

Simple and Precise Calorimetry Method for Evaluation of Losses in Power Electronic Converters

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Review of Losses Measurement Techniques

Presentation of the Calorimeter

Performance Evaluation

Measurement of Converter Losses

Conclusions

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The problem with measuring losses

- ▶ **Converters are efficient**

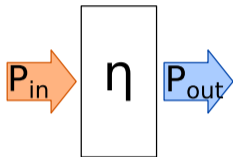
- ▶ 98 – 99 % efficiency common
- ▶ $\frac{P_{in}-P_{out}}{P_{in}}$ very inaccurate as $P_{in} \approx P_{out}$
- ▶ P_{in} or P_{out} may be difficult to measure if not dc or if large EMI

- ▶ **They can be complex**

- ▶ The opposition method requires 2 converters
- ▶ This complicates their control

- ▶ **They become smaller and smaller**

- ▶ Power density increases
- ▶ Losses cannot be neglected even though η increases.



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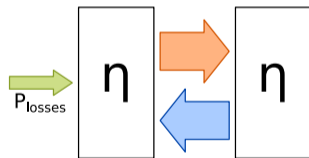
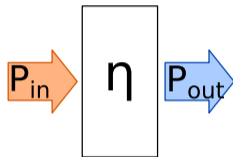
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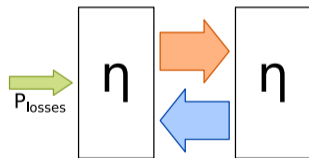
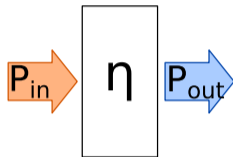
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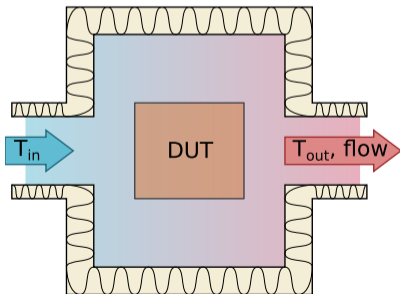


Calorimetry

Flow calorimeter

- + Allow for continuous operation
- monitoring of 2 temperatures, 1 flowrate
- more complicated to design and run

$$P = \Delta T C_p \dot{m}$$

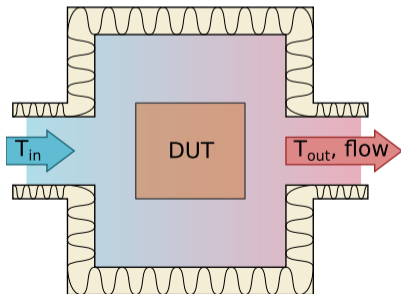


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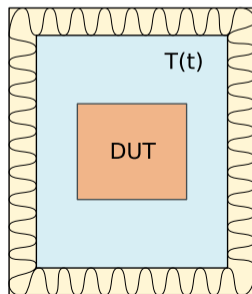
$$P = \Delta TC_p \dot{m}$$



Adiabatic calorimeter

- Only short-time operation
- + Monitoring of a single temperature
- + Very simple detail (in basic version)

$$P = \frac{\Delta TC_{Th}}{t}$$



Review of Losses Measurement Techniques

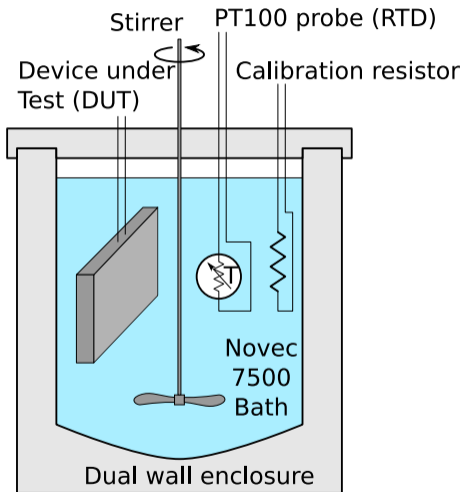
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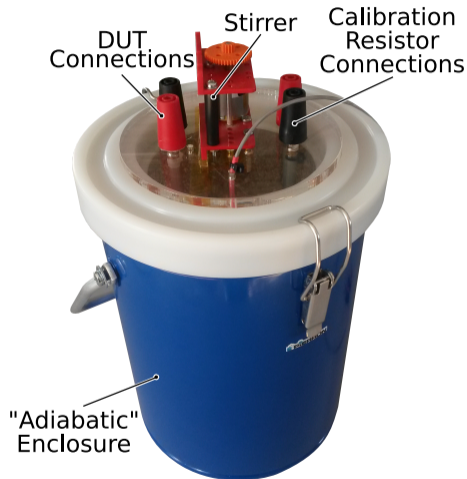
Conclusions

