The attached slides were presented at following talks:

N. Fries, M. Dreyer; Capillary transport of cryogenic liquids in porous structures; Space Cryogenics Workshop; Arcadia, California; June 2009.

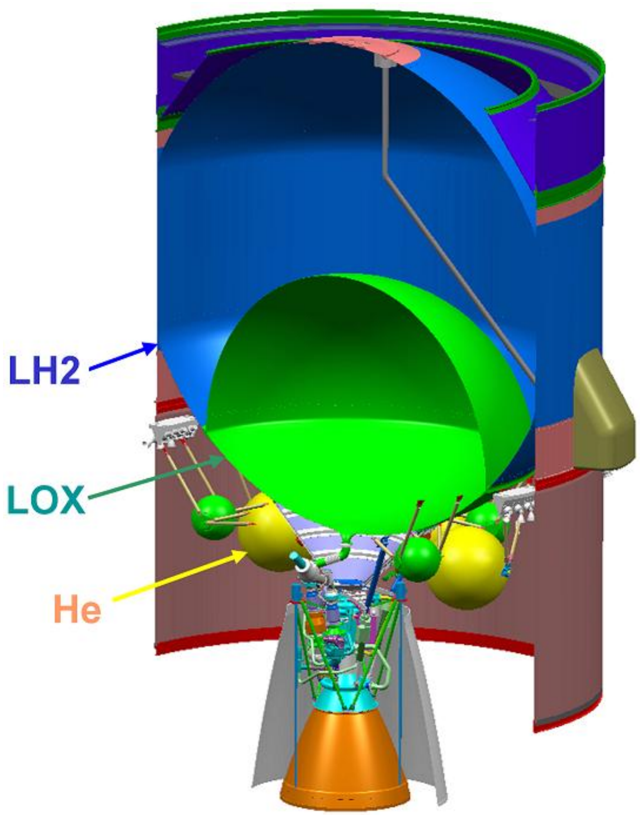
N. Fries, M. Dreyer; Capillary transport of cryogenic liquids in porous structures; International Cryogenic Engineering Conference; Tucson, Arizona; June 2009.

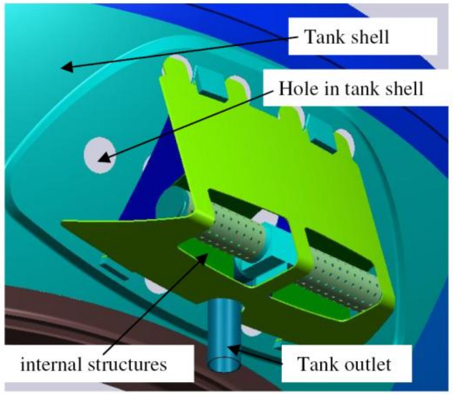
Capillary transport of cryogenic liquids in porous structures

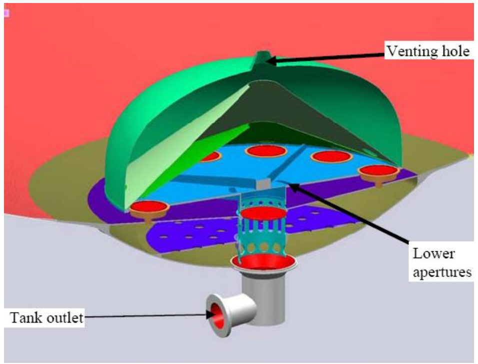
N.Fries and M.Dreyer

Center of Applied Space Technology and Microgravity (ZARM), Bremen, Germany

Porous media in propellant management







Cryogenic upper stage (projected ESCB)

Images : ESA & Behruzi (Astrium)

Porous materials

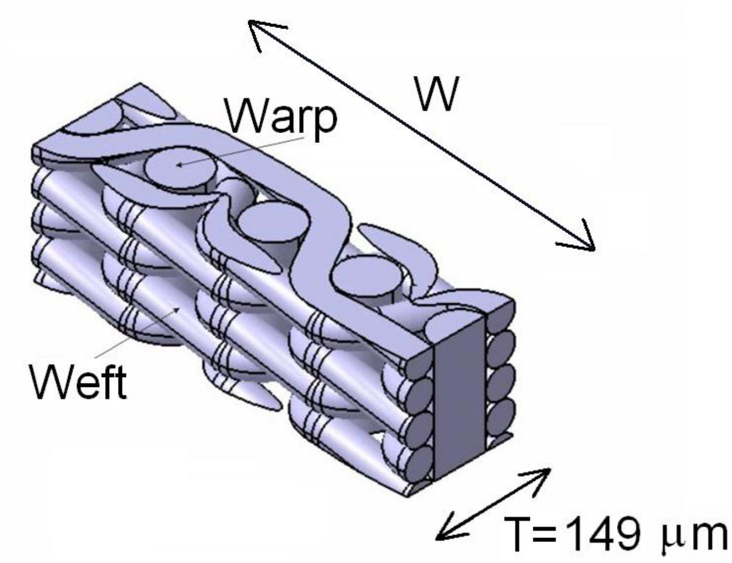
→ allow liquid to enter but block out gas (bubble point)

Metallic Screen

e.g. Dutch-Twilled-Weave

(DTW) 200 x 1400

Porosity 0.24

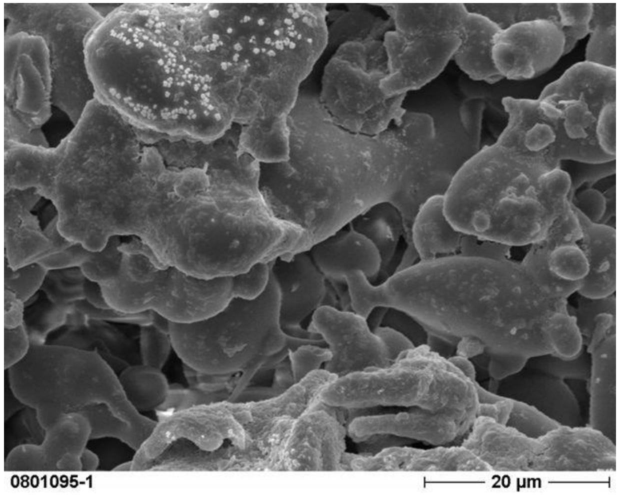


Glass filter frit

Off the shelf / industrial product

Available with several different pore sizes

Inexpensive, machinable



F. Krause: Frit P5

Why investigate capillary transport?

- Capillary rise during initial tank filling
- Refilling of cryogenic PMDs after coast phases
- Capillary transport of cold liquid to propellant tank components which are to be cooled
- Cryogenic heat pipes

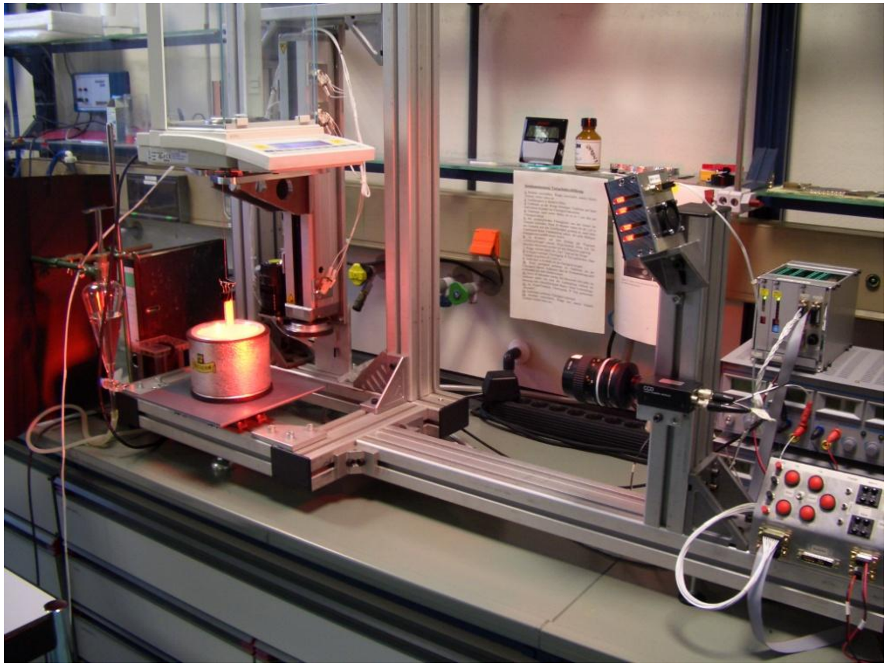
Due to handling reasons: LN2 instead of LH2 and LOX

