Bayerisches Zentrum für
Angewandte Energieforschung e.V.

Thermal Conductivity of PCM

Introduction

Hans-Peter Ebert

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OVERVIEW

- Motivitation
- Thermal conductivity · thermal diffusivity
- Measurement methods
- Final remarks

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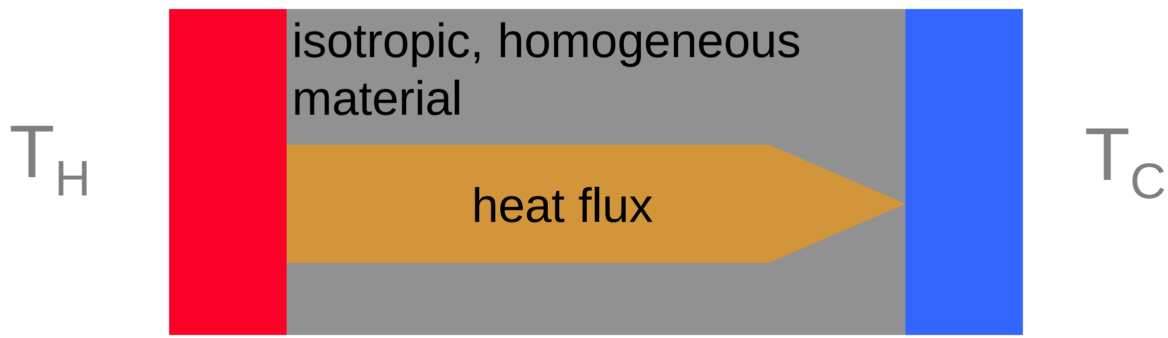
Jean Baptiste Joseph Fourier
(1768 - 1830)

Fourier's law defines the thermal conductivity λ:

$$\vec{q} = -\lambda \nabla T$$



Thermal conductivity λ is a material property!

$$[\lambda] = \frac{W}{m^2} \cdot \frac{m}{K} = \frac{W}{m \cdot K}$$

WHY THERMAL CONDUCTIVITY HAS TO BE KNOWN?

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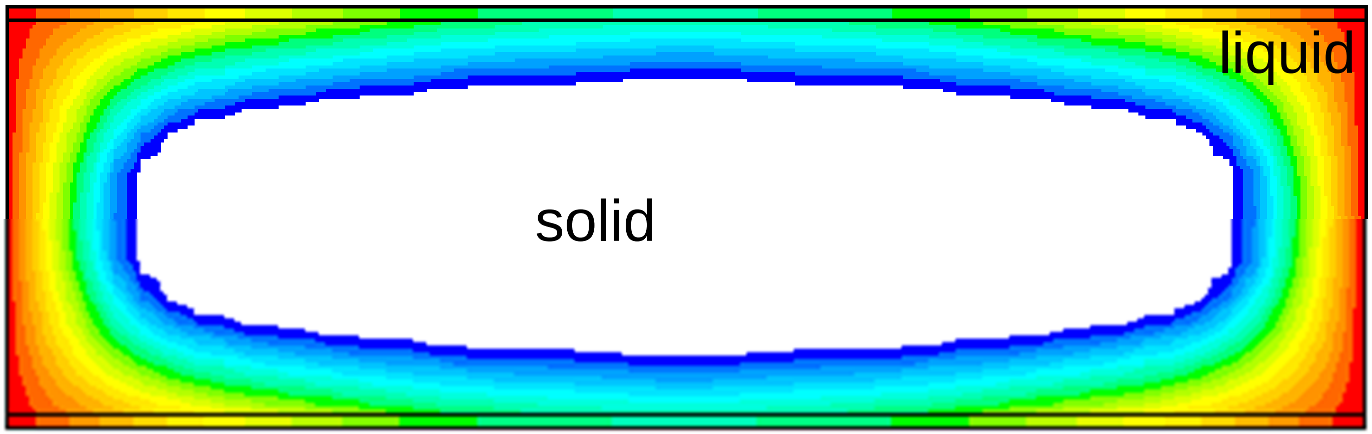
- input data for simulations



- product comparison (product data sheets)

In all cases you need reliable thermal conductivity data!

