DIAGNOSIS OF THE ACOUSTIC DISCHARGE MEASUREMENT ON THE BASIS OF TEMPERATURE MONITORING

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ABSTRACT

The paper introduces first the dependency of the acoustic velocity in water from physical quantities like temperature, salinity and pressure. Then an approximate method for the determination of the water temperature from transit time measurements is introduced. Ideas are presented how the temperature measurement can be used for monitoring the proper operation of the measurement installation. Finally, an example of an eight path measurement is given.

1 INTRODUCTION

The acoustic discharge measurement method ADM bases on the superposition of the propagation velocity of an acoustic signal with the fluid velocity. To determine the mean velocity of the flow according to the equation (see [1])

$$\bar{v}_{ax} = \frac{L}{2 \cdot \cos\alpha} \cdot \left(\frac{1}{t_u} - \frac{1}{t_d} \right) \tag{1}$$

the transit times t_u and t_d of an upstream and a downstream signal are needed. If the upstream and downstream measurement are processed in another way, instead of the path velocity, the acoustic velocity c can be obtained as is shown in section 3. This velocity contains information about the water temperature which can be retrieved (see section 2). In case of path arrangements in one horizontal plane in the middle of the pipe, a common way to compute the flow is to assume a Nikuradse type of profile. For the determination of this profile the water temperature is needed because the dynamic viscosity and the density which are needed for the Reynolds number in Nikuradses formula are temperature dependent. This dependency is very weak. Monitoring the temperature makes still sense in order to identify outliers. Additionally in a multipath application all path temperatures can be monitored.

2 ACOUSTIC VELOCITY IN WATER

The acoustic velocity in water depends on temperature, pressure and salinity. Different formula can be looked up at the following Internet site: http://www.npl.co.uk/acoustics/techguides/. For instance the following formula for sea water (Mackenzie 1981) is directly copied from this Internet page:

C(D,S,T) = $1448.96 + 4.591T - 5.304 \times 10^{-2}T^2 + 2.374 \times 10^{-4}T^3 + 1.340(S-35) + 1.630 \times 10^{-2}D + 1.675 \times 10^{-7}D^2 - 1.025 \times 10^{-2}T(S-35) - 7.139 \times 10^{-13}TD^3$

$$\tag{2}$$

        T = temperature in degrees Celsius
        S = salinity in parts per thousand
        D = depth in metres

Range of validity: temperature 2 to 30 °C, salinity 25 to 40 parts per thousand, depth 0 to 8000 m.

Another formula with pressure instead of depth and no offset in the salinity S is given by del Grosso [2]

$$c(p,S,T) = 1402.39 + 0.156p + 5.011T - 0.05509T^2 + 0.2215*10^{-3}T^3 + 1.33S + 0.13*10^{-3}S^2 \\ - 0.0128TS + 0.097*10^{-3}T^2S \quad (3)$$

