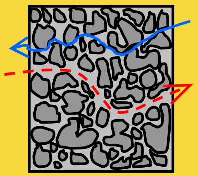
Heat and mass Transfer in superfluid helium through porous Media



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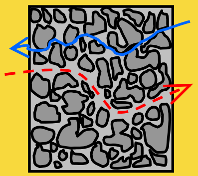
Introduction

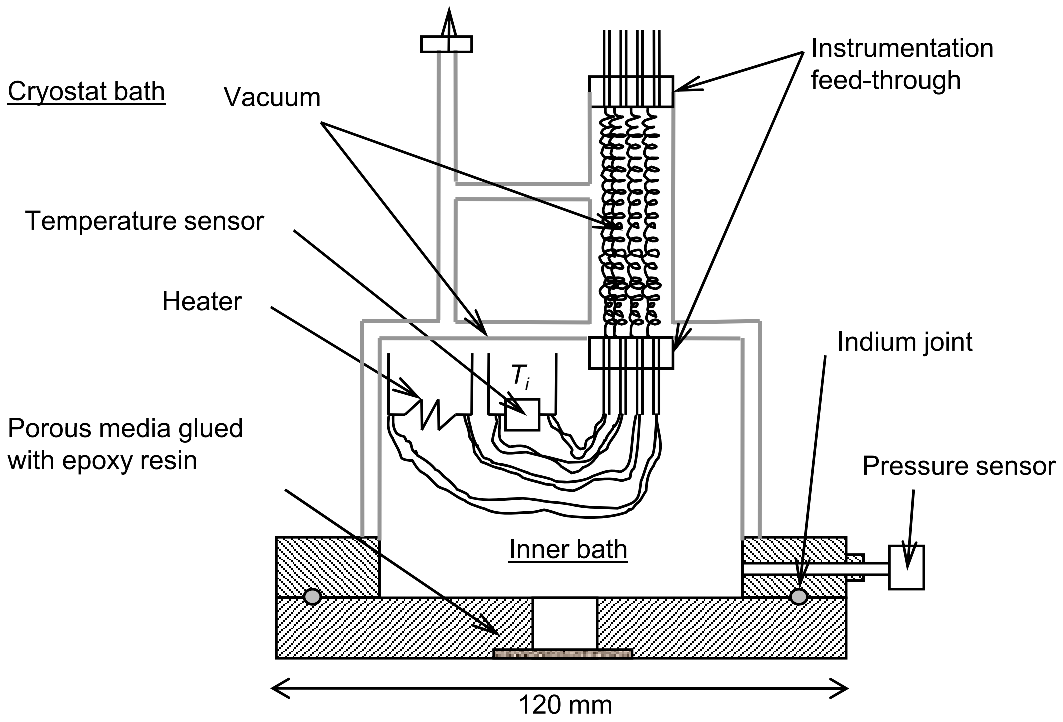
- For the next generation high field magnets, Nb_3Sn is considered
- Higher heat deposition than in current magnets is expected
- Insulation constitutes the main thermal resistance to He II cooling
- New insulation is under development for improved cooling efficiency



- Ceramic materials insulation are investigated as possible candidate
  - good wrapping capability
  - excellent resistance to heat
  - reduce coil fabrication complexity and costs
- Porosity much higher than conventional insulation and this would increase cooling efficiency
- Heat transfer studies on porous media focused on Large *q* and *ΔT* in the steady regime and in the transient regime

Experimental set up (steady state regime)

- The instrumentation is composed
  - Silicon piezo-resistive pressure sensor, two Allen Bradley carbon resistors, heater located in the inner bath

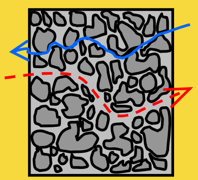


ΔT Sensitivity : ± 20 µK to ± 200 µK, ΔT error : ± 0.2 mK, Q error : 0.5%, Tb regulation ± 1 mK

Samples

- The CSi samples
  - Large average pore diameter
  - Study in the pure Gorter-Mellink regime

- The 97 % pure Al2O3 samples
  - Smaller pore diameter
  - Study in the Landau regime and the intermediate regime (Landau + Gorter-Mellink)



Material	Al_2O_3	CSi#1	CSi#2
Average Pore Diameter (μm)	2	20	10.8
Porosity, ε (%)	32	58	62
Thickness, e (mm)	2, 3 and 4	1.2	1.5
Cross-Sectional Area, A (⟐10^6 m^2)	2 mm : 300 3 mm : 402 4 mm : 305	20.7	16.0

Tortuosity Concept

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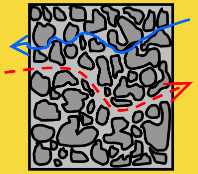
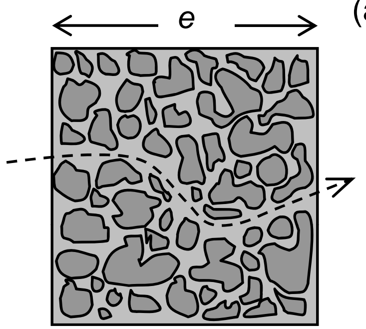