EQUATION OF HEAT TRANSFER

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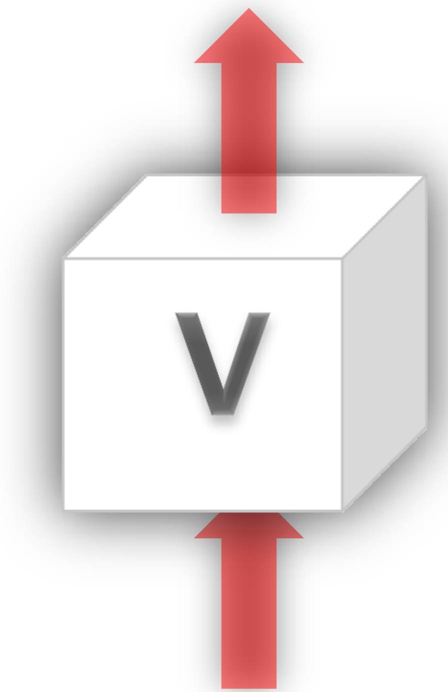
Energy balance of a volume V with surface S between the times t_1 and t_2



homogeneous medium

EQUATION OF HEAT TRANSFER

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$$\int_{t_1}^{t_2}\int_{S} \lambda(\vec{x})\nabla T d\vec{f} dt + \int_{t_1}^{t_2}\int_{V} \Phi(\vec{x},t) d^3\vec{x} dt = \int_{V} c(\vec{x})\rho(\vec{x})\left[T(\vec{x},t_2) - T(\vec{x},t_1)\right] d^3\vec{x}$$

net heat flow via the surface S

heat source or sink

increase of the internal energy due to a increase of temperature

Φ = heat source (z.B. phase change, chemical reaction, radiative heat transfer)
ρ = density
c = specific heat
λ = thermal conductivity
T = temperature

EQUATION OF HEAT TRANSFER

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$$\int_{t_1}^{t_2}\int_S \lambda(\vec{x})\nabla T d\vec{f} dt + \int_{t_1}^{t_2}\int_V \Phi(\vec{x},t) d^3\vec{x} dt = \int_V c(\vec{x})\rho(\vec{x})\left[T(\vec{x},t_2) - T(\vec{x},t_1)\right] d^3\vec{x}$$

$$\int_S \lambda(\vec{x})\nabla T d\vec{f} = \int_V \nabla(\lambda(\vec{x})\nabla T) d^3\vec{x}$$

$$\left[T(\vec{x},t_2) - T(\vec{x},t_1)\right] = \int_{t_1}^{t_2} \frac{\partial T}{\partial t} dt$$

EQUATION OF HEAT TRANSFER

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$$\int_{t_1}^{t_2}\int_V \left\{ \nabla(\lambda(\vec{x})\nabla T(\vec{x},t)) + \phi(\vec{x},t) = \rho(\vec{x})c(\vec{x})\frac{\partial T(\vec{x},t)}{\partial t} \right\} d^3\vec{x}\,dt$$

General Equation of Heat Transfer
(Parabolic partial differential equation)

$$\nabla(\lambda(\vec{x})\nabla T(\vec{x},t)) + \phi(\vec{x},t) = \rho(\vec{x})c(\vec{x})\frac{\partial T(\vec{x},t)}{\partial t}$$

SIMPLIFIED ONE-DIMENSIONAL EQUATION OF HEAT TRANSFER

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$$\frac{\partial}{\partial x}\left(\lambda(x)\frac{\partial}{\partial x}T(x,t)\right)+\phi(x,t)=\rho(x)c(x)\frac{\partial T(x,t)}{\partial t}$$

- no sources of heat
- constant thermal conductivity, density and specific heat

$$\frac{\partial^2}{\partial x^2}T(x,t)=\frac{\rho\cdot c}{\lambda}\frac{\partial T(x,t)}{\partial t}$$

$$\frac{\partial^2}{\partial x^2}T(x,t)=\frac{1}{\alpha}\frac{\partial T(x,t)}{\partial t}$$

α: thermal diffusivity

SIMPLIFIED ONE-DIMENSIONAL EQUATION OF HEAT TRANSFER

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$$\frac{\partial^2}{\partial x^2} T(x,t) = \frac{\rho \cdot c}{\lambda} \frac{\partial T(x,t)}{\partial t}$$

