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PTB Sommerschule 2009

Die Rolle präziser Durchflussmesstechnik für die Effizienzsteigerung beim Betrieb von Kraftwerken und Fernheiznetzen

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Braunschweig + Berlin

PTB : National Metrology Institute of Germany

PTB

Staff: 1800 Employees
600 staff scientists,
200 third party
funded scientists

Budget: 130 M€ / a

Sites: Braunschweig + Berlin

Founded: 1887
Hermann v. Helmholtz and
Werner v. Siemens

6 scientific sections in Braunschweig
2 scientific sections in Berlin

Department “Heat”

Department Heat: Staff + Tasks

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Legal Metrology

Conformity assessment / pattern approval for heat meters according to

- Measurement Instruments Directive / EichG / EO
- EN 1434
- OIML R75

80 % of all Heat Meters in Europe are approved by PTB

R&D Projects: Enhancing Energy-Efficiency in Power Plants / District Heating&Cooling Networks

a) Establish Traceability / Calibration for Ultra-Sonic Flow Meters used in Power plants / District Heating

b) Establish "On-Site" Fundamental Measurement methods in Power Plants / District Heating

Measurement capabilities: Flow

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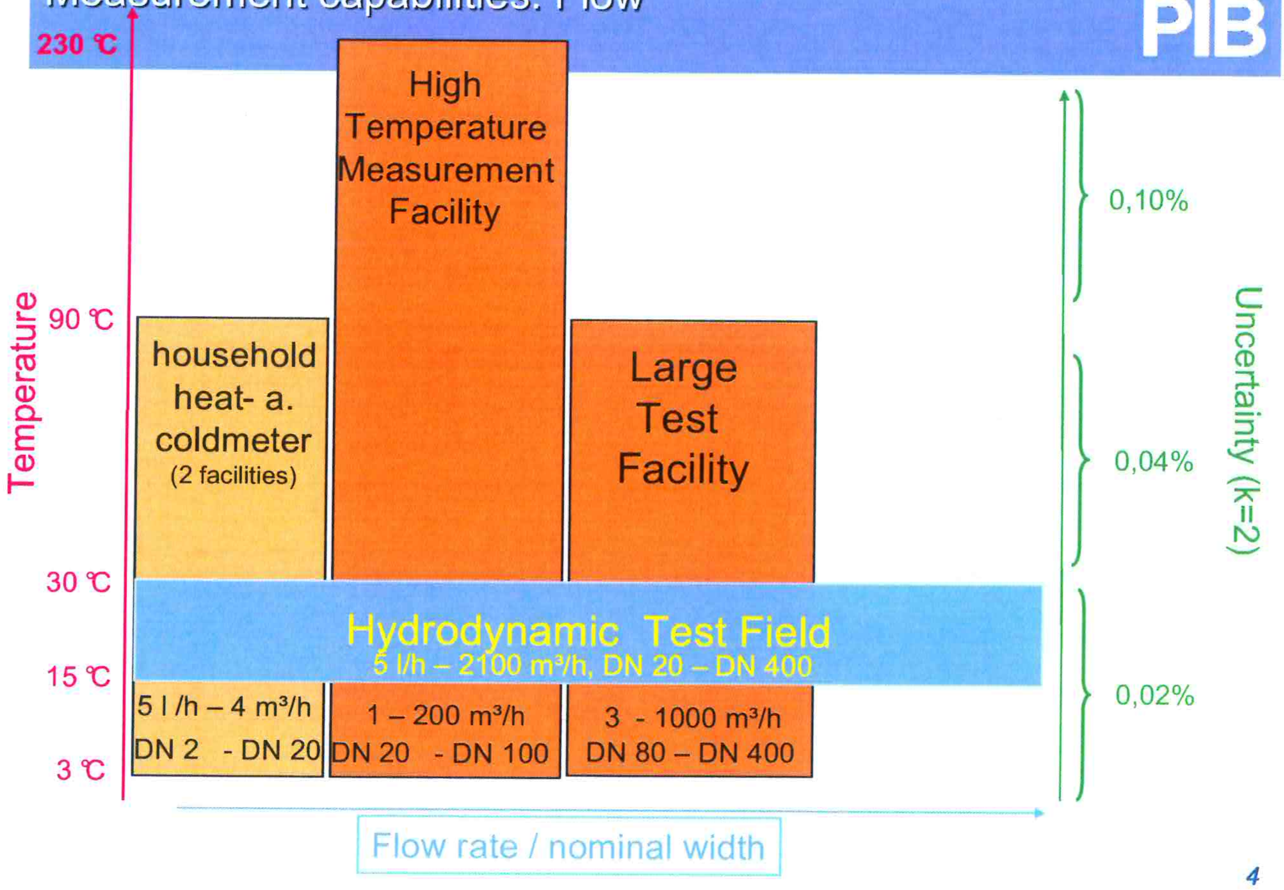
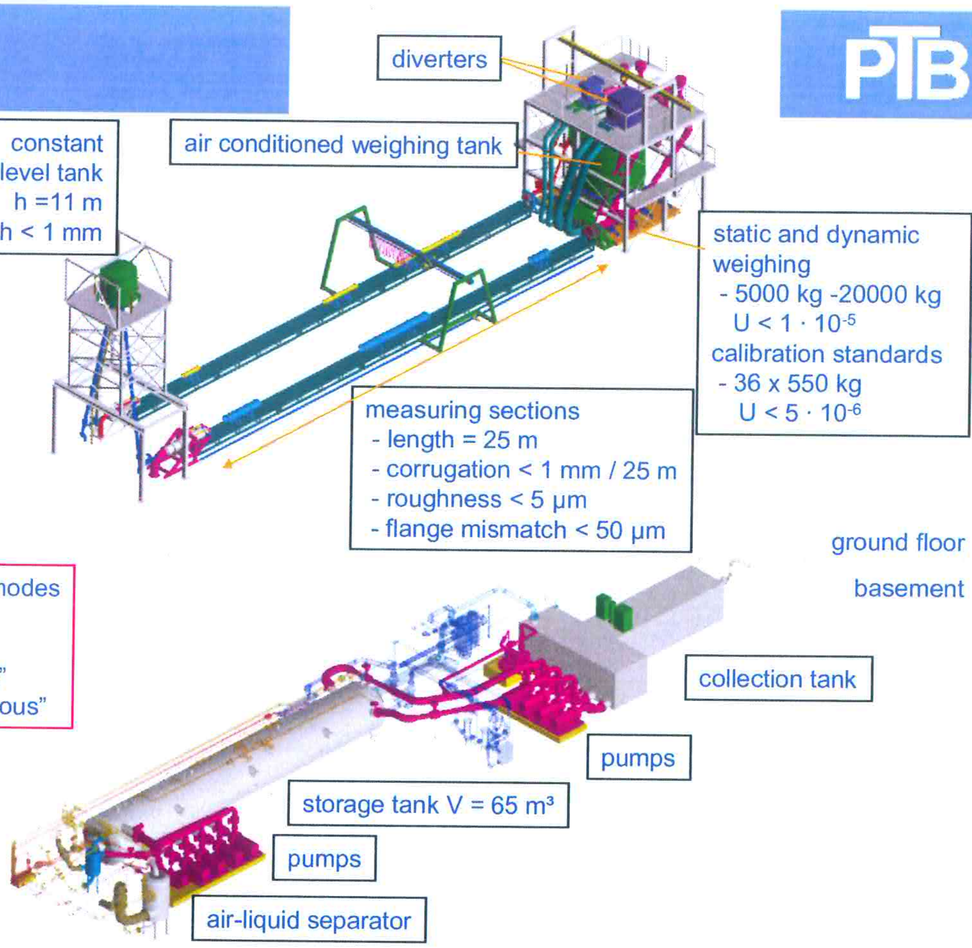


Large Test Facility

volume flowrate:
3 m³/h - 1000 m³/h
temperature range:
3 ℃ - 90 ℃
temperature drift:
< 50 mK/h
Reynold´s number:
< 5,5 · 10^6
measurement
uncertainty (k=2):
< 4· 10^{-4}



independent operation modes
- pumps
- constant level tank
- pressure-based “single”
- pressure based “continous”

Was wissen wir?

Durchfluss-Sensoren in Kraftwerken / Netzeinspeisungen / Übergabestationen

sind oft

- steinalt (Drift, Ablagerungen,…..)
- nicht wirklich kalibriert (z.B. 10 MW Grenze, Herstellerzertifikat / Prüfstellen: “kalte” Messung, “gute” Messbedingungen, ….)
- gar nicht rekalibriert
- falsch ausgelegt

und weisen Messfehler im Prozentbereich auf.

