Instrumentation and Sensors for CSP Performance Testing

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Overview

1. Motivation
2. Measurement Approaches in a Parabolic Trough Plant
3. Description of Clamp-On Systems
   I. Temperature
   II. Mass Flow Rate
4. Application of Dynamic Performance Model (PDPM) in Andasol Loop
   I. Parameterization
   II. Validation
5. PDPM approach for solar field or subfields

1. Motivation
Quantities to Measure for Thermal Performance

$$\eta_{th} = \frac{\dot{Q}_{th}}{\dot{Q}_{Solar}} = \frac{\boxed{\dot{m}} \cdot \boxed{c_p} \boxed{\left(T_{\mathrm{out}} - T_{\mathrm{in}}\right)}}{\boxed{A_{\mathrm{net}}} \cdot \boxed{E_{\mathrm{b}}} \cdot \boxed{\cos(\theta)} \cdot \boxed{\chi^{3/2}}}$$

2. Measurement approaches

Measurement Approaches:

(i) Standard plant instrumentation

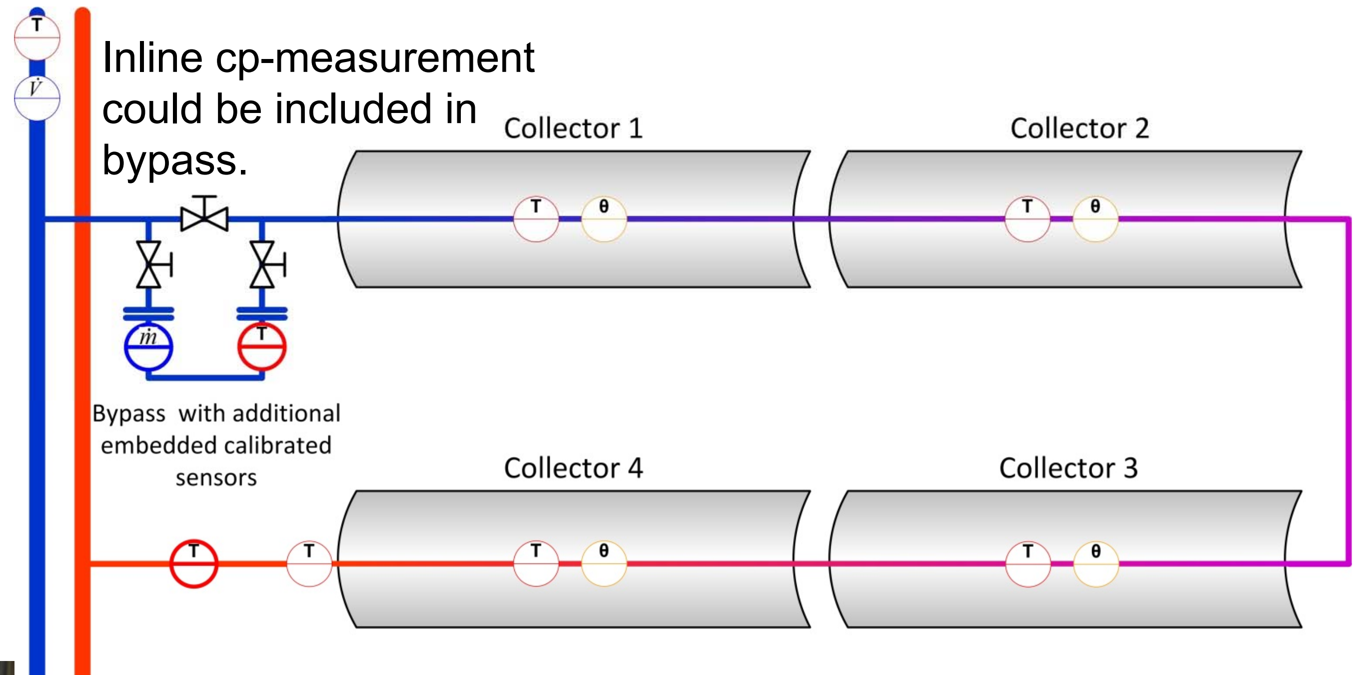
(ii) Embedded calibrated instrumentation

(iii) Mobile heat unit with instrumentation and BOP

(iv) Bypass with calibrated instrumentation

(v) Mobile field laboratory ("Clamp On")

2. Measurement approaches (iv)
Bypass (recommended)



Pro
+ High measurement accuracy
+ Mounting effort (if loop prepared for bypass use)
+ Data independence

Contra
- Flexibility
- Mounting effort / Leakage risk (if loop not prepared for bypass use)