Stationary heat transfer:

$$\frac{\partial^2}{\partial x^2} T(x) = 0$$

$$\frac{\partial}{\partial x} T(x) = const. = -\frac{q}{\lambda}$$

PRINCIPLES OF THERMAL SIMULATIONS

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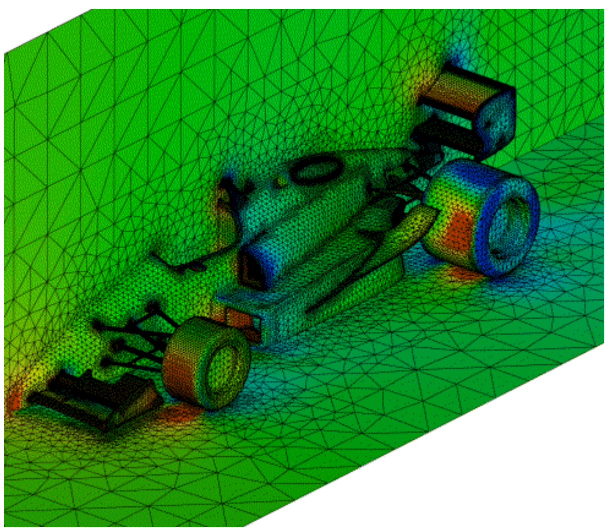
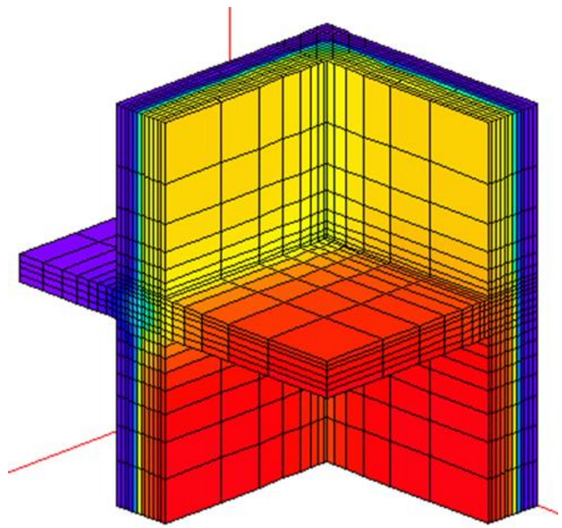
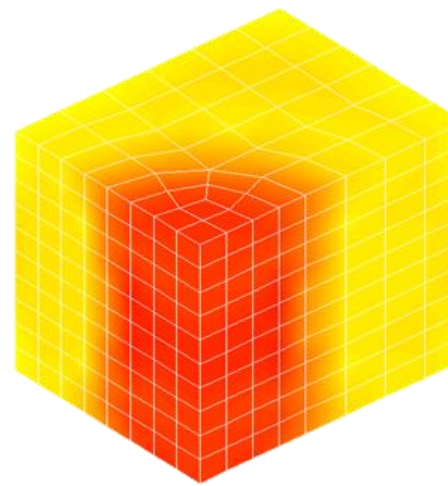
Common methods: finite-difference-, finite-volume-method, analytical methods

$$\rho \cdot c_p \cdot \frac{\partial T}{\partial t} = \lambda \cdot \frac{\partial^2 T}{\partial x^2} \quad \Rightarrow \quad \rho \cdot c_p \cdot \frac{T_i^{n+1} - T_i^n}{\Delta t} = \lambda \cdot \frac{T_{i+1}^n - 2 \cdot T_i^n + T_{i-1}^n}{(\Delta x)^2}$$

In all cases **Equation of Heat Transfer** is the underlying “working equation” and conduction effects are separated from heat storage effects.







HOW WE COULD DETERMINE THERMAL CONDUCTIVITY?

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Fourier´s law

$$\vec{q} = -\lambda \nabla T$$

Prerequisites:

- stationary conditions
- determination of the temperature gradient
- determination of the heat flow

Equation of heat transfer

$$\lambda \Delta T(\vec{x}, t) = \rho \cdot c \frac{\partial T(\vec{x}, t)}{\partial t}$$

Prerequisites:

- instationary conditions
- defined boundary and initial conditions
- known solution of the equation of heat transfer

COMPARISON OF STATIONARY AND NON-STATIONARY METHODS

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NON-STATIONARY methods	STATIONARY methods
Solution of heat transfer equation is needed	Simple theory
„Short“ measurement times	Stationary conditions are needed
Inhomogeneous specimens can be critical	Integration over the measurement area – larger specimens can be investigated
Small specimen dimensions can be investigated, Advantageous for high T and high p	Large specimens
Thermal contact resistances not always critical	Thermal contact resistances are critical

GENERAL

- It is no problem if the experiment is conducted far below the melting point > determination of λ_s.
- It is no problem if the experiment is conducted far above the melting point > determination of λ_l.
- The thermal conductivity of the liquid phase is lower than the thermal conductivity of the solid phase.
- In the case that two phases exist within the specimen during a thermal conductivity measurement the results have to be carfully discussed.