Trotzdem werden gerade diese Messgeräte verwendet, um
- Kraftwerke und Netze zu steuern
- KWK Förderung zu bekommen
- große Kunden abzurechnen

Status quo

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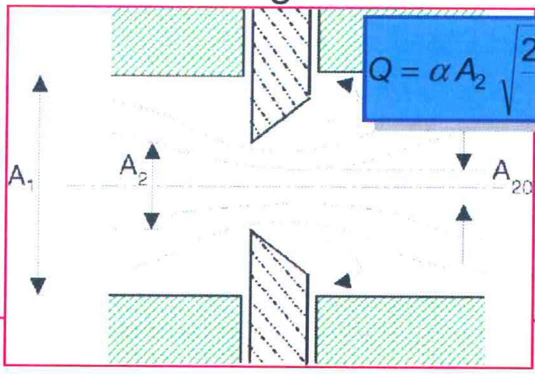
In Power Plants, mostly differential pressure devices used
- orifice plates
- ventouri tubes

Problems:
- nonlinear relation between measurement signal and flow - rate

- strong dependence of the measurement signal on
  - form
  - symmetry
  - turbulence of the flow

  (installation effects)

- drift (fouling effects)



$$Q = \alpha A_2 \sqrt{\frac{2\,(p_1 - p_2)}{\rho}}$$

Experimental counter actions I: "calibration"

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"calibration" - measurements of the devices using tube geometry identical to the installation in the power plant

idea: comparable fluid velocity distributions

but:
measurement performed at
- different temperatures (ambient instead of 280 °C)
- different pressures

correction / extrapolations necessary
- thermal and pressure related expansion
- viscosities, densities

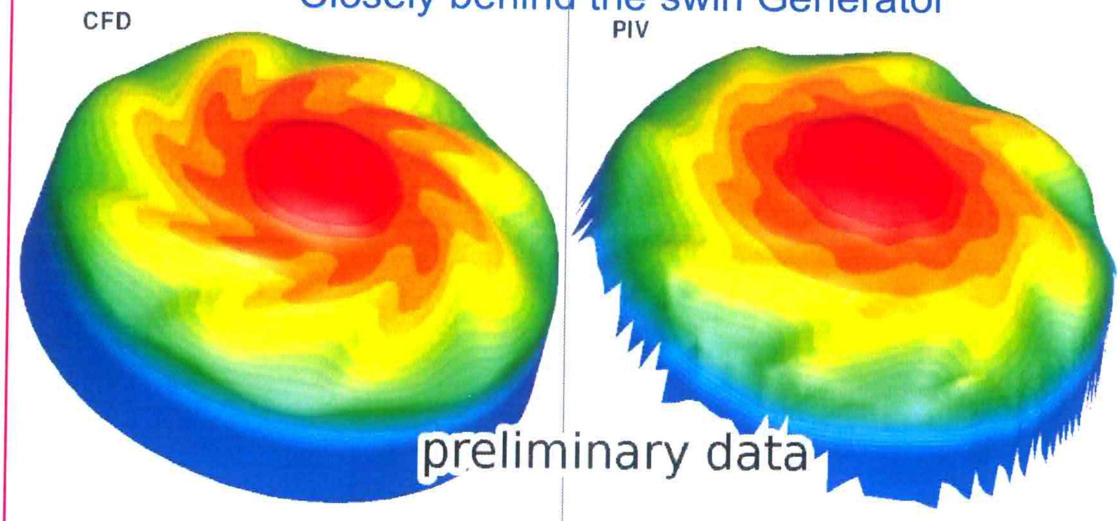
  (according to ISO-Standard 5167, based on Reynold´s "law" and other commonly used simple model equations)

Example: Axial velocity distribution in a swirl

Method:
Computational Fluid Dymanics (CFD) simulations verified with laseroptical (Particle Image Velocimetry: PIV) Measurements

Verification:

Closely behind the swirl Generator

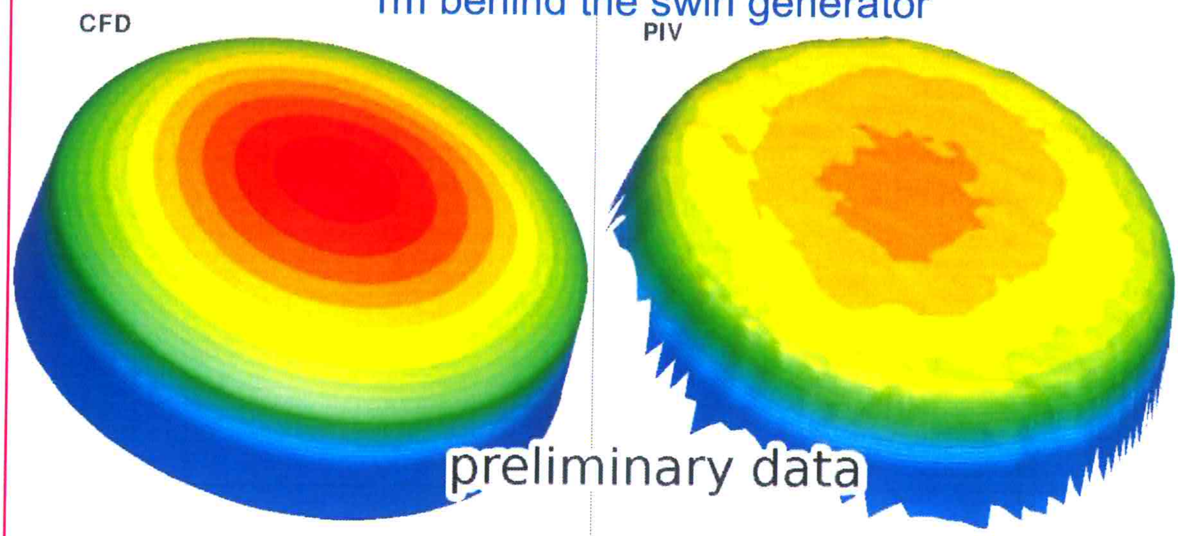


Example: Axial velocity distribution in a swirl

Method:
Computational Fluid Dymanics (CFD) simulations verified with laseroptical (Particle Image Velocimetry: PIV) Measurements

Verification:

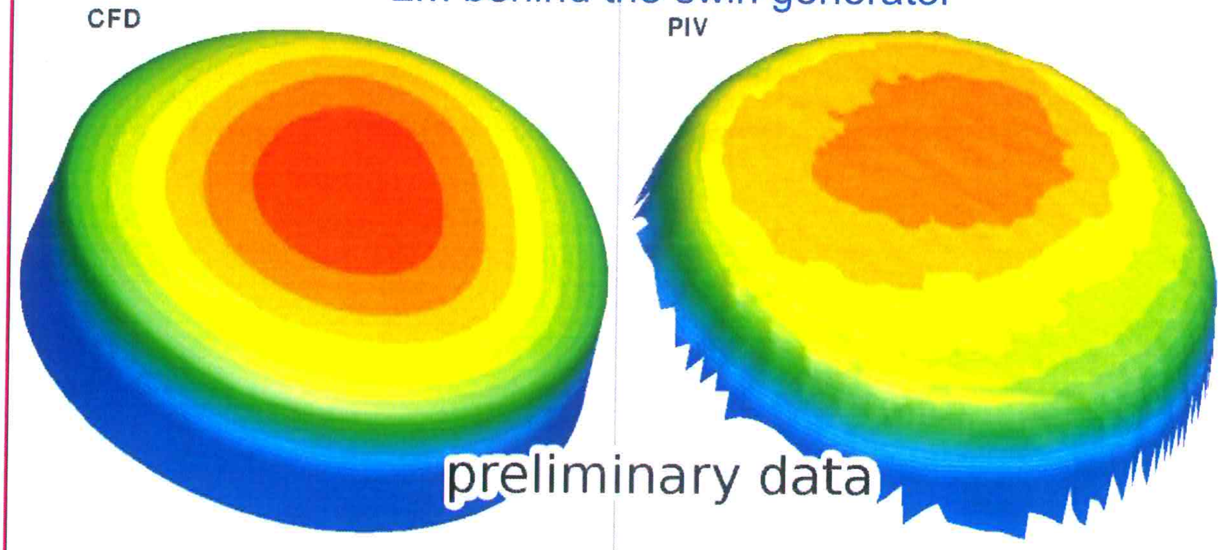
1m behind the swirl generator



Example: Axial velocity distribution in a swirl

Method:
Computational Fluid Dymanics (CFD) simulations verified with laseroptical (Particle Image Velocimetry: PIV) Measurements