- Average length of the flux line (heat or flow) is longer than the thickness
- $$\omega = \frac{\ell}{e} > 1$$
- In a 1D media, the tortuosity is reduced to a scalar value, ω
- Valid concept only when the heat travels in the fluid phase
  - No heat transfer coupling between the liquid and the solid
- The gradients and effective cross-sectional area

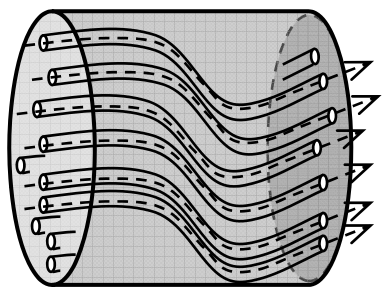
$$\vec{\nabla} T = \frac{dT}{dx} \approx \frac{\Delta T}{\ell} = \frac{1}{\omega} \vec{\nabla} T_e \qquad q = \omega \frac{Q}{\varepsilon A} = \omega q_e$$



(a)

$$\omega = \frac{\ell}{e} > 1$$

$$A_\omega = \frac{\varepsilon A}{\omega}$$



(b)

Landau regime (1/3)

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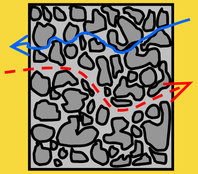
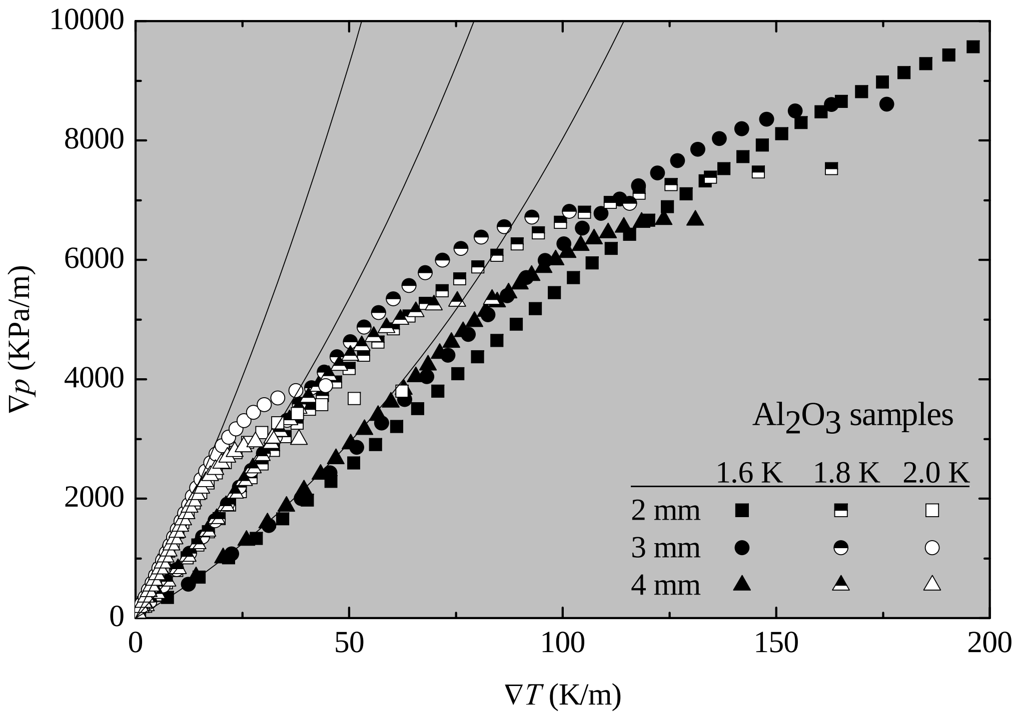


- The pressure gradient is proportional to the temperature gradient

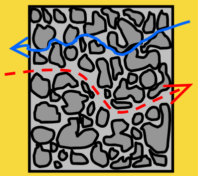
$$\vec{\nabla} p = \rho s \vec{\nabla} T$$

- The experimental data agree with the theory for small gradients
  - Temperature dependent and thickness independent

- Deviation from theory : Apparition of vortices (superfluid turbulence)



Landau regime (2/3)



- Pressure gradient causes a laminar flow and the Darcy law is valid

$$\vec{\nabla} p_e = \omega \mu_n \frac{\vec{v}_n}{K_e}$$

- Heat flux q related to v_n by $q=\rho s T v_n$ in ZNMF

- Darcy law transformed in a qe-ΔTe relation and integrated

$$q_e = K \frac{1}{e} \int \frac{(\rho s)^2 T}{\mu_n} dT$$

- We use an averaged permeability $K=K_e/\omega^2$
  - Not clear if the Darcy law is intrinsically a function of e or ℓ
  - Not an unpardonable mistake since heat transfer depends on K_e *and* ω