ROUND ROBIN TEST

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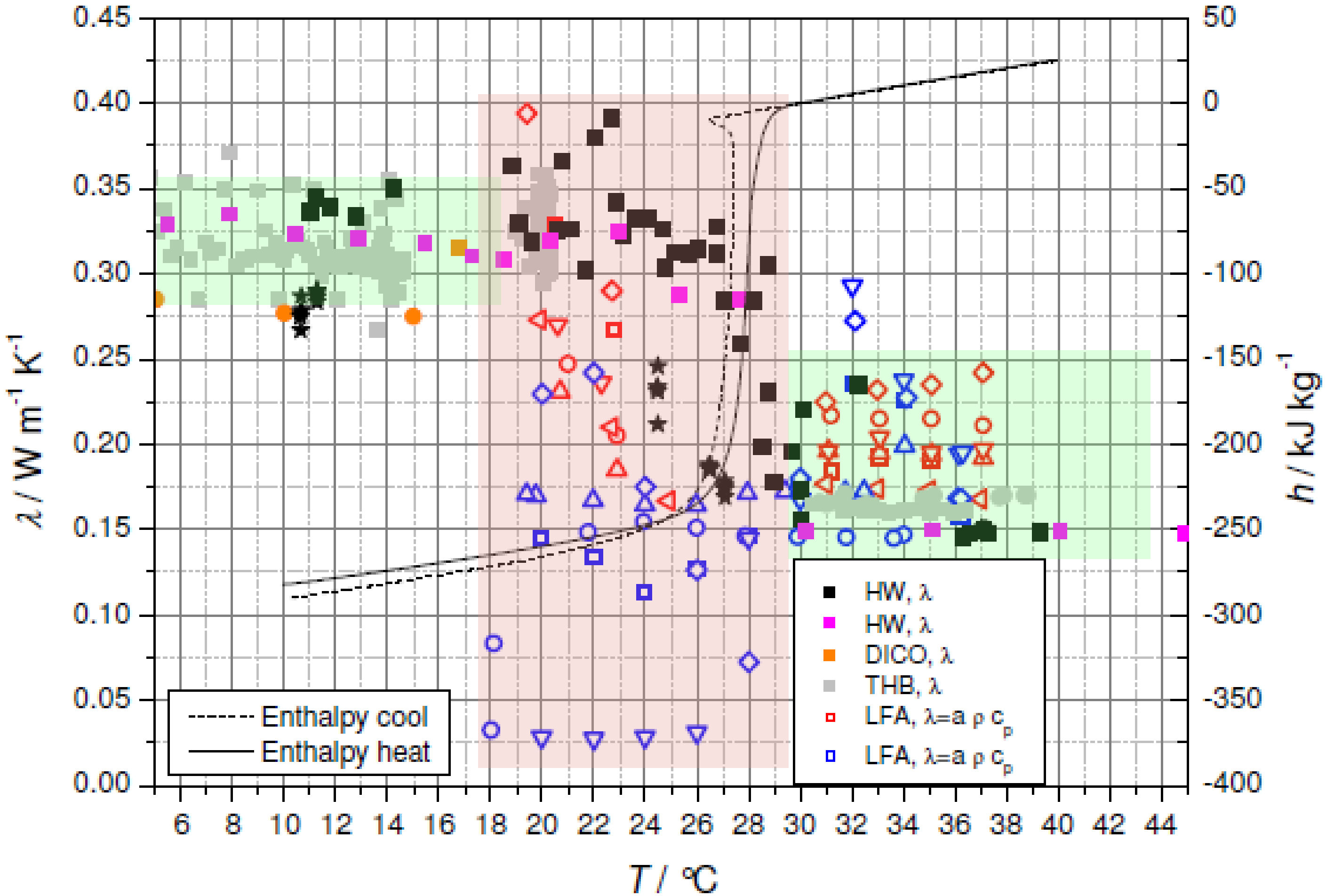
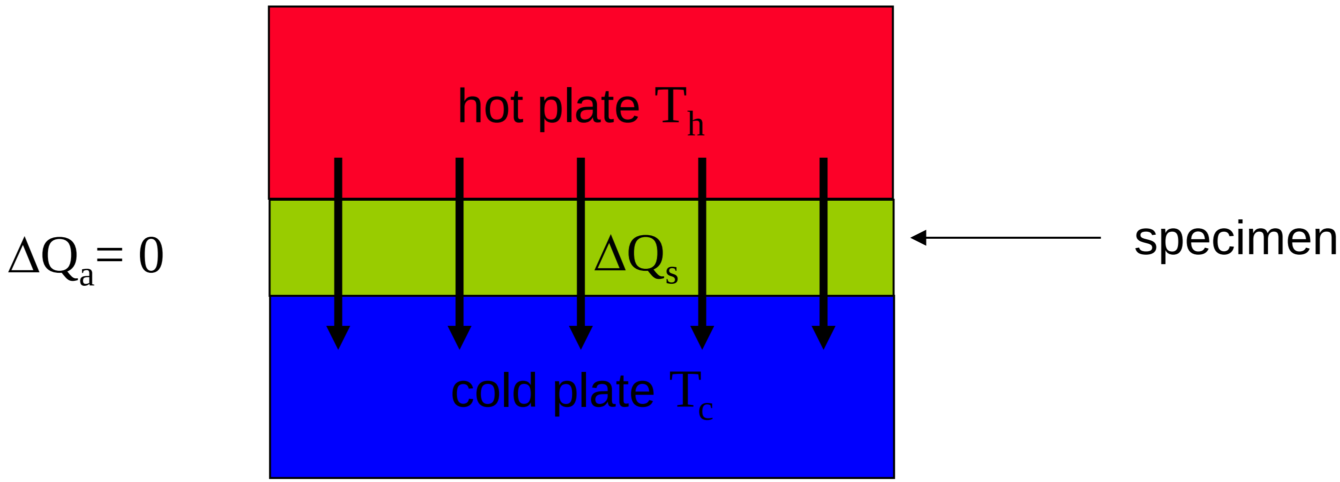