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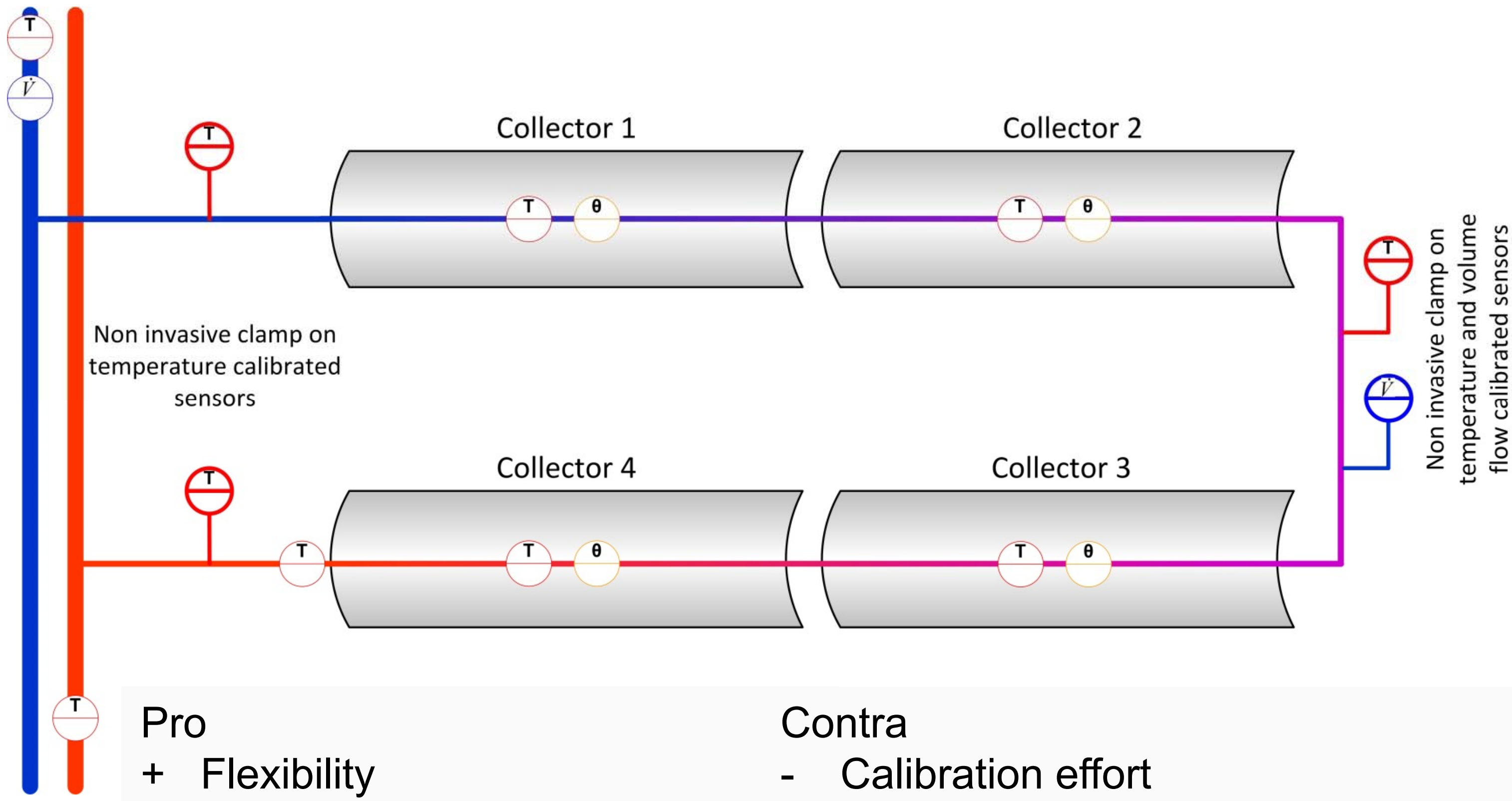
2. Measurement approaches (v)

Mobile field laboratory (recommended if no bypass flanges)



Pro
+ Flexibility
+ Measurement accuracy
+ No interference with plant operation
+ Data independence

Contra
- Calibration effort
- Mounting effort (Time-consuming)