Verification: 2m behind the swirl generator

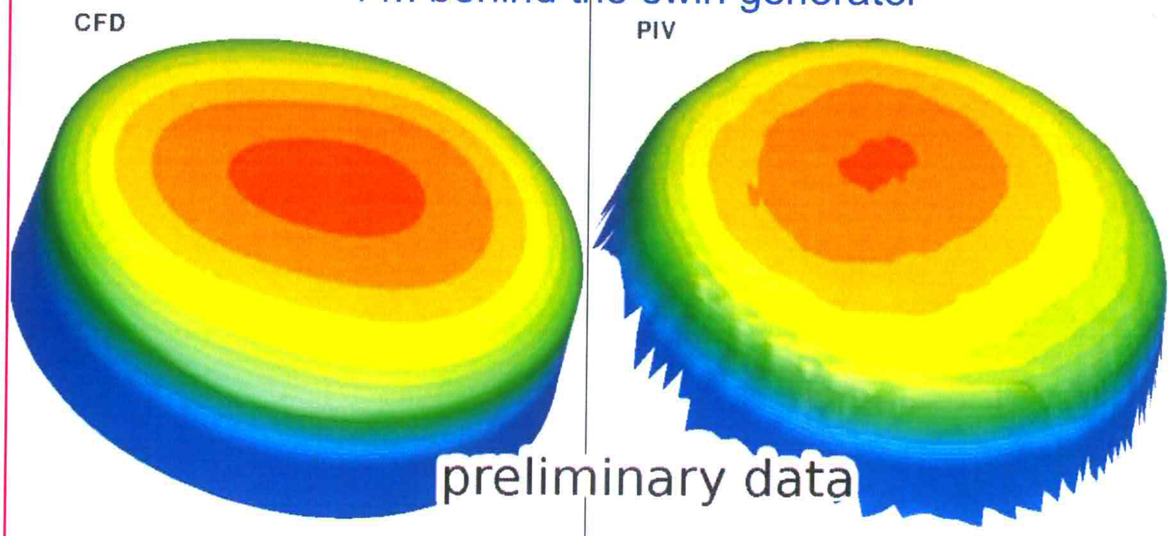


1

Example: Axial velocity distribution in a swirl

Method:
Computational Fluid Dymanics (CFD) simulations verified with laseroptical (Particle Image Velocimetry: PIV) Measurements

Verification: 4 m behind the swirl generator



2

Example: Axial velocity distribution in a swirl

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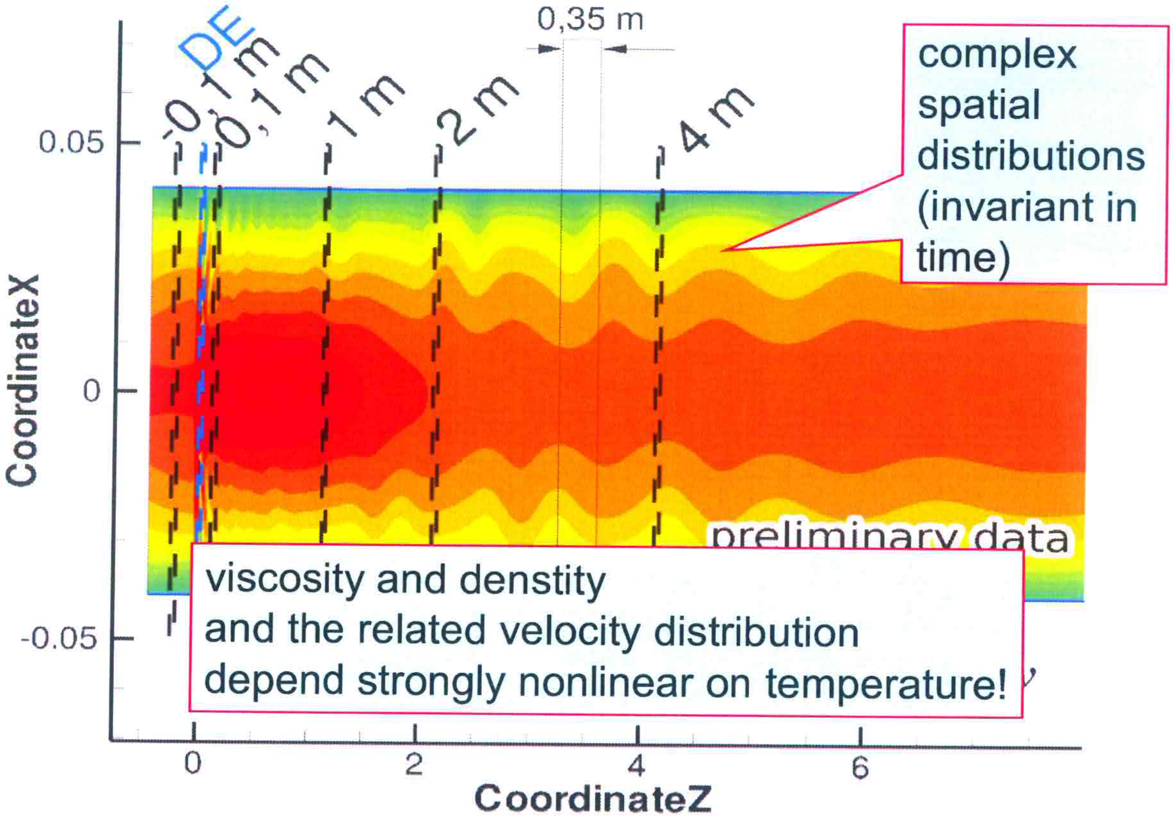

