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GWF

IGHEM Vancouver

Session 6 / Local velocity measurements

Acoustic Flow Metering with Clamp-On Transducers
General Considerations and Uncertainty

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MOTIVATION

- I'm not talking about Clamp-On flow meters that can be used to determine whether something is flowing and typically +/-10% doesn't play a role (industrial applications). Rather, I'm talking about clamp-on flow meters that are in the range of +/-2% or better (hydropower applications).

- The reason why Clamp-On flow meters are used in hydro power plants is usually because they can be installed without stopping the flow. Another reason is, that the customer wants to avoid many holes in the penstock in high-pressure applications (> 60 bar).

- Clamp-On flowmeters are not listed in either IEC60041:1991 or ASME PTC 18:2020 performance test codes, they are not approved for turbine efficiency testing. They are used exclusively for process control.

- However, the standard IEC 62006:2010 Hydraulic machines – Acceptance tests of small hydroelectric installations mentions Clamp-On flowmeters. It applies to installations with unit power up to about 15 MW and diameter of < 3 m.

- The systematic uncertainty for a single path Clamp-On flow meter is indicated with +/-2.5% (8-path wetted +/-1.0%) and limited to v > 1.5 m/s, D > 0.8 m, straight pipe L/D > 10 upstream and L/D > 3 downstream.

- Clamp-On flow meters with one single path can be used for class B tests to determine the performance characteristics and shall not be used for class C acceptance tests. **The use of simplified ultrasonic techniques for acceptance tests should be subject to mutual agreement between the parties.**

INTENTION

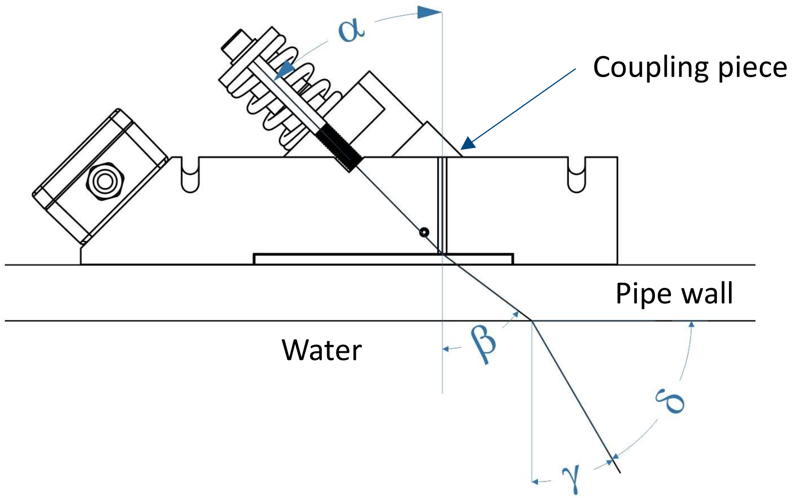
- With this presentation I intend to take a detailed look at the Clamp-On technology and to point out the boundary conditions and dependencies for high quality measurements.

  Influence on measured velocity
  - ✓ Path angle
  - ✓ Speed of sound
  - ✓ Penstock effects (diameter, wall thickness)

  Influence on Q calculation
  - ✓ Temperature
  - ✓ Flow disturbance, variations in the velocity profile

- In practice, I have already experienced Clamp-On systems being offered where the service technician then determined that the sliding bar was not sufficient long for these larger diameters, or, for example, no signal was received at all because the wall thickness was too thick, or the frequency of the selected transducer was too high.

