[1] <= Tp < F(row'+1,col')[1]
3. Around the {row', col') that is found, search for neighboring rows and columns such that min(col_i) <= x_0 <= max(col_i) and (min(row_j) <= y_0 < = max(row_j)), where the col_i and row_j are the rows and columns neighboring to row' and col'.
4. Execute Rays Casting method on all the rows, columns that satisfy the condition in step 3.

   If none of the selected quadrilaterals in step (3) satisfy the ray casting then the point is outside the quadrilaterals and then pick one of the quadrilaterals that satisfied the step (3).

3 Calibration Procedure

The flow and temperature VFR calibration procedure is described in the USS Design Center Users Guide.

Note

Flow and temperature VFR calibration is only available in USS Water Demo application version 2.30.00.xx or later.

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4 Results and Conclusions

Calibration measurements were done on an Audiowell DN20 pipe at 10°C, 25°C, and 55°C at different flow rates as shown in Figure 4-1. Then flow measurements were done at 30°C and the resulting error with respect to reference flow measurement with and without calibration is shown in Figure 4-2. As can be seen from the figure, the calibration significantly reduces the error in measured flow volume to approximately ±3% at 100-150 lph.

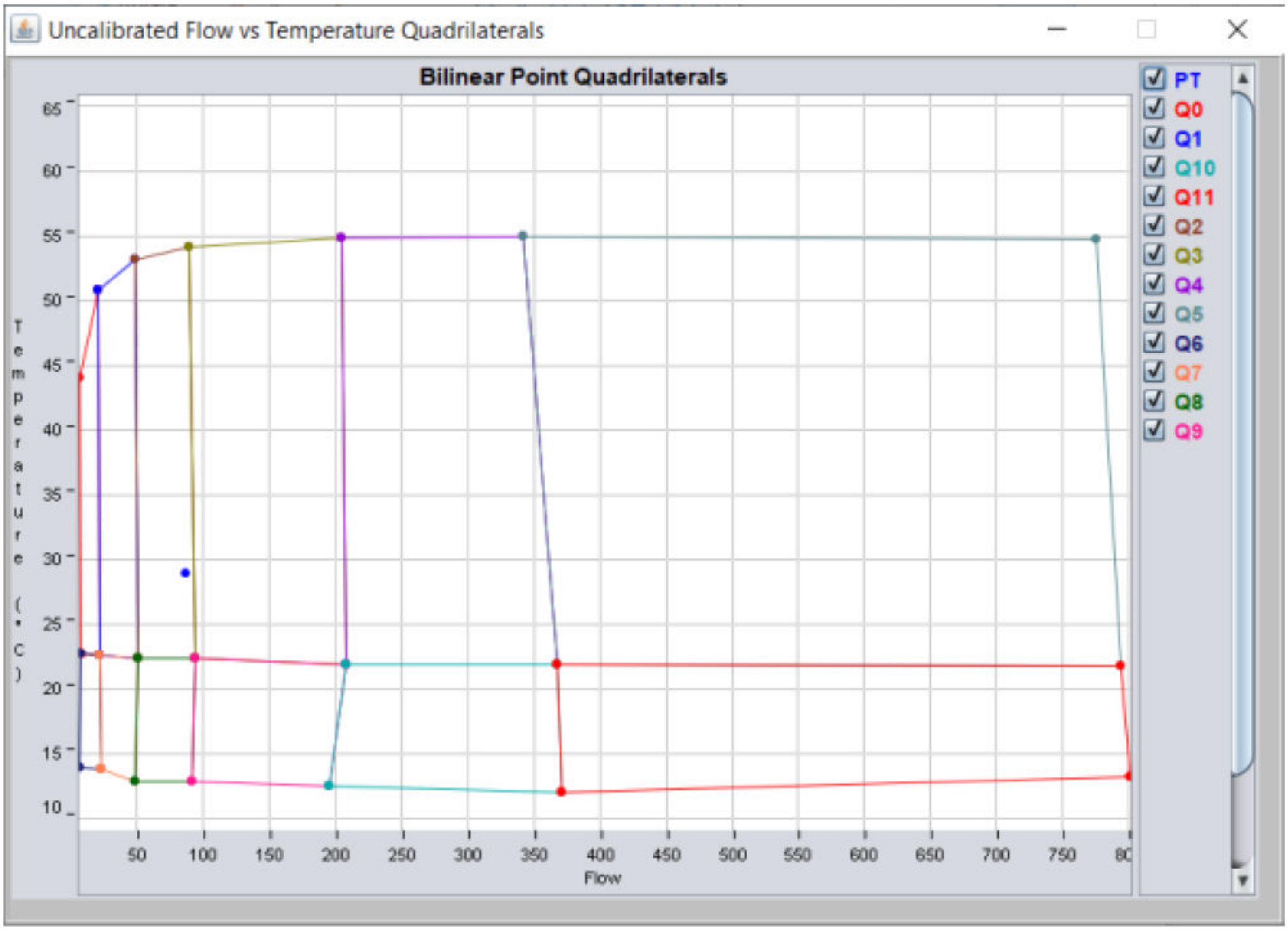

Figure 4-1. Calibration Quadrilaterals

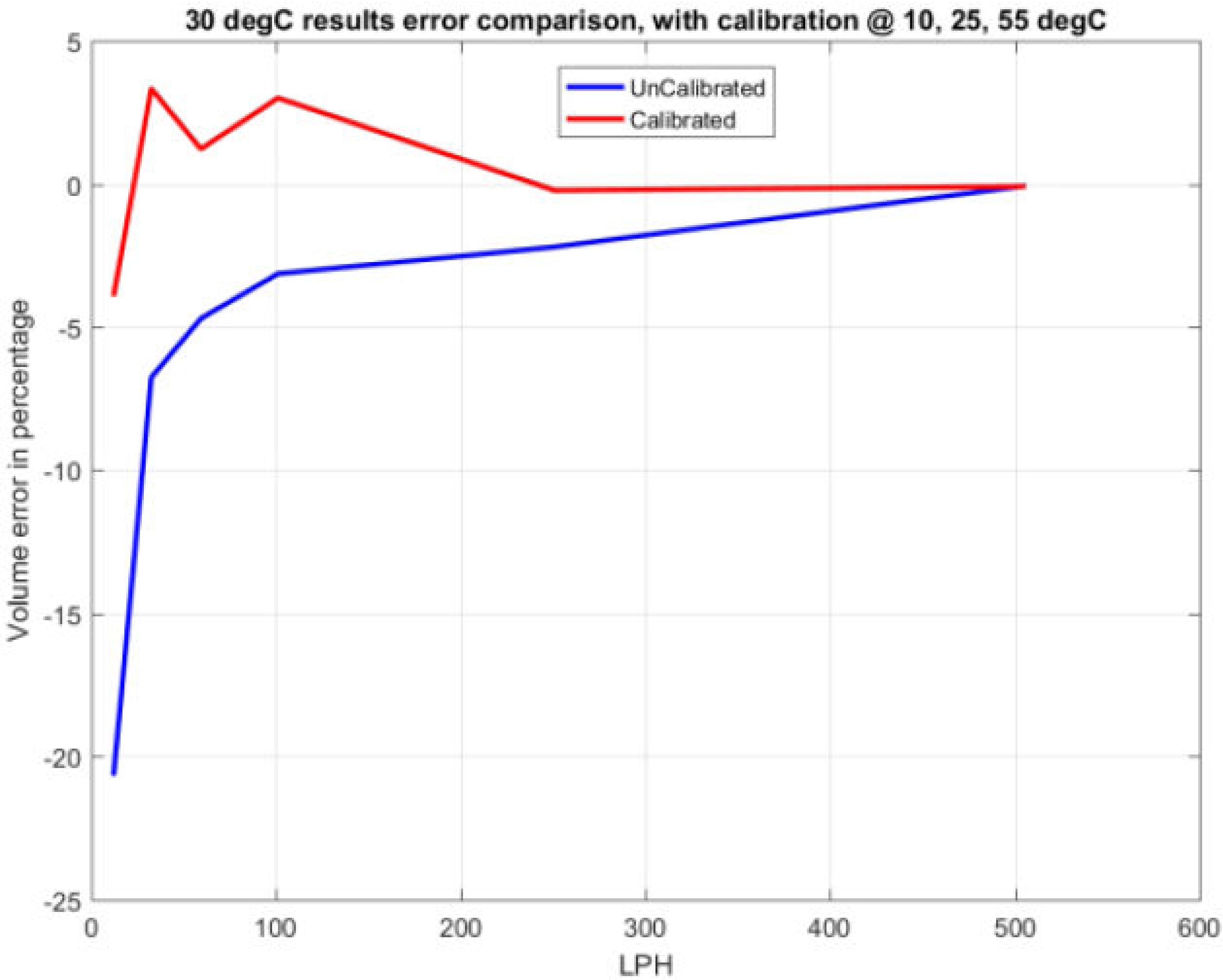

Figure 4-2. Calibrated and Uncalibrated Volume Flow Error at 30°C

5 References

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