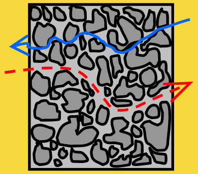
Landau regime (3/3)

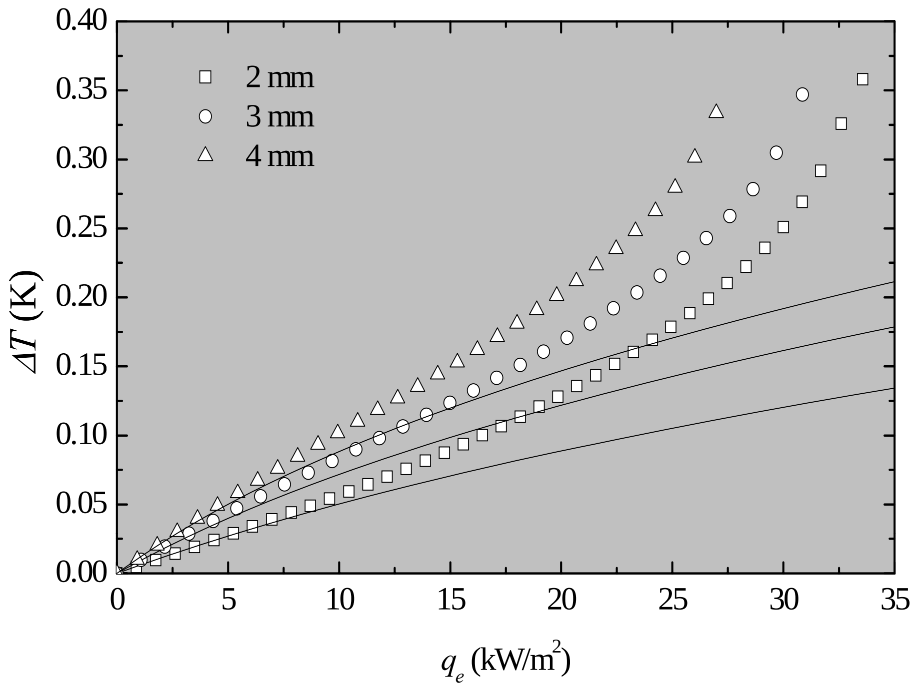
- Typical results at 1.8 K and permeability *K* between 3.6 and 3.8 10^{-14} m^2

- Cross-sectional area used in q_e for the 2 mm sample was reduced from 4.5 to 3.0⟐10^{-4} m^2 to match the ∀*p-qe* and ∀*T-qe* curves of other samples

- We have no explanation to this other than evoking a partial plug

- ∀*T*-∀*p* data agree with the theory, modification reflects the phenomenon

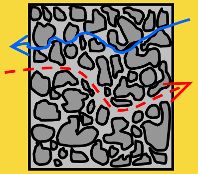


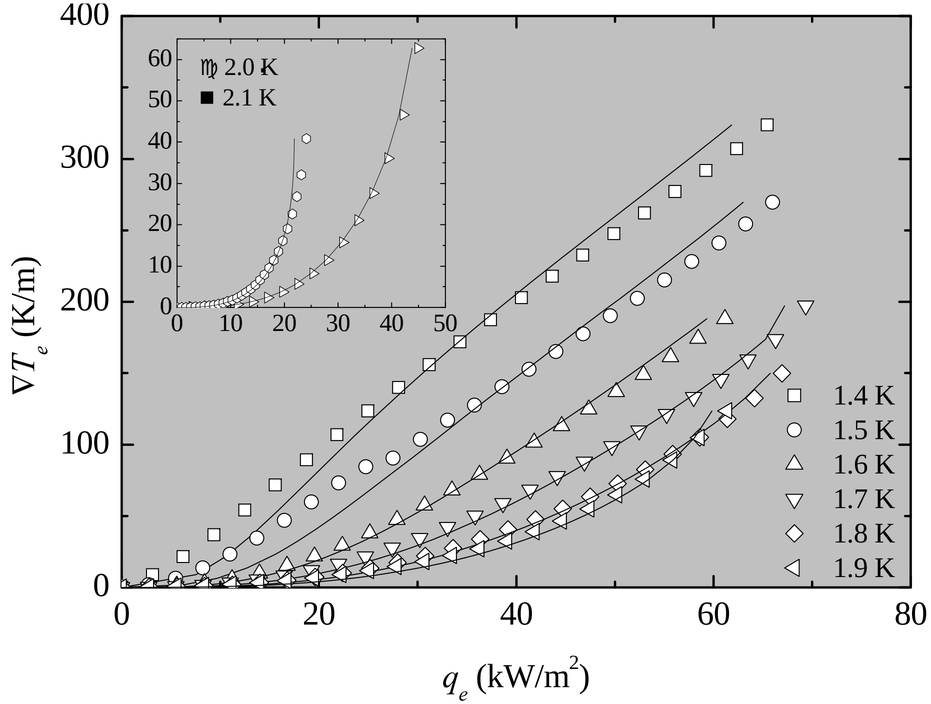


Pure Gorter-Mellink regime

$$q_e^{\,3} e = \frac{1}{\omega^{4/3}} \int \frac{s^4 (\rho_s T)^3}{A \rho_n} dT$$