Figure 1: Thermal conductivity of n-octadecane measured with different measurement methods

STATIONARY GUARDED HOT PLATE METHOD



$$\Delta Q = \Lambda \cdot A \cdot (T_h - T_c) \cdot \Delta t$$

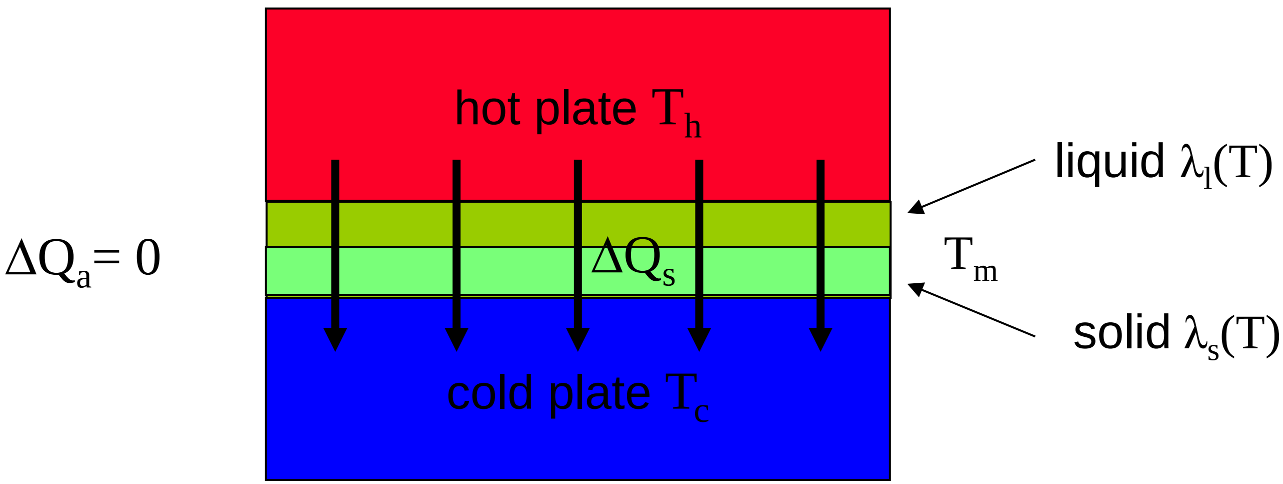
with: measurement area A , thermal conductivity λ und thermal conductance Λ