General view



- ▶ Adiabatic calorimeter (simple design)
 - ▶ Dewar jar with plastic lid
 - ▶ Not perfectly adiabatic
- ▶ Heat collected by a liquid
- ▶ external dimensions: $\Phi = 170 \text{ mm}$, $h = 215 \text{ mm}$
- ▶ volume *approx* 700 mL

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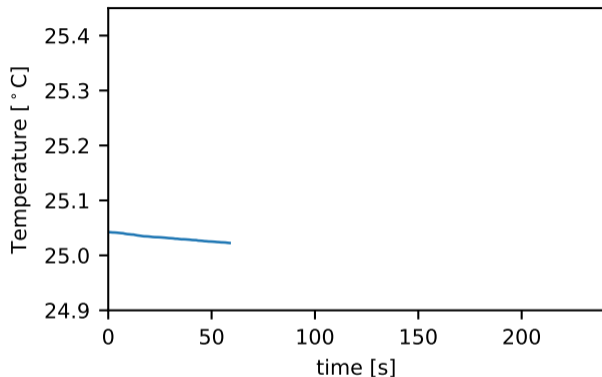
Selection of the Fluid

	DI Water	Fluorinert FC-40 (3M)	Novec 7500 (3M)
resistivity ($\Omega \cdot \text{cm}$)	1.8×10^7	1×10^{15}	2.2×10^8
GWP	-	> 9000	90
toxicity	none	low	low
residues	none	none	none
spec. heat ($\text{kJ} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$)	4.2	1.1	1.1
boiling point ($^{\circ}\text{C}$)	100	165	128

- ▶ Many fluids can be used: transformer oil, vegetable oil, fluorinert. . .
- ▶ Novec 7500 is used here because of low toxicity, low GDP
- ▶ Chemically compatible with electronics, dries without residues.

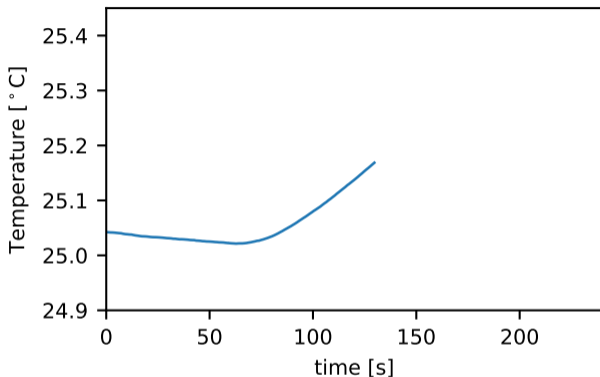
Measurement Principle

- ▶ First stage: no power dissipation
 - ▶ Temp. slope depends on $T_{bath} - T_A$
- ▶ Second stage: power P dissipated
 - ▶ Over set duration t
- ▶ Third stage: no power dissipation
 - ▶ Transient until bath temp. is uniform
 - ▶ Stabilization comparable to first stage
- ▶ ΔT is extracted from measurement



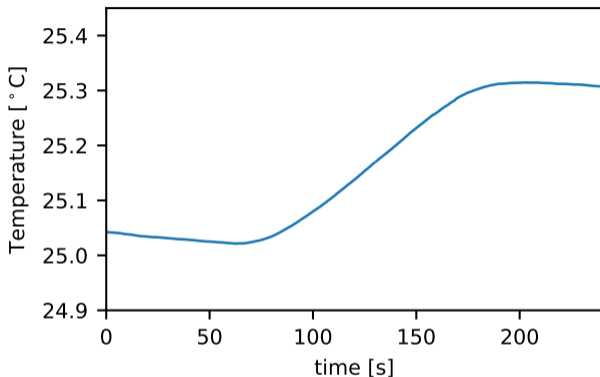
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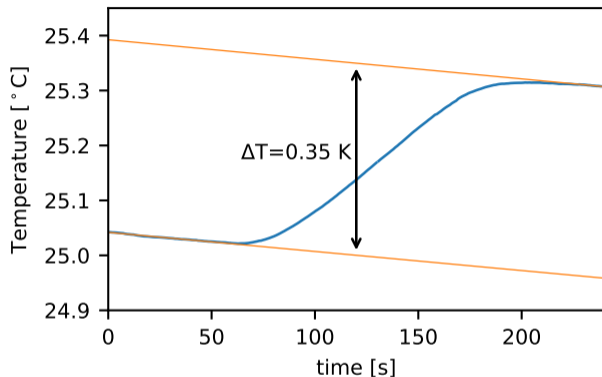
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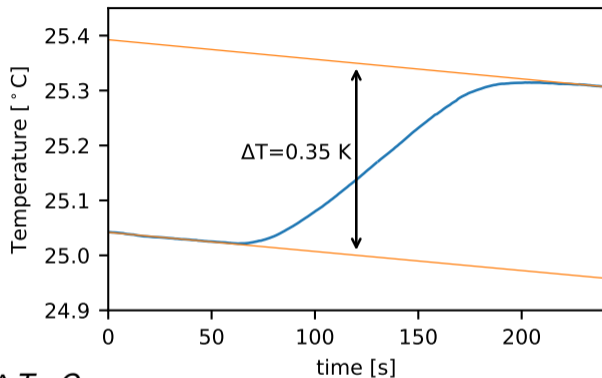
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$$P = \frac{\Delta T \cdot C_{Th}}{t} \quad (1)$$