PATH ANGEL

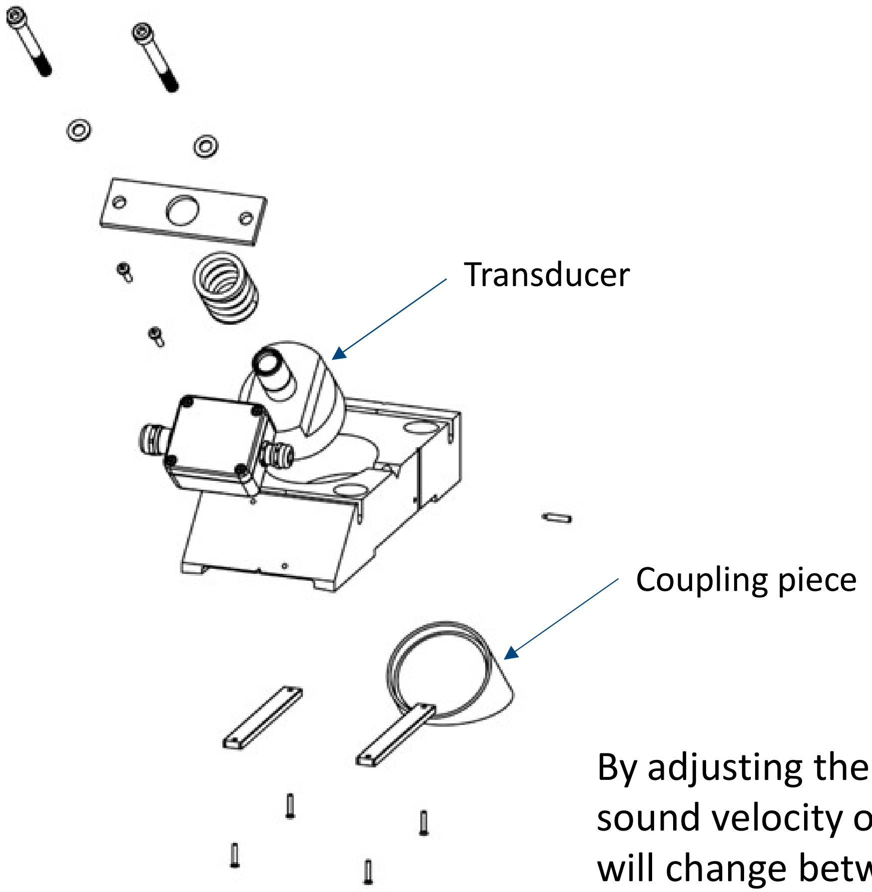


$$\sin\gamma = \frac{\sin\alpha\ C_w}{C_{cp,L}}$$

$C_{cp.L}$	= Speed of sound in coupling piece (longitudinal)
C_w	= Speed of sound in water
α	= Angle in coupling piece
δ	= Path angle in water

Path angle γ depends on the angle α, the speed of sound of the coupling piece and the speed of sound in water.
The travel time along the acoustic path in pipe wall depends on the transversal speed of sound of the pipe material.

TRANSDUCER ASSEMBLY

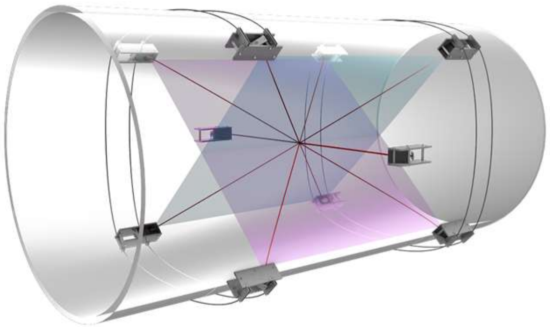


By adjusting the material of the coupling piece between a sound velocity of 2.200 m/s and 2.900 m/s, the path angle will change between 62° to 70°.

SPEED OF SOUND

T	P	C_w	δ	Error v
5° C	50 bar	1.433,77 m/s	67,945°	1,45%
10° C	50 bar	1.455,00 m/s	67,601°	0%
15° C	50 bar	1.473,86 m/s	67,295°	-1,30%

T = Temperature
P = Pressure
C = Speed of Sound (Belogol’skii and Sekoyan et al., 1999)
δ = Path angle
Error v = Error in axial velocity



Fluid temperature has several interacting effects. It affects the speed of sound, fluid density, viscosity and hence the Reynolds number and the velocity profile. Changes in the speed of sound in the fluid have the effect of changing the angle of the beam in the fluid and hence the sensitivity of the flowmeter. For processes where the fluid temperature is likely to change it is important that a flowmeter with speed of sound compensation is employed.

PENSTOCK EFFECTS

W [m]	D [m]	ΔL_{PW}	ΔL_{FS}	ΔA	ΔQ
0,015	1,010 (-1,00%)	+33,33%	-1,00%	-2,00%	-1,45%
0,016	1,008 (-0,80%)	+25,00%	-0,80%	-1,60%	-1,16%
0,017	1,006 (-0,60%	+17,65%	-0,60%	-1,20%	-0,87%
0,018	1,004 (-0,40%)	+11,11%	-0,40%	-0,80%	-0,58%
0,019	1,002 (-0,20%)	+5,26%	-0,20%	-0,40%	-0,29%
0,02	1,00	0	0	0	0
0,021	0,998 (+0,20%)	-4,76%	+0,20%	+0,40%	+0,29%
0,022	0,996 (+0,40%)	-9,09%	+0,40%	+0,80%	+0,59%
0,023	0,994 (+0,60%)	-13,04%	+0,60%	+1,20%	+0,88%
0,024	0,992 (+0,80%)	-16,67%	+0,80%	+1,60%	+1,18%
0,025	0,990 (+1,00%)	-20,00%	+1,00%	+2,00%	+1,48%