Experimental counter actions II: Clamp-on US

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Use of US clamp-on sensors to generate additional monitoring signals and then correct the drift (fouling) of the process meter

Idea: repeatability and long term stability of clamp-on US meters is "very good" (manufactorer´s opinion)

Best marketing idea

PTB´s experimental experiences with clamp-On US meters do not support manufactorer´s opinion

Aditionally:
Uncertainty of clamp-on systems much larger than the process meter

Therefore:
Metrologically questionable

Mathematical Counter Actions

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data monitoring / data reconsiliation / retrofit models based on VDI 2048:
„Uncertainties of measurements during acceptance tests on energy-conversion and power plants“

basic idea:
describe the power plant as a simple set of correlated mass and energy balancing equations

all the (mass) flow rate measurements correlate

all the measurements can be used:
better statisic → lower uncertainty ?

Concept of Determining Uncertainties

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Preconditions

1. Use of variances: statistical and unknown systematical contributions are treated identical
2. model equation exists , linearization possible

Model Equation:

$$y = f(x_1, x_2)$$

$$R = \frac{U}{i}$$

Combined Variance:

$$u_c^2(y) = \left(\frac{\partial f}{\partial x_1}\right)^2 u^2(x_1) + \left(\frac{\partial f}{\partial x_2}\right)^2 u^2(x_2) + 2\,\frac{\partial f}{\partial x_1}\frac{\partial f}{\partial x_2}\,u(x_1, x_2)$$

Covariance

Using sensitivity coefficients

$$u^2(y) = c_1^2\,u_1^2 + c_2^2\,u_2^2 + 2\,c_1\,c_2\,u(x_1, x_2)$$

$$u(x_1, x_2) = u(x_1)\,u(x_2)\,r(x_1, x_2)$$

Correlation coefficent
$-1 < r < 1$

Example

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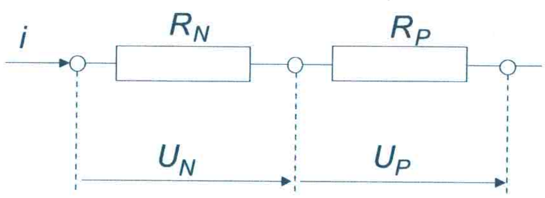
Measurement Setup



Model equation:

$$R_P = \frac{U_P}{i} = \frac{U_P}{U_N} R_N$$

Repeated Measurements →

$U_{P,0}$ ... Mean value: Voltage Resistance under Test = 0,1025 V
$U_{N,0}$ ... Mean value : Voltage Normal-Resistance = 0,1011 V

Combined Variance:

$$u_c^2(R_P) = c_{U_N}^2 u^2(U_N) + c_{U_P}^2 u^2(U_P) + c_{R_N}^2 u^2(R_N) + 2\, c_{U_N} c_{U_P} u(U_N, U_P)$$

Example

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Relative combined variance:

$$\frac{u_c^2(R_P)}{R_P^2} \approx \frac{u^2(U_N)}{U_N^2} + \frac{u^2(U_P)}{U_P^2} + \frac{u^2(R_N)}{R_N^2} - \frac{2\, u(U_N)\, u(U_P)\, r(U_N, U_P)}{U_N U_P}$$

Uncertainties $u(U_P)/U_P$ = 1.10-5 und $u(U_N)/U_N$ = 1.10-5

Normal-resistance: → calibration certificate: $u(R_N)/R_N$ = 2.10-6

Mean value of the unknown resistance: $R_{P,0}$ = 101,385 Ω

Results:

Relative uncertainty maximal for r = -1:

$$\frac{u_c(R_P)}{R_P} = 2{,}0.10^{-5}$$

No correlation taken into account:

$$\frac{u_c(R_P)}{R_P} = 1{,}4.10^{-5}$$

Minimum Value for r = +1

$$\frac{u_c(R_P)}{R_P} = 2.10^{-6}$$

How large is the correlation coefficient r in this special case ?