Calibration: P known (dc resistor), C_{Th} calculated

Measurement: C_{Th} known (dc resistor), P calculated

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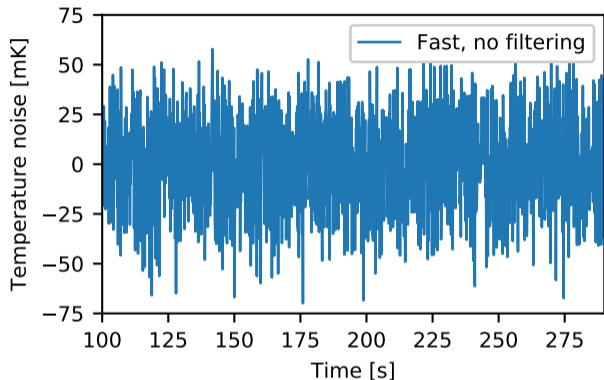
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Temperature Measurement Resolution

Acquisition chain

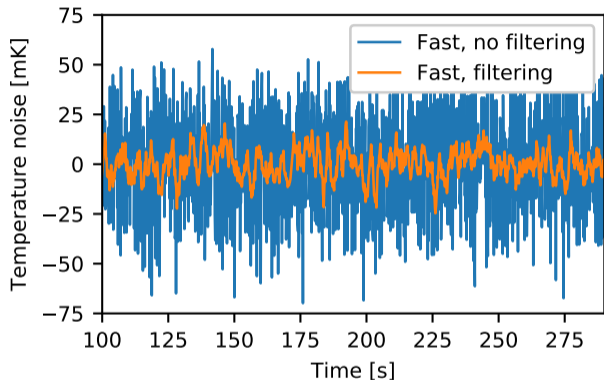
- ▶ PT100 (platinum resistor) sensor
- ▶ High resolution ohmmeter (Keithley 2100)
- ▶ 4-wire connection
- ▶ Filtering
- ▶ High integration time



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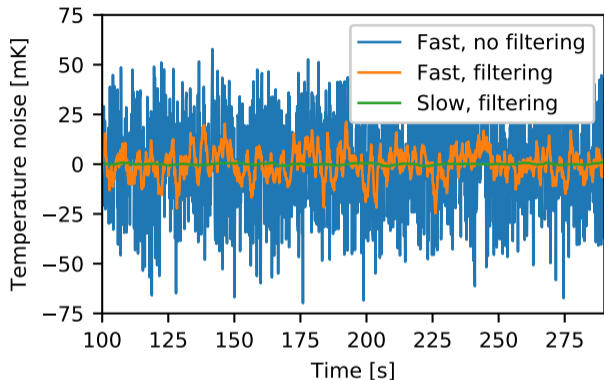
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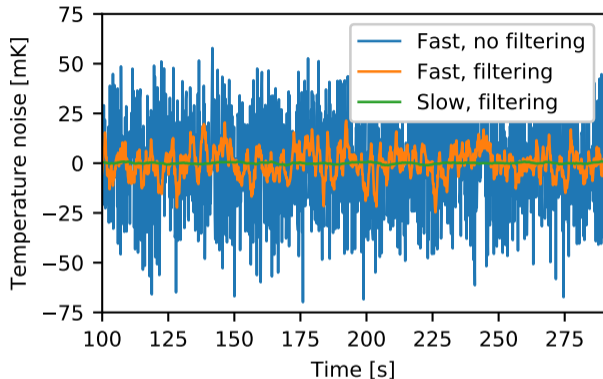
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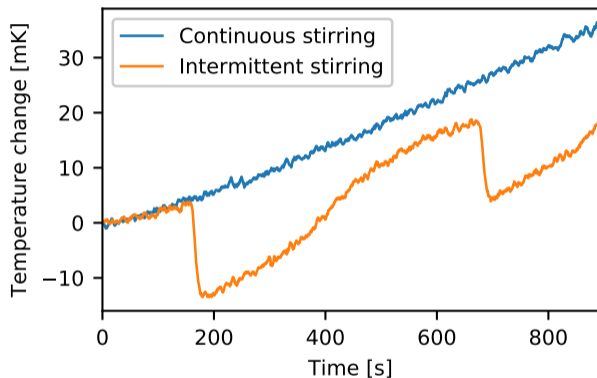
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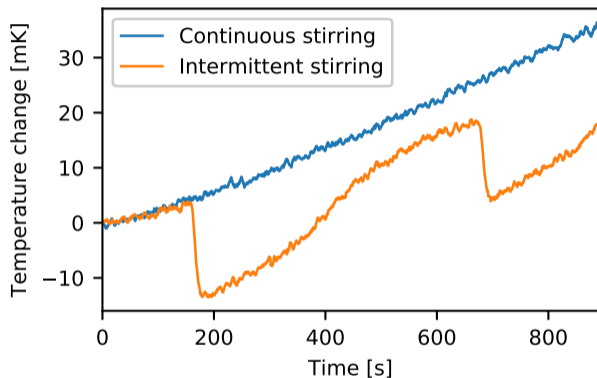
- 0.25 K absolute temperature accuracy
- 1 mK relative temperature accuracy

