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Fast Method to Check the Thermal Performance of Metal-Covered VIP

D. Büttner,

C. Stark, M. Keller, J. Fricke

Bavarian Center for Applied Energy Research

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Metal-covered VIP

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Vacuum insulation panel with metal envelope

metal envelope **vacuum panel core**

stainless steel
0.8 ... 4 mm
surface: plane
or with lug pattern

Thermal Performance of Metal-Covered VIP

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Characterisation of thermal performance:

Foil lift-off method to determine the internal pressure is not applicable.

Thermal measurements:

- stationary measurement of thermal conductivity:
  very slow, both sides of VIP must be accessible
- transient measurement of **effusivity**:
  problem: 2 layers with extreme different properties,
  → special method required

Measurement of Effusivity: Set-up

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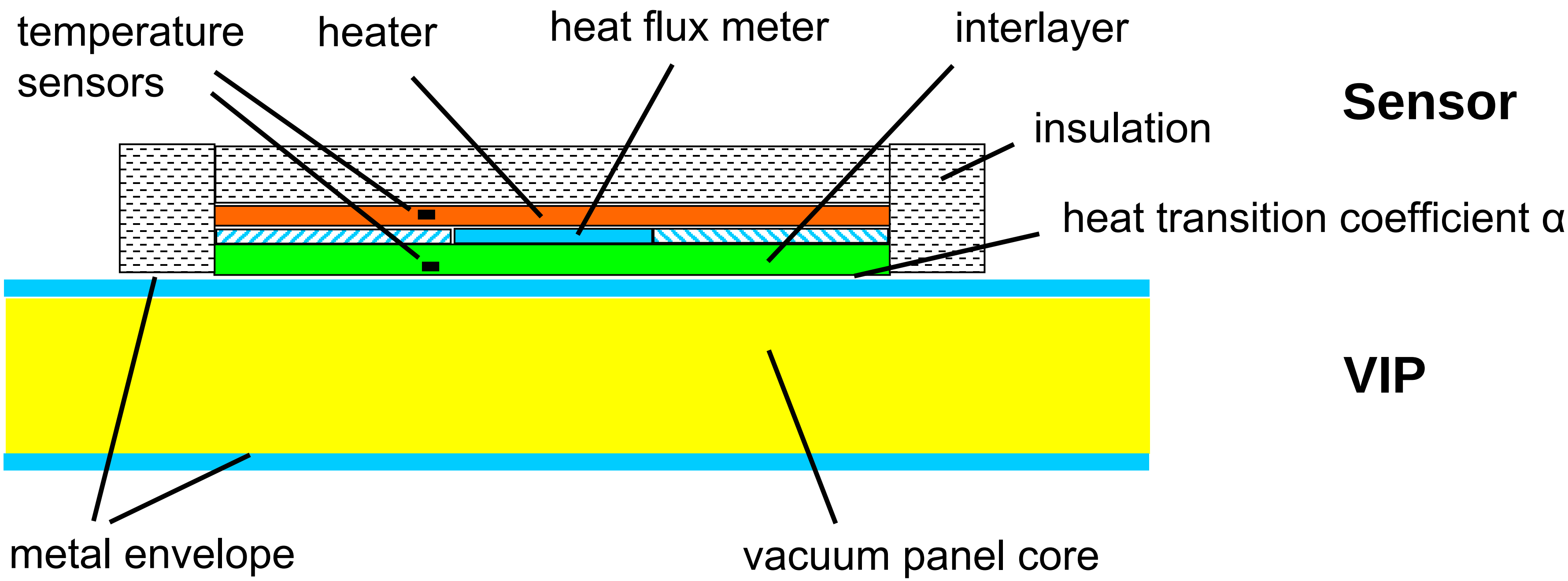
Sketch of the measurement set-up



thickness d_E
surface roughness ?

effusivity b

heat capacity per area: C''_E , C''_H for envelope, heater

Measurement of Effusivity: Theory

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Effusivity: $b = \sqrt{\lambda \rho c_p}$

Heat flux into a semi-infinite homogeneous region ($x \geq 0$) for a sudden temperature rise $T_0 \rightarrow T_{ref}$ at time $t = 0$ at surface $x = 0$:

$$\dot{q}(t) = \frac{b \cdot \Delta T_{ref}}{\sqrt{\pi \cdot t}} \qquad \Delta T_{ref} = T_{ref} - T_0$$

Problem:

2 layers with extremly different thermal properties,
effusivity of layer 2 is to be measured.