Empiric Covariance of x_1 und x_2:

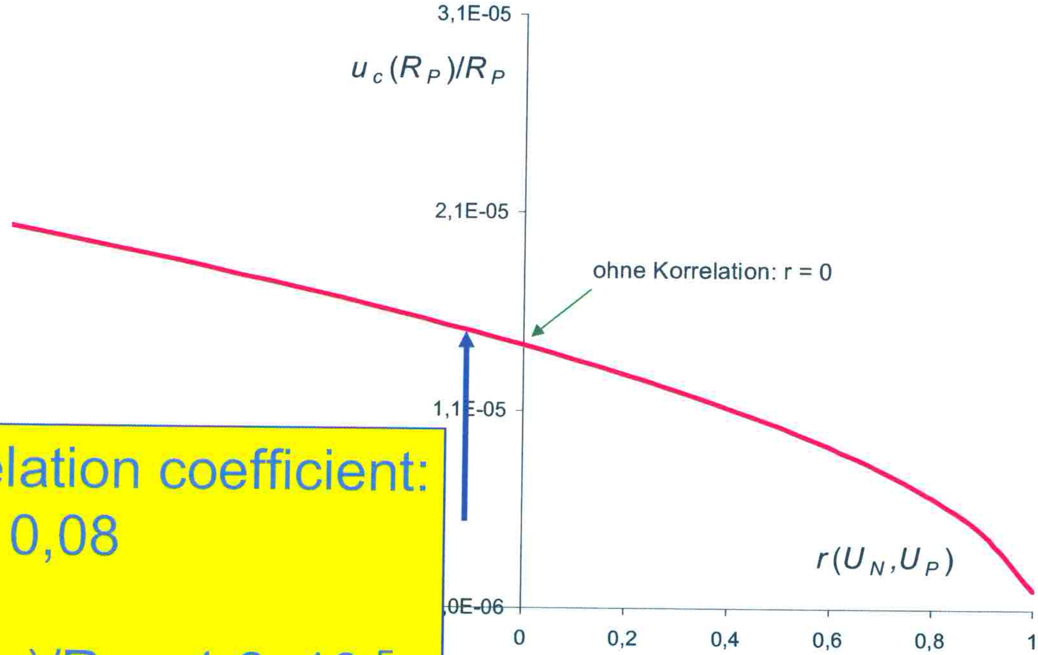
$$u(x_1, x_2) = \frac{1}{N(N-1)} \sum_{i=1}^{N} (x_{1i} - x_{10})(x_{2i} - x_{20})$$

Example:

$x_1 = U_P$
$x_2 = U_N$

Measurem.	x_1	x_2	$(x_{1i} - x_{1,0})$	$(x_{2i} - x_{2,0})$	$(x_{1i} - x_{1,0})*(x_{2i} - x_{2,0})$
1	0,1025	0,1008	2,0E-05	-2,9E-04	-5,8E-09
2	0,1023	0,1014	-1,8E-04	3,1E-04	-5,6E-08
3	0,1025	0,1009	2,0E-05	-1,9E-04	-3,8E-09
4	0,1029	0,1009	4,2E-04	-1,9E-04	-8,0E-08
5	0,1032	0,1008	7,2E-04	-2,9E-04	-2,1E-07
6	0,1026	0,1010	1,2E-04	-9,0E-05	-1,1E-08
7	0,1023	0,1012	-1,8E-04	1,1E-04	-2,0E-08
8	0,1022	0,1012	-2,8E-04	1,1E-04	-3,1E-08
9	0,1021	0,1013	-3,8E-04	2,1E-04	-8,0E-08
10	0,1022	0,1014	-2,8E-04	3,1E-04	-8,7E-08
MeanVal	0,1025	0,1011	1,1E-17	3,1E-17	
Variance	1,2E-07	5,7E-08			
StandDev.	3,5E-04	2,4E-04			
				Summe =	-5,82E-07
				$u(x_1,x_2)$= Kovarianz = -6,47E-09	
				Korrelationskoeffizient = -0,08	

combined uncertainty including real correlation



correlation coefficient:
r = - 0,08

$u_c(Rp)/R_p = 1,6 \cdot 10^{-5}$

Conclusions:

covariances contribute to measurement uncertainty

depending on the correlation coefficient
the combined measurement uncertainty is
enhanced or lowered

the statement:
more measurements ➡ better statistic ➡ lower uncertainty
is **not always valid**, if correlation is taken into account.

Application to measurements in power plants (according to VDI 2048)

same preconditions:

- concept of variances
- linearisation possible
- the model-equation exists and is true

addionally:

- steady state
- no periodic variation of measurement values in time

same procedure

more than 2 variables => use matrix calculation

results are valid
(however: uncertainty will be enhanced or lowered)

What about the the preconditions?

