Physikalisch-Technische Bundesanstalt
Braunschweig and Berlin
National Metrology Institute

Unsicherheitsquantifizierung von CFD Simulationen

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On-site calibration of flow meters in district heating systems

PTB

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OPTOLUTION messtechnische lösungen

ILA Intelligent Laser Applications GmbH

PTB

EnEff:Wärme
Forschung für energieeffiziente Wärme- und Kältenetze

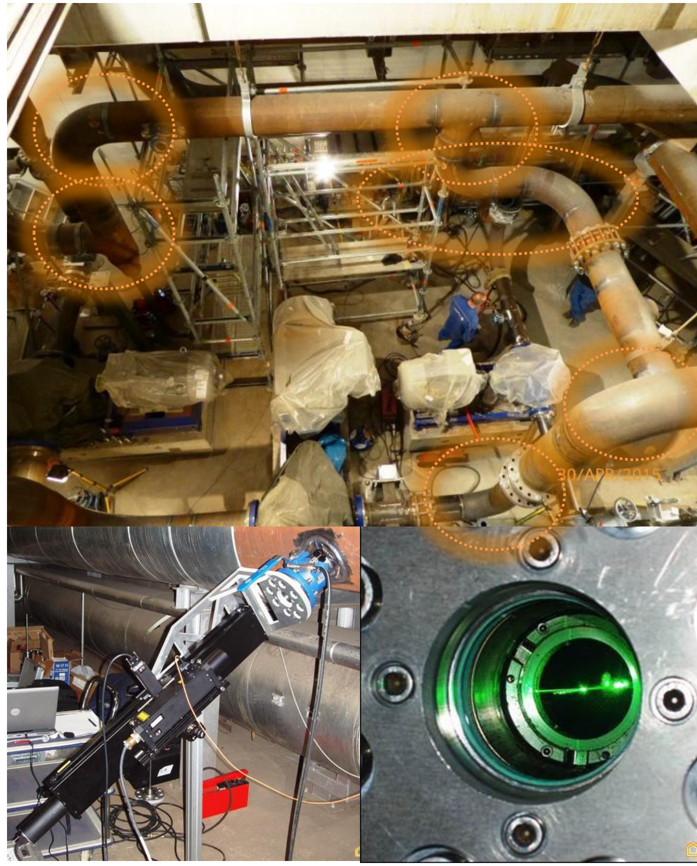
Gefördert durch:
Bundesministerium für Wirtschaft und Energie
aufgrund eines Beschlusses des Deutschen Bundestages

Goal:

on-site calibration of installed flow meters in the Berliner district heating system

Challenge:

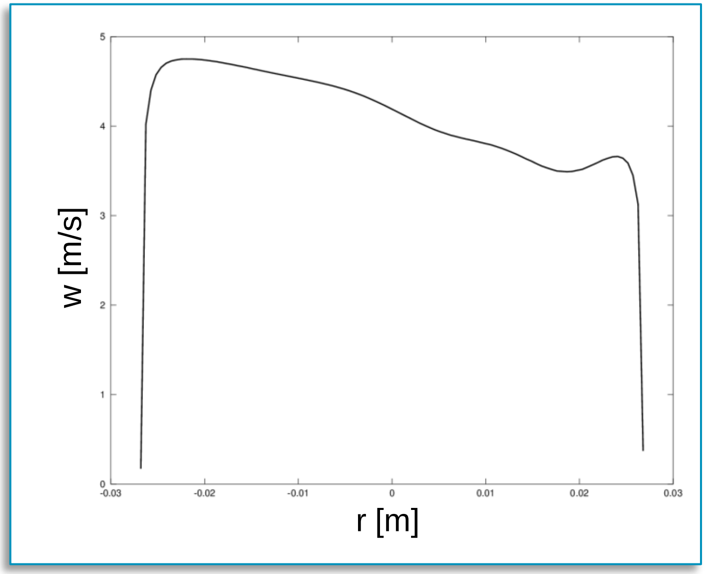
- Measurement of one path with Laser-Doppler-velocimetry
- limited access to measurement positions
- huge diameters (> 400 mm), high temperatures (>80°C), high Volume Flow
- Combinations of elbows and T-Junctions disturb flow profiles in front of the flow meter



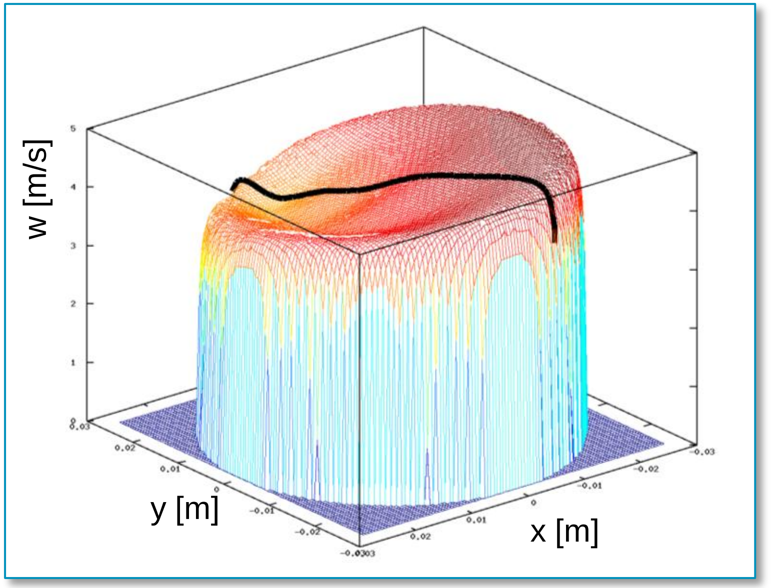
non symmetric Profiles → **huge error in integration of only one path**

Idea:

- Measurement of one path with Laser-Doppler-Velocimetry
- CFD-Simulation of flow downstream a disturbing geometry
- Reconstruction of the flow profile on the measurement cross section



CFD



volume flow Q

uncertainty?