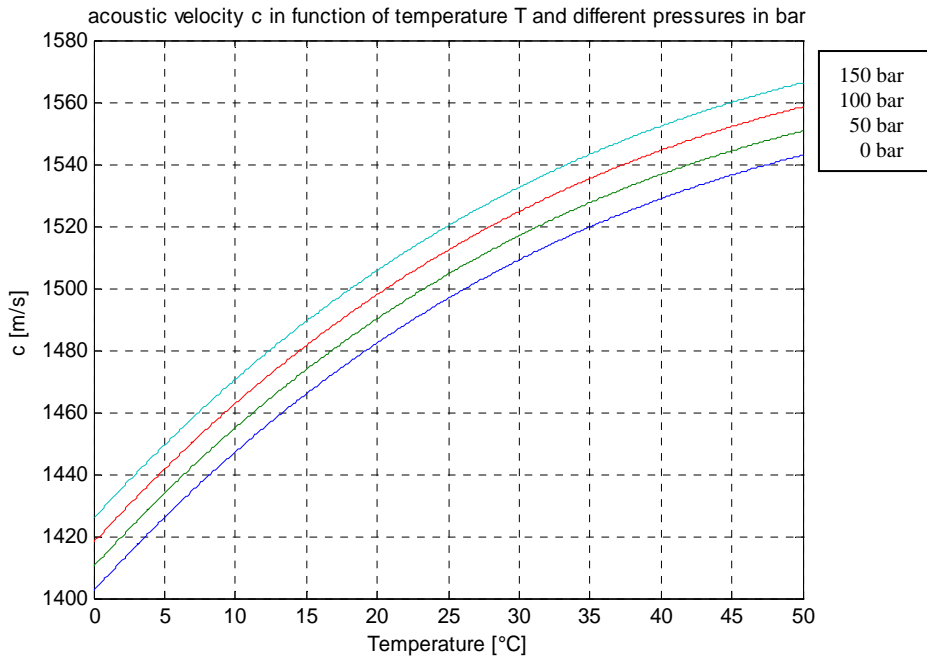S : salinity in part per thousand,   p : pressure in bar,   T : temperature in °C

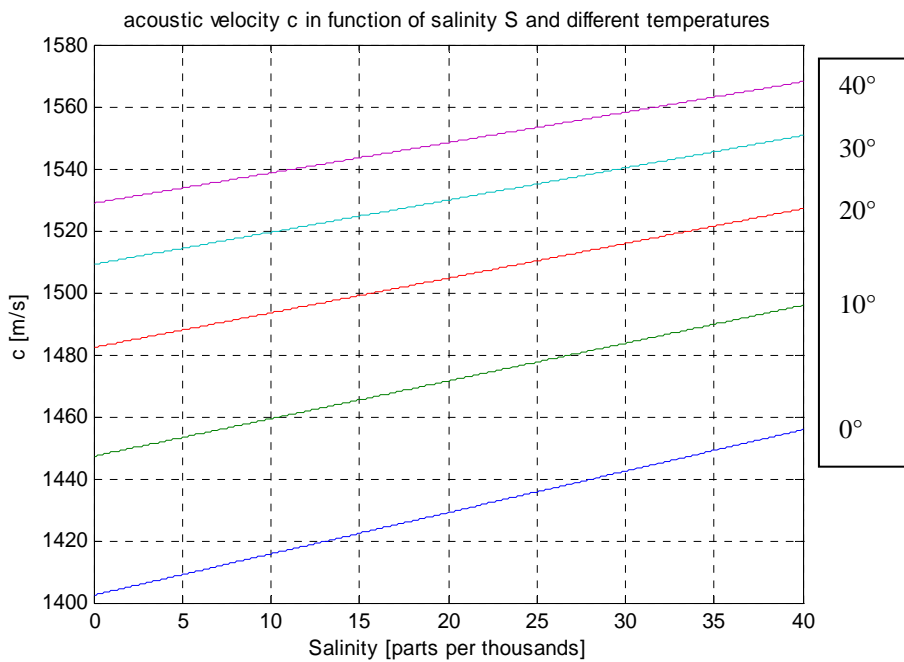Fig. 1 : Del Gross0's formula for acoustic velocity in sea water for S=0

Fig. 2 : Drenthen's formula for acoustic velocity in sea water for p=0

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Both dependencies of c, the one on the pressure p as the one on the salinity S are in a first approximation linear. The temperature dependency however cannot be considered linear in the temperature range of interest.