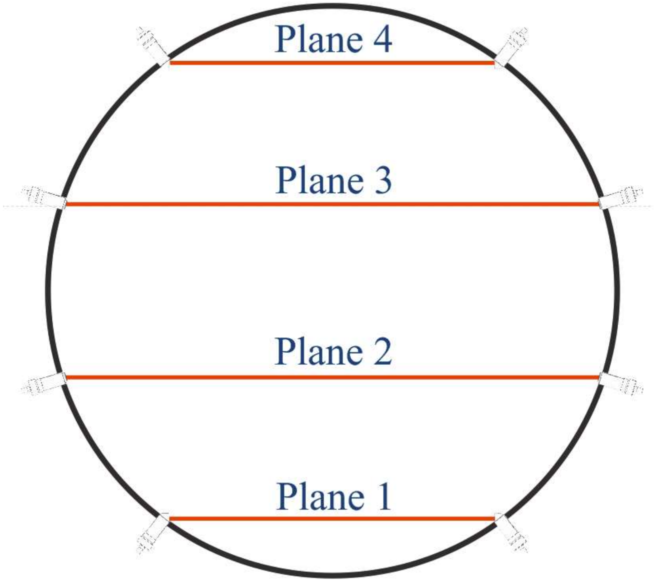
w = Wall Thickness, D = inner Diameter, ΔL_{PW} = Change of Path Length in Pipe Wall (important for absolute time measurement), ΔL_{FS} = Change of Path Length in Flow Section, A = Cross Section, Q = Discharge, v = 1,00 m/s

DISCHARGE CALCULATION

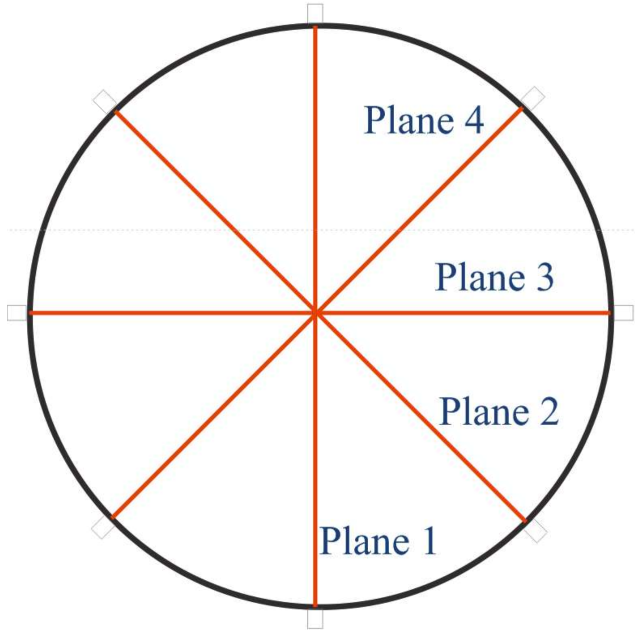
$$Q = \frac{D}{2} \sum_{i=1}^{N} w_i \ \overline{v}_{ax,i} \ L_{proj,i}$$

$$Q = k \ \frac{\sum_{i=1}^{N} \overline{v}_{ax,i} \ A}{N}$$

k = Correction factor



„Wetted“ Transducers (parallel planes)



Clamp-On (axial planes)

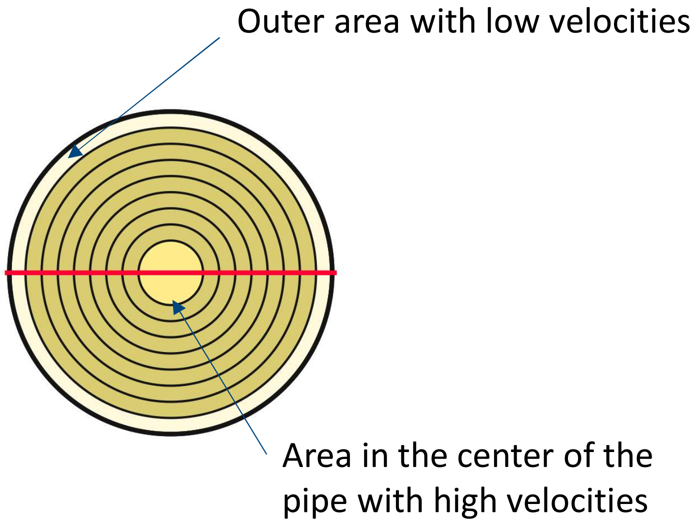
VELOCITY PROFILE CORRECTION / SINGLE PATH FULLY DEVELOPED FLOW

Correction factor k for:
- non disturbed velocity profiles
- fully developed flow