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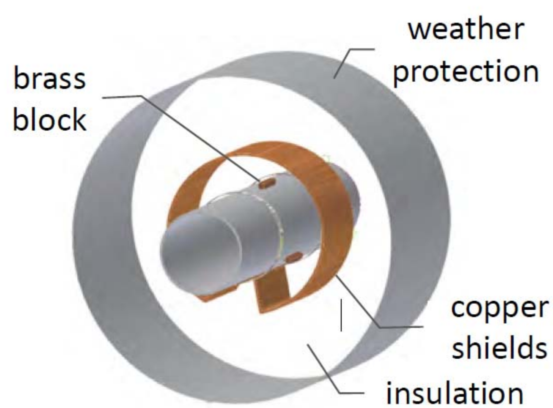
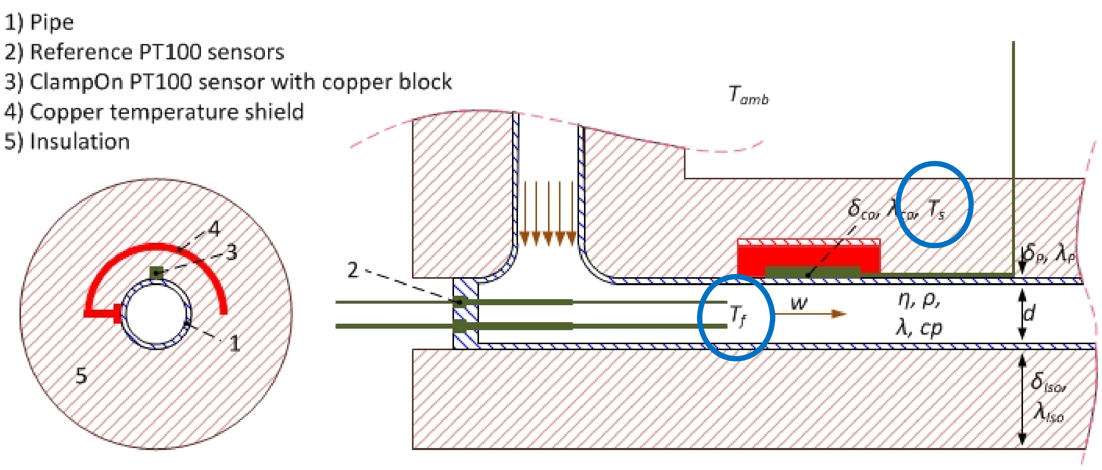
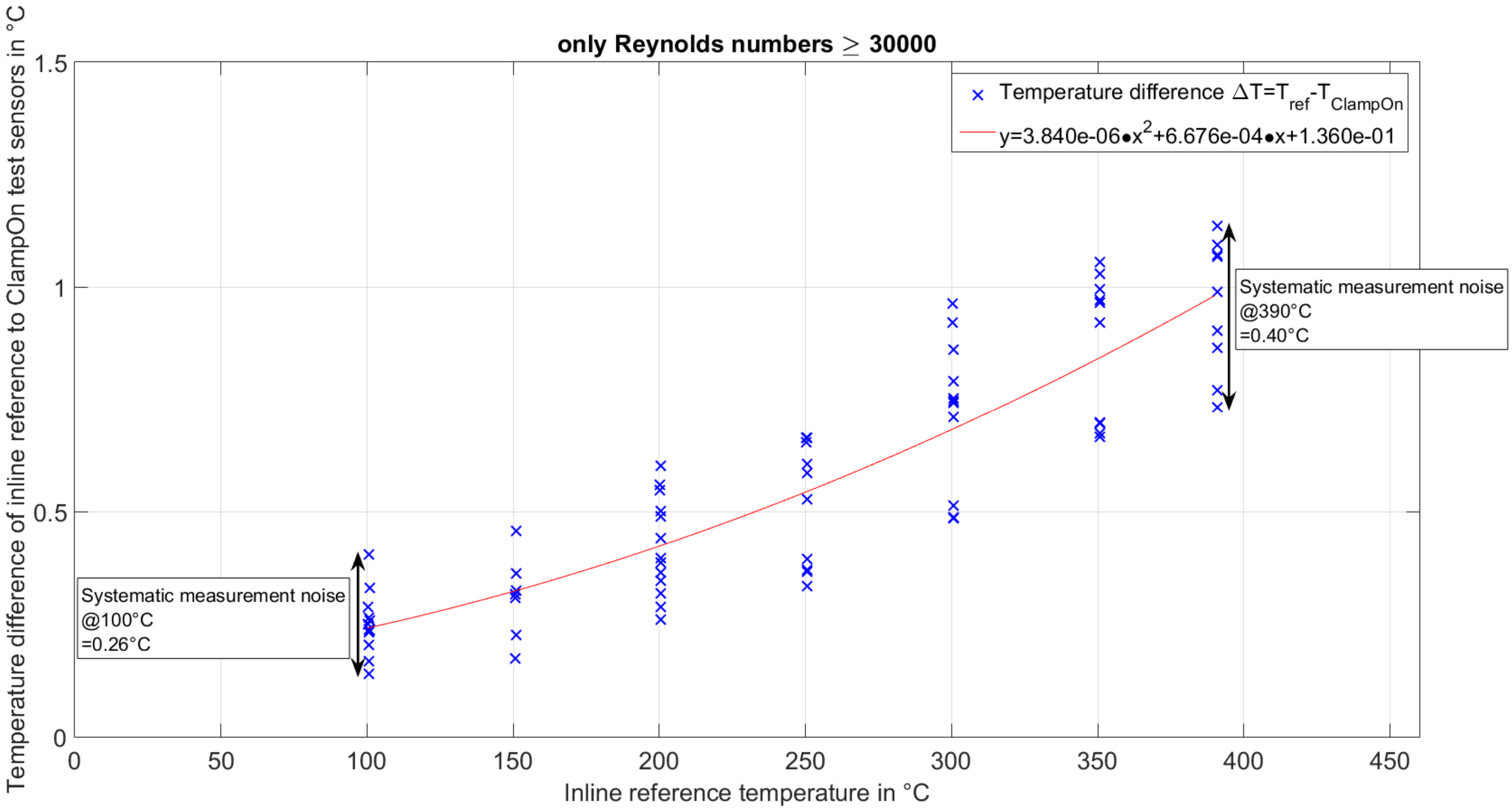
3. Clamp-On: Temperature