Fast Measurement Procedure

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The pre-heated sensor is put onto the metal envelope

- Short-term range: accelerated heating-up of metal envelope:
  - Overheating of heater with $T_H(t) = T_{ref,A} > T_{ref}$ for $0 \leq t \leq t_A$,

    t_A: optimized end of overheating to avoid overshoot of envelope temperature T_E above the long-term reference temperature T_{ref} ;
  - Intercooling: heater cools down from $T_{ref,A} \rightarrow T_{ref}$, envelope temperature still rises towards T_{ref} .
  - When $T_H(t) \approx T_{ref}$: controlled heating to keep $T_H(t) = T_{ref}$ = constant.
- Long-term range: effusivity measurement on VIP core.

Accelerated Heating-up of Metal Envelope (Theory)

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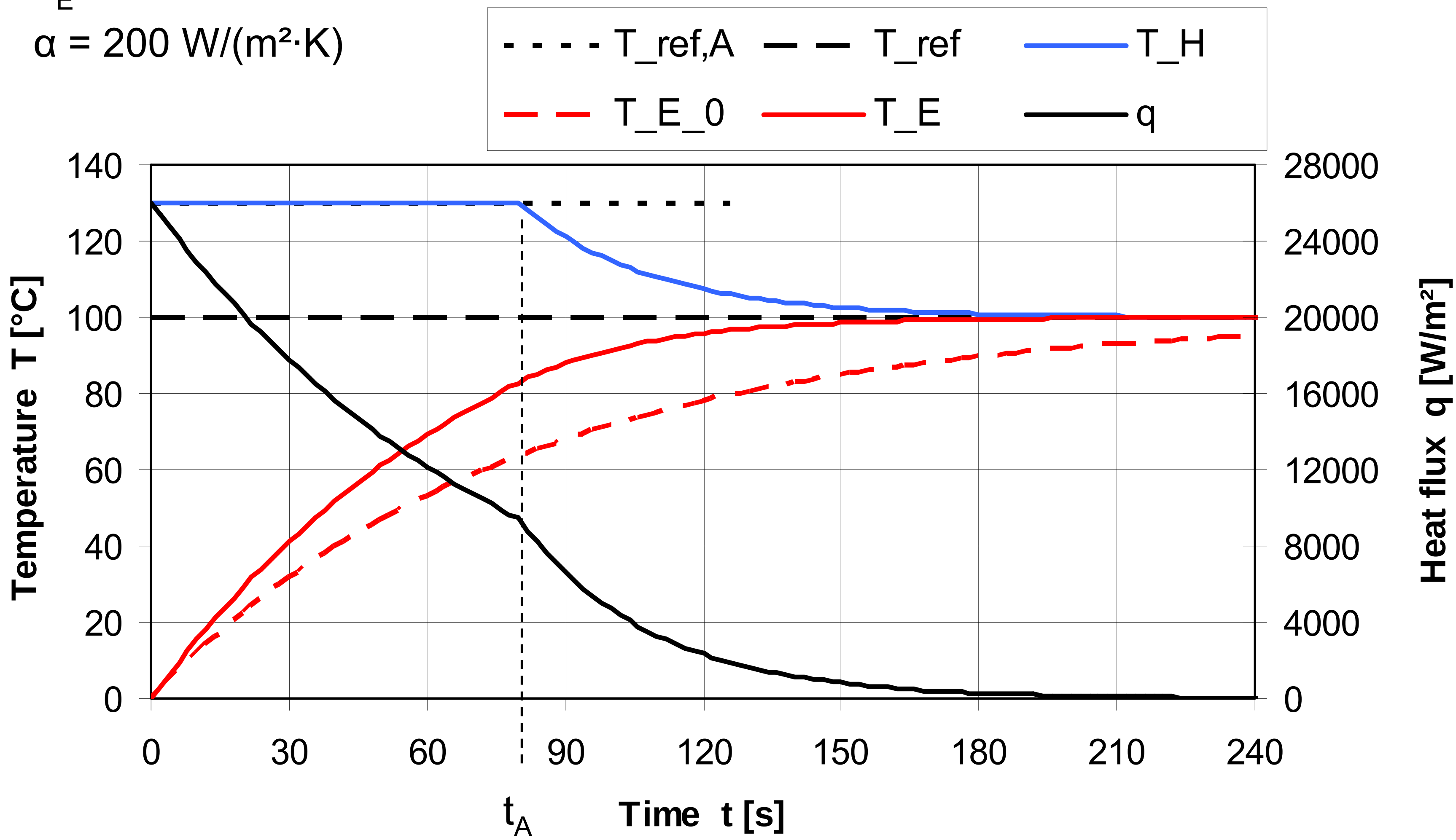
$d_E = 4$ mm
$\alpha = 200$ W/(m²·K)