Sensitivity of a double elbow out-of-plane

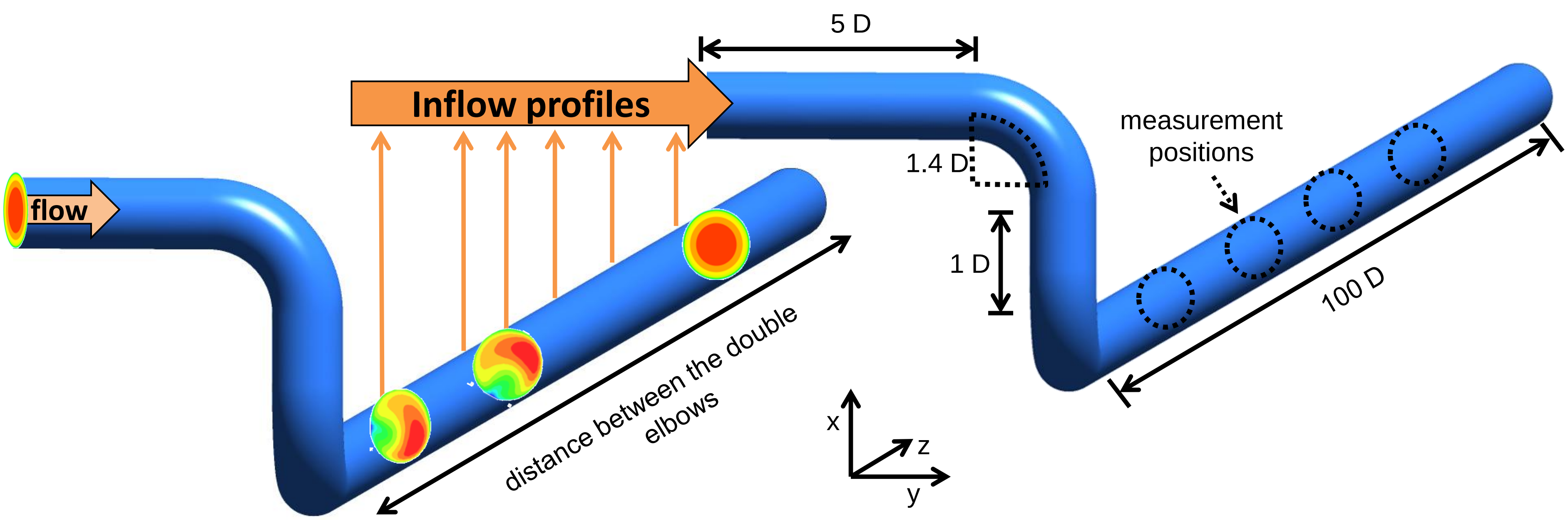
- Double elbow with ideal inlet profile
- Two Double elbows out-of-plane in a row:
  - Double elbows creating swirl with **same** direction
  - Double elbows creating swirl with **opposite** directions

Numerical set up:

- pipe diameter 53.6 mm
- Re number = 3 e5
- solver: Ansys CFX
- turbulence model: k-ω (wilkox 1986)

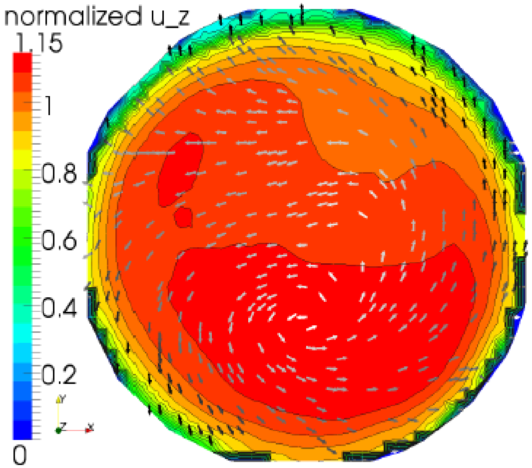
Mesh:

- structured hexahedral O-grid 3.2 mil. elements
- wall distance $y^+ = 1$

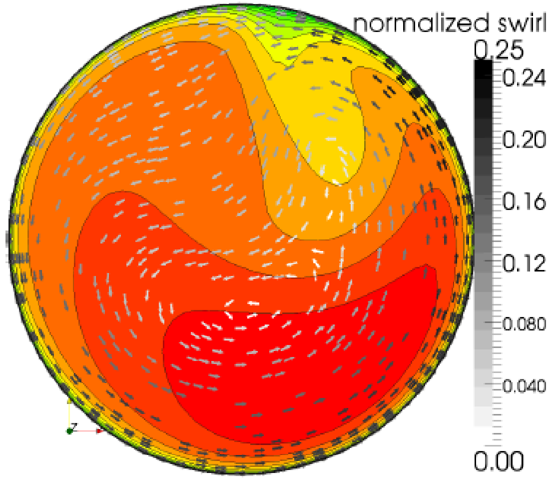


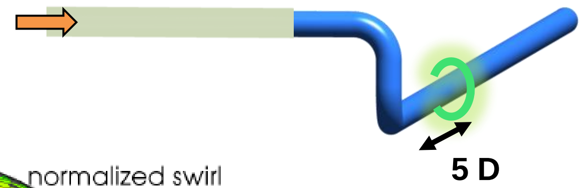
Sensitivity of a double elbow out-of-plane