Investigation of preconditions

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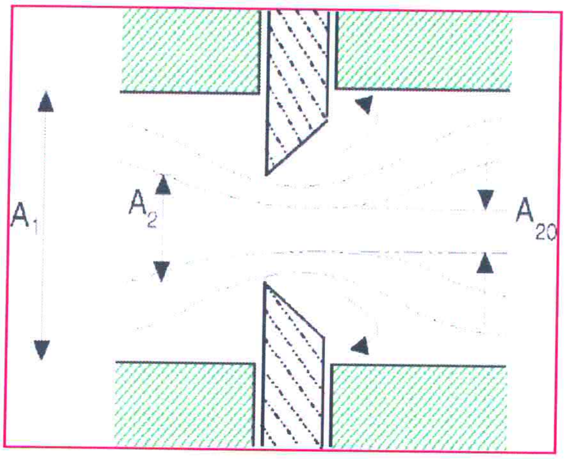
Concept of covariances: we dont have anything better

Linearization: the orifice plate as an example



Volume-Flowrate (m³/h)

$$Q = \alpha A_2 \sqrt{\frac{2(p_1 - p_2)}{\rho}}$$

not linear
large dynamic range for Δp-measurement
large temperature dependence of viscosity, density
strong installation effects

Model equation:
no full thermodynamic model of the measurement processes exist
only a set of simple equations related with mass- and energy conservation

Conclusion

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Correlation methods give correct results (lower or enhance uncertainty) if:

- model of process correct
- preconditions are met

Effectiveness for data monitoring :
Final remarks of the VDI 2048:
„ … it has been shown, how serious errors can be revealed by correction calculation and how contradicions can be eliminated… “

leakage

drift of a sensor

Effectiveness for data reconsiliation / retrofit measures
method is overstressed: dangerous (personal opinion)

Also: Gegenmaßnahmen

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Prozess-Messgeräte bei „richtigen“ Durchflüssen und Geometrien, aber bei „falschen“ Temperaturen und Drücken „kalibrieren“

gute Idee, Extrapolation auf Prozessbedingungen aber sehr viel komplexer als in den Normen vorgeschlagen

Clamp-On Sensoren als Monitorsignal oder zur „Vor-Ort-Kalibrierung“ einsetzen

Metrologisch fragwürdig

Fehler „wegrechnen“

Geht nicht

Das heißt:

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- Kraftwerke und Netze effizient steuern
- KWK Förderung einfordern
- Abrechnungen korrekt durchführen

erfordert Messgeräte,

die unter Prozessbedingungen kalibriert bzw. rückgeführt sind

Kalibrierung auf „passendem“ Prüfstand (Durchfluss, Temperatur Geometrie)	Kalibrierung komponentenweise auf „fast passenden“ Prüfständen, metrologisch valide Exptrapolation	Kalibrierung vor Ort Durchfluss, Temperatur Geometrie)

Plan A

Plan B

Plan A

Plan A: Direct calibration (at least for feedwater flow meters)

Build up test facility (international primary standard):

volume flow-rate range:	3000 m^3/h < Q < 7000 m^3/h,
temperature:	T ~ 300 °C
pressure:	p ~ 200 bar
traceable to SI:	optical methods (U < 0,1 %)

operation model: public private partnership

investment: 20 Mio. €

business plan: exists

rentability: yes

Plan B

New High Temperature test facility
(Q=200 m^3/h, T = 3 °C ... 230°C)

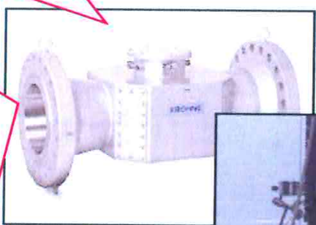
Selected input-variable traceability **in PTB-Labs**:
- metrological secured expralolation methods

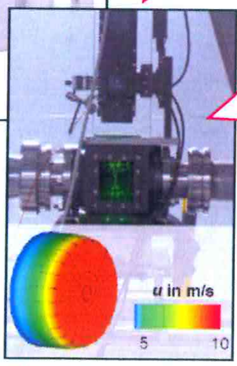
fundamental measurements **in situ**
- laser measurement techniques

R&D Projects

flow profile measurement and simulation in US-sensors

temperature-effect measurement and modelling in US-Sensors





R&D Projects
- Laser Flow measurement without sevice interruption
- combination laser and process-measurement techniques