- Class-A Pt100 with 4 wire connection
- Good thermal coupling realized through brass block, thermal conductive paste and hose clamps (torque 15 Nm)
- Homogenized temperature in the direct environment of the sensor via brass block
- Reduction of environmental influences through copper shield and insulation

3. Clamp-On: Temperature
Temperature Diff. between Inline and ClampOn (uncorrected)



3. Clamp-On: Temperature

Remaining Uncertainty of ClampOn Temperature Measurem. After Correction

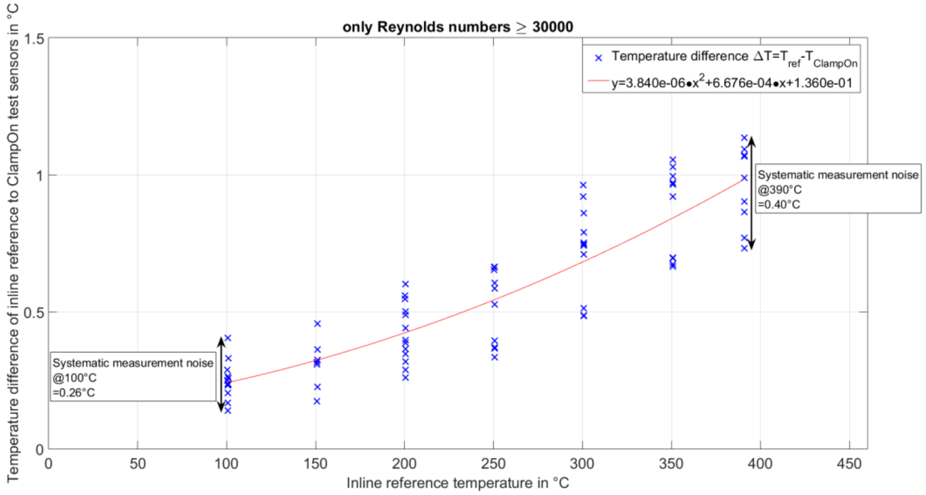
2x

Inline Reference T_{ref} 2xPT100 redundant measurement of T_fluid	**Uncertainty (T_{ref})**	**ClampOn $T_{CO,w/}$** with correction	**Uncertainty ($T_{CO,w/}$)** incl. systematic uncertainty of ClampOn method
100.67 °C	±0.16° K	100.72 °C	±0.34° K
150.83 °C	±0.18° K	150.61 °C	±0.43° K
200.45 °C	±0.21° K	200.19 °C	±0.49° K
250.52 °C	±0.26° K	250.22 °C	±0.50° K
300.58 °C	±0.28° K	300.81 °C	±0.54° K
350.78 °C	±0.31° K	350.55 °C	±0.60° K
390.95 °C	±0.33° K	390.78 °C	±0.62° K

- Uncertainty of ClampOn measurement is only doubled compared to inline PT100
- Uncertainty of ClampOn-measurement technique remain below 0.6 K.

3. Clamp-On: Temperature

Temperature Correction ClampOn

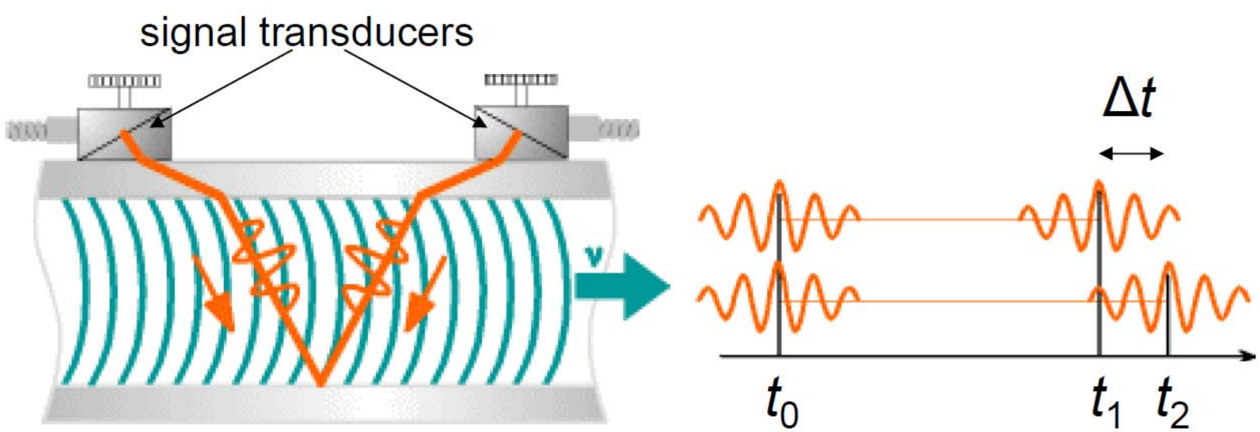


- Correction reduces uncertainty significantly
- Dimensionless approach is being developed to correct clampOn temperature also for other fluids and ambient conditions
  Correction $\Delta\Theta_{P\text{-}f}$