Capillary rise of cryogenic liquids

Short Dewar flask

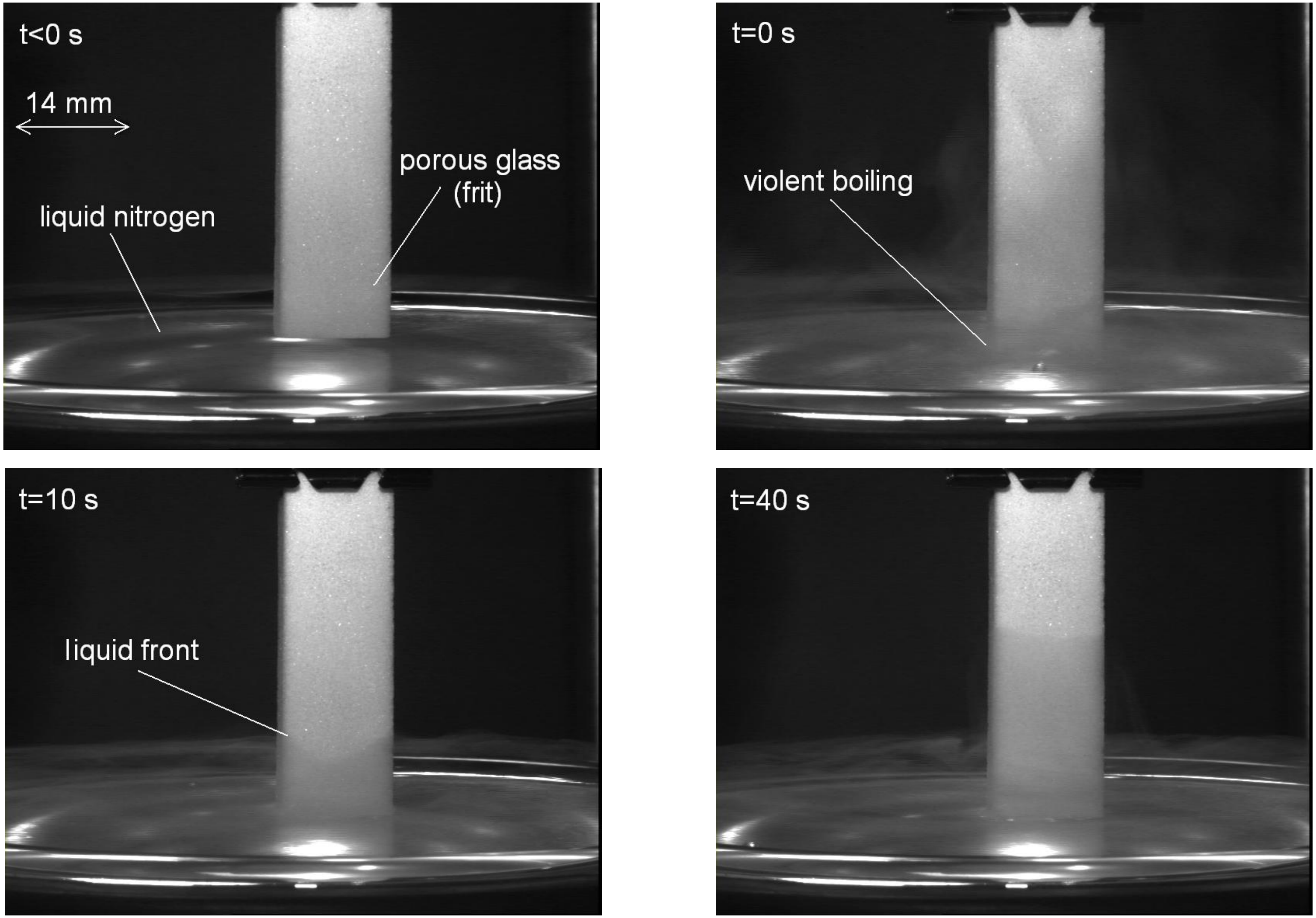
+ Optical access

- Thermal environment



Capillary rise of cryogenic liquids

PoreNet
GRADUIERTENKOLLEG



Frit P2 with LN2

Capillary rise of cryogenic liquids

Video clip

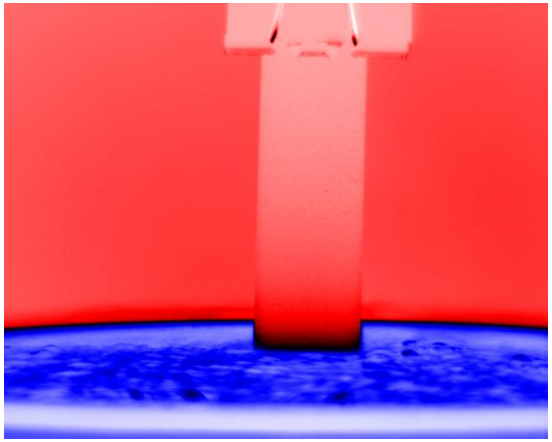
PoreNet GRADUIERTENKOLLEG

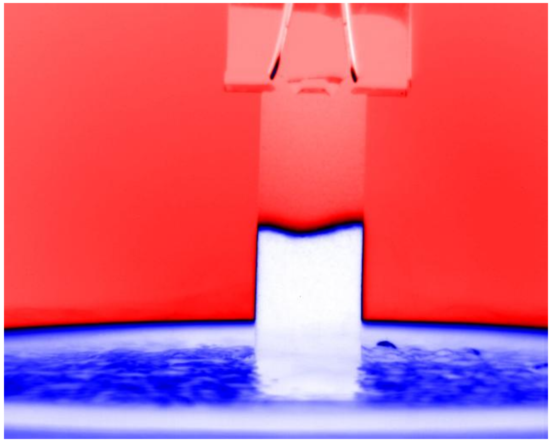
Infrared camera FLIR SC 7600

640 x 512 resolution
14 bit dynamic range
1.5 – 5.1 µm wavelength (2.5 – 5.0 µm due to germanium optics)

Video clips:

1. IR
2. Visible and IR





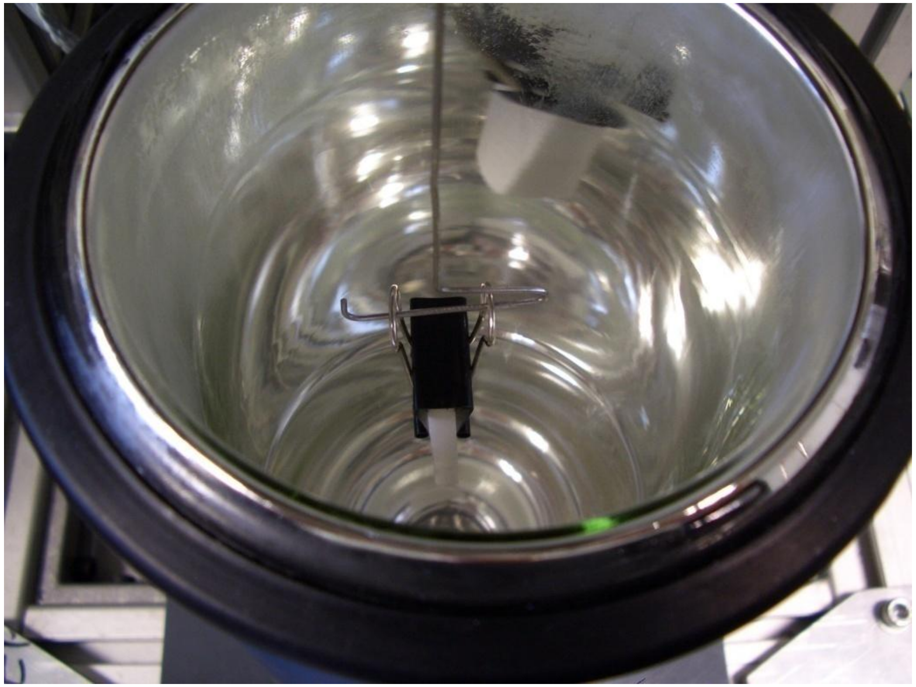
Color indicates photon count of pixel

Cooling the sample before contact

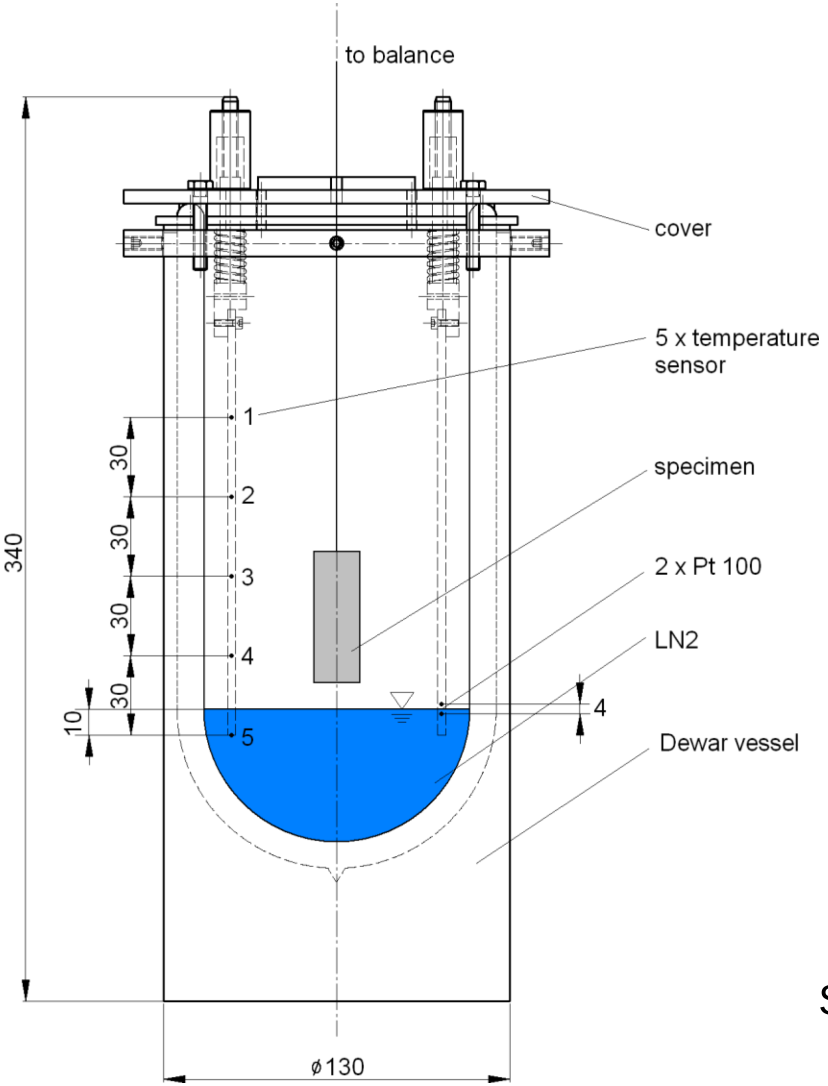
Deep Dewar flask

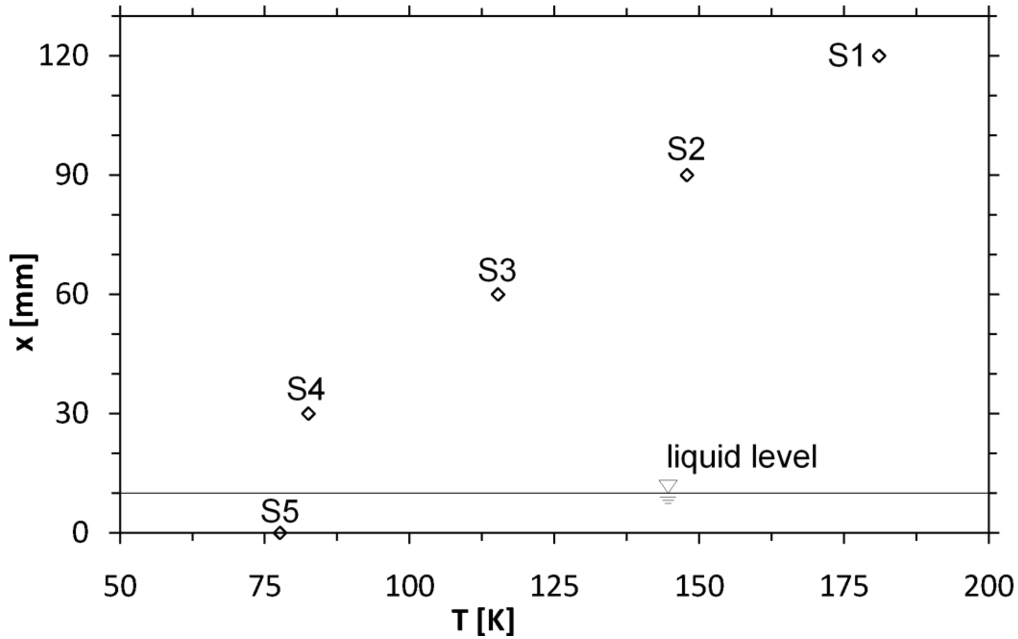
+ Thermal environment

- Optical access



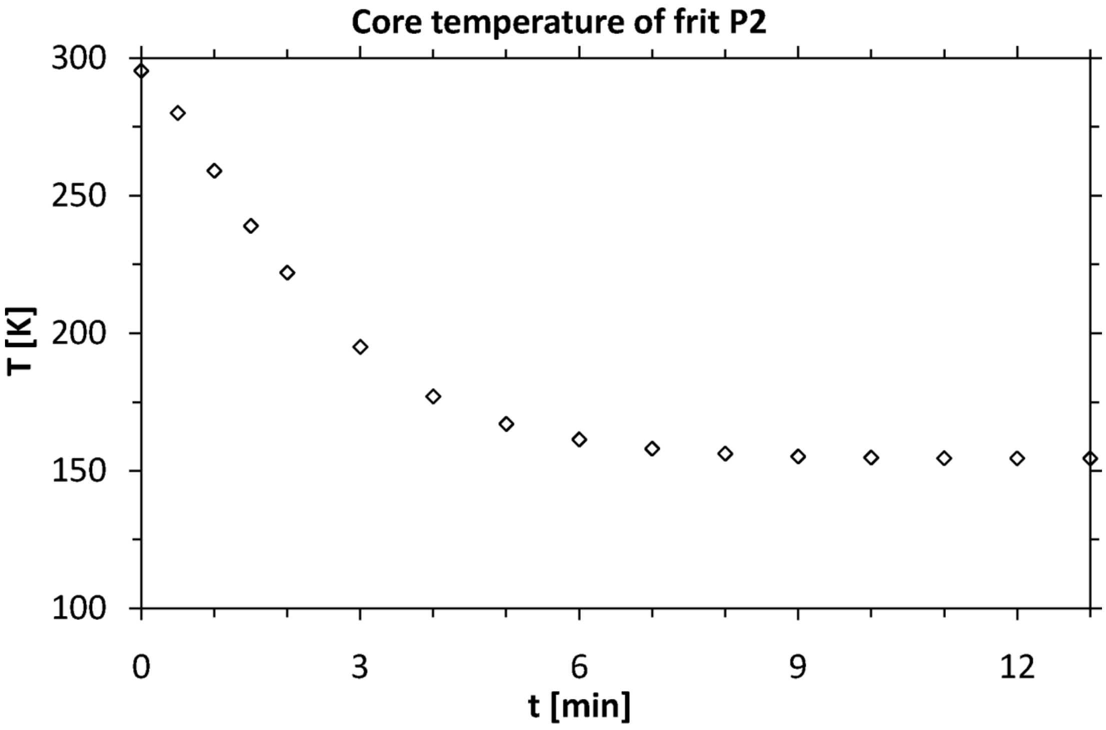
Experimental setup

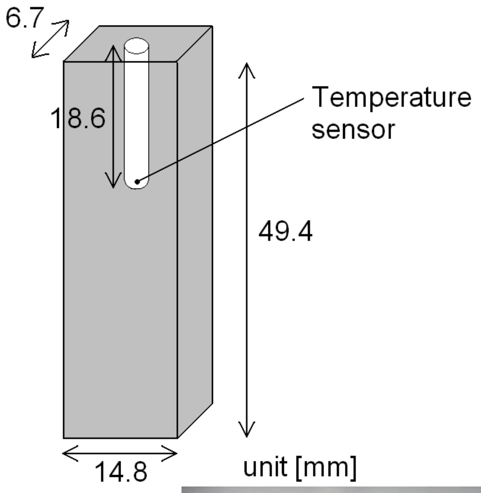


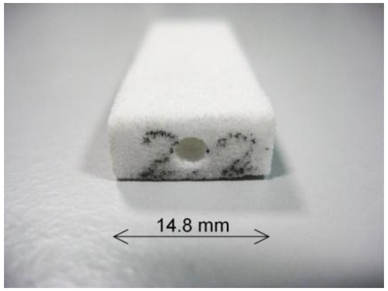


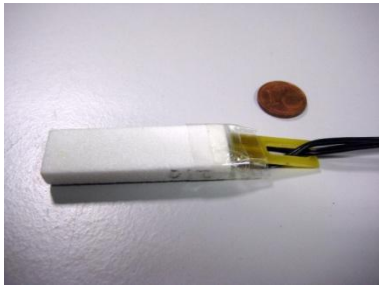
Sensors: rack with 5 LakeShore DT-670 Silicon Diodes