For pure temperature dependency a formula of Bilaniuk and Wong of fifth order for the temperature range from 0° to 70°C can be used (also on the above website) :

$$c(T) = 1402.38742 + 5.03821344T - 0.0580539349T^2 + 0.33200087*10^{-3}T^3 - 1.445379*10^{-6}T^{-4}$$
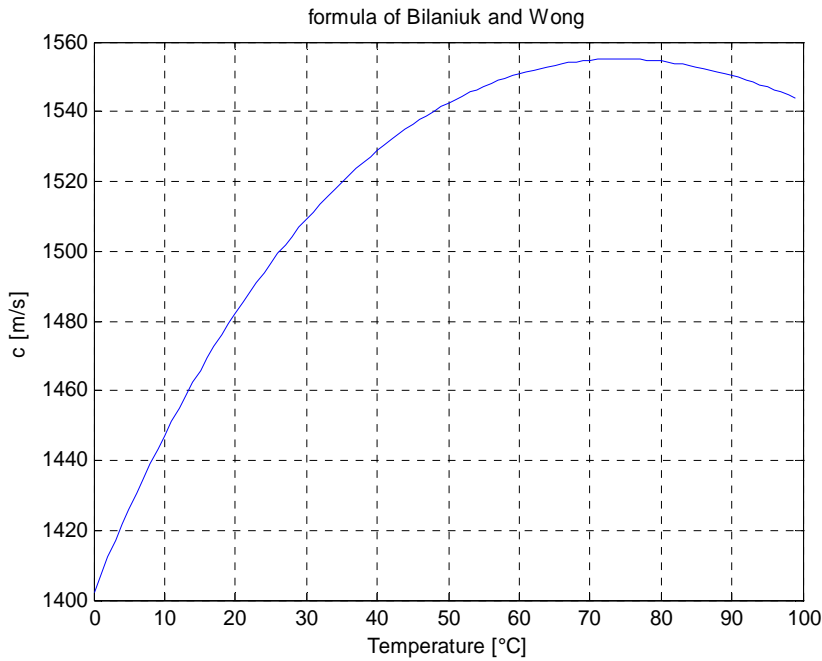$$+ 2.99402365*10^{-9}T^5 \tag{4}$$

Fig. 3 : pure temperature dependency of c [Bilaniuk and Wong]

The temperature gradient dc/dT from 0° to 70°C decreases monotonically from 5m/s per °C at low temperature to 0m/s at 70°C. In the interesting temperature range from 5° to 30° the gradient is between 4m/s per °C and 3m/s per °C.

$$5m/°Cs > (dc/dT) \geq 0 \qquad \left[0° - 70°C\right]$$

3   DETERMINATION OF THE TEMPERATURE FROM TRANSIT TIME MEASUREMENTS

From the upstream and downstream transit time measurement one obtains the acoustic velocity along the path in the following way :

$$\frac{1}{t_d} + \frac{1}{t_u} = \frac{1}{L}(c - v\cos\varphi + c + v\cos\varphi) = \frac{1}{L}2c$$

$$c = \frac{L}{2}\frac{t_u + t_d}{t_u t_d} = \frac{L}{2}\frac{2t_d + \Delta t}{(t_d + \Delta t)t_d} \tag{5}$$

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In order to obtain the temperature from the acoustic path velocity, one has to find the inverse of the curve shown in Fig.3. For a temperature range up to 100°C the problem of nonuniqueness poses an additional difficulty. This can be overcome by splitting the curve into two section, one from 0° to 70°C and one above. If we restrict ourselves for the lower temperature range [0° 70°C] only, the direct curve fitting over this whole range leads either to a polynomial of high order with enough precision but awkward to implement or to a polynomial of lower order which can be implemented easily but which is not accurate enough. Therefore the following approach has been chosen : the temperature range from 0° to 70°C has been split up into four nonequidistant temperature intervals for each of which a parabolic polynomial fitting is performed. This way simple implementation remains guaranteed with an accuracy of 0.1% and better.