$$\Lambda = \frac{\lambda}{d}$$

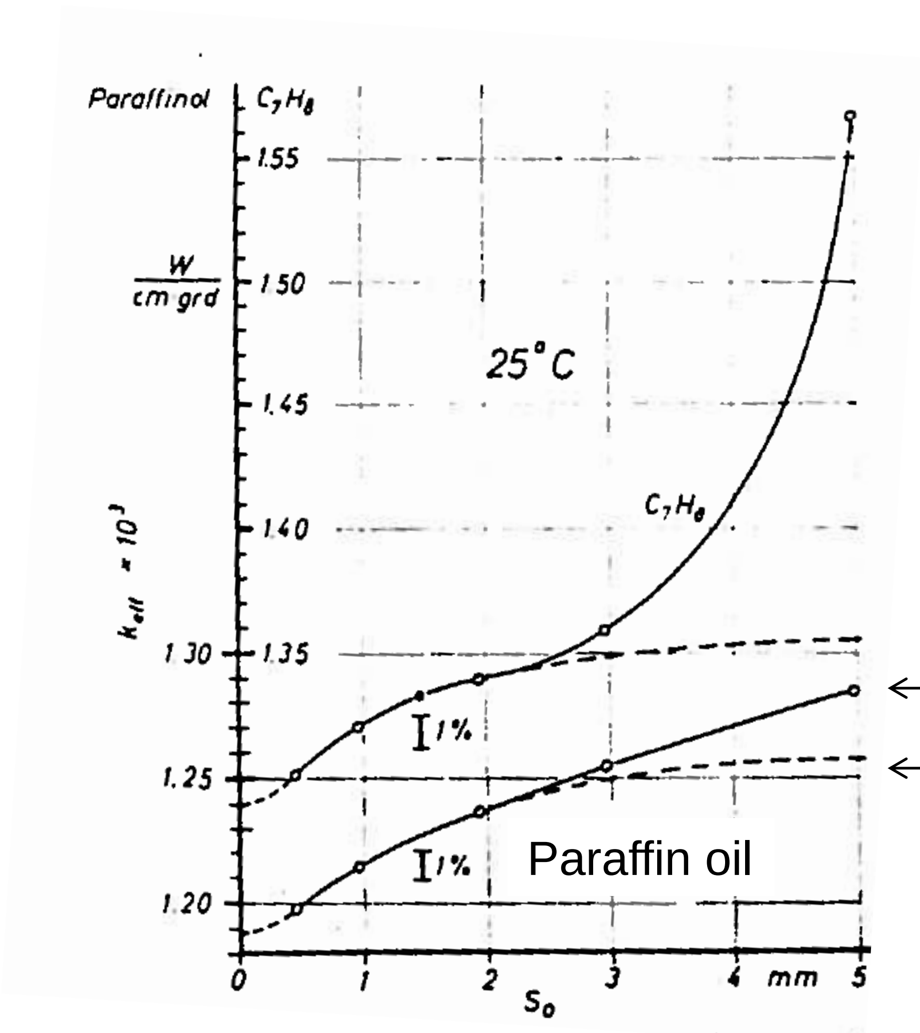
with: d = specimen thickness

STATIONARY GUARDED HOT PLATE METHOD

$$T_h > T_m > T_c$$



STATIONARY GUARDED HOT PLATE METHOD
Some remarks about radiative transfer within paraffins



convection effect

radiation effect (+ 7% !)