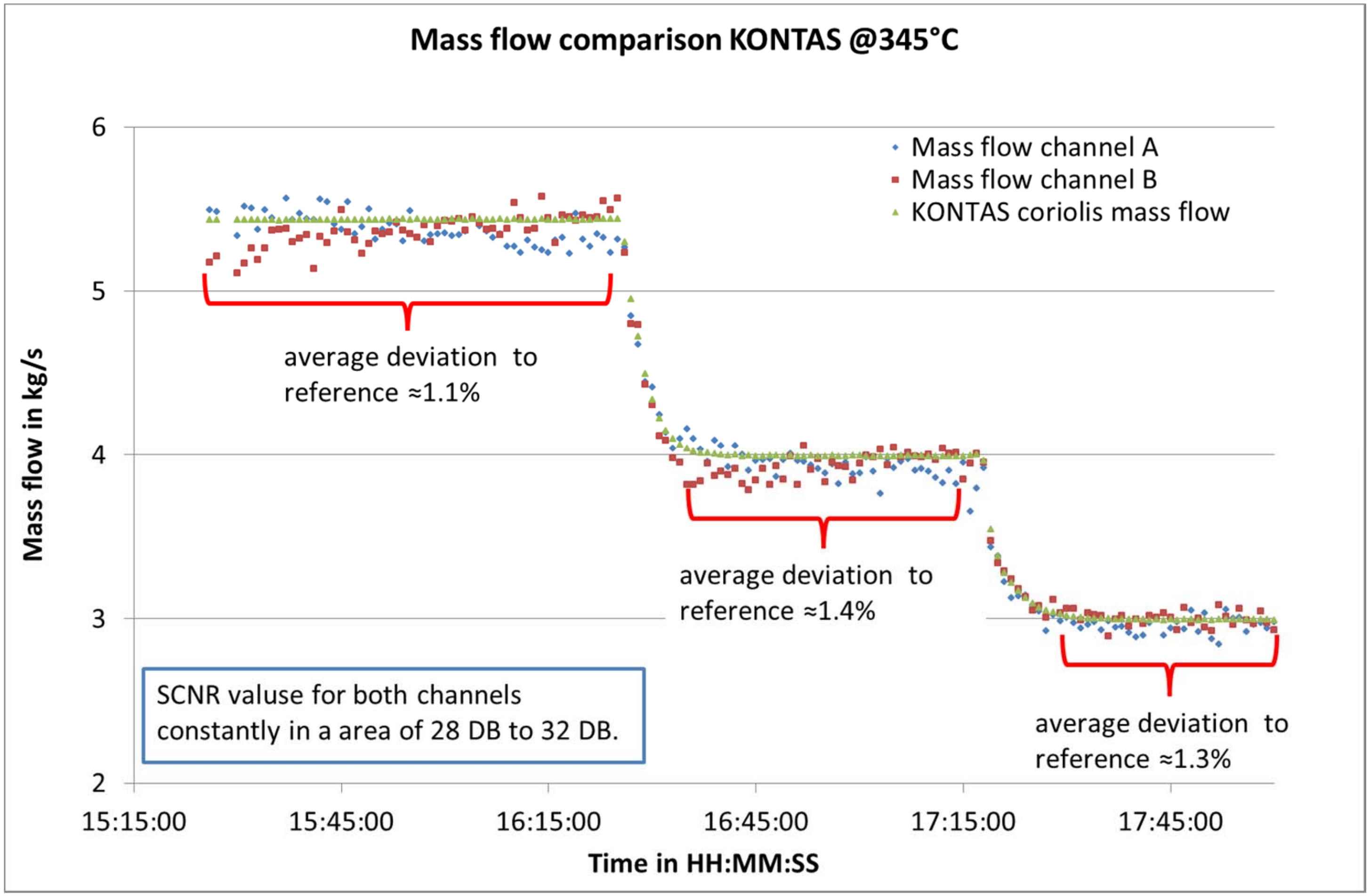
$$\Delta\Theta_{P-f} = a_1 \cdot (Re + dm)^m \cdot (Pr + dn)^n \cdot \left(\Delta\Theta_{f-amb}\right)^p \cdot (Bi + dq)^q \cdot \left(\lambda_{Iso}/\lambda_f\right)^s \cdot (\delta_P/d_i)^u \cdot (\delta_{Iso}/d_i + dv)^v$$