Effect of stirring



- ▶ Stirring required for bath uniformity
- ▶ Small dc motor attached to stirrer
- ▶ Causes small temperature rise ($2.4 \text{ mK} \cdot \text{min}^{-1}$)
- ➔ Corresponds to a 70 mW power flow

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→ Negligible effect as it is small and canceled by the ΔT calculation

Effect of Power Level

- ▶ Using a resistor supplied with dc current
 - ▶ Power dissipated for 1 min:
 - ▶ 29.2 W
 - ▶ 18.7 W
 - ▶ 10.5 W
 - ▶ 4.7 W
 - ▶ 1.2 W
- $C_{Th} = (1657 \pm 5) \text{ J} \cdot \text{K}^{-1}$ (0.3 % error)

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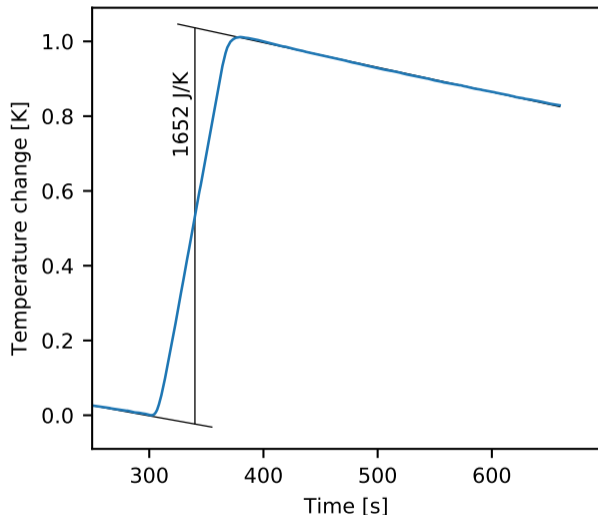