Accelerated Heating-up: Overheating (ideal case)

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Overheating of heater with $T_H = T_{ref,A} > T_{ref}$ at $0 \leq t \leq t_A$

$$\Delta T_{E,A}(t) = \Delta T_{ref,A} \cdot \left[1 - \exp\left(-\frac{t}{\tau_E}\right)\right]$$

$$\dot{q}_{E,A}(t) = \alpha \cdot \Delta T_{ref,A} \cdot \exp\left(-\frac{t}{\tau_E}\right) = \dot{q}_{E,A,0} \cdot \exp\left(-\frac{t}{\tau_E}\right)$$

with the characteristic time $\tau_E = \frac{C''_E}{\alpha} = \frac{\rho_E \cdot c_E \cdot d_E}{\alpha}$

and the initial heat flux $\dot{q}_{E,A,0} = \alpha \cdot \Delta T_{ref,A} = C''_E \cdot \Delta T_{ref,A} / \tau_E$

Accelerated Heating-up: Intercooling (ideal case)

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Intercooling until $T_H = T_{ref}$ at $t_A \leq t \leq t_B$.

$$T_H(t) = T_{ref} + \left[T_{ref,A} - T_{ref}\right] \cdot \exp\left(-\frac{t - t_A}{\tau_{E,H}}\right)$$

$$T_E(t) = T_{ref} + \left[T_{E,A} - T_{ref}\right] \cdot \exp\left(-\frac{t - t_A}{\tau_{E,H}}\right)$$

$$\dot{q}(t) = \alpha \cdot \left(T_H - T_E\right) = \alpha \cdot \left[T_{ref,A} - T_{E,A}\right] \cdot \exp\left(-\frac{t - t_A}{\tau_{E,H}}\right)$$

with the characteristic time $\tau_{E,H}$:

$$\frac{1}{\tau_{E,H}} = \frac{\alpha}{C''_H} + \frac{\alpha}{C''_E} = \frac{1}{\tau_H} + \frac{1}{\tau_E}$$

Accelerated Heating-up: Typical Values

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Characteristic times:

VIP envelope made of stainless steel with $\rho_E \cdot c_E = 4 \cdot 10^6$ W·s/(m³·K), and a heater with $C''_H = 9 \cdot 10^3$ W·s/(m²·K):

α	[W/(m²·K)]	1000	200	200
d_E	[mm]	1	1	4
C''_E	[W·s/(m²·K)]	$4 \cdot 10^3$	$4 \cdot 10^3$	$16 \cdot 10^3$
τ_E	[s]	4	20	80
$\tau_{E,H}$	[s]	2.8	13	29

Effusivity of VIP Core

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The long-term range is described by the

modified equation:

$$\dot{q}(t) = \frac{b \cdot \Delta T_{ref}}{\sqrt{\pi \cdot (t - t_0)}}$$

with the unknown **effective starting time t_0**
due to non-idealised starting conditions.