3. Clamp-On: Volume Flow

- Fluid flow measured via travel time differences of ultrasonic signals
- Ultrasonic signal is acoustically coupled to the pipe
- For T>200° C: Sensor heads thermally decoupled via wave injector from pipe
- Pipe geometry and material properties (pipe and HTF) included in calculation

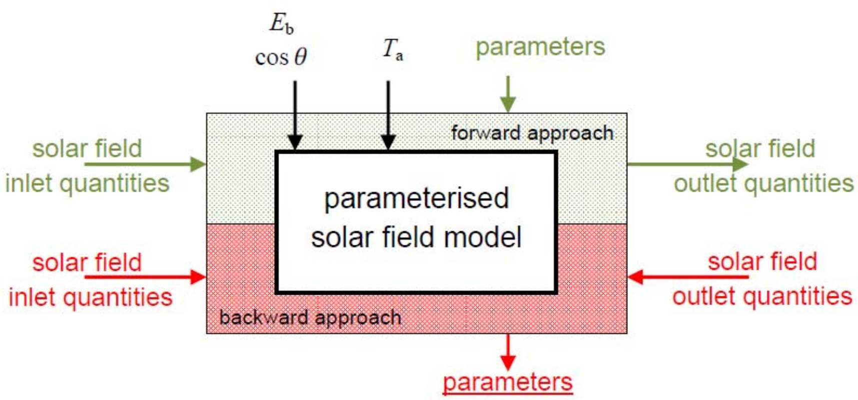


3. Clamp-On: Volume Flow/ Mass Flow



- Uncertainty of ultrasonic mass flow measurement remain 1.4% of mass flow rate

4. Parameterized Dynamic Performance Model (PDPM)
applied in Andasol Loop



Modelling approach for parameter identification from test data for field performance prediction for given field parameters and ambient conditions.

$$\dot{Q}_{th} = \chi^{3/2}\cdot A_{net}\cdot E_b\cdot\cos(\theta)\boxed{\eta_{opt,0}}\cdot\kappa(\theta)\cdot f_{endloss}\cdot f_{shade}\cdot f_{focus} - \boxed{c_1}\cdot(T_m - T_{amb}) - \boxed{c_2}\cdot(T_m - T_{amb})^2 - \boxed{c_3}\frac{dT_m}{dt}$$

with

$$\kappa(\theta) = 1 - \boxed{b_1}\theta - \boxed{b_2}\theta^2$$

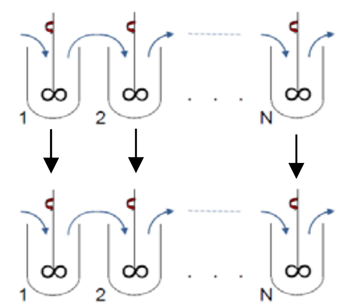
Residence time effects are considered through a CSTR model (continuous stirred tank reactor)

Perfect mixing of fluid in each tank is assumed

coefficients	definition
$\eta_{opt,0}$	optical efficiency
b_1, b_2	IAM coefficients
c_1, c_2	thermal loss coefficients
c_3	specific heat capacity coefficient