Laminar: $$k = \frac{1}{1{,}33}$$

Turbulent: $$k = \frac{1}{1{,}0 + 0{,}01\sqrt{6{,}25 + 431\,Re^{-0{,}237}}}$$ (Plaut & Webster)

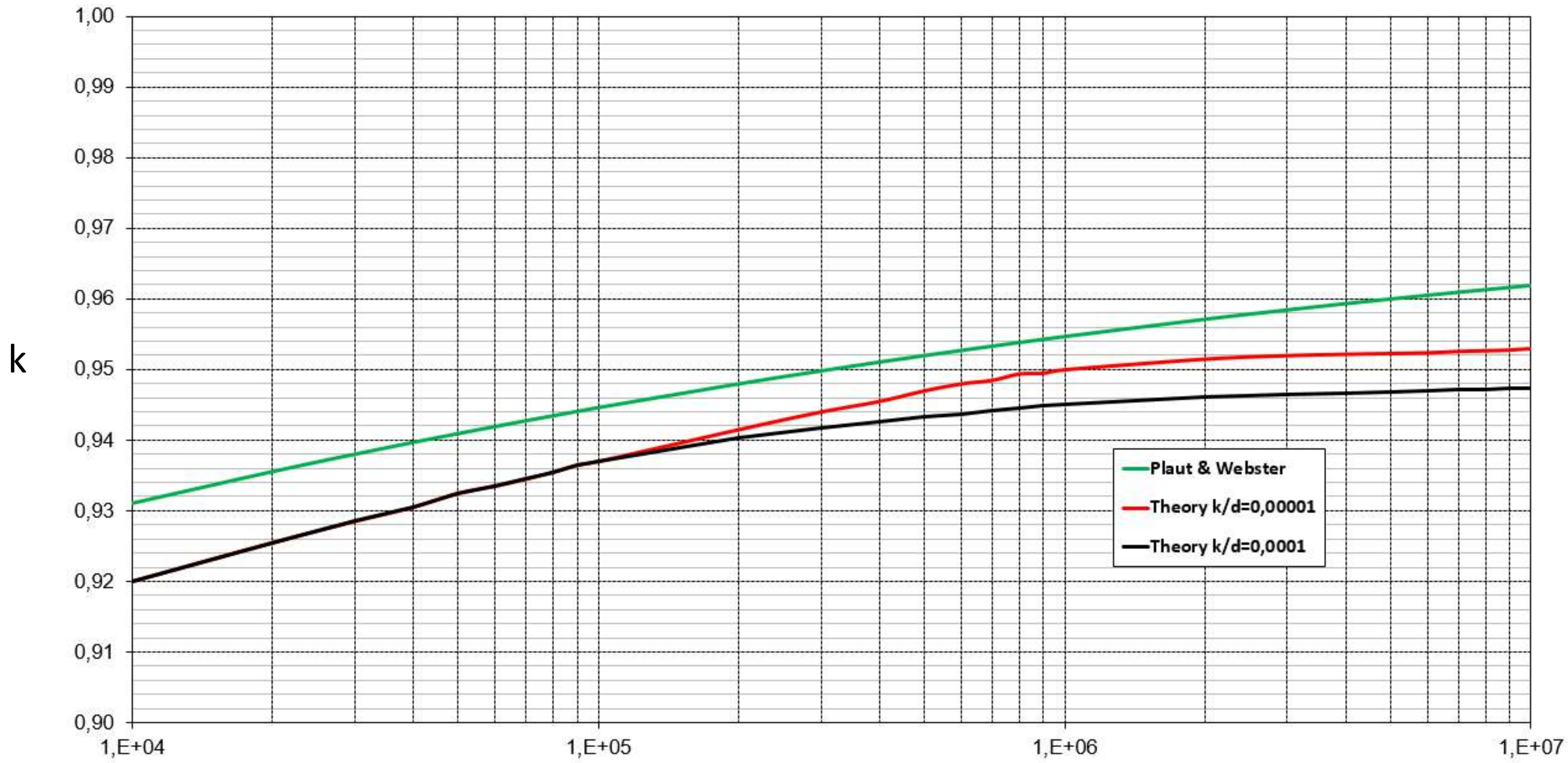
$$k = \frac{1}{(1{,}119 - 0{,}011\,Log\,Re)}$$ (L.C. Lynnworth)