Chilldown in cold gas









Mass of LN2 in frit P5

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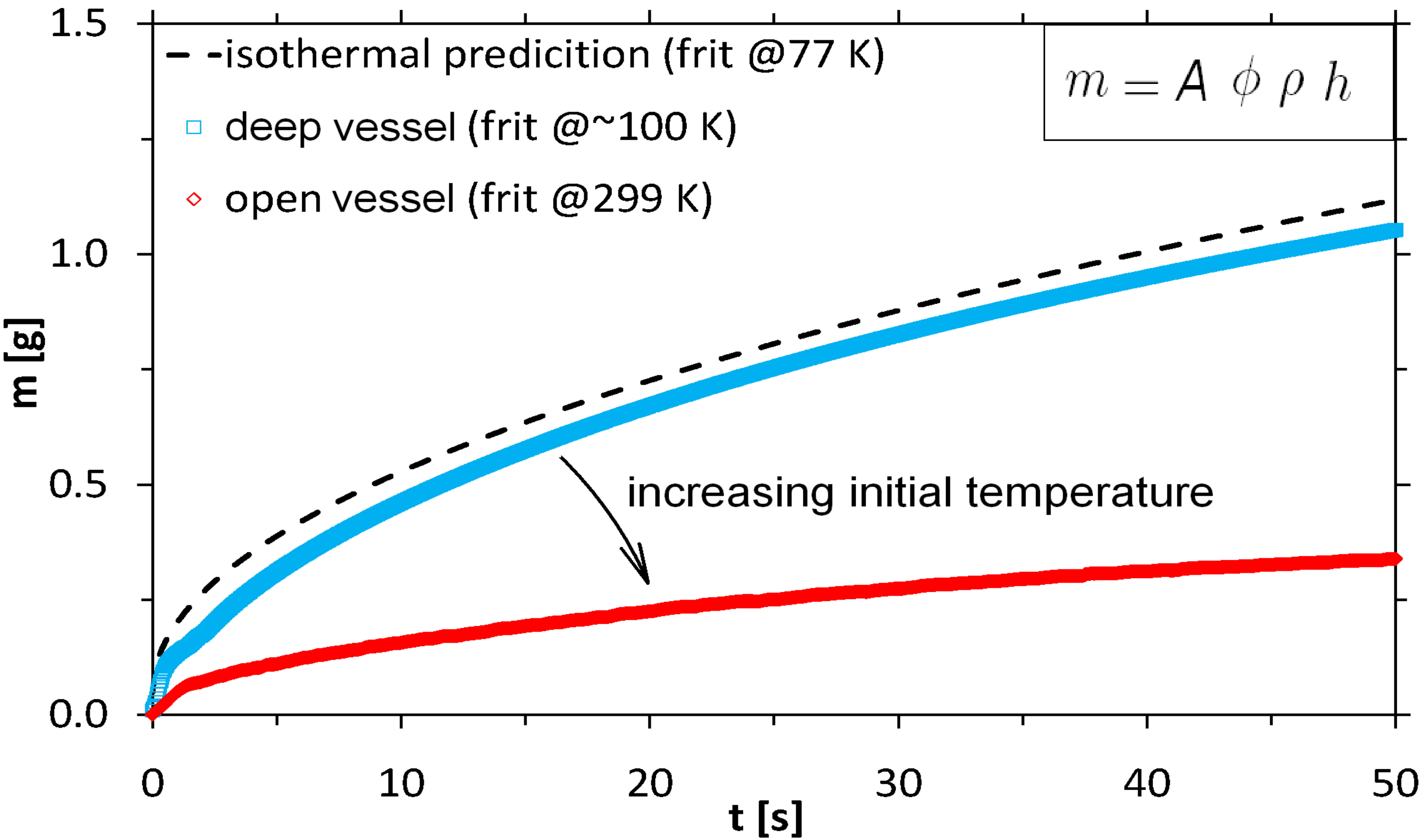
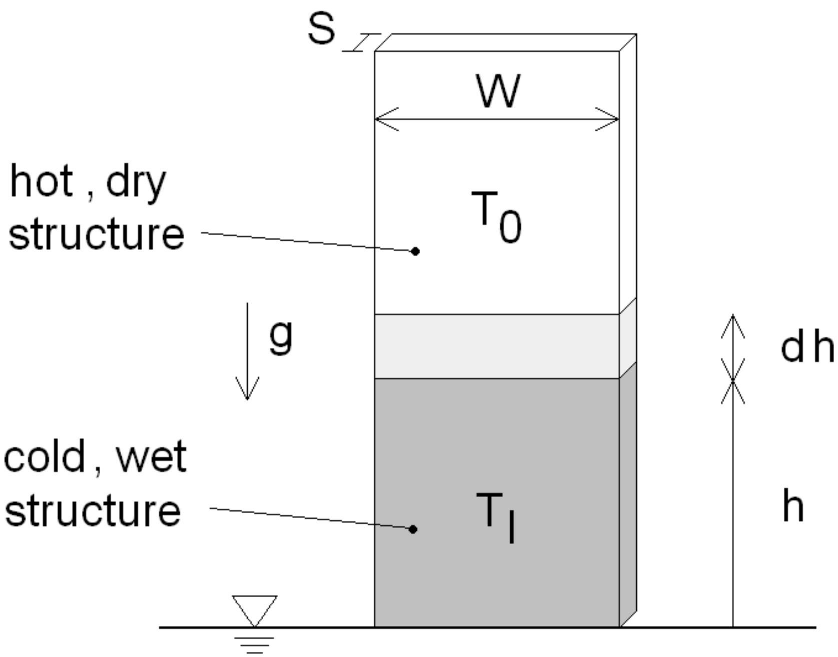


Model



Main assumptions:

- No heat conductance in the porous medium
- Adiabatic environment
- Liquid at saturation temperature

$$\Delta T = T_0 - T_l$$

$$\dot{V}_s = WS(1-\phi)\dot{h}$$

Energy balance

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Heat to cool the porous structure

$$\dot{Q} = \dot{V}_s \rho_s c_s \Delta T$$

Heat of evaporation

$$\dot{Q} = \dot{V}_l \rho_l \Delta H_v$$

→ the volume of evaporated LN2 can be calculated

Mass balance

The rise is slowed down by a factor of $\frac{1}{1+\delta}$

$$\delta = \frac{(1-\phi)c_s\rho_s\Delta T}{\phi\Delta H_v\rho_l}$$

Classic rise models:

N. Fries, K. Odic, M. Conrath, M. Dreyer; The Effect of Evaporation on the Wicking of Liquids into a Metallic Weave; Journal of Colloid and Interface Science 321: 118-129, 2008.

Comparison with experiments

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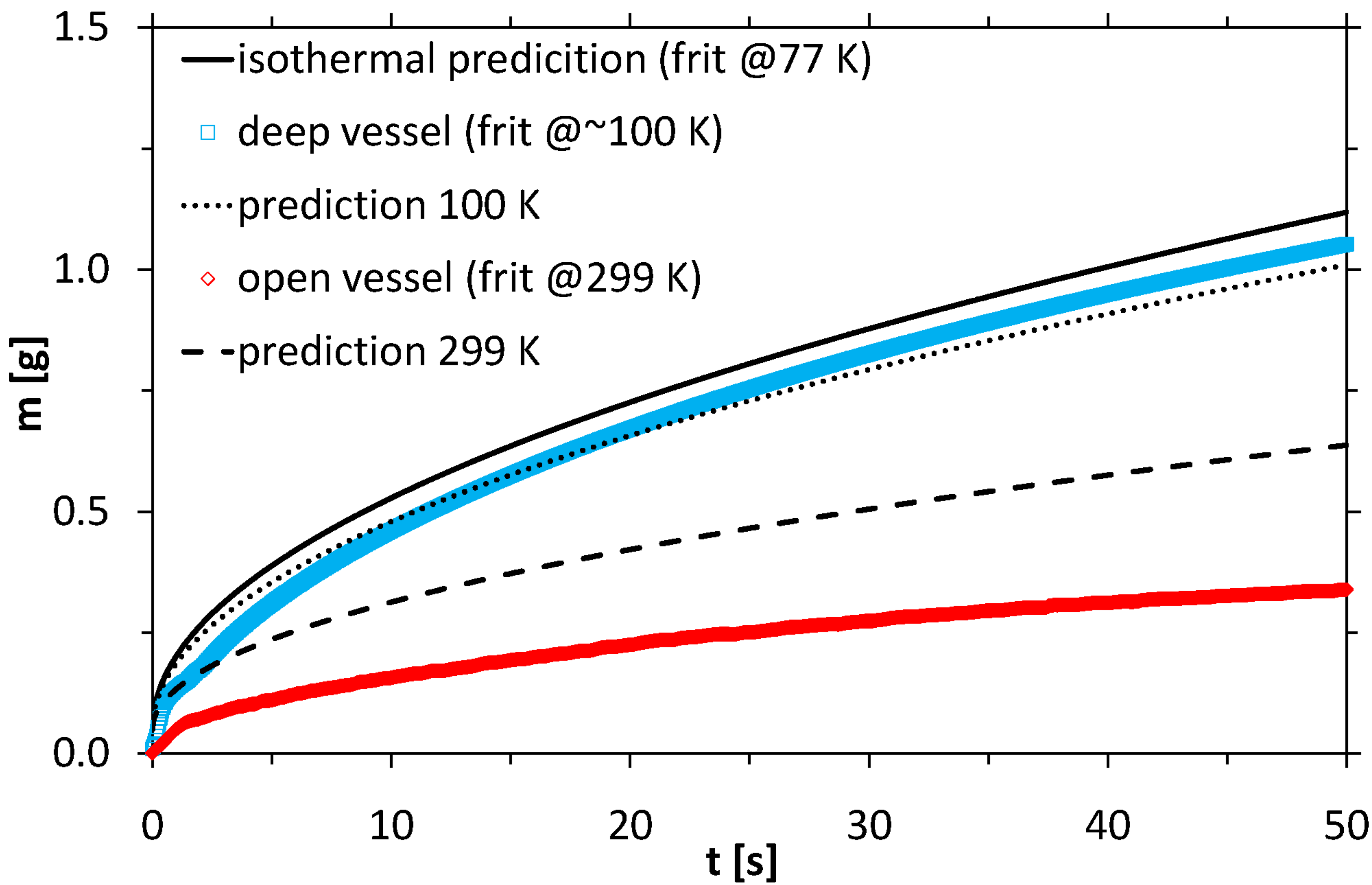

