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APPLICATION NOTE - Measurement methodology for water

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Table 1: Revision list

date	comment	author
2006-09-04	First release	Carl Carlander
2013-01-29	UFO2 update	Carl Carlander
2014-02-07	typos (this document)	Carl Carlander

The purpose of this application note is to give an example of a measurement methodology for water meters including temperature estimation up to 74.2°C and Reynolds number based calibration. The application note describes both the calibration and the measurement procedures.

Introduction

When a flow meter is not equipped with a temperature sensor it is not normally possibly to perform any temperature compensation. This application note therefore suggests a software method to calculate the temperature of water below 74°C only using the already measured sound propagation times. This method can also be adopted to calculate the temperature of any fluid with a known and distinct relationship between temperature and speed of sound. In the case of water for example the relationship is well known and distinct between 0 and 74°C. In applications with a temperature range exceeding these limits a temperature sensor can instead be directly connected to one of the interfaces of the UFO2 ASIC.

An example of an implementation of this temperature estimation method is described below together with the calibration and measurement procedures.

Calibration

The flow meter is calibrated at a representative temperature. For example the temperature in the middle of the operating temperature range. The measurement should include measurements at zero flow and at a sufficient number or flow rates. The flow rates can also be repeated a number of times. Each measurement is made long enough to produce a stable average reading. The correct water temperature and the correct flow velocity are recorded together with the up- and downstream transit times measured by the UFO2. The high frequency clock and the automatic gain of UFO2 are preferably calibrated before every measurement.

The recorded average temperature is used to estimate the speed of sound $sos_(calc)$ in water during the measurements. A polynomial function or a table look up can for example be used. Table 2 show the relationship between speed of sound in water and temperature.

Table 2: The speed of sound in water from 0°C to 74.2°C

Temp [°C]	0	5	10	15	20	25	30	35
SOS [m/s]	1402.387	1426.167	1447.279	1465.943	1482.358	1496.704	1509.144	1519.826
Temp [°C]	40	45	50	55	60	65	70	74.2
SOS [m/s]	1528.880	1536.425	1542.565	1547.395	1550.996	1553.443	1554.803	1555.147

When the speed of sound is estimated two time correction factors can be determined as in equation 1 and 2

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The first time correction, called the speed of sound delay d_{sos}, is used in order to compensate for the time in the sing-around loop that does not arise as a result of sound traveling in the fluid. The d_{sos} will represent the time delay in the electronics, the time for the sound propagation through the transducer windows and the time delay between the actual arrival of the acoustic signal and its detection. If d_{sos} is set correctly the speed of sound calculated as in equation 6 will come out right.

The second time correction, called the zero flow calibration delay d_{zc}, is used in order to compensate for any unbalance between the down- and upstream transit time measurements. If d_{zc} is set correctly the velocity calculated as in equation 3 will come out zero when the actual flow velocity is zero. The d_{zc} can be calculated using the average transit times recorded at the zero flow measurements.

$$d_{sos} = \frac{tt_{down} + tt_{up}}{2} - \frac{L}{sos_{calc}(T)} \tag{1}$$

$$d_{zc} = \frac{tt_{up}(\text{at zero flow}) \;\; - tt_{down}(\text{at zero flow})}{2} \tag{2}$$

In equation 1 and 2, L denotes the transducer distance, tt_{down} and tt_{up} the measured down- and upstream transit times.

The transducer distance L is a constant describing the distance in between the two transducers. The transducer distance is defined as the full length that the sound travels in the media. In case of for example a flow meter design with reflectors the full sound path needs to be included in L.

The down- and upstream transit times tt_{down} and tt_{up} are used as measured by the UFO ASIC. The reason for using both the upstream and downstream transit times is that it makes the speed of sound calculation insensitive to flow velocity.

The next step is to calculate the flow velocity V as in equation 3.

$$V = \frac{L}{2}\left(\frac{1}{tt_{down} - d_{sos} + d_{zc}} - \frac{1}{tt_{up} - d_{sos} - d_{zc}}\right) \tag{3}$$

In order to create a calibration curve based on Reynolds number the kinematic viscosity ν is estimated using the earlier estimated water temperature for each flow rate. A polynomial function or a table look up can for example be used. Table 3 show the relationship between the kinematic viscosity in water and temperature.