Time stamp i-1

Time stamp i



$$m_i^j = (m_{i-1}^j - \Delta m_{i-1}^j) + \Delta m_i^{j-1}$$

$$h_i^j = \frac{m_{i-1}^j h_{i-1}^j + \Delta m_i^{j-1} h_i^{j-1}}{m_i^j}$$

$$T_i^j = f(h_i^j), \quad \rho_i^j = g(h_i^j)$$

$$\Delta m_i^j = \rho_i^j \cdot V_i$$

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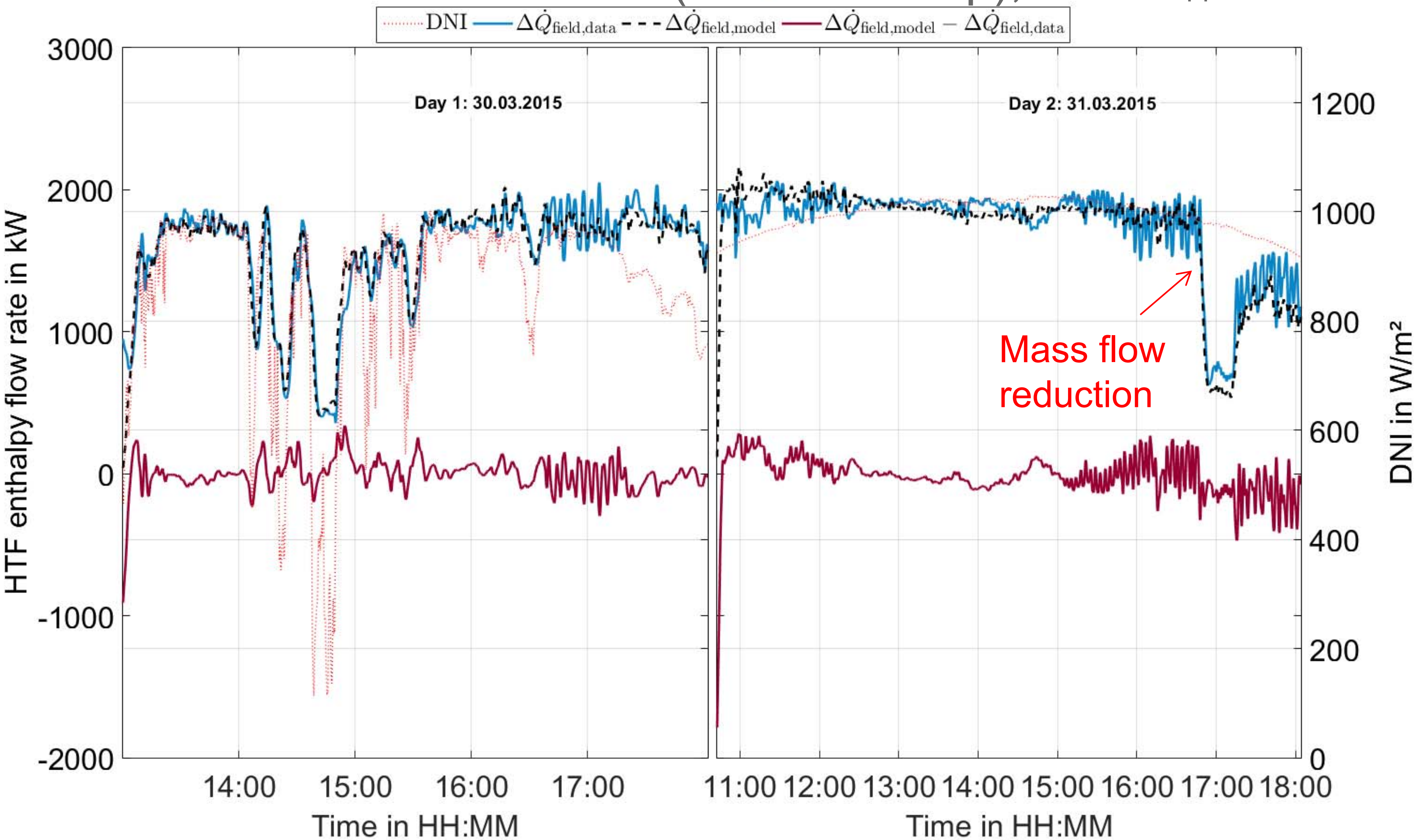
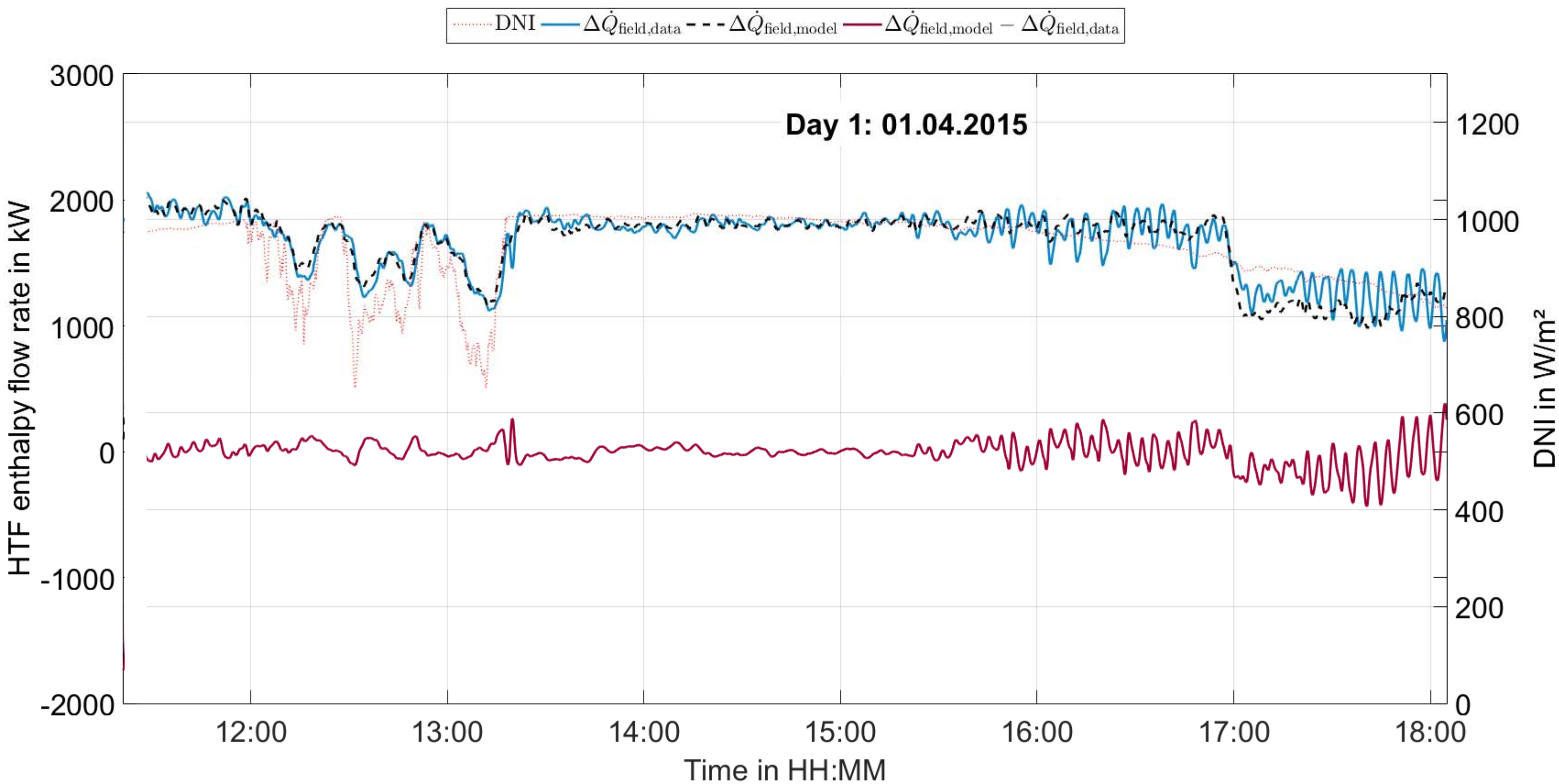
4. Parameterized Dynamic Performance Model (PDPM)