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Conclusions

- Experiments are performed to study the capillary rise of liquid nitrogen in porous media.
- Capillary rise can be observed using mass recordings, and optical methods in visible light and infrared.
- The higher the initial temperature of the structure, the slower the capillary rise process.
- This is described by our model qualitatively.
- More research needs to be conducted to fully understand the processes.

Acknowledgement

Funding by the DFG through Research Training Group 1375 PoreNet is gratefully acknowledged.

Many thanks to the great staff at ZARM for support:

- F. Ciecior
- P. Prengel
- R. Mairose
- H. Faust
- E. Frank
- M. Meistering

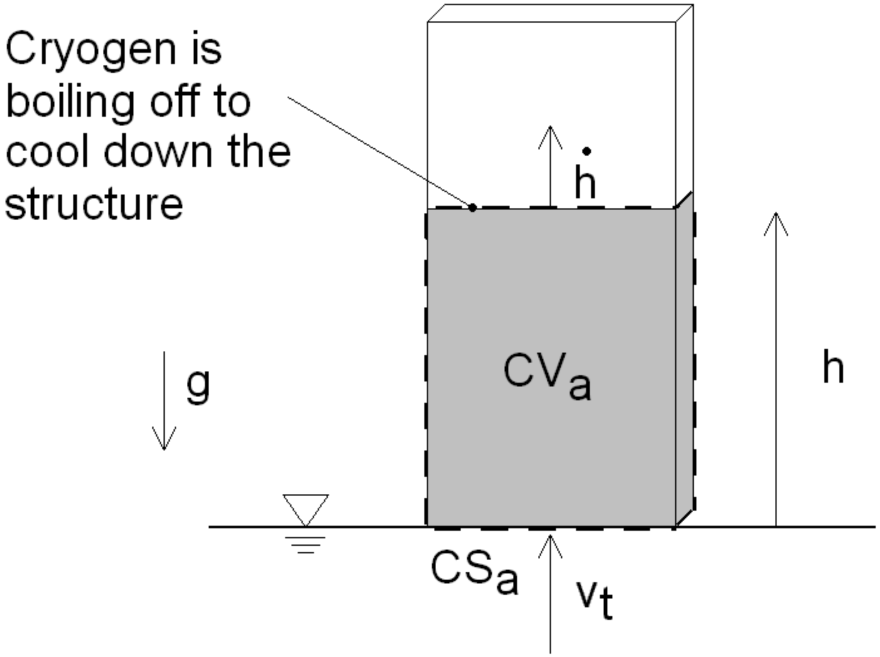

Thank you for your attention!
Do you have questions?

Flow velocity in the structure

$$\left(\frac{dm}{dt}\right)_{syst} = 0 = \frac{d}{dt}\left[\iiint_{CV_a} \rho_l dV_a\right] + \iint_{CS_a} \rho_l(\boldsymbol{v_{rel}} \cdot \boldsymbol{n}) dS_a$$

$$v_t = \dot{h} + \frac{\dot{V}_l}{WS\phi} = (1+\delta)\dot{h}$$

$$\delta = \frac{(1-\phi)c_s\rho_s\Delta T}{\phi\Delta H_v\rho_l}$$



Momentum balance

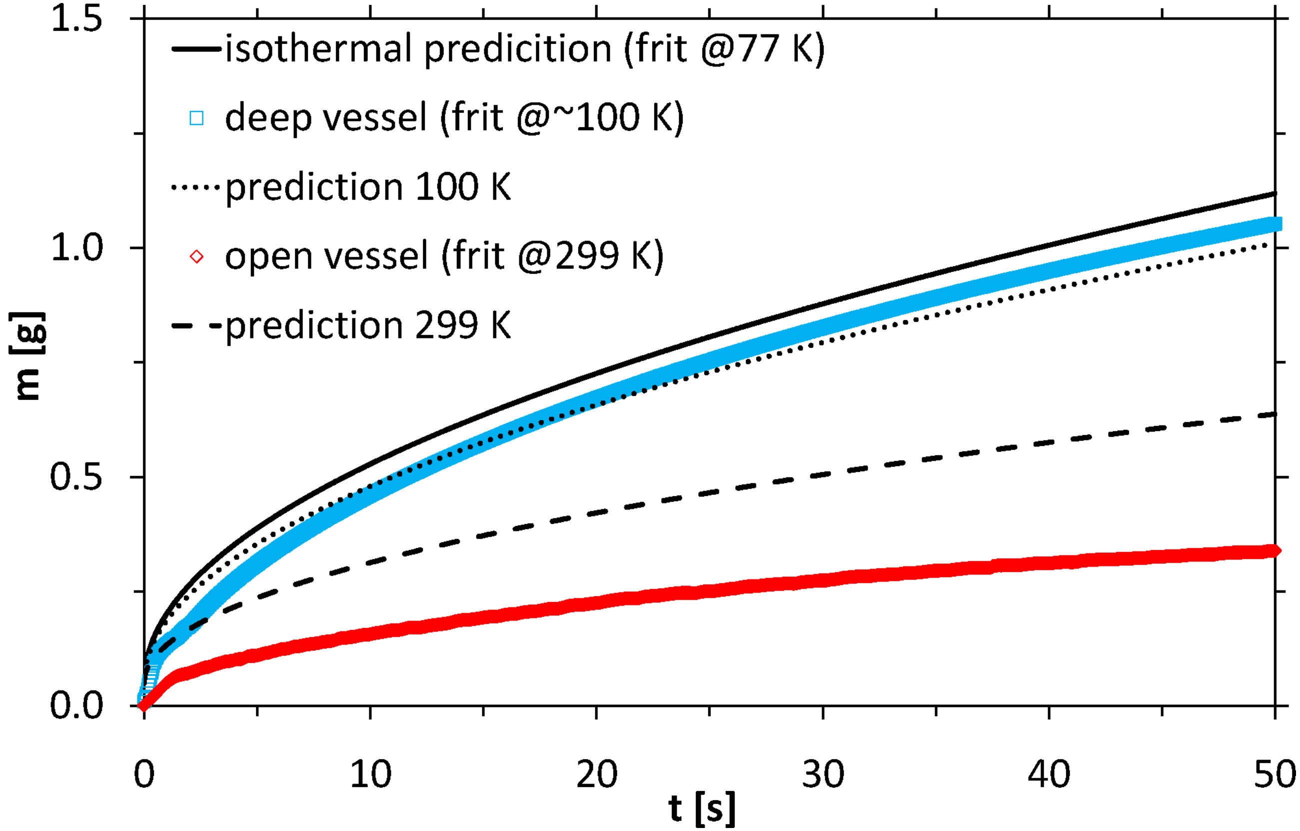
$$\underbrace{\frac{2\sigma\cos\theta_s}{R_s}}_{\text{surface tension}} = \underbrace{\frac{\phi}{K}\mu h v_t}_{\text{viscosity}} + \underbrace{\rho g h}_{\text{gravity}} + \underbrace{\frac{d\left(\rho h\dot{h}\right)}{dt}}_{\text{inertia}}$$

$$v_t = \dot{h} + \frac{\dot{V}_l}{WS\phi} = (1+\delta)\dot{h}$$

$$\frac{2\sigma\cos\theta_s}{R_s} = \frac{\phi}{K}\mu h\dot{h}(1+\delta) + \rho g h + \frac{d\left(\rho h\dot{h}\right)}{dt}$$