Evaluation:

$$\frac{1}{\dot{q}^2} = \frac{\pi}{b^2 \cdot (\Delta T_{ref})^2} \cdot (t - t_0) = \frac{\pi}{\lambda \cdot \rho \cdot c \cdot (\Delta T_{ref})^2} \cdot (t - t_0) = A \cdot t + B$$

Numerical Simulations

For optimization of measurement design and procedure:

Numerical simulations with variation of parameters

d_E , α , λ_{VIP} , guard ring width

Example:

Metal-covered VIP with

$d_E = 1$ mm ,

$\alpha = 200$ W/(m²·K) ,

$\lambda = 16 \cdot 10^{-3}$ W/(m·K)

Simulations: Accelerated Heating-up

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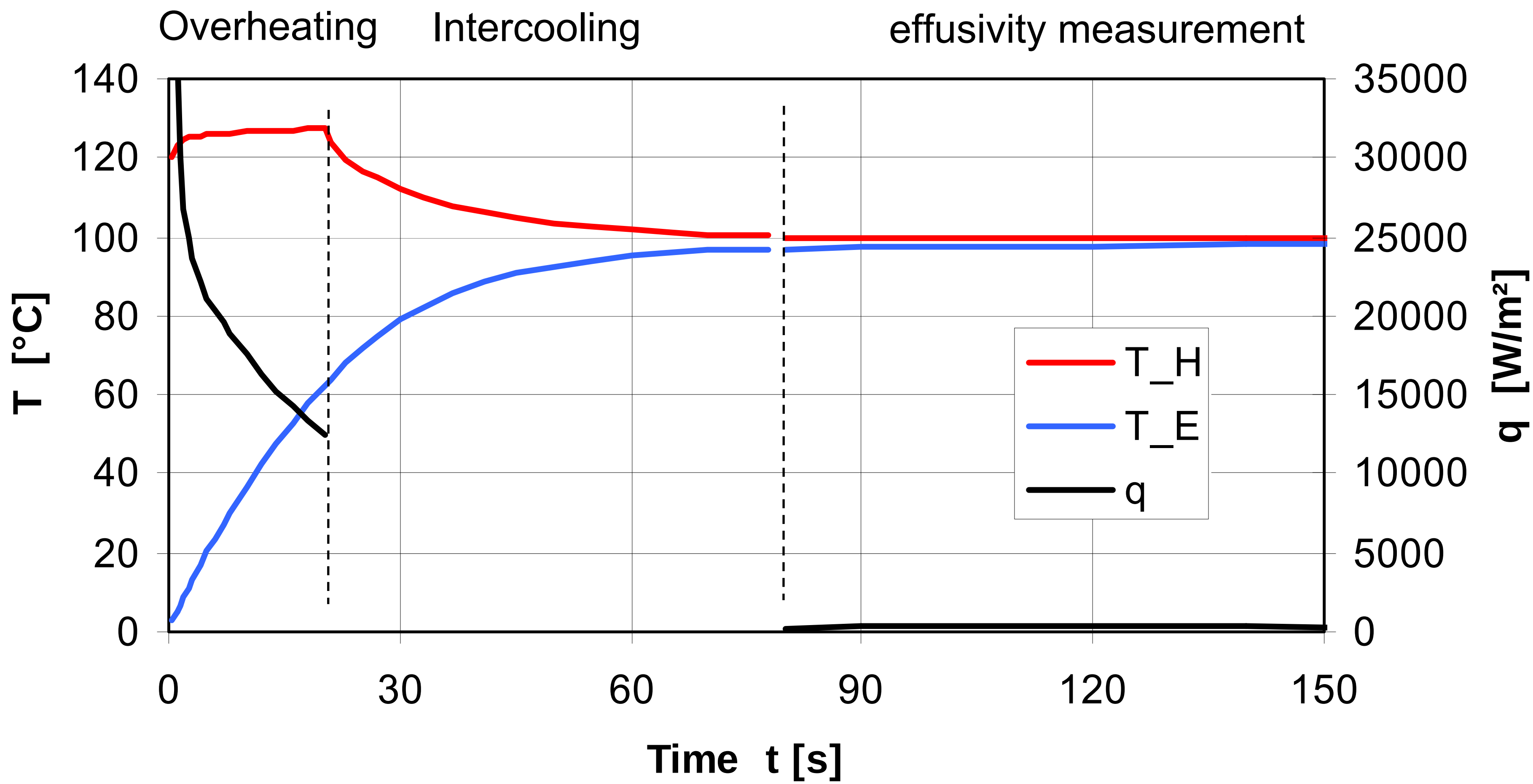
d_E = 1 mm , α = 200 W/(m²·K) , λ = 16·10⁻³ W/(m·K)