Table 3: The kinematic viscosity of water from 0°C to 74.2°C

Temp [°C]	0	5	10	20	30	40
ν [m²/s]	$1.792\ 10^{-6}$	$1.519\ 10^{-6}$	$1.308\ 10^{-6}$	$1.004\ 10^{-6}$	$0.805\ 10^{-6}$	$0.661\ 10^{-6}$
Temp [°C]	50	60	70	80	90	100
ν [m²/s]	$0.556\ 10^{-6}$	$0.477\ 10^{-6}$	$0.417\ 10^{-6}$	$0.367\ 10^{-6}$	$0.328\ 10^{-6}$	$0.296\ 10^{-6}$

Now the Reynolds number for each flow rate can be calculated as in equation 4.

$$Re = \frac{Vd}{\nu} \tag{4}$$

where V is the flow velocity, d the flow path diameter and ν the kinematic viscosity. In water the kinematic viscosity will change from 1.792 $\mu m^2/s$ at 0°C to 0.296 $\mu m^2/s$ at 100°C . The kinematic viscosity ν is the ratio of the dynamic viscosity to the density.

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The final step before creating the calibration curve is to calculate the calibration factor for each flow rate. The calibration factor is used to compensate for any nonlinear flow meter behavior in the flow range. Mainly the flow velocity profile and its interaction with the flow tube design might change over the flow range of the meter. The calibration factor C is expressed as the ratio between the true flow velocity V_{true} and the measured flow velocity V as shown in equation 5.

$$C = \frac{V_{true}}{V} \tag{5}$$

A calibration table can now be created using each Reynolds number Re and each calibration factor C. An example of such a table is shown in table 4.

Table 4: An **example** Reynolds number based calibration table. This table features an optional zero flow cut-off below Re=129,9.

Re [-]	1.299 e+002	1.300 e+002	4.070 e+002	6.954 e+002	1.260 e+003
C [-]	0	8.367 e-001	8.967 e-001	9.363 e-001	9.956 e-001
Re [-]	3.669 e+003	1.174 e+004	3.149 e+004	6.535 e+004	
C [-]	1.110	1.181	1.230	1.246	

Measurement

The up- and downstream transit times are measured. The following procedure is performed after each recording of the transit times. The time corrections d_{sos} and d_{zc} are determined during the calibration procedure and are not recalculated during the measurement procedure.

The speed of sound sos is calculated as in equation 6.

$$sos = \frac{2L}{tt_{down} + tt_{up} - 2d_{sos}} \tag{6}$$

In equation 6, L denotes the transducer distance, tt_{down} and tt_{up} the measured down- and upstream transit times and d_{sos} the speed of sound delay.

The temperature is estimated using the sos in for example a table look up using table 2.

The flow velocity is calculated as in equation 3.

The kinematic viscosity is determined using the estimated temperature in for example a table look up using table 3

The Reynolds number Re is calculated as in equation 4.

The calibration factor C is determined by a calibration table look up using Re.
The calibrated flow velocity V_{cal} is calculated as in equation 7.

$$V_{cal} = CV \tag{7}$$

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Summary

The *calibration* procedure is summarized below:

1. The speed of sound sos_{calc} is determined using the measured temperature and table 2
2. The time correction d_{sos} is calculated as in equation 1
3. The time correction d_{zc} is calculated as in equation 2
4. The flow velocity V is calculated as in equation 3
5. The kinematic viscosity ν is determined using the measured water temperature table 3
6. The Reynolds number Re is calculated as in equation 4
7. The calibration factor C is calculated as in equation 5
8. The calibration table is created using Re and C

The *measurement* procedure is summarized below:

1. The speed of sound sos is calculated as in equation 6
2. The temperature is estimated using the sos in table 2
3. The flow velocity is calculated as in equation 3
4. The kinematic viscosity is determined using the estimated temperature in table 3
5. The Reynolds number Re is calculated as in equation 4
6. The calibration factor C is determined by a calibration table look up using Re
7. The calibrated flow velocity V_{cal} is calculated as in equation 7