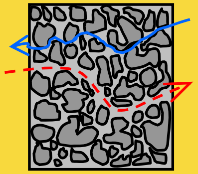
- 10% average relative error (12% at 1.4 K and 7% at 2.1 K)
- Underestimation of ∇T_e at low *q* and overestimation at high *q*
- Estimated ∇T_e can be 50% of the data at low *q* and 90% at higher *q* near T_λ





Tortuosity, ω

- Tortuosity constant within 10% for both samples
- Concept of 1D tortuosity is valid in ZNMF
- ω is found to be lower at 2.1 K for both samples
  - Accuracy of the physical properties of He II close to T_λ
  - He II Equivalent conductivity is dropping

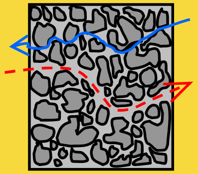


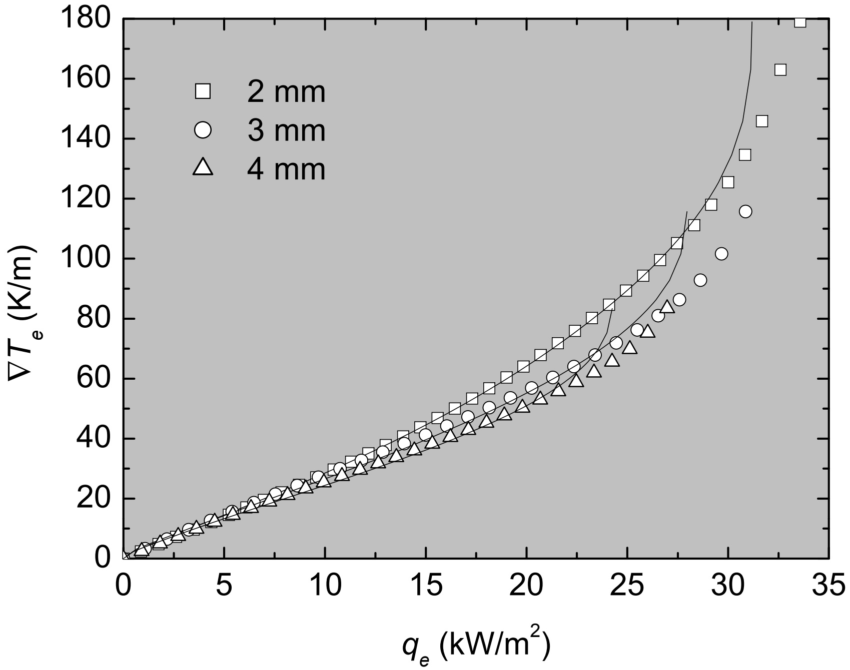
Tortuosity, ω								
Tb (K)	1.4	1.5	1.6	1.7	1.8	1.9	2.0	2.1
CSi#1	1.71	1.74	1.75	1.77	1.79	1.81	1.78	1.67
CSi#2	1.58	1.61	1.61	1.63	1.65	1.65	1.61	1.49

Intermediate regime (1/2)

$$\left|\vec{\nabla} T_e\right| = \frac{1}{K}\frac{\mu_n}{(\rho s)^2 T} q_e + \omega^4 \frac{A\rho_n}{s^4(\rho_s T)^3} q_e^{\,3}$$

- Minimizing $\delta=|(q_{exp}-q_{th})/q_{th}|$ adjusting ω with K identical for all thickness
- δ between 5 and 10% over the entire q-range
  - δ can be as high as 50% at low q and 10% at high q
- At low q GM term should be null since (q_c)





Intermediate regime (2/2)

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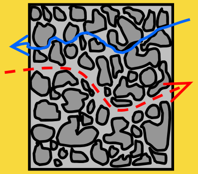
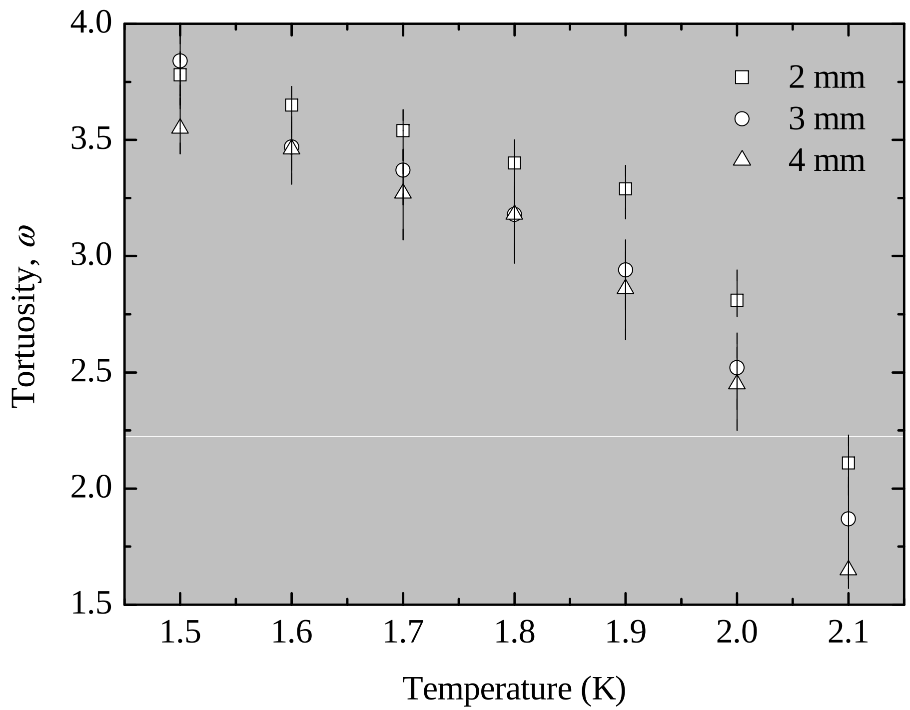