IMPORTANT

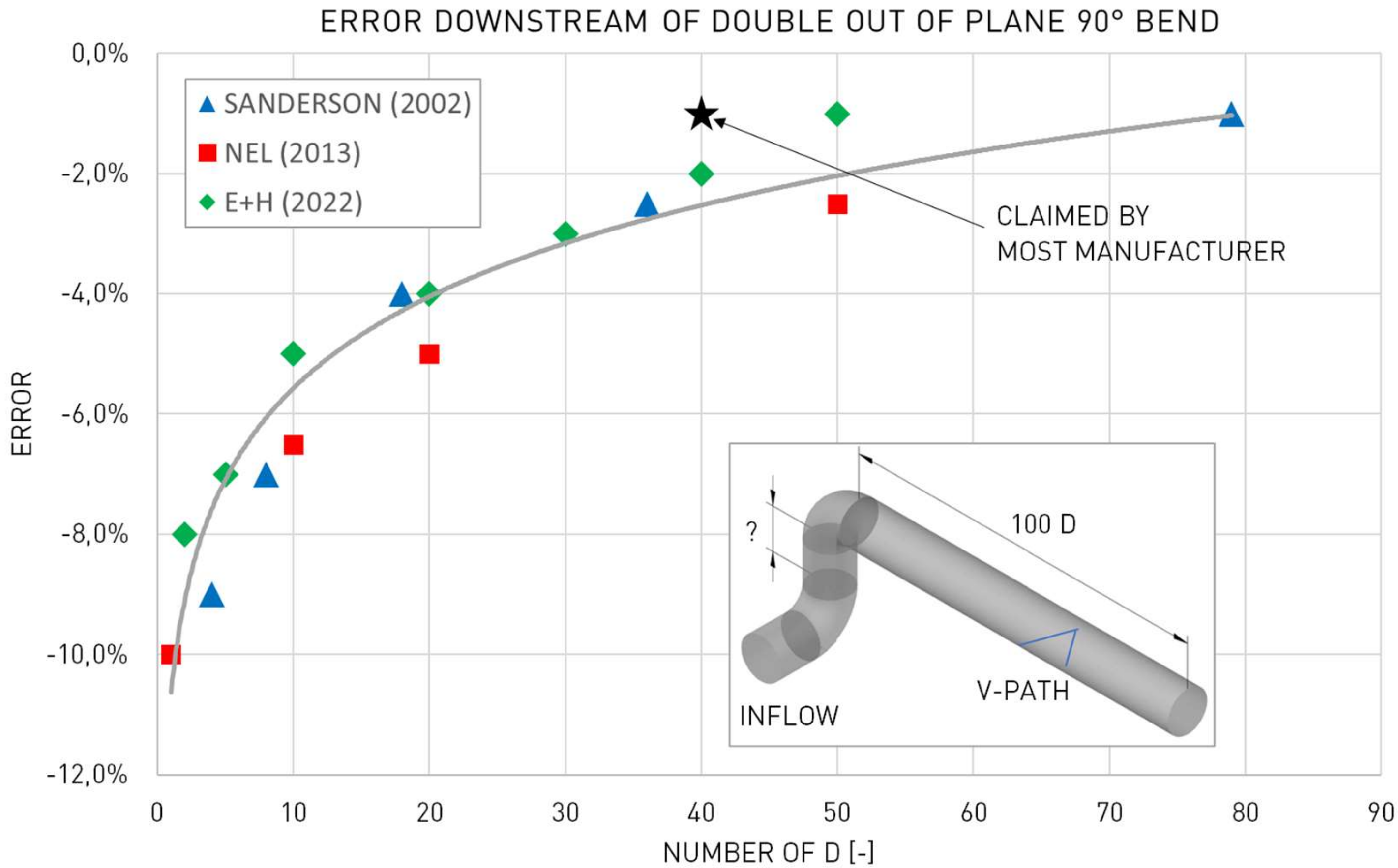
As the correction factor for the meter depends on the Reynolds number the knowledge of the kinematic viscosity is particularly important, which depends mostly on the water temperature. It would be of great advantage if a temperature sensor may be integrated in the meter.

VELOCITY PROFILE CORRECTION / SINGLE PATH FULLY DEVELOPED FLOW



k factor against Reynolds Number for varying pipe roughness and the approximation from Plaut & Webster for fully developed turbulent flow.

FLOW DISTURBANCE DOUBLE OUT OF PLANE 90°-ELBOW



STANDARDIZED FLOW DISTURBANCE COMPENSATION BY CFD

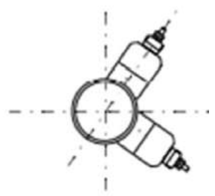
Computational fluid dynamics (CFD) are employed to generate correction factors that compensate for the error introduced from disturbed inlet conditions.