Poltz, int. J. Heat Mass Transfer Vol. 8 pp. 609 – 620 (1964)
Thermal Conductivity of Liquids III

DYNAMIC HOT-WIRE METHOD

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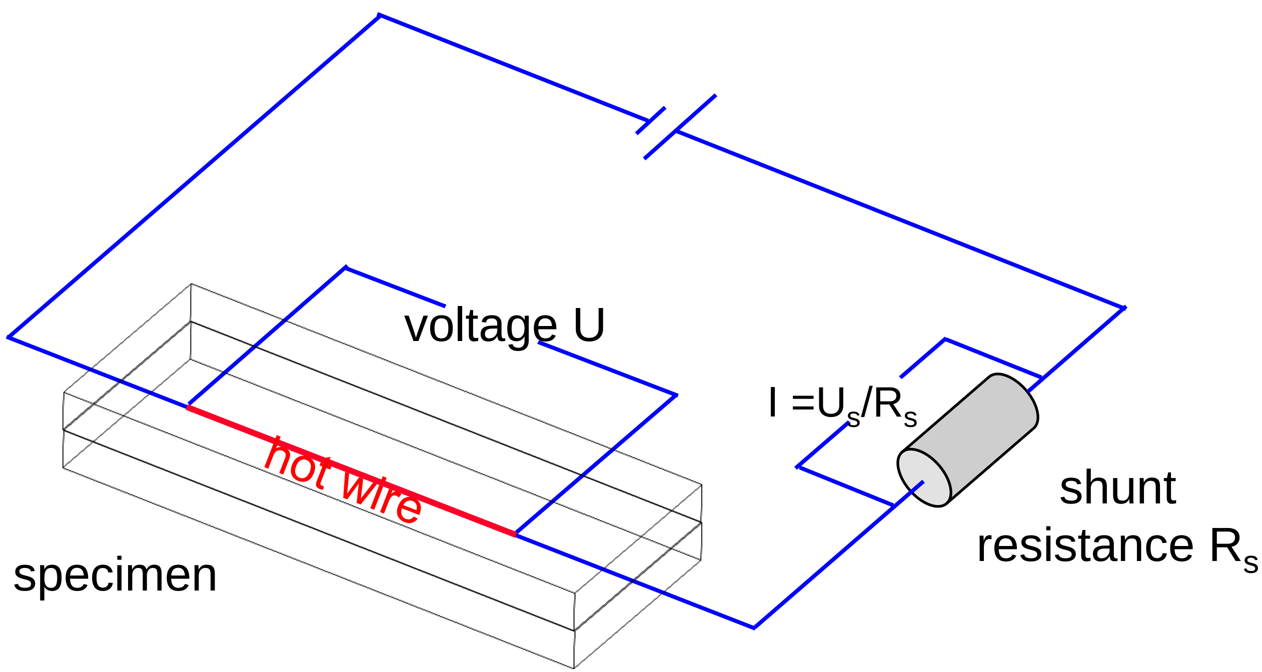
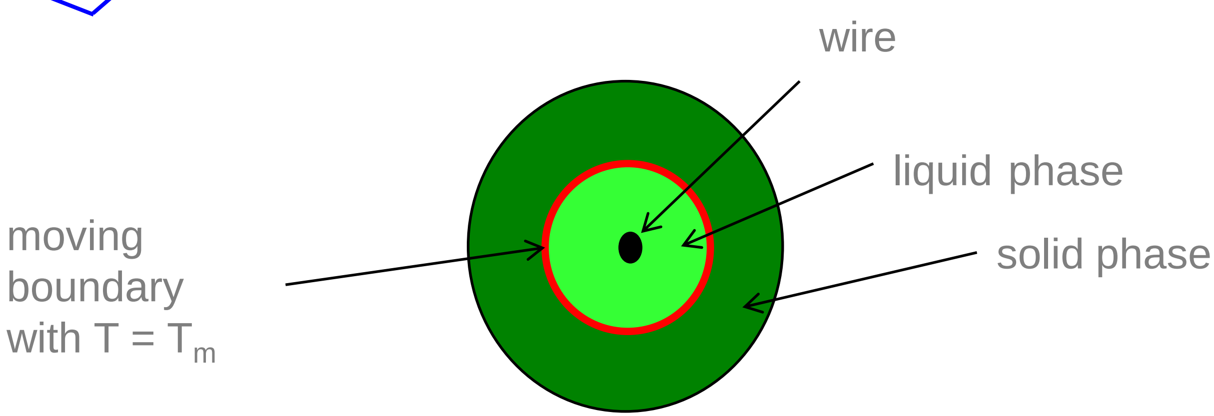
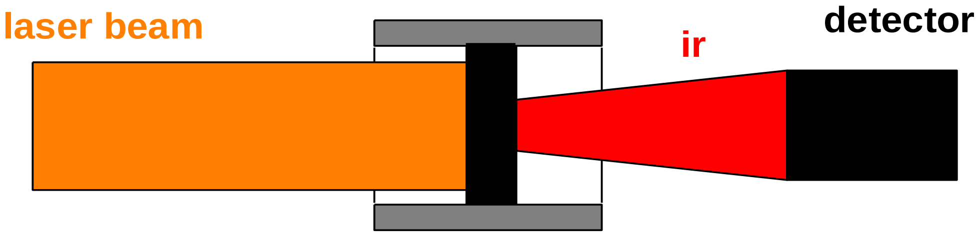