Solution in Lucas Washburn regime

$$h^2 = \frac{4\sigma \cos\theta_s}{\phi\mu} \frac{K}{R_s} \left(\frac{1}{1+\delta} \right) t$$



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Solution in Lucas Washburn regime

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$$h^2 = \frac{4\sigma \cos\theta_s}{\phi\mu} \frac{K}{R_s} \left(\frac{1}{1+\delta} \right) t$$

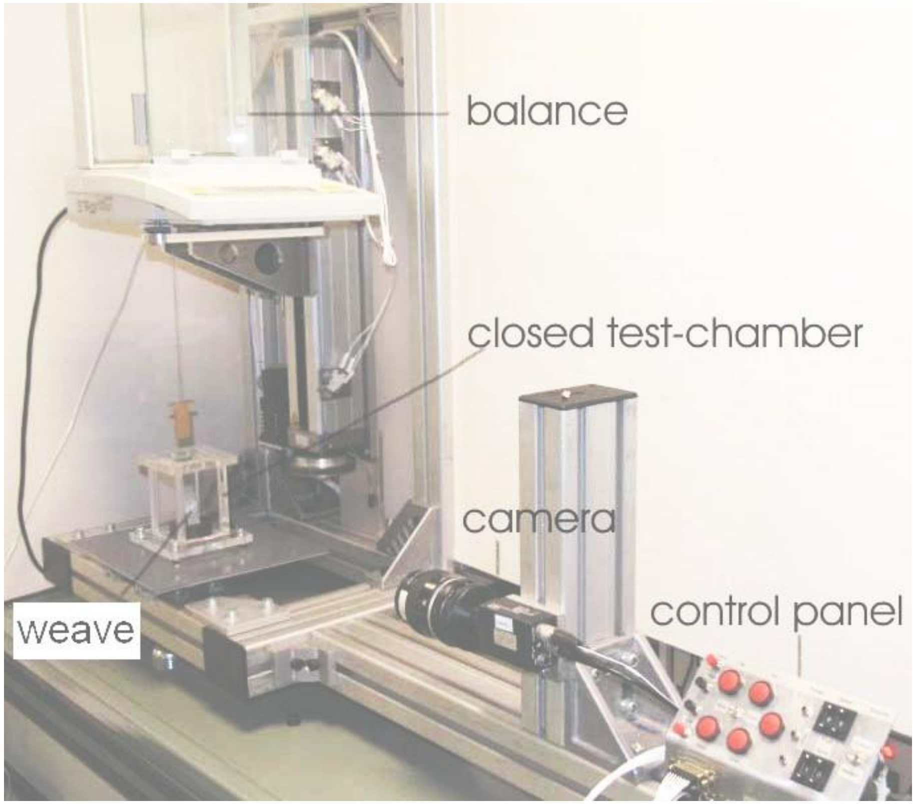
Example LN2 in DTW

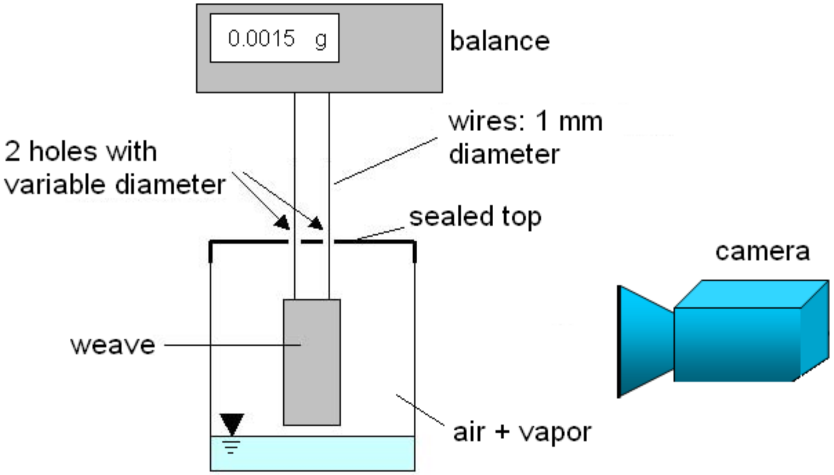
$$\phi = 0.24$$
$$c_s = 477\ J/kgK$$
$$\Delta T = 20\ K$$
$$\Delta H_v = 198.6\ kJ/kg$$
$$\rho_l = 808.5\ kg/m^3$$
$$\rho_s = 7900\ kg/m^3$$

$$\delta = 1.49$$

→ One expects a decrease in velocity by a factor of 0.63!

Measurement method

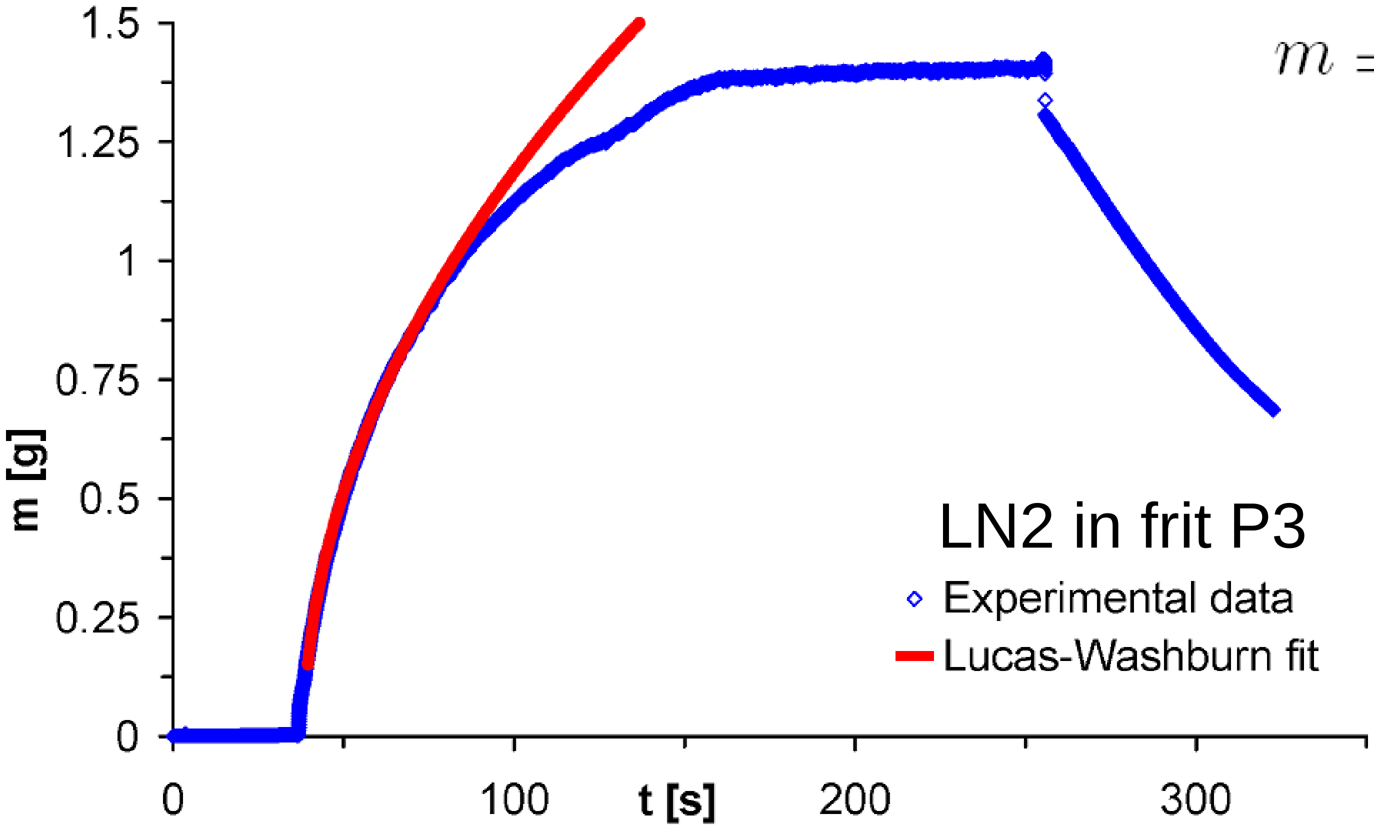




Experimental set-up

Capillary rise of cryogenic liquids

PoreNet GRADUIERTENKOLLEG

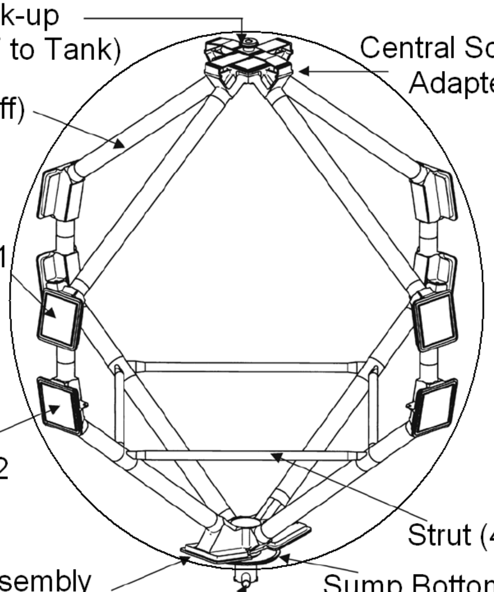


$$m = A\ \phi\ \rho\ h$$

Cryogenic capillary rise follows classic Lucas-Washburn model!