Correction factors for several disturbance elements at mounting distances from 2D to 100D and several flow rates have been introduced.

2 manufacturers are known to follow this approach:

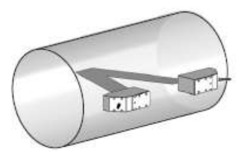
Endress + Hauser:

Uncertainty:	**+/- 2%** with a double V-path rotated 90° relative to each other rotationally independent
Inlet conditions:	2D
Disturbance:	90° elbow, double out of plane elbow, expansion, reducer
Parameter:	Disturbance distance

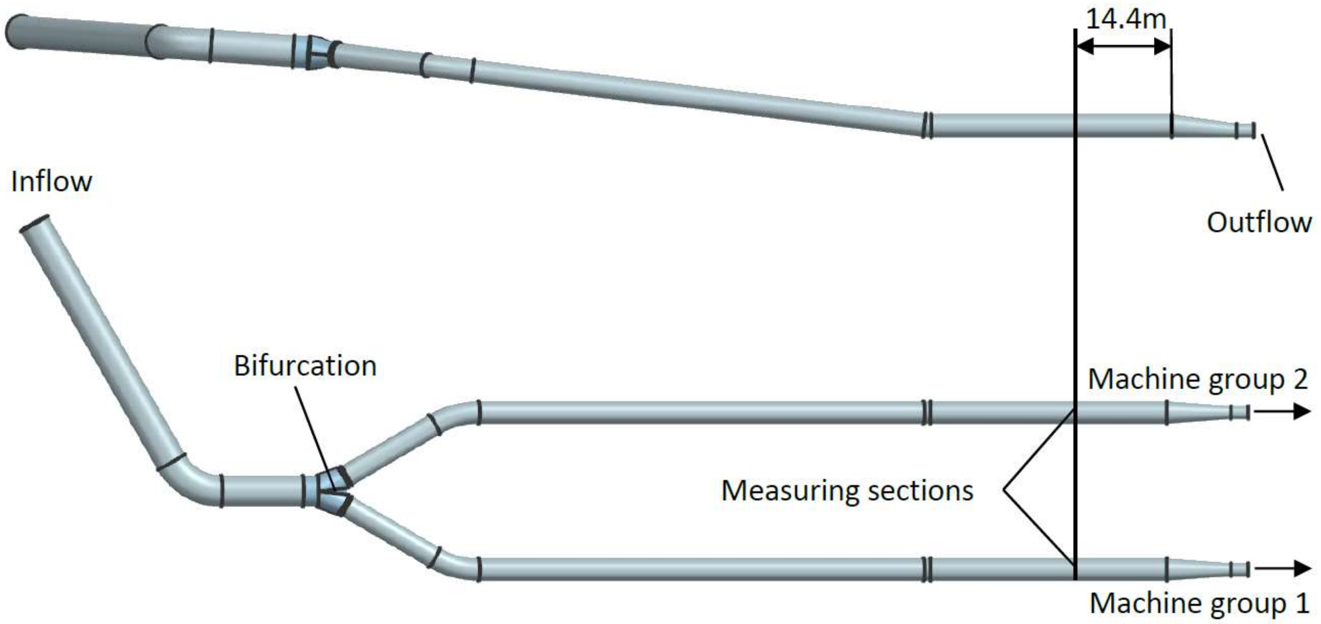


Flexim (Emerson):

Uncertainty:	**+/- 1%** with a single V-path arrangement
Inlet conditions:	2D
Disturbance:	90° elbow, 90° double elbow, double out of plane elbow 45° elbow, 45° double elbow, reducer
Parameter:	Disturbance distance

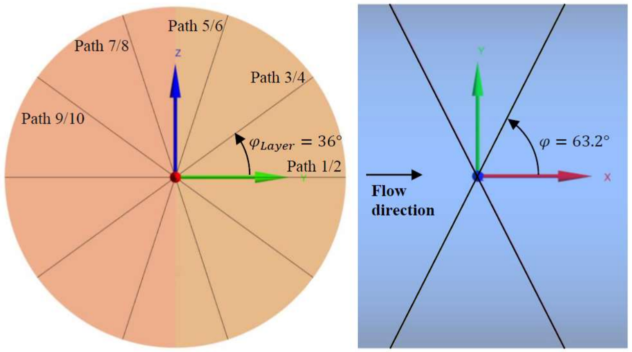


ON DEMAND FLOW DISTURBANCE COMPENSATION BY CFD



Source: etaeval GmbH

Pressure: 80 bar
Flow measurements turbine mode
10 path Clamp-on flowmeter
5 Planes crossed
1 Path speed of sound compensation



ON DEMAND FLOW DISTURBANCE COMPENSATION BY CFD

- For the analysis of the uncertainty of the flow rate measurements based on the mean value out of 5 planes not only different flow rates were simulated, but also various operating conditions of the two machine groups.