The gradient dT/dc is the inverse of dc/dT and varies therefore between

$$0.2°s/m < (dT/dc) < \infty \qquad \left[0° - 70°C\right]$$

In our laboratory we carried out an experiment, in which we were scanning a water temperature range from around 0°C up to 70°C. The sound path was implemented in a tank with a path length of 0.49507 m and still water. A reference temperature measurement was also recorded. From the experiment two graphs can be plotted : T versus $T_{ref.}$ and the difference between c as calculated by the RISONIC2000 flow measurement unit and c as calculated via the reference temperature versus the temperature.

absolute acoustic velocity accuracy
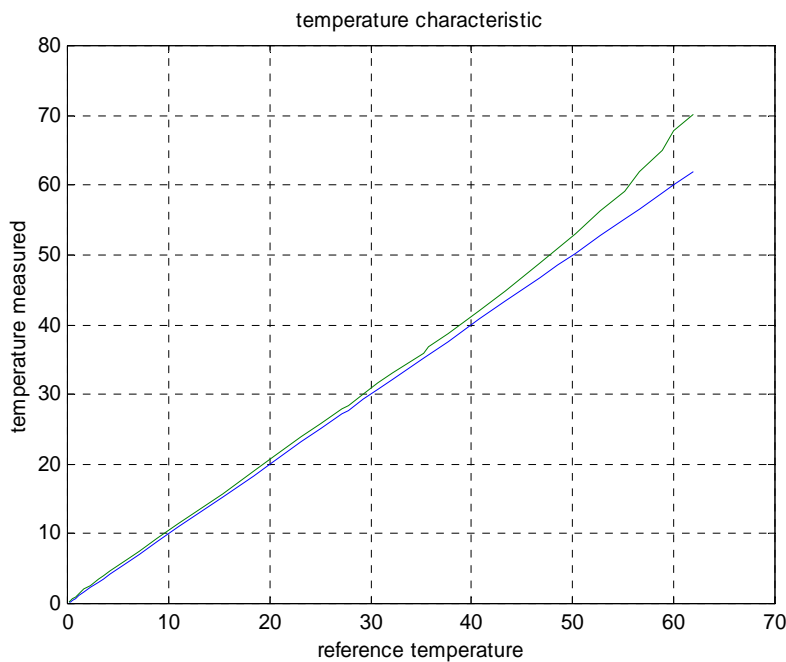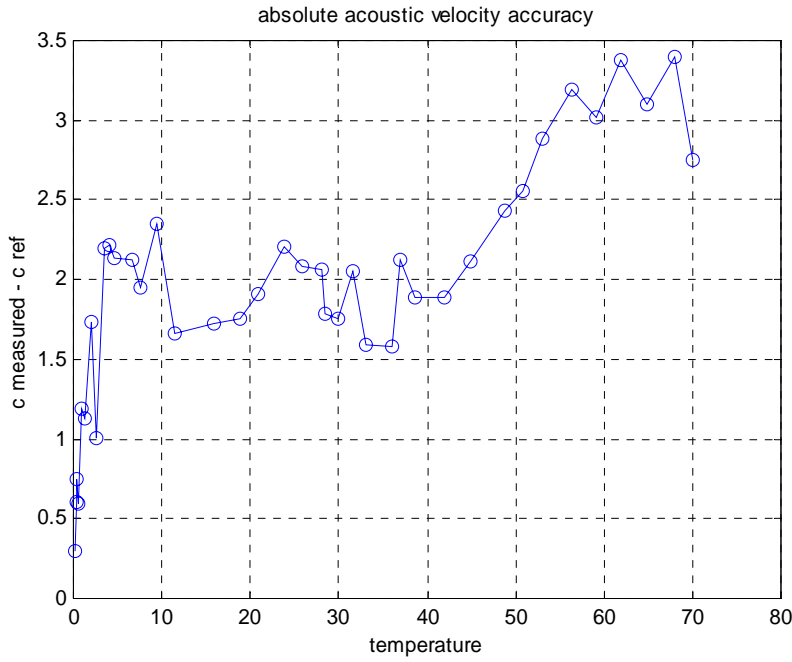
Both figures above show that the measured acoustic velocity and the temperature derived from the measured acoustic velocity have a positive offset. In the range from 0°C to 40°C the offset is very low: the offset in the acoustic velocity c is less than 2.3m/s which is less than 0.1533% (2.3/1500), the offset in the water temperature T is less than 1.2°C. For temperature higher than 40°C the measured temperature is drifting away (up to 8°C). This additional offset has a much less influence on the acoustic velocity c, as the relationship between T and c becomes very flat for this temperature range. As the path lengths are short, an offset in the transit time determination has a stronger impact on the accuracy of the acoustic velocity than for larger path lengths.