Introduction

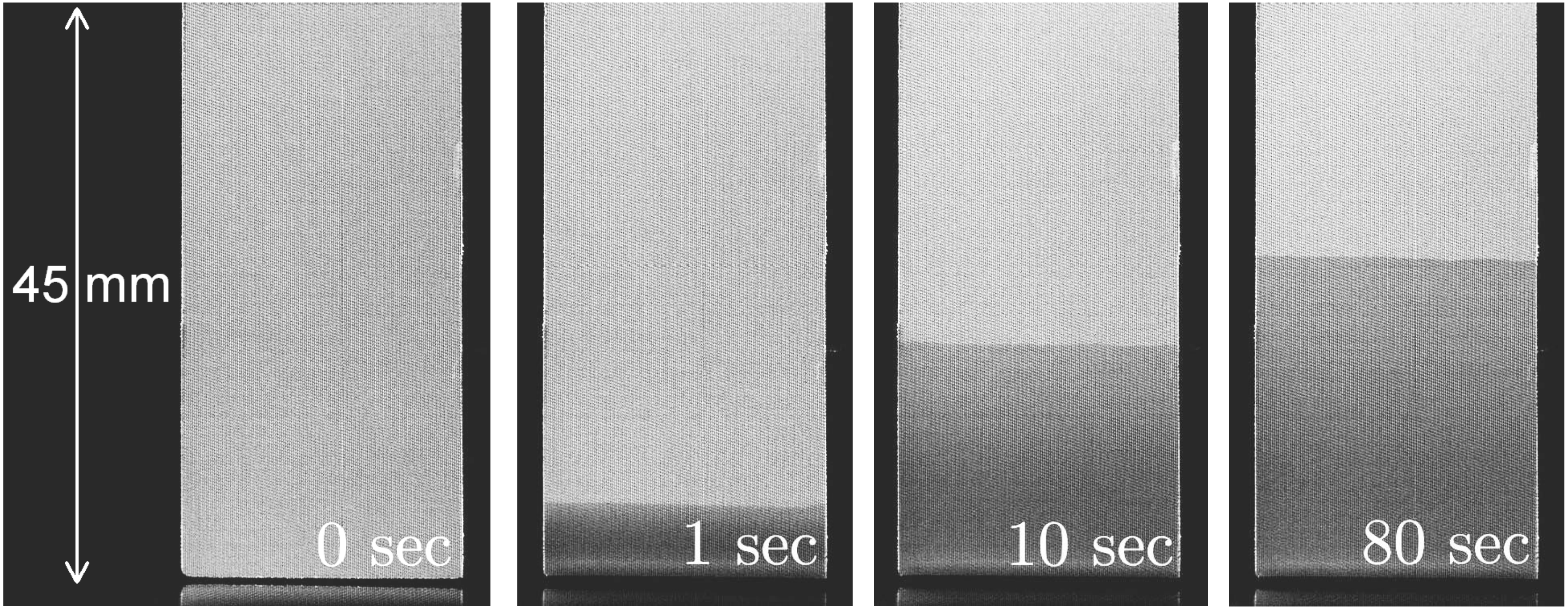
ATV approaching ISS



ATV propellant tank

- PMD (propellant management device) [P.Behruzi, G.Netter]