- For each simulated flow rate and for each machine group a correction factor k_{CFD} was determined. A resulting $k_{CFD,ave}$ factor was derived as an average value from all simulations.

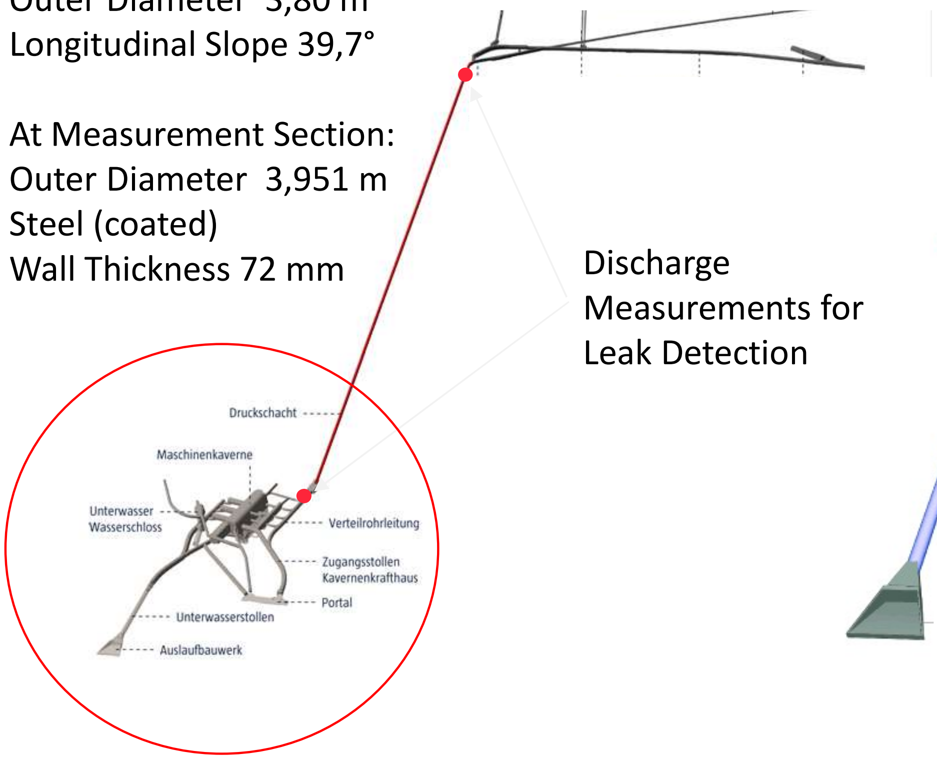
- Thus, for each simulated case, an uncertainty error of the flow rate remains, which lies in the range of -0.34% and 0.33% over the flow rates of 44 m³/s to 66 m³/s.

- It should be noted that in addition to the integration error the overall measuring uncertainty must include the uncertainties due to installation, time measurement, acoustic transmission in the conduit wall, temperature and electronics.

VERIFICATION CLAMP-ON KOPSWERK II

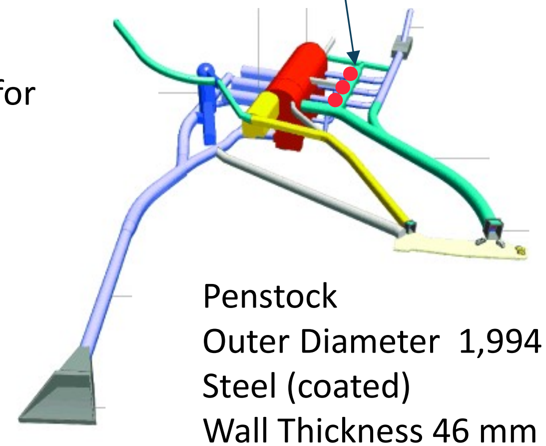
Tunnel 1,2 km
Difference in Altitude 710 m
Outer Diameter 3,80 m
Longitudinal Slope 39,7°

At Measurement Section:
Outer Diameter 3,951 m
Steel (coated)
Wall Thickness 72 mm



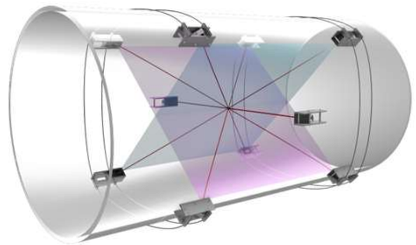
Discharge Measurements for Leak Detection