PIV-Measurement



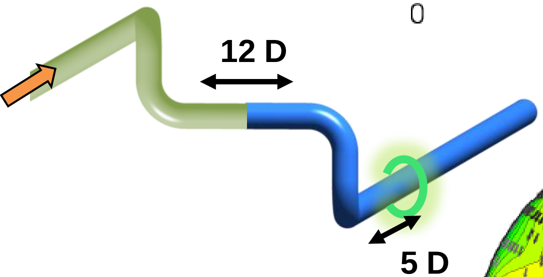
CFD



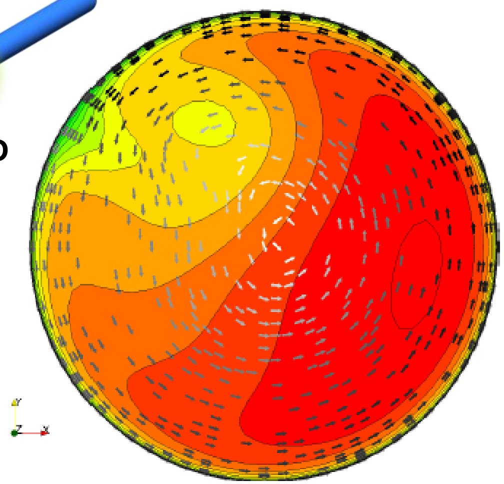


straight pipe in front

*Experimental data obtained by Ulrich Müller, Optolution Messtechnik GmbH

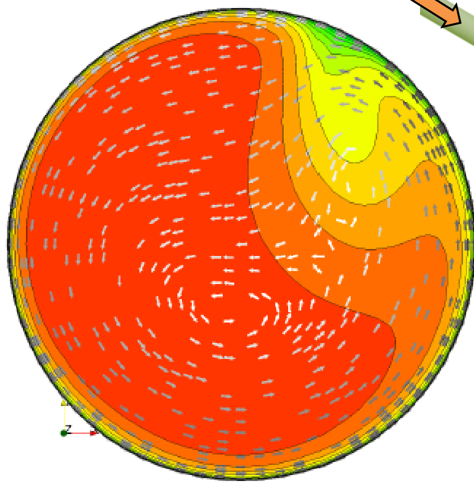


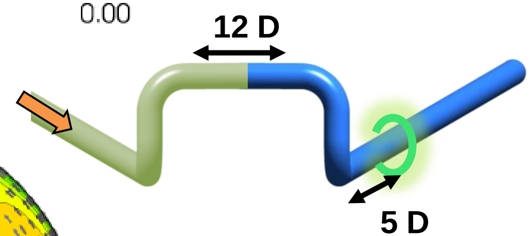
CFD



two double elbows with same swirl direction

CFD

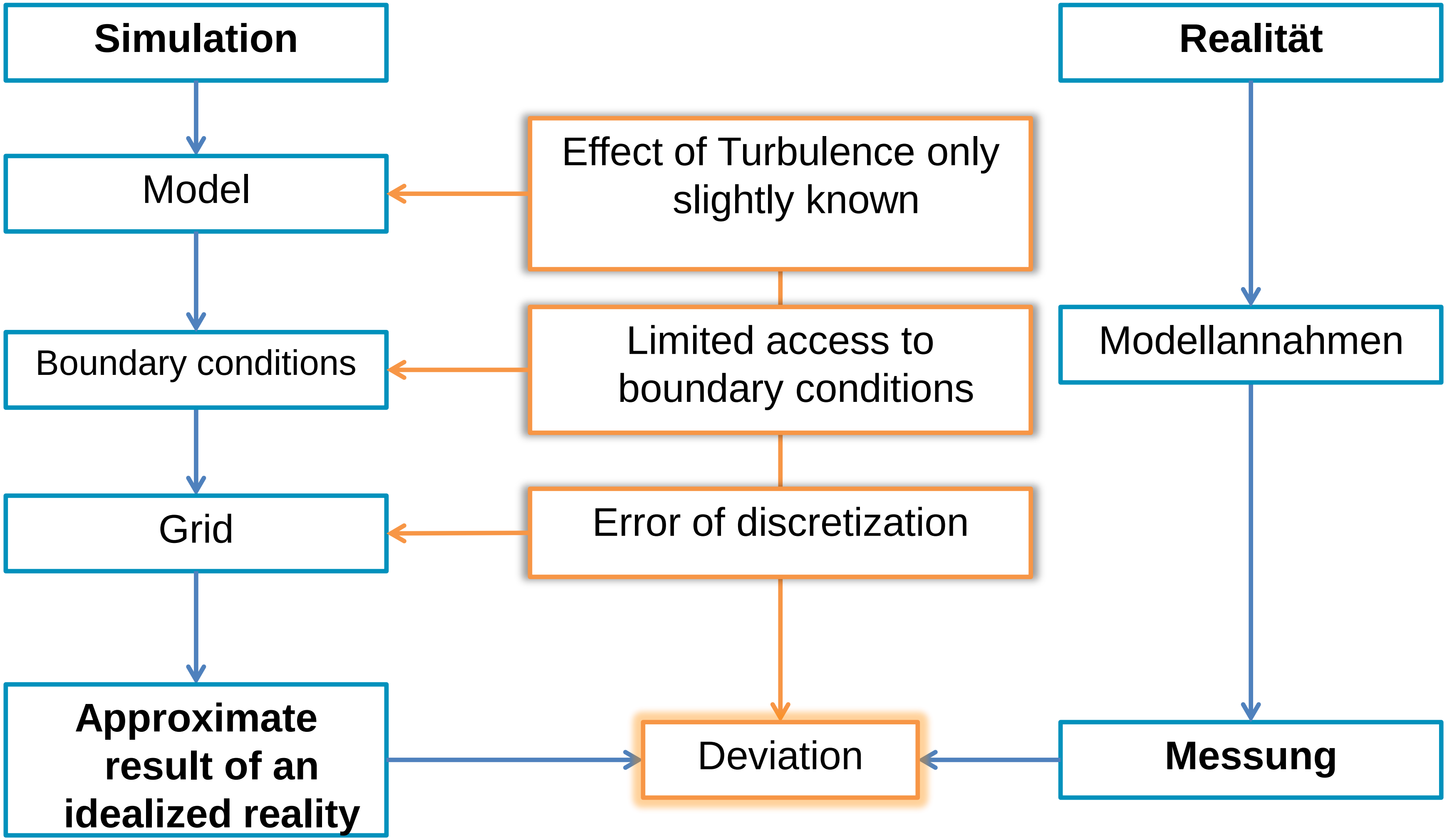




two double elbows with opposite swirl direction

Uncertainty quantification of CFD

Vergleichbarkeit von Messung und Simulation



Polynomial Chaos - basic concept

INPUT

variation of boundary condition(s)