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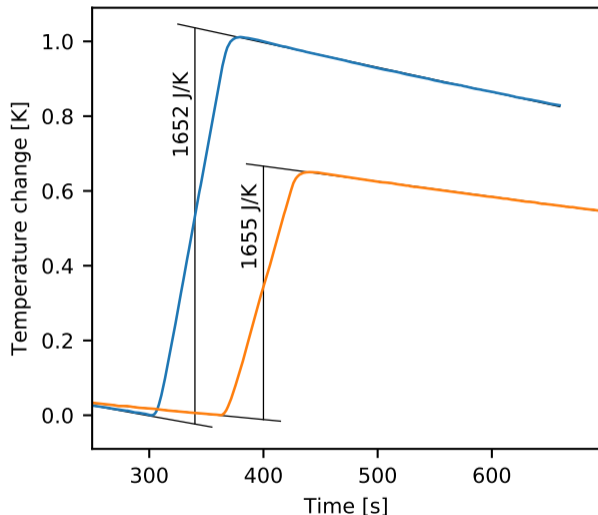
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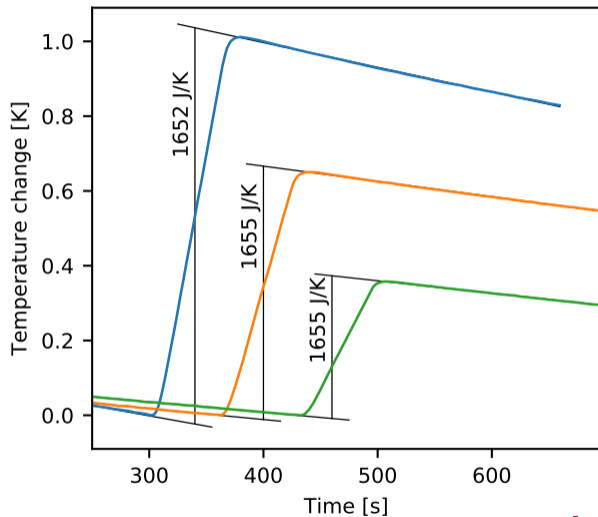
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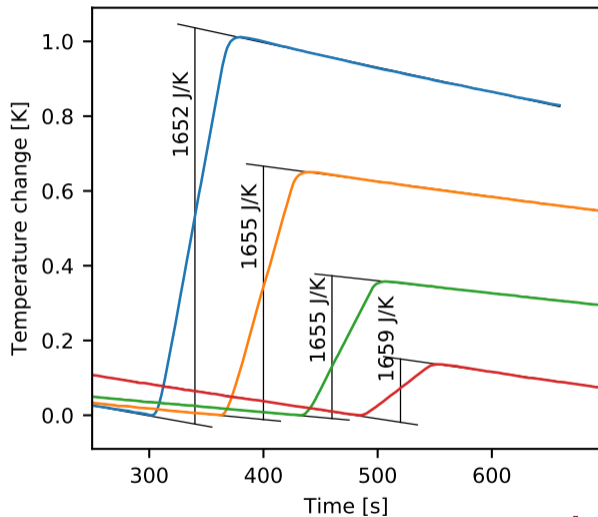
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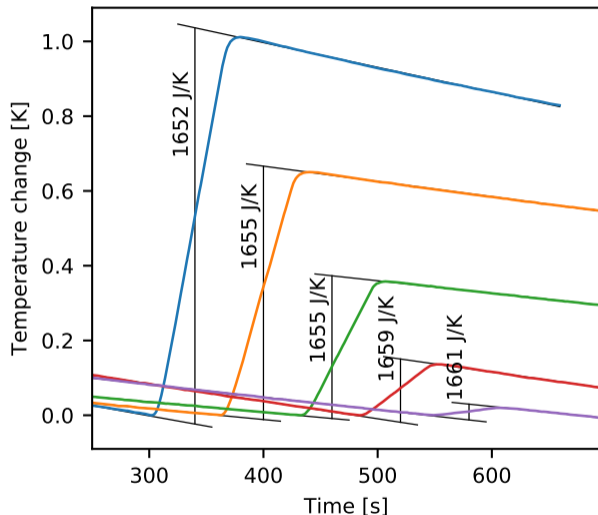
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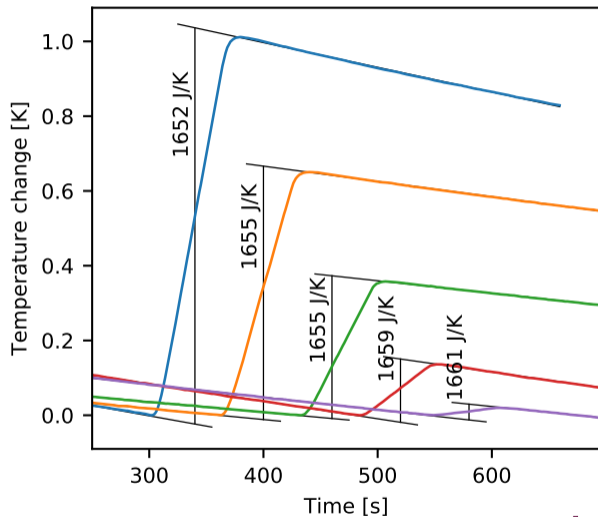
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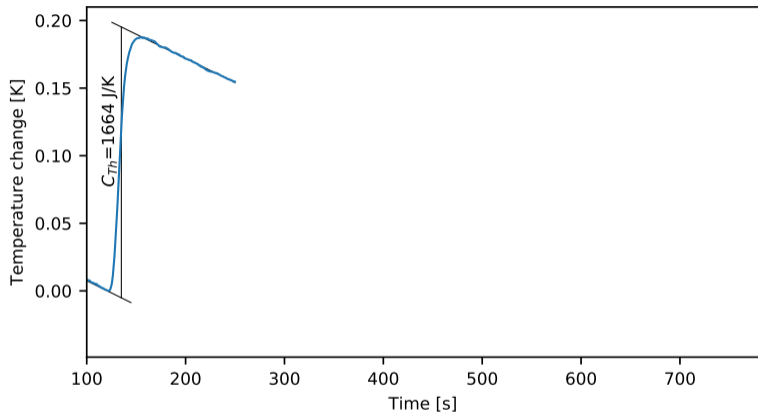
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Effect of measurement duration