Parameterization Data Set (Andasol Loop), backward approach



4. Parameterized Dynamic Performance Model (PDPM)

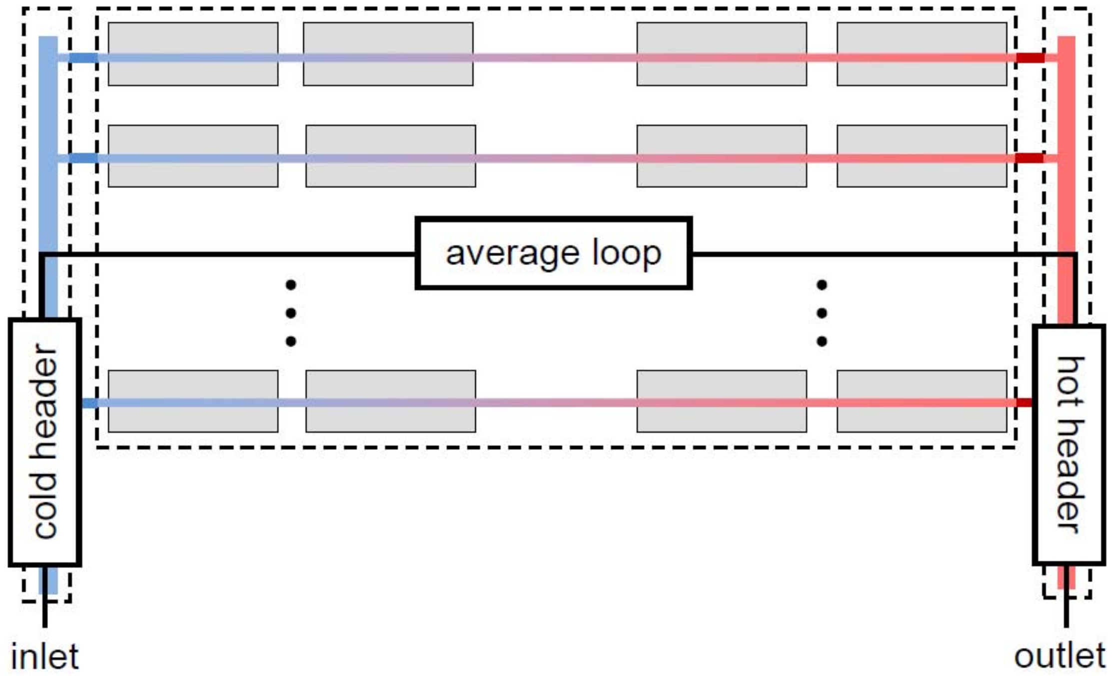
Validation Data Set (Andasol Loop), forward approach



- Independant validation data set which was not used to identify parameters
- Good agreement: Deviation in integrated enthapy flow over plotted period: ~0.4%

5. PDPM approach for solar field or subfields

- Condensing all parallel loops into one average loop
- Only overall performance characteristics, no individual loop characteristics
- Target quantity: Thermal power of solar subfield, not of indivdual loops



THANK YOU

for your attention.

THANK YOU

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