probability distribution

Model

Simulation with a turbulence model

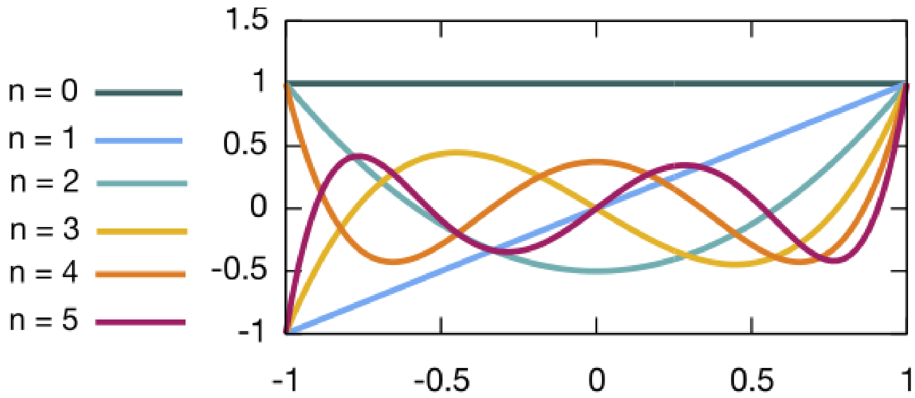
OUTPUT

interpolation with orthogonal polynomials

integration

statistical quantities

Legendre Polynomials

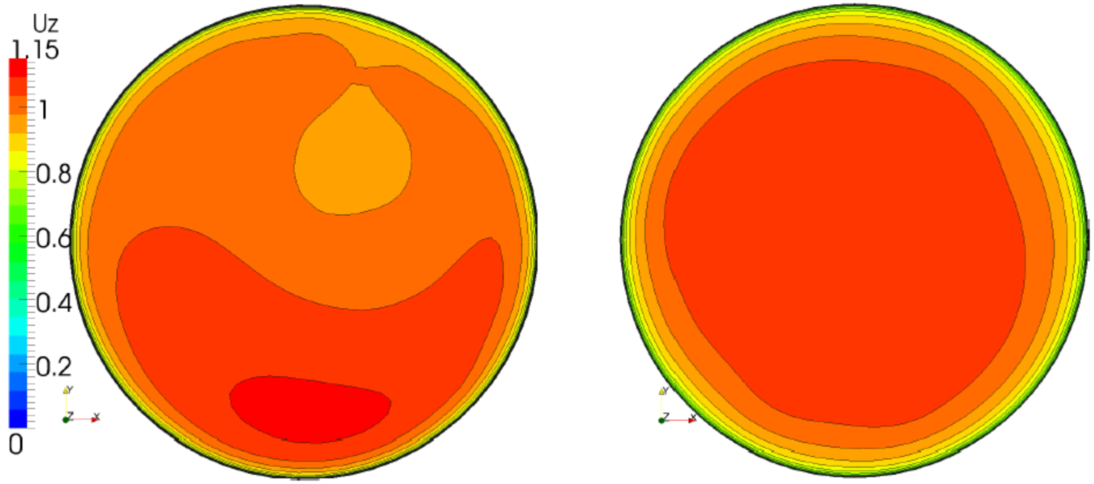


Faster convergence then Monte Carlo methods!

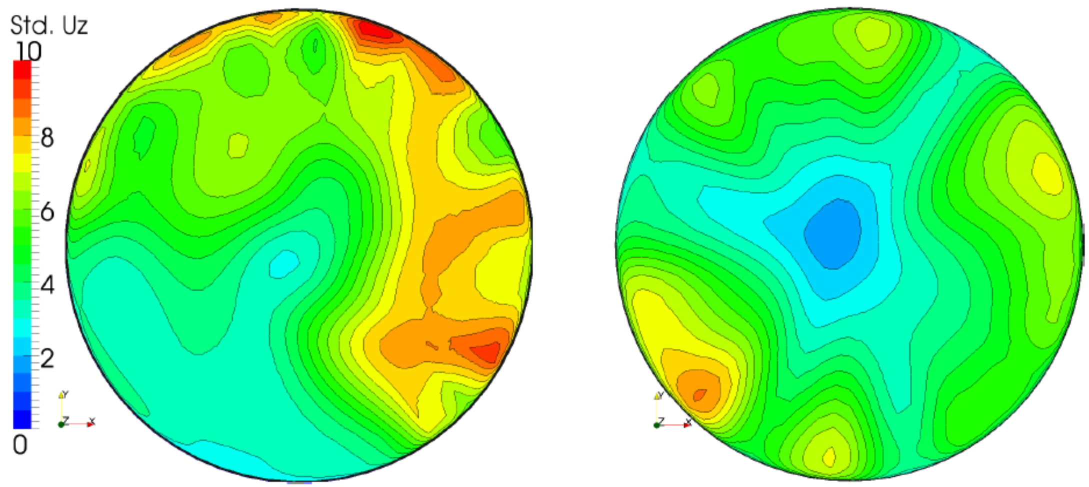
Uncertainty of a double elbow out-of-plane

5 D distance **17 D distance**

Mean (Expectation) Value



Standard deviation

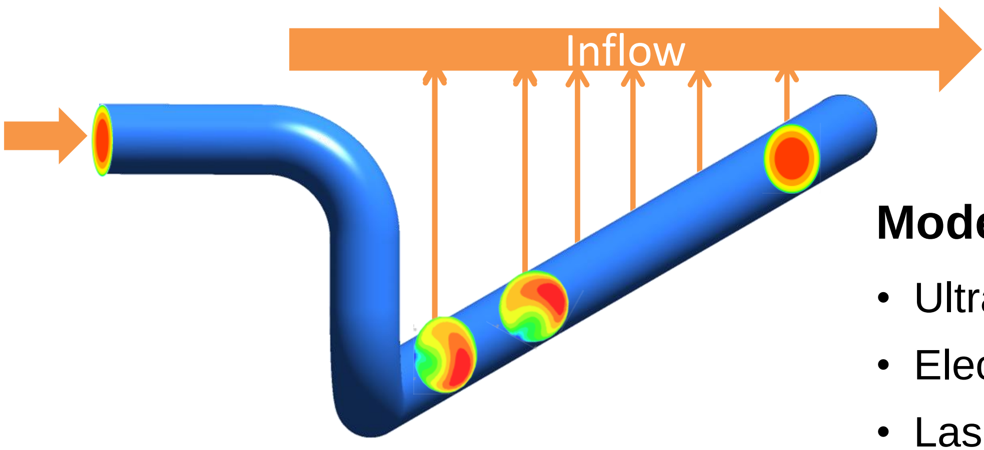


Conclusion

- CFD can capture the main qualitative effects seen in the experiment
- Profiles are sensitive to the inflow conditions
- The azimuthally position of the asymmetry is varying

Next step:

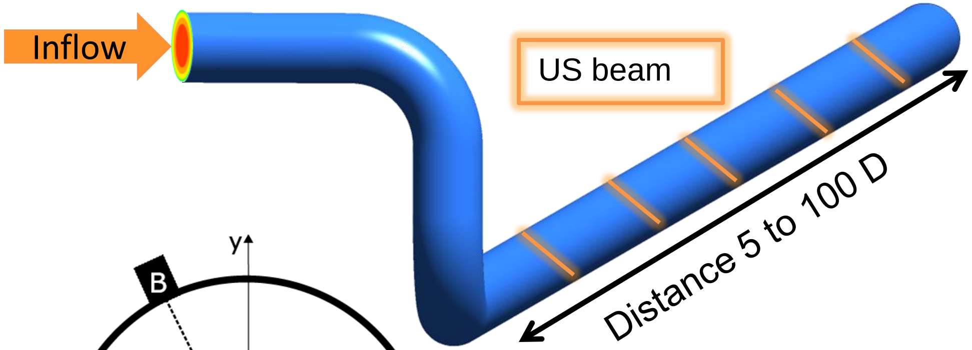
- Modeling the measurement principle of a flow meter
- Define the angular position of the flow meter as random
- Quantify uncertainties of the Flow meter with Polynomial Chaos

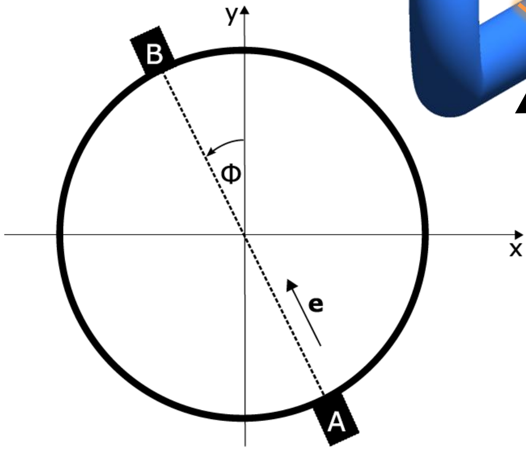


Modeled measurement principles:

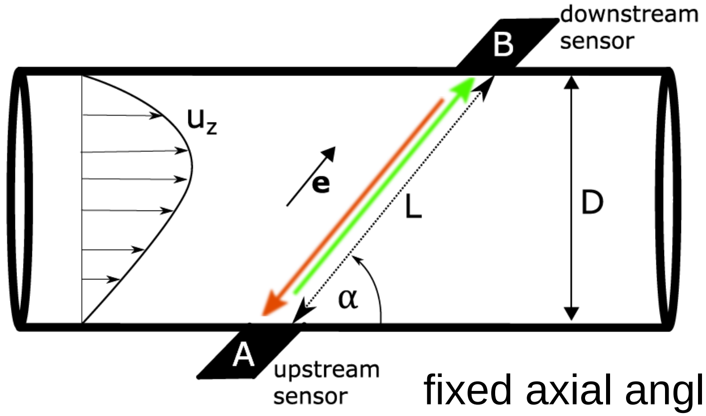
- Ultrasonic flow meter
- Electromagnetic flow meter
- Laser Doppler Velocimeter

Sensitivity of an ultrasonic flow meter





Random angular position ϕ



fixed axial angle $\alpha = 45°$

Transit time single beam with straight line wave propagation

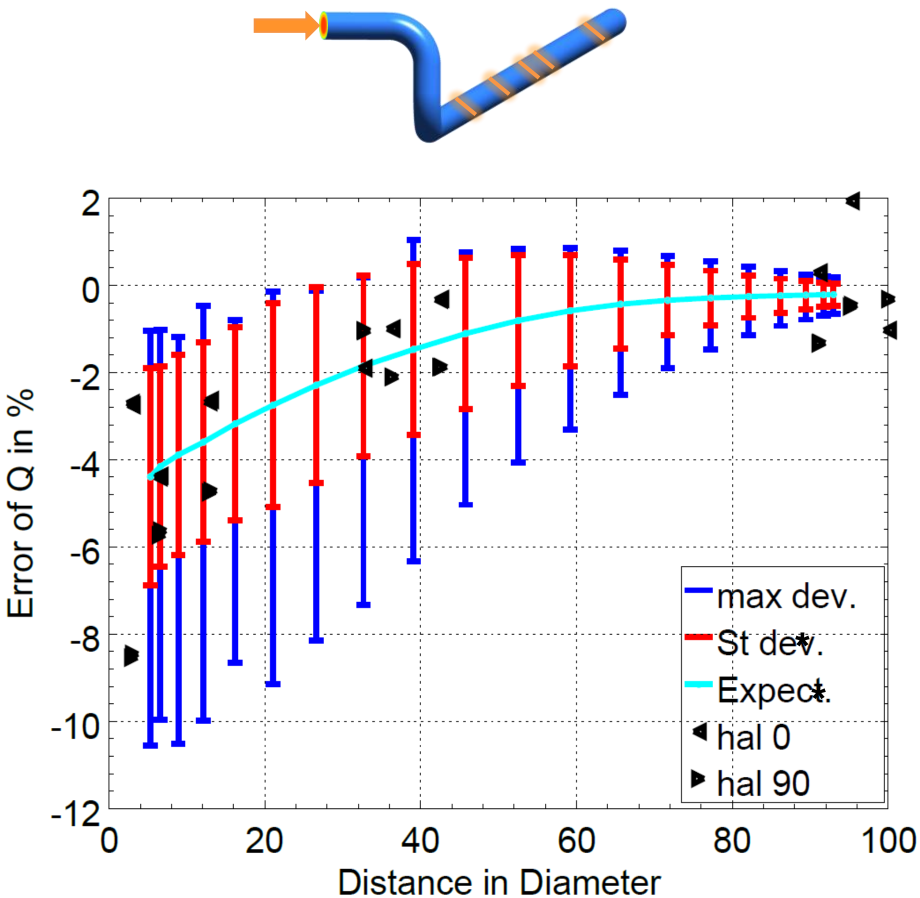
$$Q_m = kA\bar{u}_p = \frac{kA}{Le_z}\int_0^L u(l)\,e\,dl$$