- Fair agreement between model and data
  - Extracted ω decreases with T
  - 10% permeability K variation induces 5% tortuosity ω variation

- Model fails to predict a constant ω over the entire range of temperature

- For T≤1.9 K ω=3.4±0.4, which corresponds to 10% variation



Experimental set up (transient regime)

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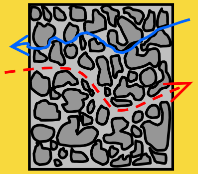
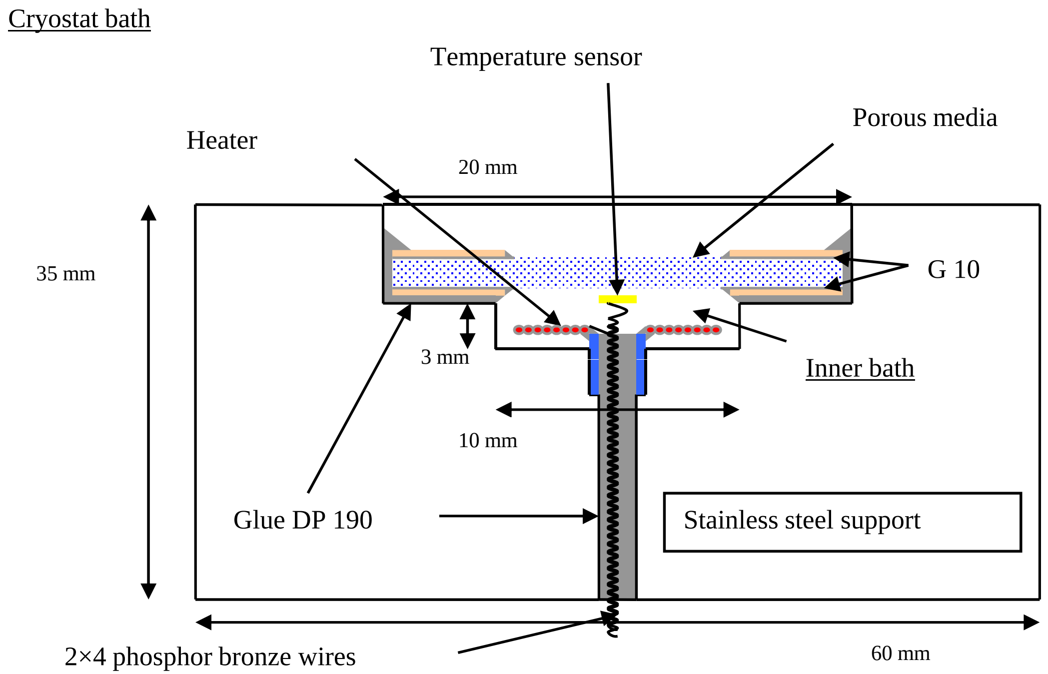
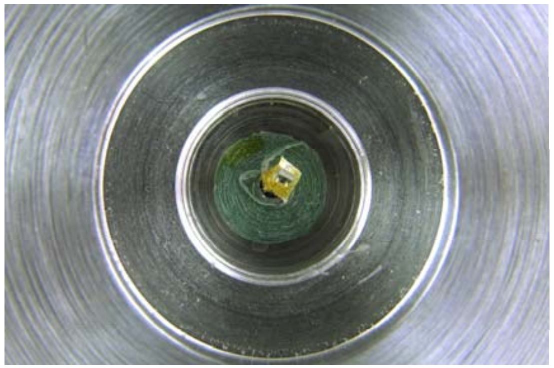
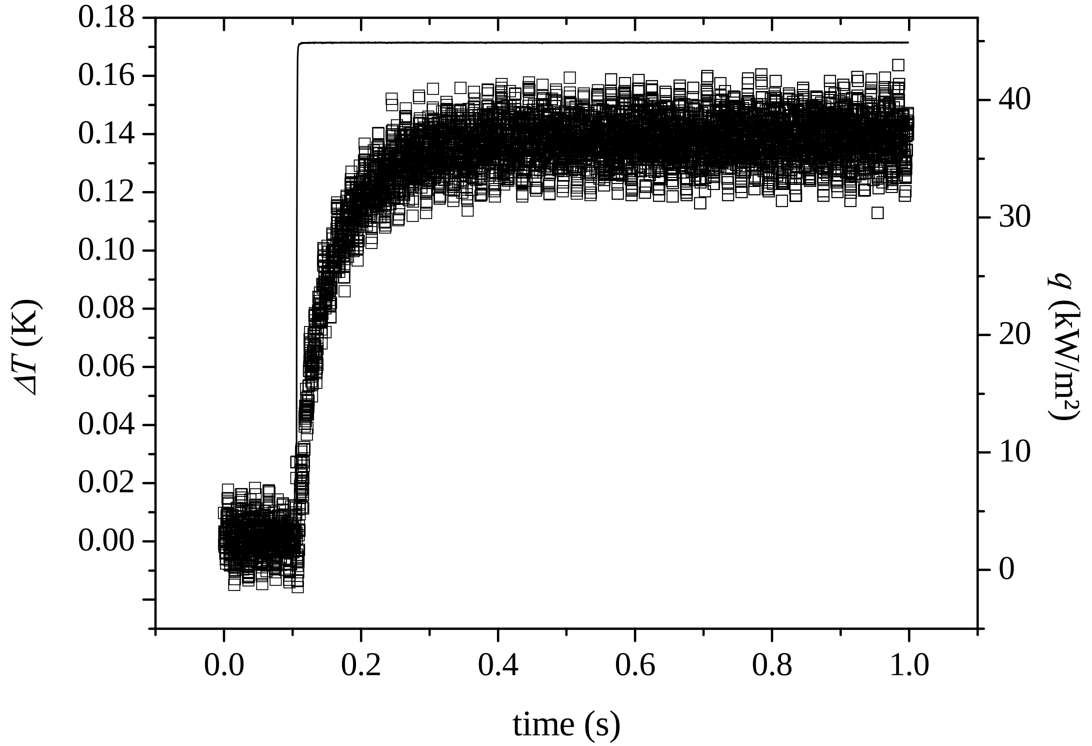