4   DIAGNOSTIC METHODS

Different diagnostic options exist depending on the path arrangement and the possible use of additional sensors or information. Equation (5) tells basically that an error in the path length and an error in the transit times cannot be distinguished. The error propagation for the velocity is as follows :

$$\frac{\Delta c}{c} = \frac{\Delta L}{L} - \frac{L}{2t_u^2}\frac{\Delta t_u}{c} - \frac{L}{2t_d^2}\frac{\Delta t_d}{c} = \frac{\Delta L}{L} - \frac{L}{2ct_u}\frac{\Delta t_u}{t_u} - \frac{L}{2ct_d}\frac{\Delta t_d}{t_d} \cong \frac{\Delta L}{L} - \frac{1}{2}\frac{\Delta t_u}{t_u} - \frac{1}{2}\frac{\Delta t_d}{t_d} \tag{6}$$

So the same relative errors in L or in Δt_d and Δt_u have the same effects on $\Delta c/c$.

Example : For a short path length of 400mm a 1mm error has the same effect as an error of
675nsec in the transit time measurement.
path length L=400mm, ΔL=1mm, ΔL /L=0.25% ➔ Δc=3.7m/s (c=1480m/s)
transit time (t_u or t_d) 270 μ sec, Δc=3.7m/s   ➔ Δt_u =675nsec

In the following an example of an implemented flow measurement at a customer's site is used several times for the illustration of the diagnostic possibilities. As this is a real flow measurement the temperature range during the recording interval was very small (less than 1°C). Nevertheless

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some conclusions can be drawn from the recorded data. The example shows that the installation is not yet optimized and that the diagnostic possibilities help to eliminate installation inaccuracies. It is useful, to validate the measurement during the commissioning phase with an independent temperature measurement of the water temperature.

Monitoring the acoustic velocities of each paths and the corresponding temperatures enables the following possibilities for fault detection and diagnosis

1) **Geometrical data error**

   A small error in length (diameter, sensor position, how deep the sensor is plugged in the pipe) determination or length calculation can cause an offset in one or more paths.
   A wrong geometrical parameterization by an error in transferring data (multiple inputs of same geometrical data can have the same effect).

   Example : 8-path installation for a pipe of 500mm diameter. This geometry leads to the following path lengths :

   path length L[mm] = [389.1   653.2   653.3   390.6   391.3   653.4   653.9   390.6]

   short paths : 1,4,5,8. max. difference in length : 2.2mm
   long paths : 2,3,6,7. max. difference in length : 0.2mm

   The discrepancy in length for the short paths is an indication that there could be inaccuracies present in the geometrical data. An error of 2mm would cause a difference in acoustic velocity c of approximately 7m/s. In many applications the path lengths typically about 10 times the length of the above installation. Therefore a geometrical error of the same magnitude has an impact of ~0.7m/s.

2) **Transit time error**

   Air bubbles can cause deviation of the acoustic velocity to somewhat larger values for the frequency range of interest (100kHz – 1MHz). Constant larger acoustic velocities are a symptom that air bubbles are present, if at the same time the geometrical data are accurate.