$$u = (u_r, u_\phi, u_z)$$

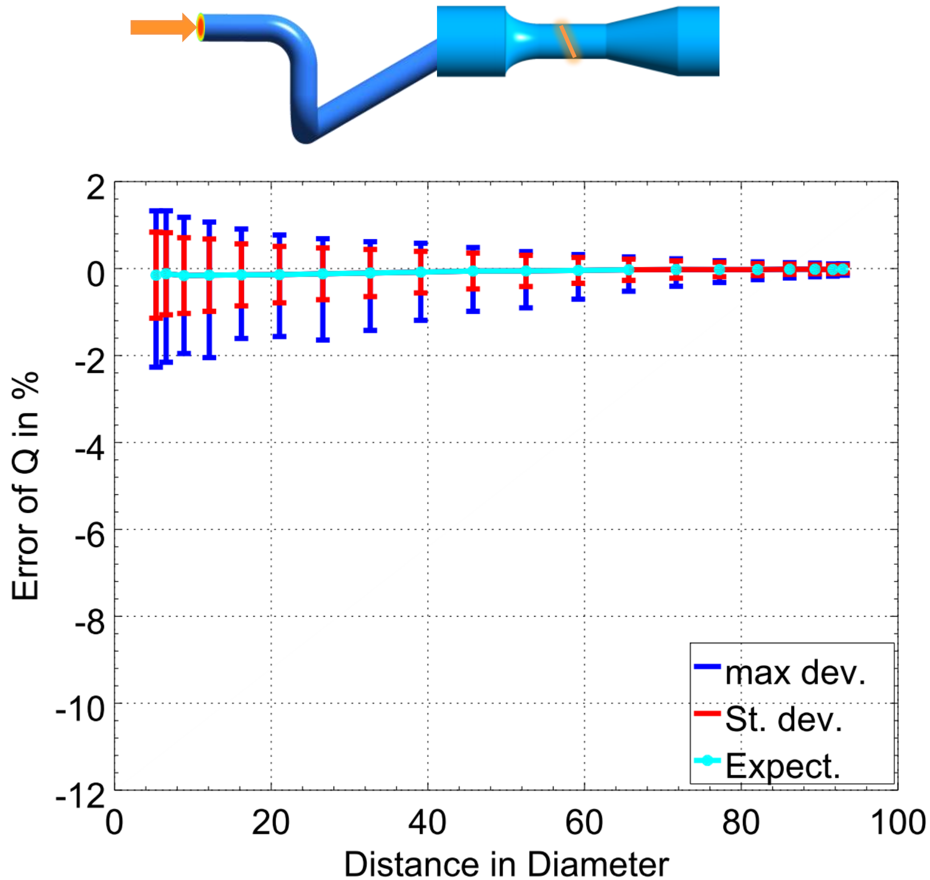
$$e = (\sin(\alpha), 0, \cos(\alpha))^T$$

$$\text{Error in } \% = \varepsilon = \frac{100}{Q_{real}}(Q_m - Q_{real})$$

Sensitivity of an ultrasonic flow meter



Venturi nozzle for flow conditioning



* Halttunen, J., 1990. Installation effects on ultrasonic and electromagnetic flowmeters: a model-based approach. Flow Measurement and Instrumentation 1, 287–292

* Mattingly, G. E., Yeh, T. T., 4-7 June 1990. Secondary flow effects due to several elbow configurations. In: ASME Fluid Measurement and instrumentation Forum 1990, Toronto, Ontario, Canada

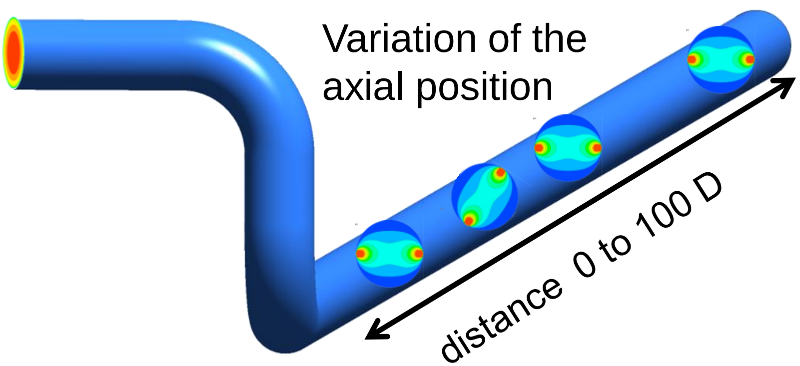
Sensitivity of an electromagnetic flow meter

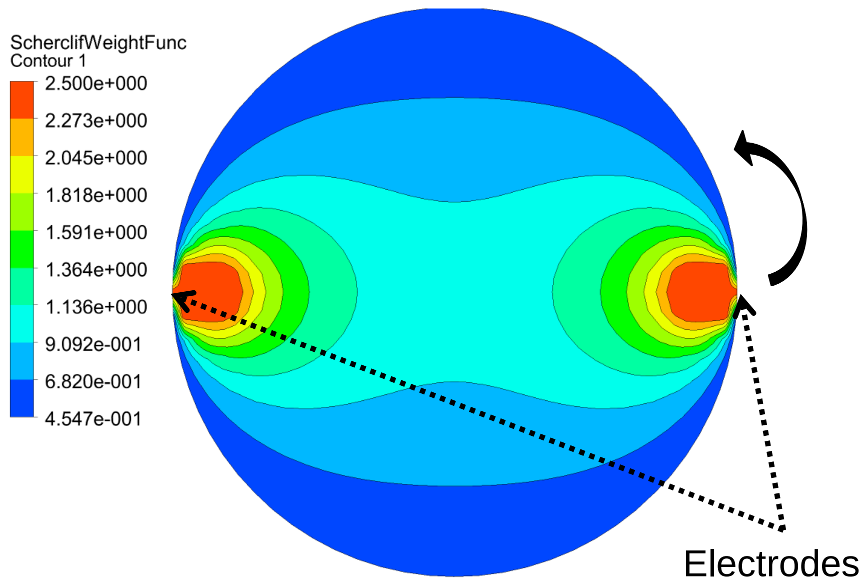
Weight function (Shercliff)

$$Q(z) = k_m \int_z^{z+l} \iint_A W(x,y) u_z(x,y,z) \,\mathrm{d}A$$

$$W(x,y) = \frac{R^4 + R^2(x^2 - y^2)}{R^4 + 2R^2(x^2-y^2) + (x^2+y^2)^2}$$

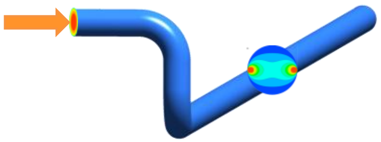
Variation of the angular position of the electrodes 0° to 360°