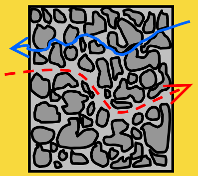




Observed phenomena

Evolution of the inner bath temperature with time @ 1.8 K

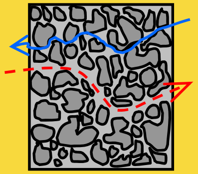




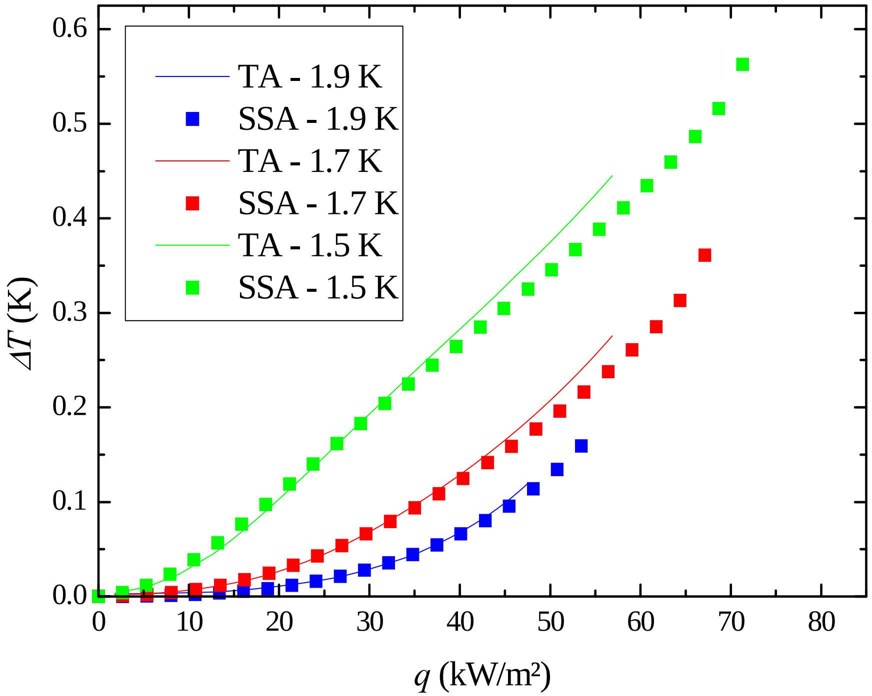
•noise signal of 40 µV for the voltage of the temperature sensor
•signal-noise ratio comprises between 25 and 39 -> 30 mK fluctuation

► need to reduce noise pick up on our set-up

Steady state regime

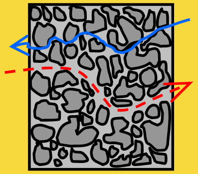


- For same ΔT , q measured with the Transient Apparatus is 6.5 % higher than with the Steady-State Apparatus