Dissipation of ≈ 300 J over:

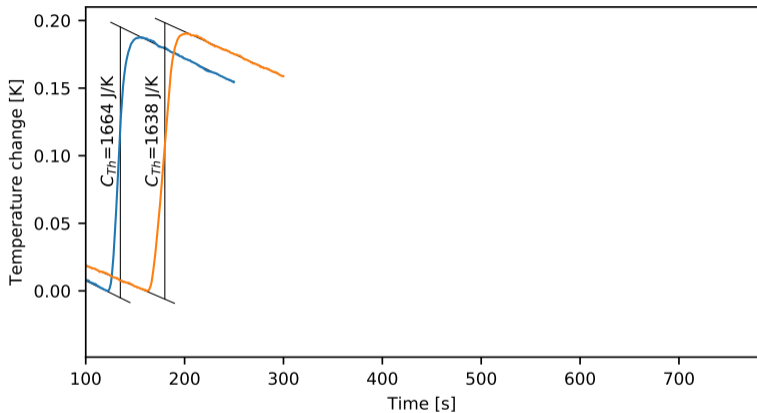
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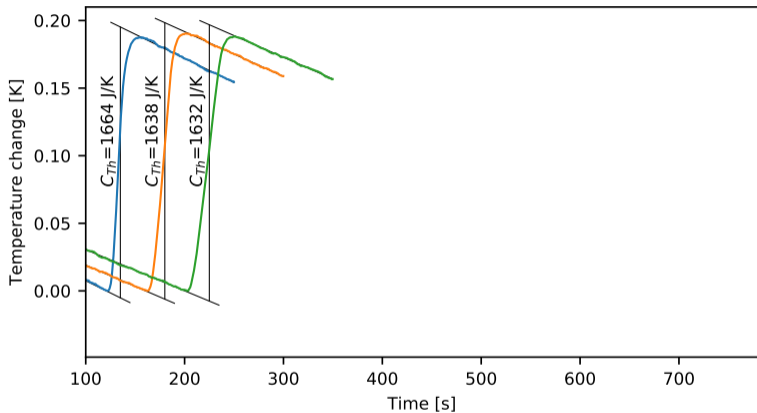
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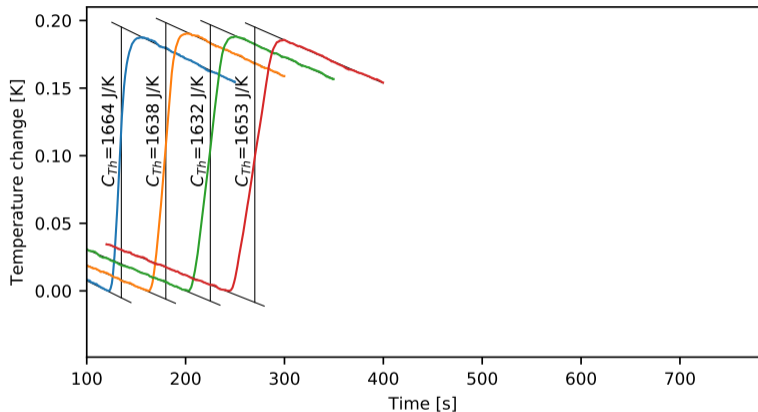
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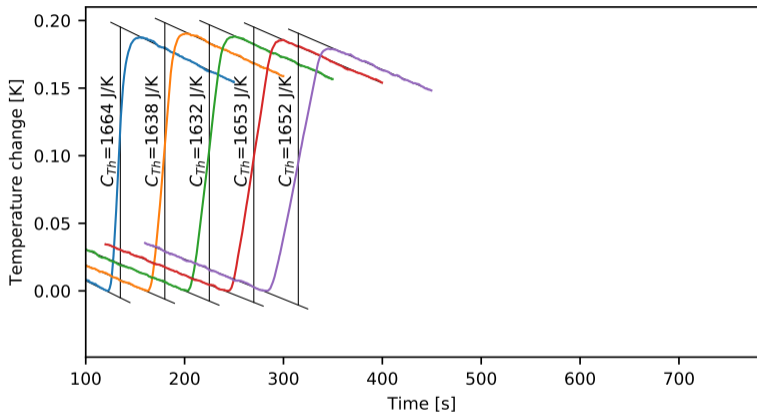
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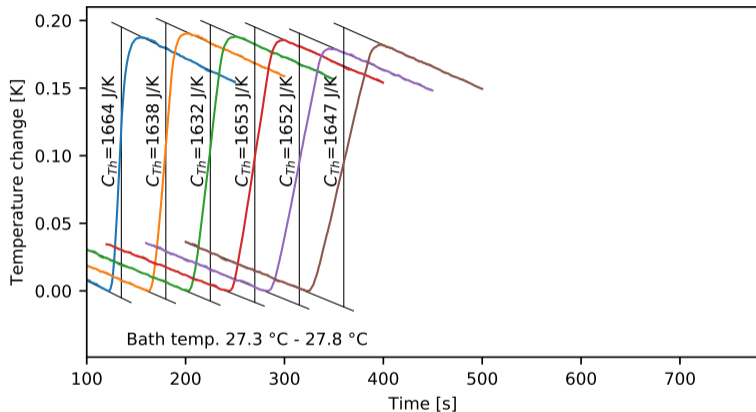
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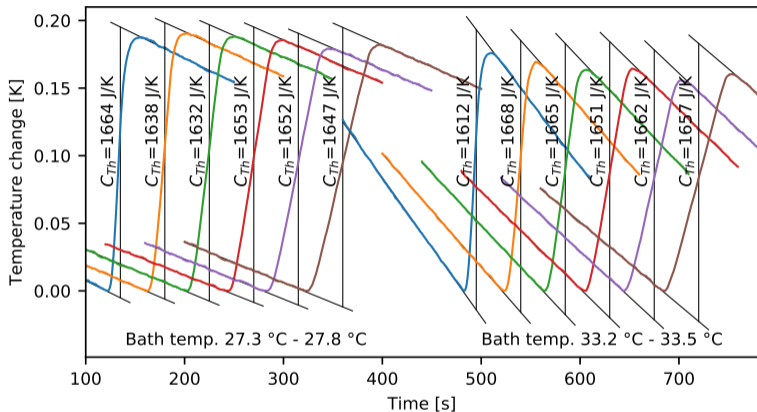