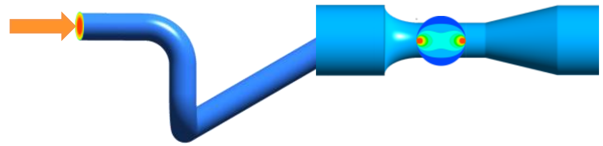


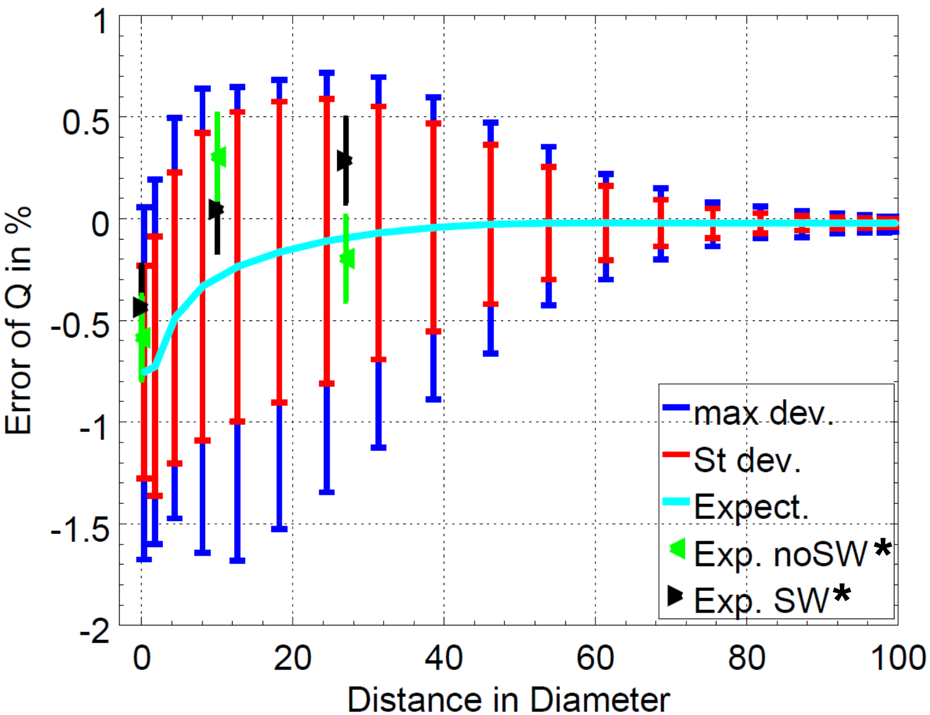
$$\text{Error in } \% = \varepsilon = \frac{100}{Q_{real}} \left(Q_m - Q_{real}\right)$$

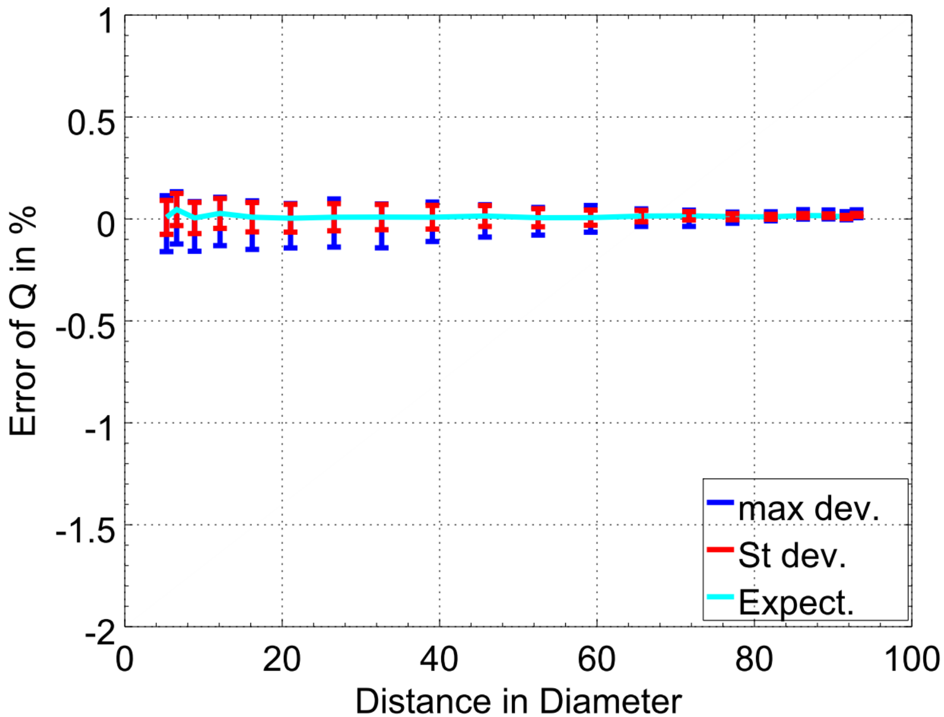
Sensitivity of an electromagnetic flow meter

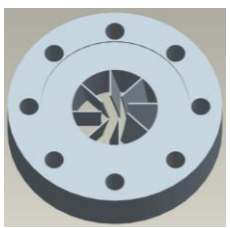


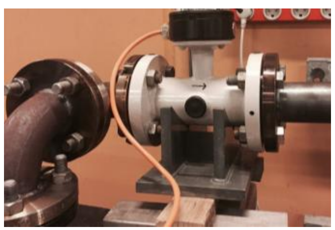
Venturi nozzle for flow conditioning







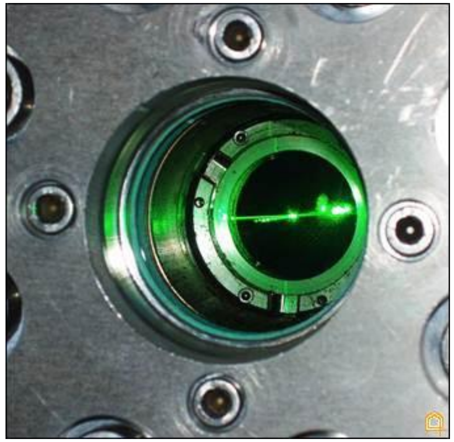




*Experimental data obtained by
J. B. Kondrup, FORCE
Technology, Denmark

In situ flow measurement with laser Doppler velocimetry (LDV)

drilling procedure certified for district heating applications (“hot tapping”)