   Example: For the 8-path arrangement each path velocity has been measured for 6 different temperatures. Unfortunately the temperature range was rather small. From the independently measured water temperatures the reference acoustic velocity has been calculated via the formula of Bilaniuk and Wong.

				path					
1	2	3	4	5	6	7	8	ref	Temp
1447.9	1465.1	1466.0	1452.3	1456.5	1466.4	1467.1	1454.2	1477.6	18.5
1448.4	1465.7	1466.5	1452.5	1457.1	1466.8	1467.6	1454.5	1477.9	18.6
1448.7	1466.0	1466.8	1453.2	1457.2	1467.2	1468.0	1455.1	1478.2	18.7
1448.7	1466.1	1466.9	1453.3	1457.4	1467.4	1468.1	1455.1	1478.8	18.9
1448.4	1466.3	1467.1	1452.7	1457.1	1467.5	1468.3	1454.7	1479.1	19.0
1450.3	1467.4	1468.3	1454.6	1458.8	1468.6	1469.4	1456.5	1479.8	19.2

Table 1 : path velocities measurements and reference acoustic velocity for six temperatures

As all acoustic path velocities are smaller than the independently derived reference velocity, one can conclude that air bubbles are most probably not the cause of the deviations.

3) Calibration with reference measurement in temperatures or velocities
   With an independent reference temperature measurement it is possible to calibrate each
   path. Offsets of each path can be examined separately.

   Example: The measurements of Table 1 can be visualized in a three dimensional diagram
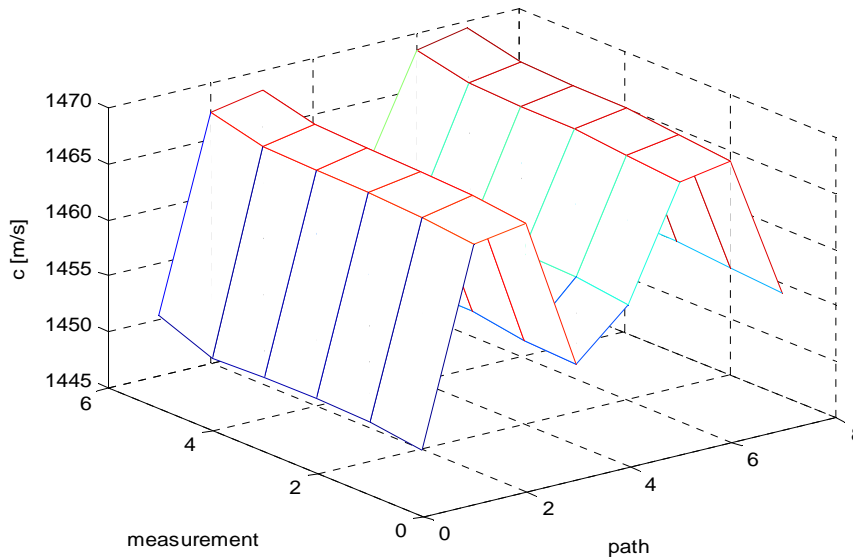   (Fig. 4)

Fig. 4: acoustic path velocities of the six measurements

All measurements show an offset. The size of the offset varies between 10.5m/s and 30m/s.

   Possible causes are :
   - inaccurate length of cables and propagation velocity assumption along the cables
   - inaccurate electronic delay assumption
   - geometrical inaccuracies
   - error in the independent temperature measurement

4) Validation of path acoustic velocities or temperatures against each another
   By looking at all the paths various possible conclusions can be drawn. Single outliers can be
   located and specially analyzed.

   Example : The measurements of the 8-path arrangement show clearly that the short path
   velocities are consistently further away from the reference velocity than the longer paths.
   Also the velocities of the short paths have a large spread of velocity values (ca. 10m/s) than
   the longer paths which exhibit a strong consistency over all measurements (ca. 2m/s). No
   single path can be classified as an outlier in this example.

5) Check for continuity of each path acoustic velocity in function of temperature

For the temperature dependency a continuous and monotone (up to 70°C) function must be expected. When the gradient or the linearized coefficient of the theoretical curve is computed, it can be compared to the values obtained from the transit time measurements.