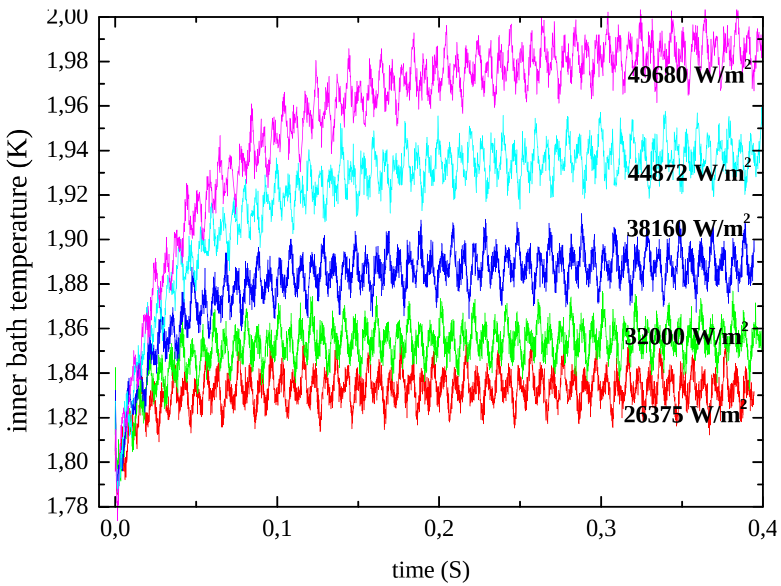


•Conduction looses through the wiring: 1.6 μW for TA and 12 μW for SSA
•Gluing method
•Position of the temperature sensor (3 % of the cross sectional area blocked)
➢Perturbation of the heat flux lines?
➢Perturbation of the normal velocity field?

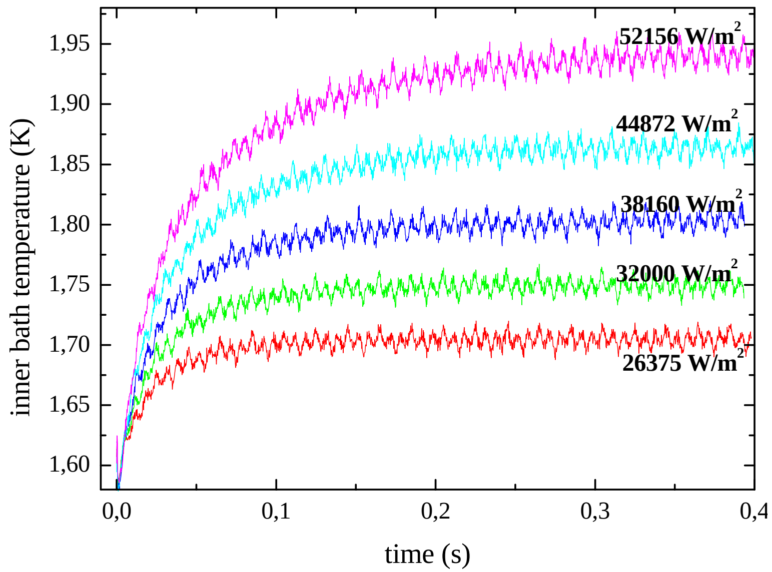
Results



Bath temperature: 1.8 K



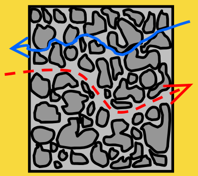
Bath temperature: 1.6 K



Experimental time constant (τ in ms) where 3τ is the time necessary to reach 95 % of the ΔT correspondent to the steady state transfer regime

Q (W/m²)	26375	32000	38160	44872	50000
1.8 K	25	38	48	75	92
1.6 K	32	42	52	60	78
1.4 K	37	40	50	55	63

Analysis (1/3)



Heat flux in the pure Gorter Mellink regime

$$q = -\left(f(T) \frac{\partial T}{\partial x} \right)^{\frac{1}{3}}$$

Combining this with the equation of energy conservation

$$\frac{\partial T}{\partial t} = \frac{1}{\rho(T) C_p(T)} \frac{\partial}{\partial x} \left(f(T) \frac{\partial T}{\partial x} \right)^{\frac{1}{3}}$$

The heat flux can be rewritten

$$q = -\frac{f(T)}{q^2} \frac{\partial T}{\partial x}$$

effective thermal conductivity *keff=f(T)/q²*

By analogy with the heat equation for a solid and considering that the variation of temperature is small enough to consider *f* constant

Effective thermal diffusivity *Deff=f/(ρCpq²)*

Diffusion thermal time constant

$$\tau_D = \frac{L^2}{D}$$

Analysis (2/3)

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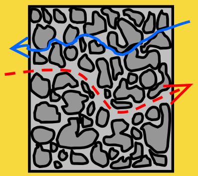