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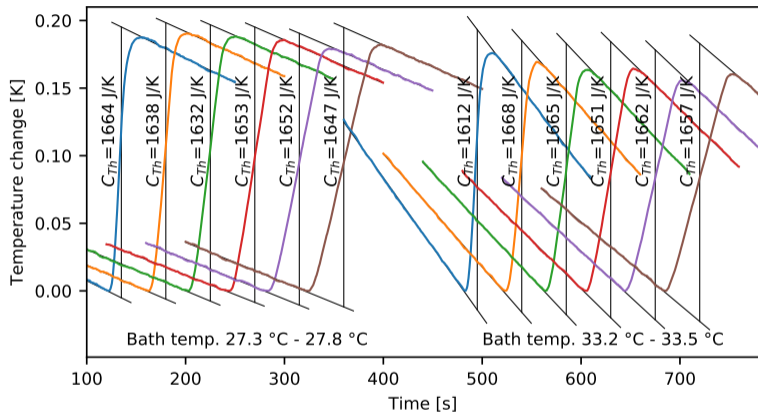


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And for different bath temp.



Overall, $C_{Th} = (1670 \pm 59) \text{ J} \cdot \text{K}^{-1}$ (3.5 % error)
Without the "10 s" measurements, error is down to 1.4 %

Sources of error:

- ▶ Relative error on temperature: 1 mK
 - ▶ Estimated error on curve fitting: 2 mK
 - ▶ Estimated error on time: 1 s
- for $\Delta T = 0.2 \text{ K}$ and $t = 60 \text{ s}$, error is 3.2 % (1.7 % for t alone)

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Possible Mitigation

- ▶ Automatic time control: error on t virtually 0
- ▶ Improved adiabaticity to reduce error on ΔT : may be complex
- ▶ Adjustment of calorimeter bath volume to increase ΔT : easy