Example : In the temperature range from 18.5°C to 19.2°C there is a theoretical gradient of 3.14m/s. For the different paths we get (see also Fig. 5) :

[3.43   3.28   3.28   3.28   3.28   3.14   3.28   3.28] :

The measured gradients have a positive offset of 5% approximately. A monitoring of this gradient can be an interesting option for supervising the installation.
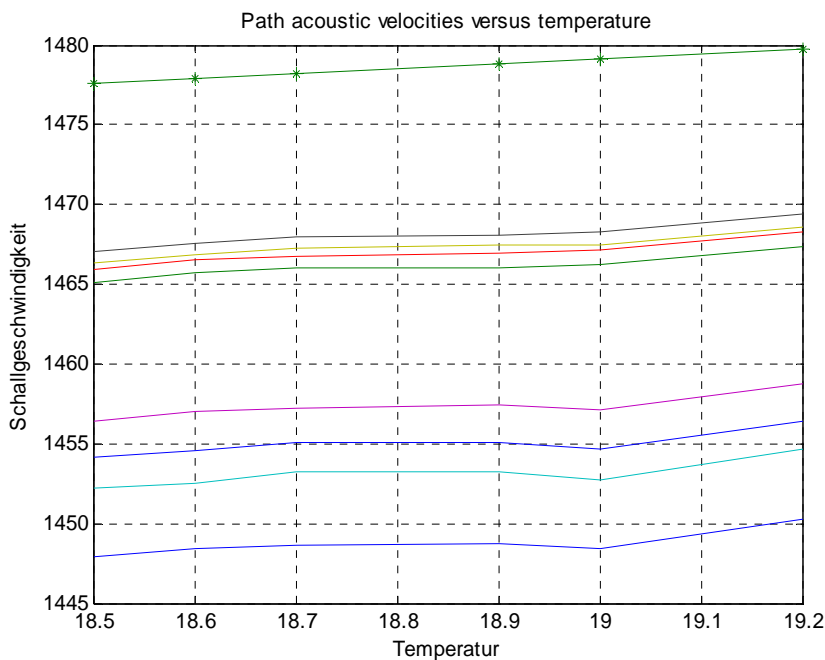

Fig.5 : measured path acoustic velocities in function of the temperature and reference curve

6) **Check for continuity of each path acoustic velocity over time**
Sudden variations in one or several path acoustic velocities indicate difficult water conditions if at the same time the reference temperature is continuous in time. It is to be investigated how the continuity of each path velocity which are used for the determination of flow can be combined with the information about the continuity of the path acoustic velocities in order to detect nonideal operating conditions. Detectors for steady state, trends and oscillatory behaviour can be applied [3].

5   CONCLUSION

Monitoring the acoustic velocities enables to detect possible faulty behaviour and also to diagnose possible causes for the underperformance or fault. With a reference temperature measurement the different paths can be calibrated at the commissioning phase. If a continuous temperature measurement is available, the possibilities of monitoring can be strongly enhanced. Further development have to be directed towards two ends :

1) Implementation in specially chosen test sites of the above mentioned monitoring functions.

2) Collection of expert knowledge in order to be able to locate and diagnose fault causes efficiently after detection of the faults. The collection of this knowledge might also lead to a strategy of additional measurements dedicated especially for finding the causes.

REFERENCES

1. Alexandre Voser, 1999: *Analyse und Fehleroptimierung der mehrpfadigen akustischen Durchflussmessung in Wasserkraftanlagen,* Diss. ETH Zürich, Nr. 13102.

2. V.A Del Grosso et al. 1974: *Journal of the Acoustic Society of America, no. 56, p.1084*

3. A. Glass, P. Gruber : Steady state detection, IEA Annex 25, Real time simulation of HVAC systems for building optimisation, fault detection and diagnosis, Source Book, p.265-276, August 1996.