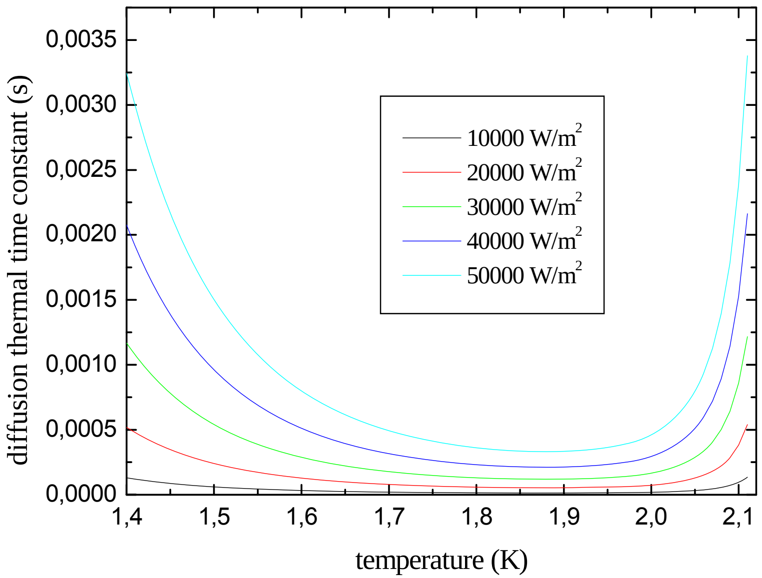
Two “volumes” can influence the time constant

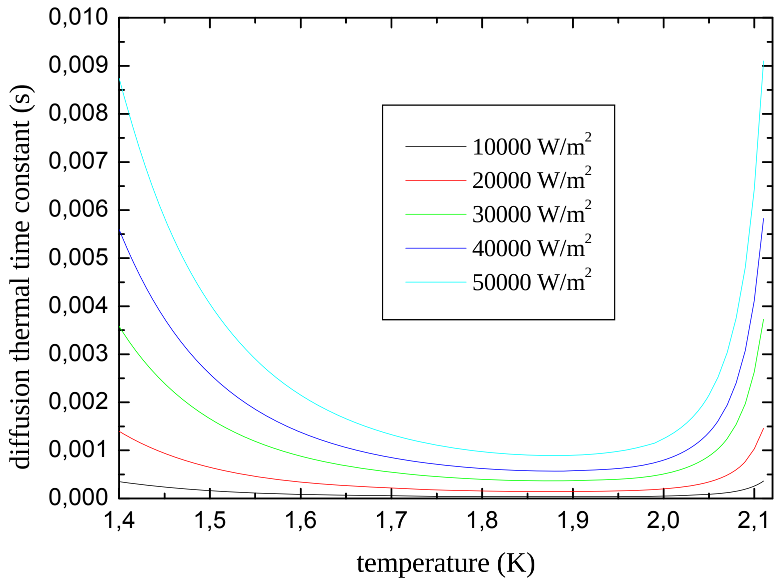
Inner bath volume

$$\tau_{D_{innerbath}} = \frac{L^2 q^2 \rho C_p}{f}$$

porous media volume
Tortuosity concept

$$\tau_{D_{PorousMedia}} = \omega^{\frac{10}{3}} \frac{e^2 q^2 \rho C_p}{f}$$

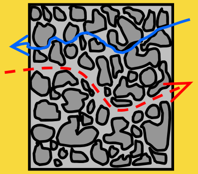




Considering the sum of the two diffusion thermal time constant of the porous media and of the inner bath, from 1.4 K to 2.1 K, the calculated time constants are very smaller compared to τ measured from experimental results

Analysis (3/3)

- Heat transfer is considered in 1D and the q perpendicular to the cross section area
  - Diffusion in the ”dead volumes” influence the response time?
  - Calculation of the maximum thermal time constant is still insufficient to explain the response time



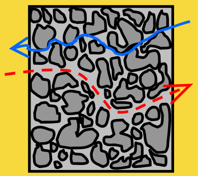
►Heat equation of He II is not sufficient to model the heat transfer of He II through porous media

- Diffusion process is slower in the porous media than in bulk He II due to the interaction with the matrix

- Development of the turbulence at the pore scale?

- Behavior of He II well described by the two-fluids model
  - Need to consider the fluid mechanics equations at the pore size scale?
  - Validation of a heat transfer model through porous media in He II

Conclusion



- In a pure Gorter-Mellink regime (pore diameter 10-20 µm)
  - Data fitted with a 1D tortuosity concept to within 10% in average
  - Evidence that the ω concept can be applied ZNMF in porous media
- In Landau regime (pore diameter 2 µm)
  - More work is needed to analyze the temperature dependency and the validity of the Darcy law
- In the intermediate regime
  - The model including Landau and GM regimes remains insufficient to predict correctly the data over the entire range of temperature
  - but up to 1.9 K, K constant within 10% variation.
- In the transient regime
  - need some improvement to reduce the problem of noise
  - Heat equation of He II in the Gorter-Mellink regime is not sufficient to understand the experimental results
  - Need to consider the two fluids model to understand the fluid movement in the porous media and to find a model at the porous media scale.