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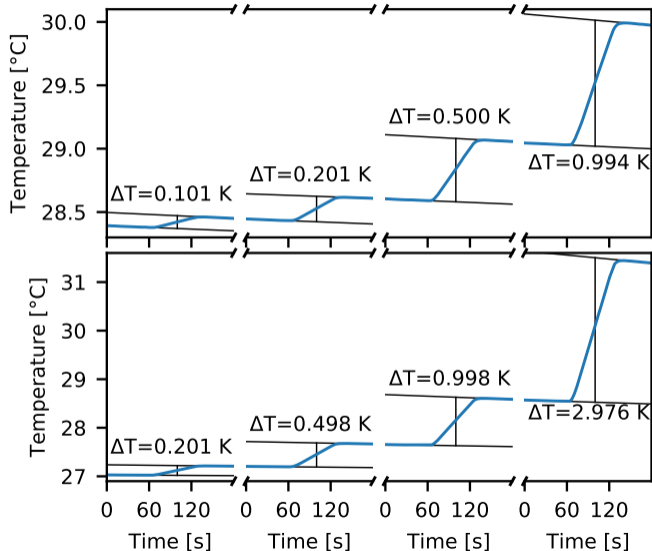
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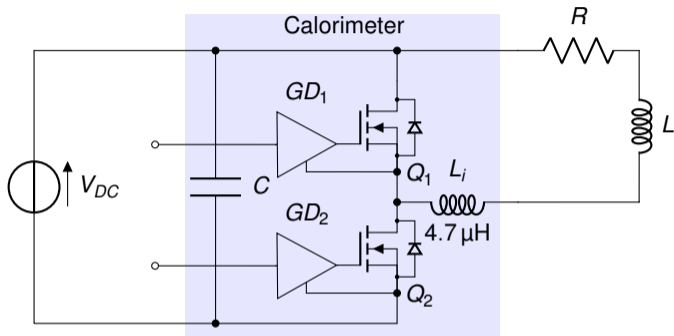
Conclusions

Calibration



- ▶ One calibration per test series (different quantities of fluid)
- ▶ $\Delta T < 50$ mK discarded
- ▶ ΔT up to 2.9 K considered
- ▶ First series $C_{Th} = 1665 \pm 1 \%$
- ▶ Second series $C_{Th} = 1350 \pm 1 \%$

Test Setup

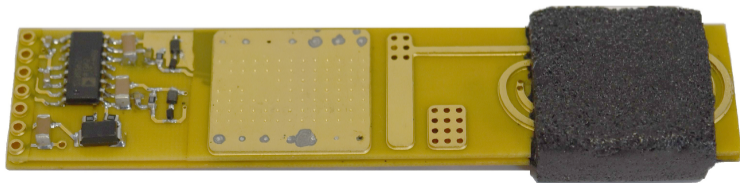


System under test:

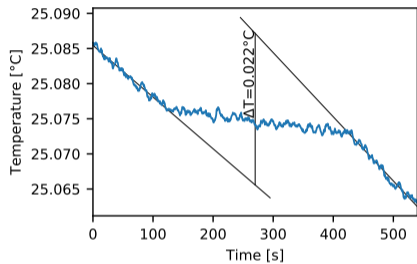
- ▶ PCB-integrated converter
- ▶ SiC MOSFETs,
- ▶ output inductor,
- ▶ decoupling capacitor,
- ▶ gate drivers.

Load kept outside of the calorimeter:

- ▶ load resistor
- ▶ additional inductor



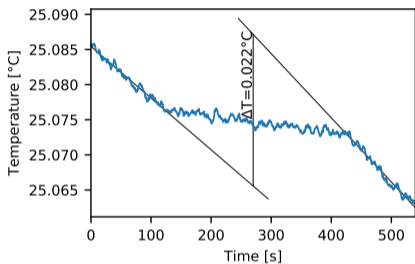
Results



Measurement resolution:

- ▶ gate drive only
- ▶ 33.5 J over 300 s
- 110 mW $\pm 5\%$

Results



Different test configurations:

- ▶ V_{DC} , load resistor and inductor, load current, f_{sw}
- ▶ Poor accuracy for low losses
- ▶ Large error due to operating time control:

E_1 total error

E_2 without error due to time measurement

	V_{DC} (V)	R (Ω)	L (μH)	I_{max} (A)	f_{sw} (kHz)	P (W)	E1 (%)	E2 (%)
1	100	30.	250	3.3	4	0.73	12.6	11.0
2	60	10.	250	6.	4	1.8	6.1	4.4
3	60	5.	250	12.	2	6.42	2.9	1.2
4	60	3.3	250	18.2	1.2	12.9	2.2	0.6
5	60	10.	0	6.	4	2.35	5.1	3.4
6	60	5.	0	12.	2	9.35	2.5	0.9

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- ▶ $\approx 500\text{€}$ (excl. ohmeter), easy to implement
- ▶ Fluid with low environmental/safety concerns

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Satisfying accuracy/resolution

- ▶ Can detect power consumption of gate drivers
- ▶ Conservative error estimation yields 3.2 %
 - ▶ Can be reduced to 1.6 % with proper timing control
 - ▶ Can be further reduced (adjusted calorimeter volume, improved calibration)

Thank you for your attention.

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This work was funded by Mitsubishi Electric Research Centre Europe and the French Agency for Technology and Research (ANRT).