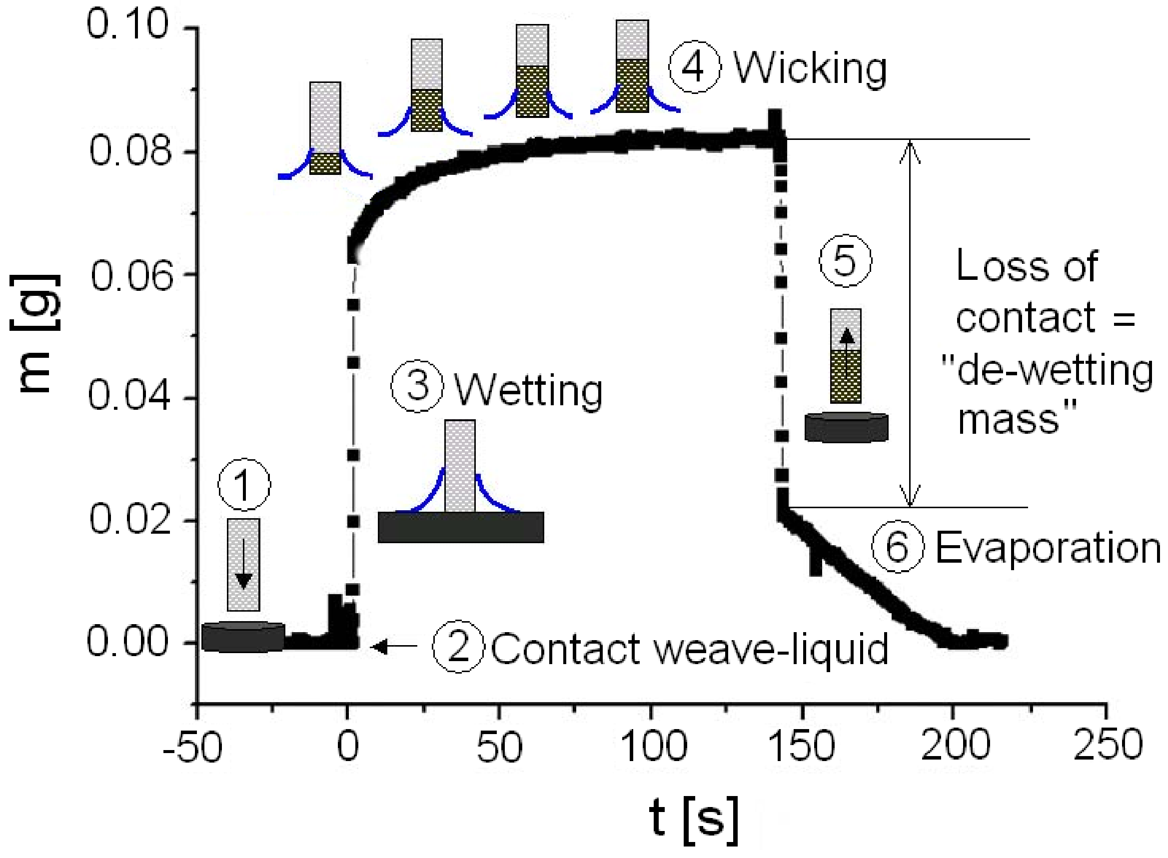
Capillary rise



Subsequent images of liquid (HFE-7500) wicking into weave

Measurement method

PoreNet GRADUIERTENKOLLEG



$$m = A \ \phi \ \rho \ h$$

Mass recording of HFE-7500 in a DTW 200 x 1400

Appendix - Darcy vs. Hagen-Poiseuille

$$\nabla p = -\frac{\mu}{K} v_s$$

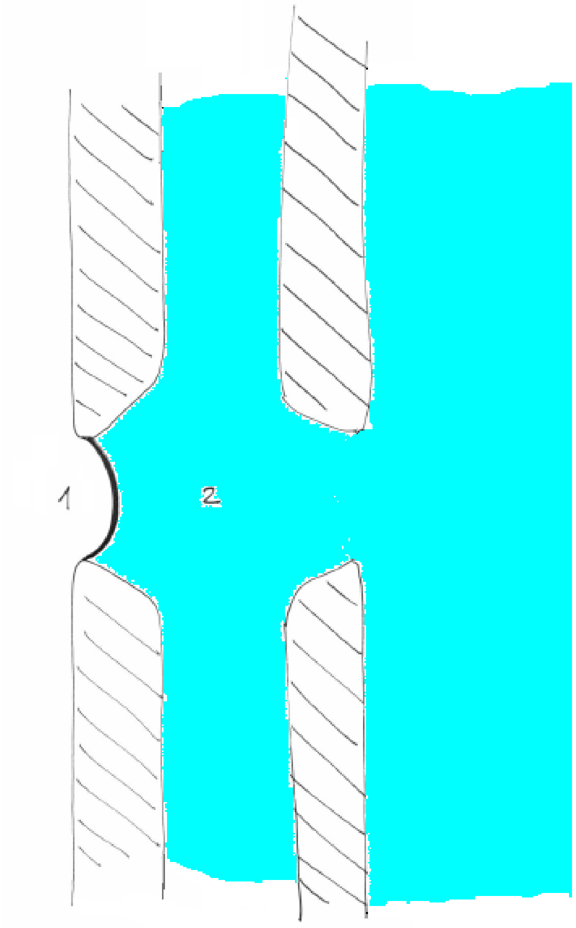
$$R^2 = \frac{8K}{\phi}$$

$$\Delta p = \frac{8 \cdot \mu \cdot h \cdot v_i}{R^2}$$

$$h^2 = \frac{\sigma \cos(\theta_s) R_e}{2\mu} t$$

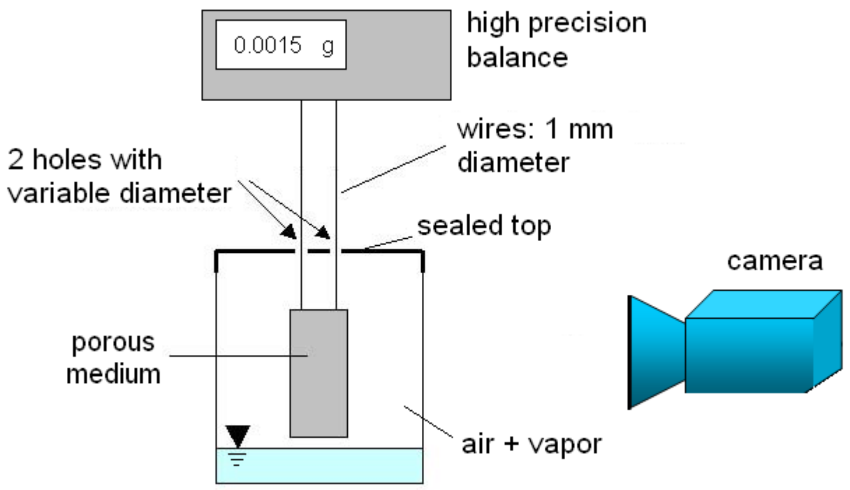
$$R_e = \frac{R_h^2}{R_s}$$

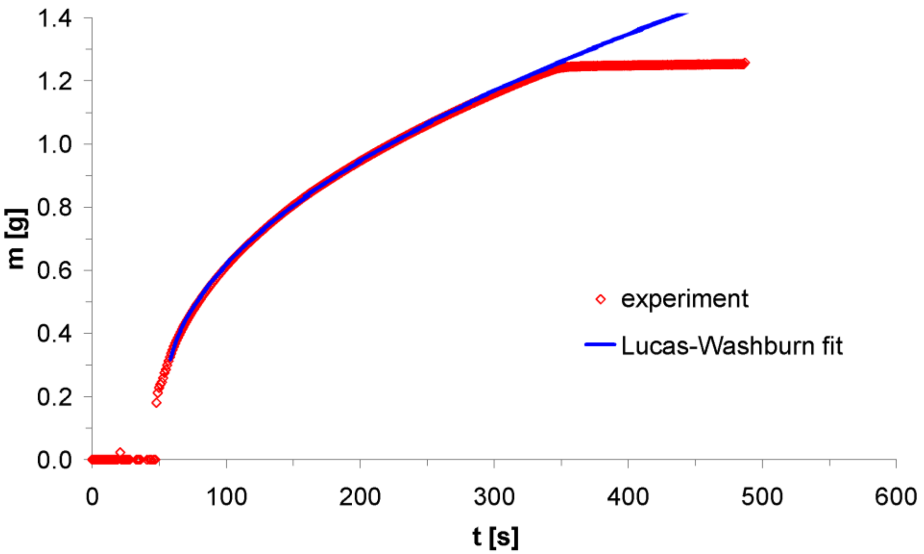
Appendix



- Bubble point (simplified model)

$$P_{BP} = \frac{2\ \sigma\ cos(\theta)}{R_{BP}}$$



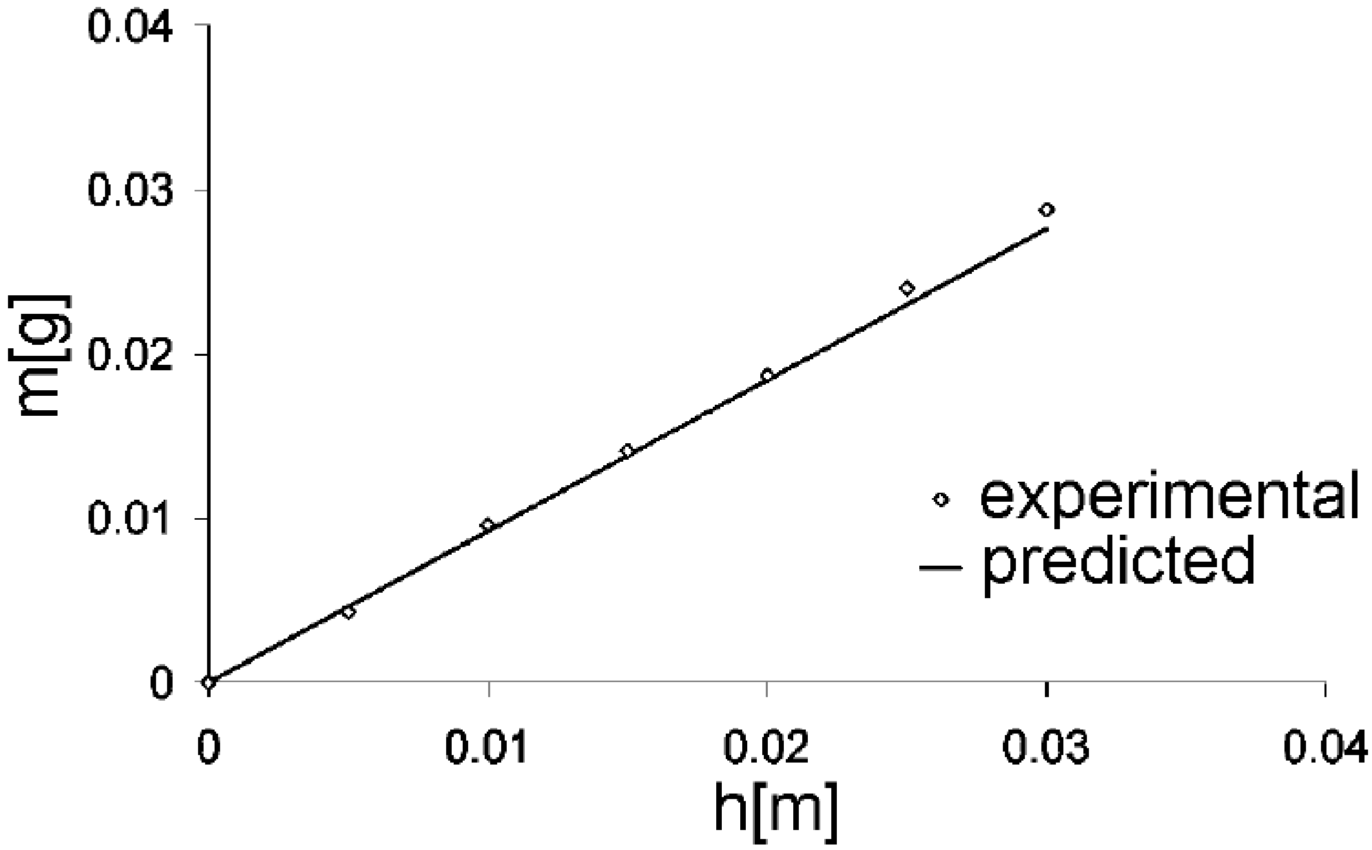


Lucas-Washburn equation

$$h^2 = \frac{4\sigma \cos\theta_s}{\phi\mu} \frac{K}{R_s} t \qquad m^2 = (TW\phi\ \rho)^2 \frac{4\sigma \cos\theta_s}{\phi\mu} \frac{K}{R_s} t$$

Appendix - Saturation

$$m = A \ \phi \ \rho \ h$$



Appendix Cleaning Procedure

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1 - Ultrasound bath (7 min) at 60°C ± 5 °C with Turco 4215 NC (10 g/l)
2 - Ultrasound bath with fresh de-ionized water (2x10 min),
3 - pH check: 5 < pH <7,
4 - Ultrasound bath with IPA (10 min),
5 - Drying of the mesh at 65°C for 2 hours,
6 - Cleanness check with normal and UV light,