Discharge Measurements for Process Control

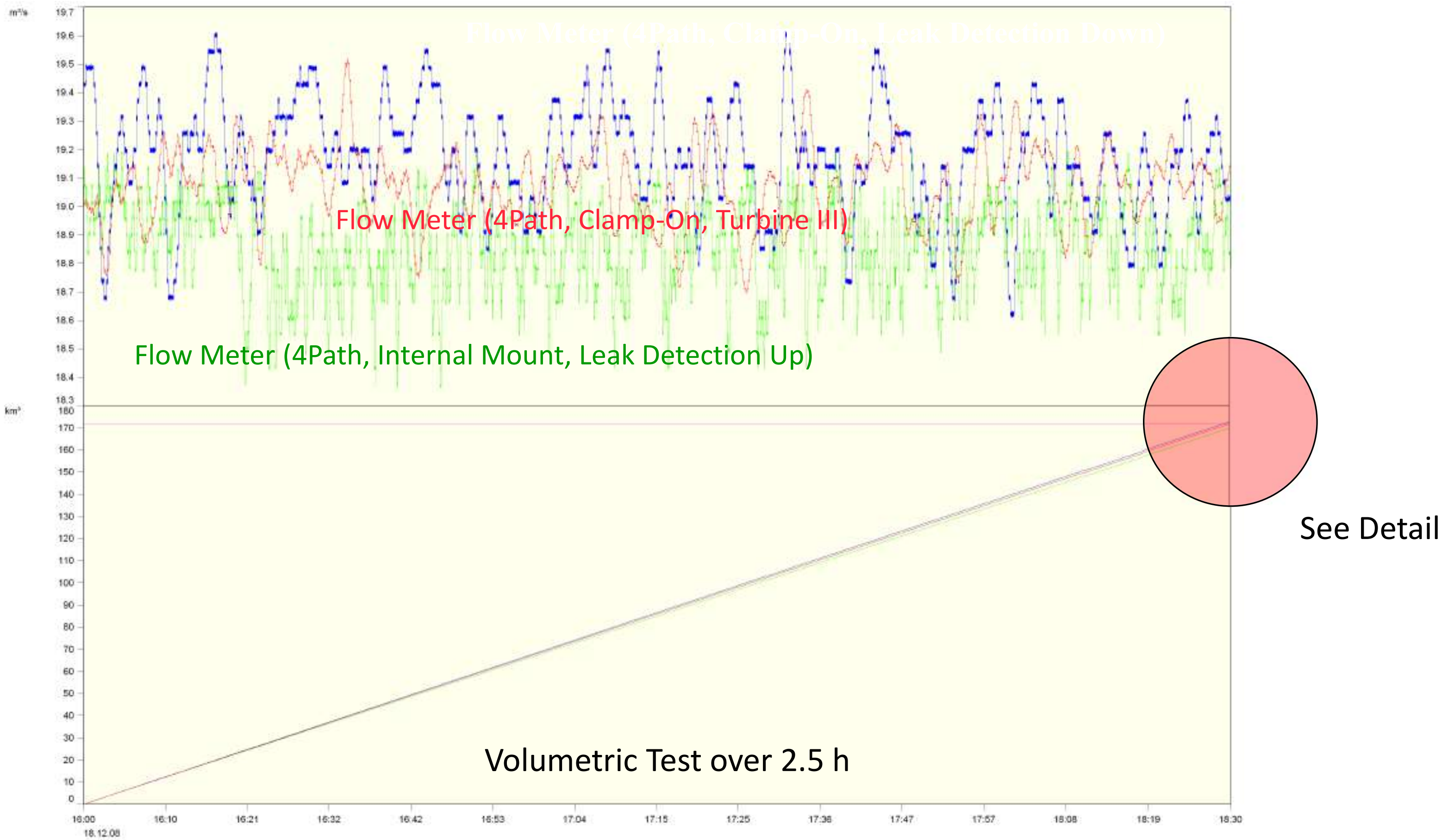


Penstock
Outer Diameter 1,994 m
Steel (coated)
Wall Thickness 46 mm

Path Arrangement
2 Planes Crossed



VERIFICATION CLAMP-ON KOPSWERK II



VERIFICATION CLAMP-ON KOPSWERK II

175000 m³

172500 m³ (Leak Detection, Down)
171520 m³ (Turbine III)
170000 m³
169670 m³ (Leak Detection, Up)

Accuracy
Leak Detection, Down: + 0,44%
Turbine III: -0,128%
Leak Detection, Up: -1,205%

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