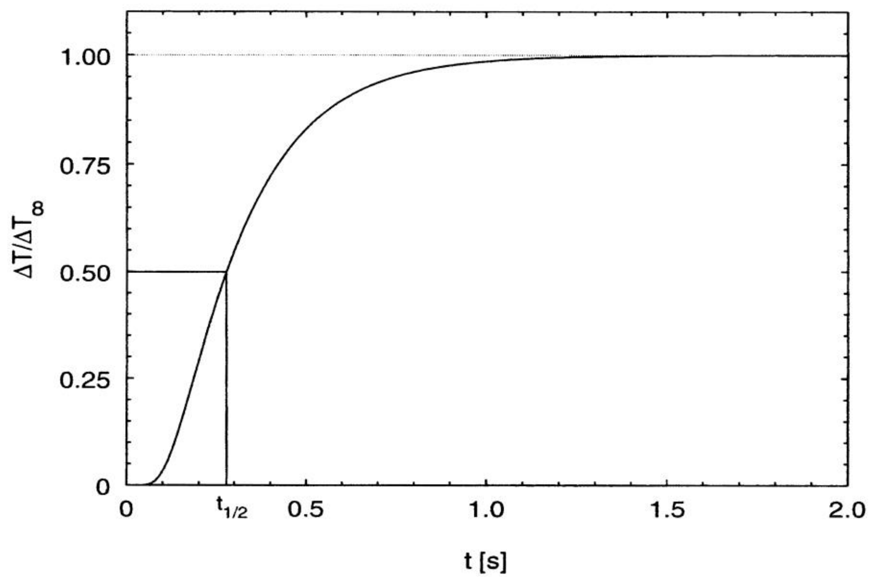


LASERFLASH METHOD

$$\lambda(T) = a(T) \cdot \rho(T) \cdot c_p(T)$$



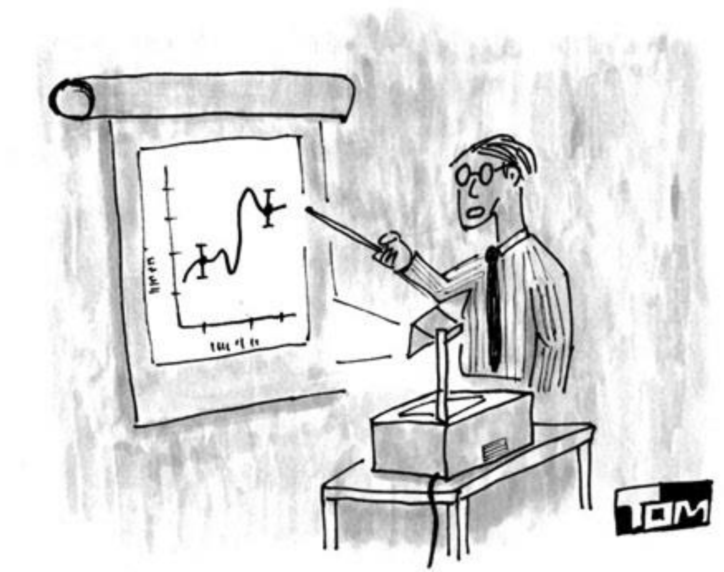
$$a = 1.38 \cdot \frac{l^2}{\pi^2 \ t_{1/2}}$$



What is the result of an evaluation procedure if the underlying working equation meets not the experimental reality?

Facts:

- The working equation considers not the phase transition (in the most cases).
- Fitting algorithms will deliver a best fit solution – in respect to the laws of mathematic – not in respect to the physics.



"WE CAN SEE HERE THAT THE AGREEMENT WITH THEORY IS EXCELLENT"