Simulations: Long-term Range

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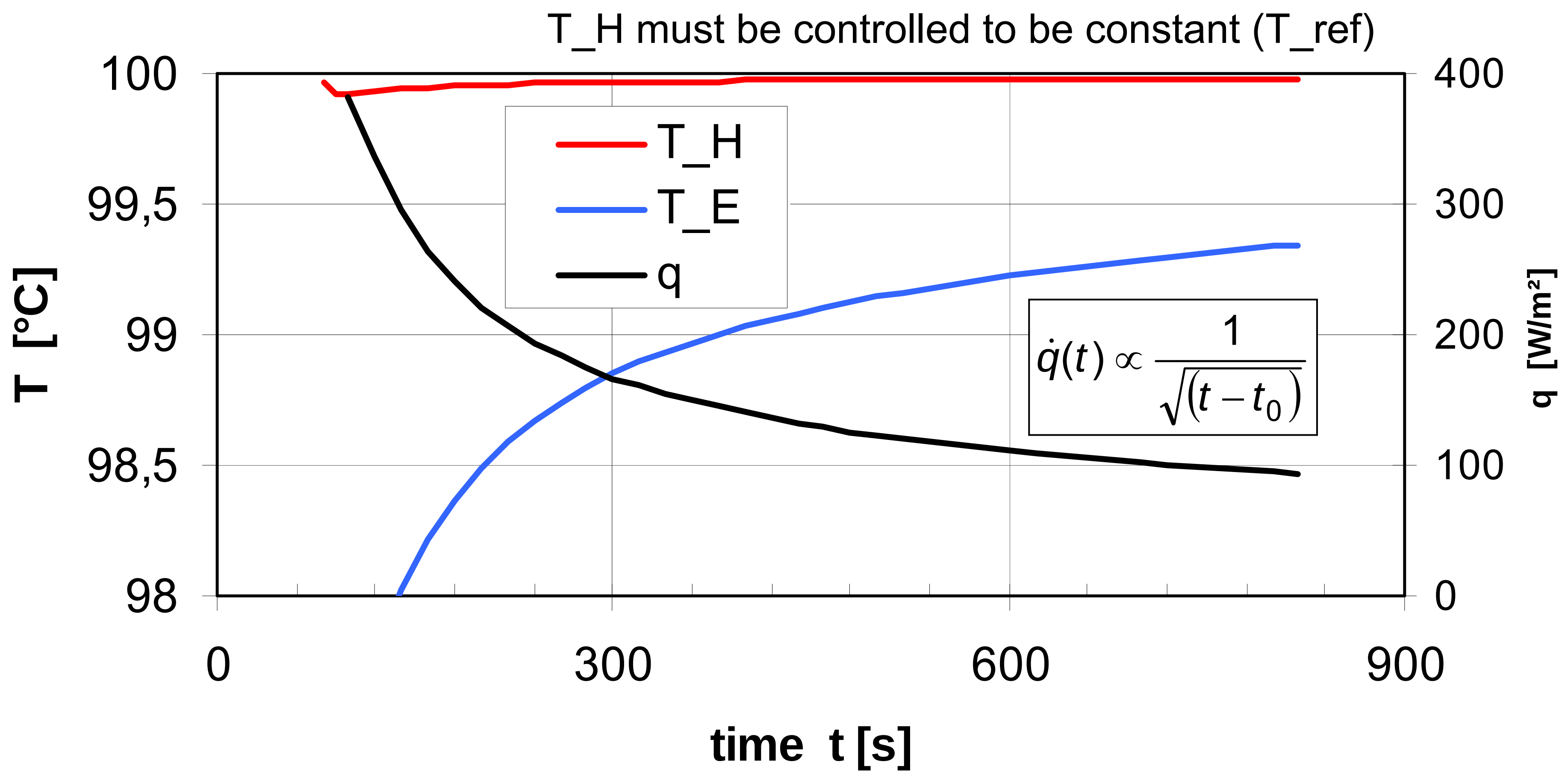
d_E = 1 mm , α = 200 W/(m²·K) , λ = $16 \cdot 10^{-3}$ W/(m·K)