contour-fitting window on the interior surface of the pipe

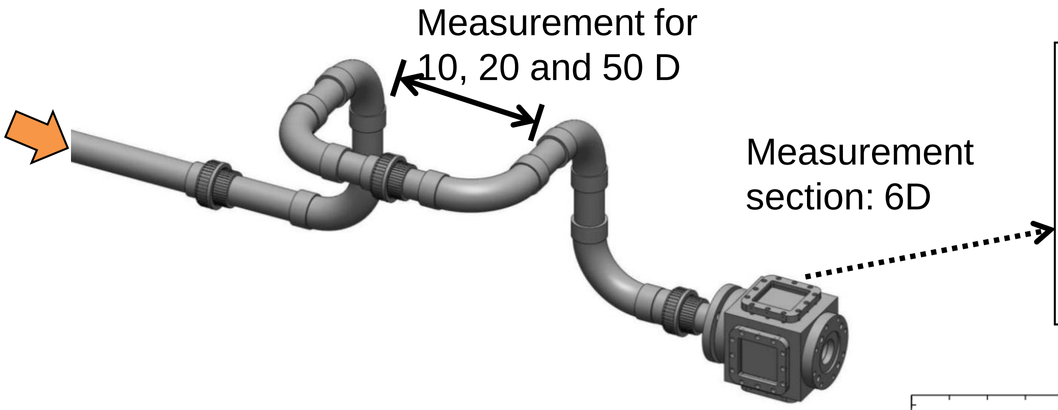
mobile Laser Doppler velocimeter

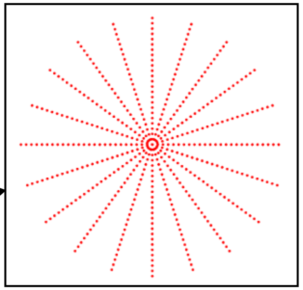
The flow rate is calculated by the integral of the axial velocity along a single path

$$Q_m = \pi \int_{-R}^{R} u\left(r\right) \left|r\right| \, dr$$

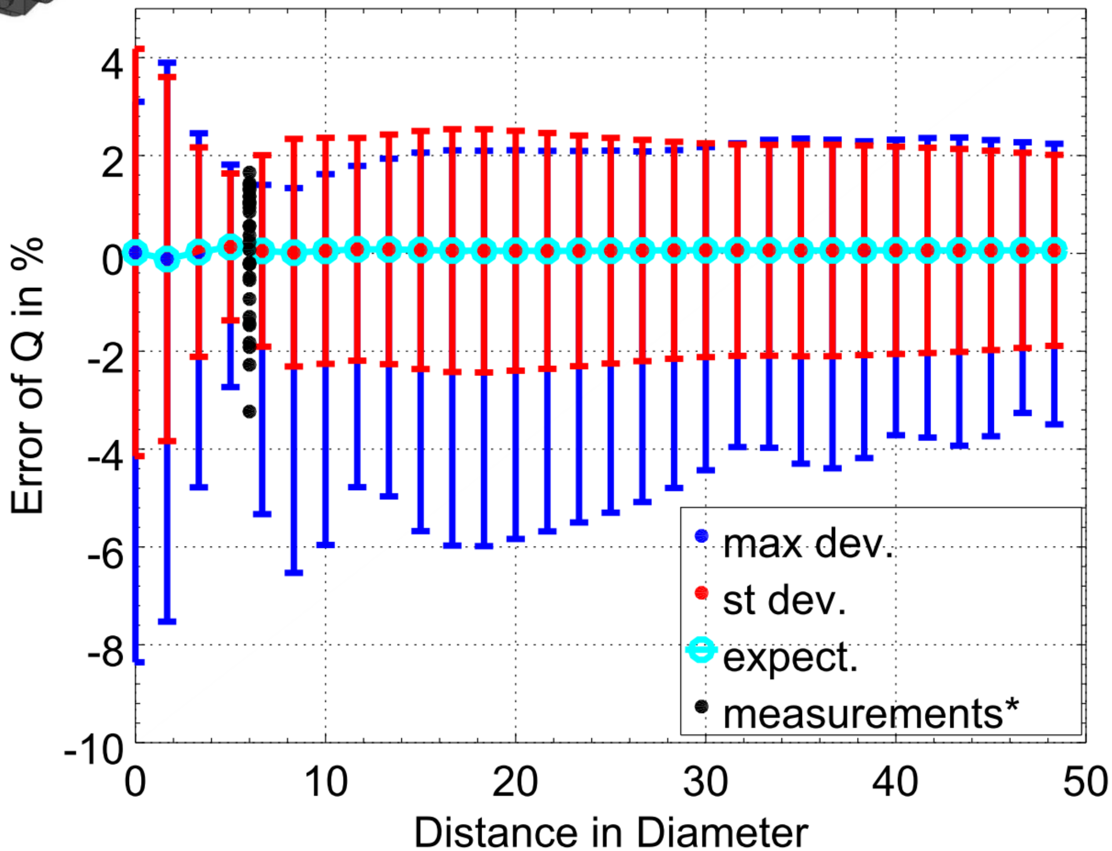
$$\text{Error in } \% = \varepsilon = \frac{100}{Q_{real}} \left(Q_m - Q_{real}\right)$$

Uncertainty of a laser Doppler velocimeter





Three measurements with each 10 path
for each path the flow rate is calculated



*Experimental data obtained by A. Swienty and Phillip Kretschmer, TU-Berlin, Department of Fluid System Dynamics

Conclusion

- Sensitivity of flow profiles behind double elbows out-of-plane was demonstrated
- Uncertainty of electromagnetic and ultrasonic flow meters can be quantified with simple RANS models
- A Venturi nozzle bring huge improvement for the measurement accuracy
- Uncertainty for single path laser Doppler measurements can be quantified

Publications:

- A. Weissenbrunner, A. Fiebach et. al, 2016, Simulation-based determination of systematic errors of flow meters due to uncertain inflow conditions, Flow Measurement and Instrumentation, http://dx.doi.org/10.1016/j.flowmeasinst.2016.07.011
- S. Schmelter, A. Fiebach, A. Weissenbrunner, 2016, Polynomchaos zur Unsicherheitsquantifizierung in Strömungssimulationen für metrologische Anwendungen, Technisches Messen 2016; 83(2): 71–76
- A. Weissenbrunner et. al, 2016, A coupled numerical and laser optical method for on-site calibration of flow meters in district heating, in preparation

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