Simulations: Evaluation of 1/q² - Linear Fit

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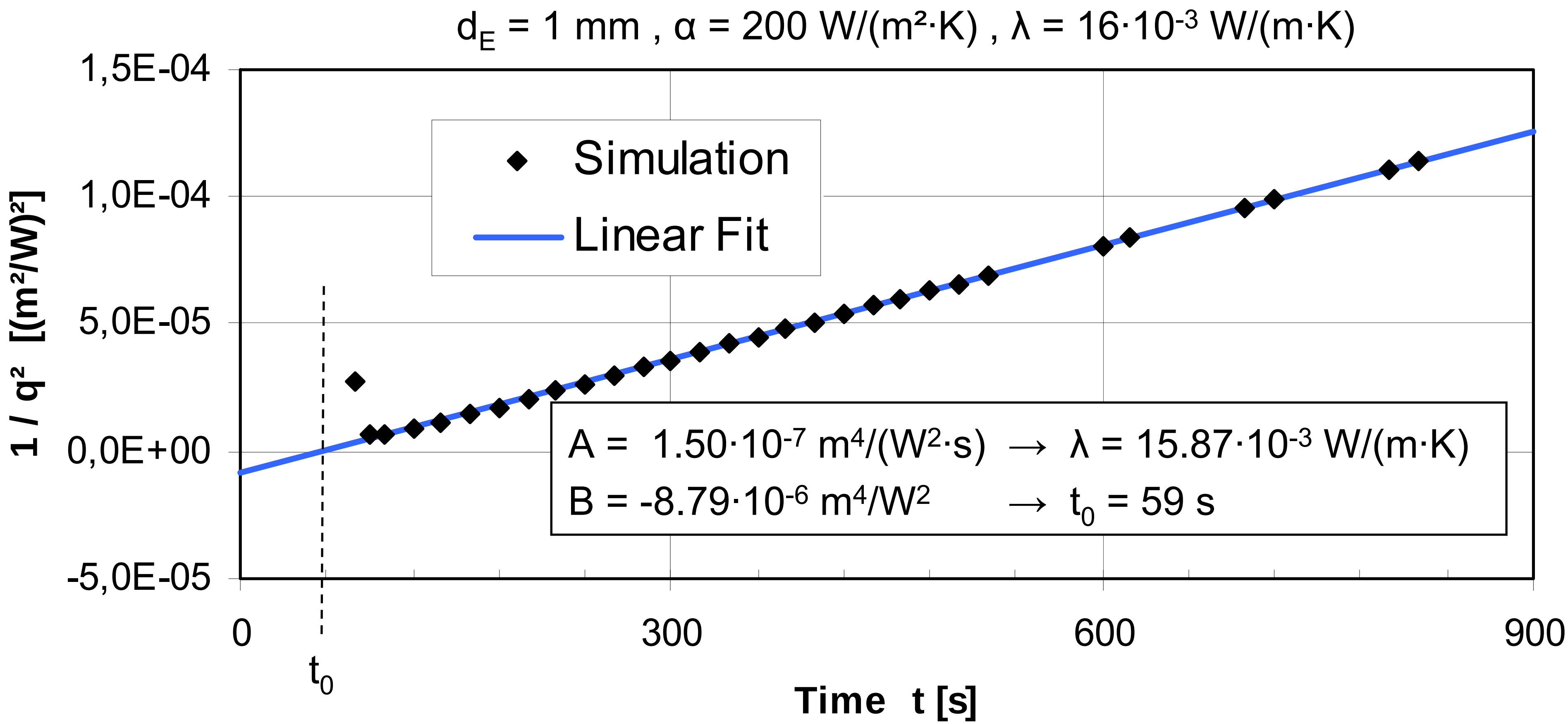
$$\frac{1}{\dot{q}^2} = \frac{\pi}{\lambda \cdot \rho \cdot c \cdot (\Delta T_{ref})^2} \cdot (t - t_0) = A \cdot t + B$$



Simulations: Evaluation of 1/q² - Linear Fit

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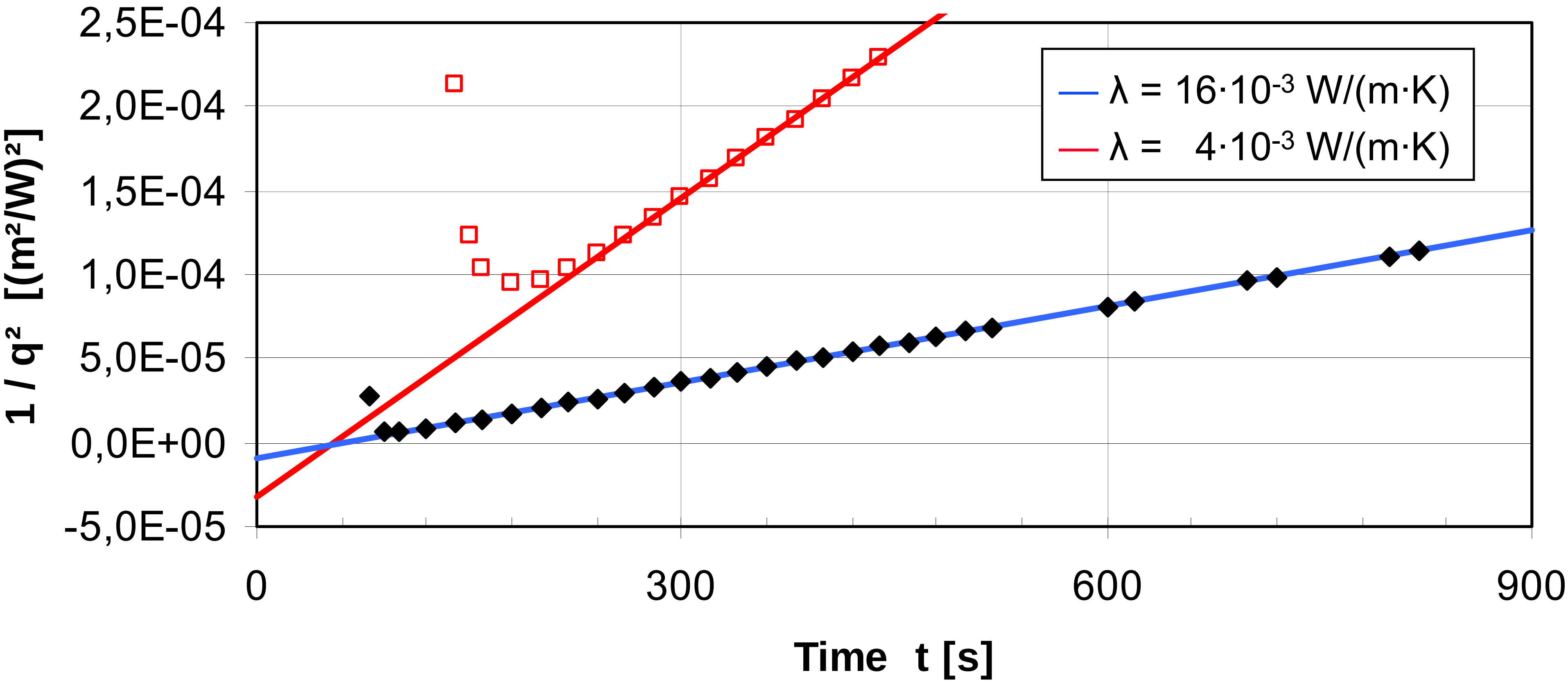
$$\frac{1}{\dot{q}^2} = \frac{\pi}{\lambda \cdot \rho \cdot c \cdot \left(\Delta T_{ref}\right)^2} \cdot \left(t - t_0\right) = A \cdot t + B$$

d_E = 1 mm , α = 200 W/(m²·K)



Simulations: Summary

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Results from simulations

- long-term range:
  evaluation procedure for effusivity b or conductivity λ is applicable
- initial (accelerated) heating-up:
  an estimate for the contact resistance can be derived (not shown)
- required width of guard ring (not shown)

Summary and Outlook

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Fast method to check the thermal performance of metal-covered VIP

- theoretical description
- numerical simulations

Currently first tests with a prototype are under way.

Construction and control of an optimized sensor is required.

Further possible applications:

The presented method is not only applicable for metal-covered VIPs, but might also be used for build-in VIPs or for VIPs which are enclosed in a protection layer.

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