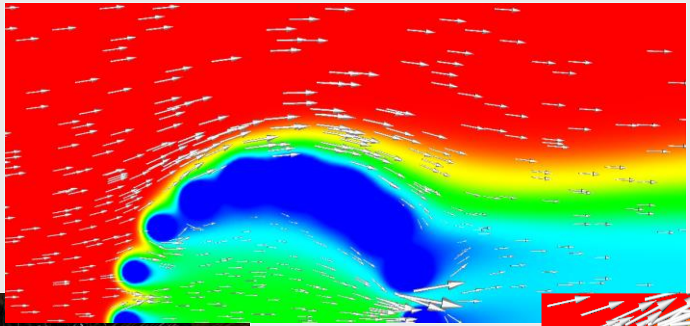
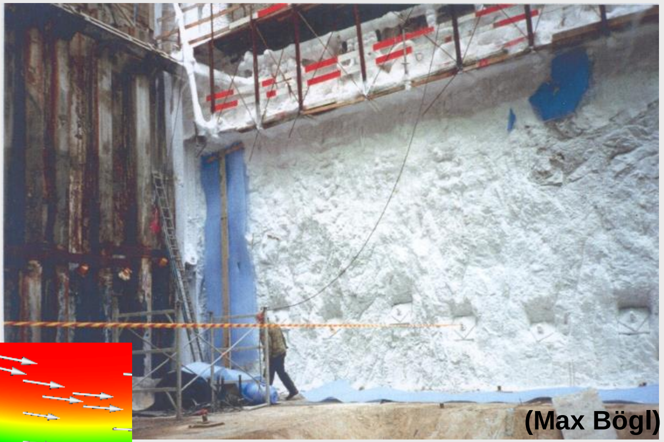
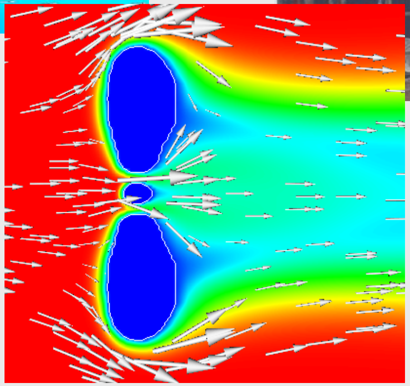
OPTIMIZATION OF ARTIFICIAL GROUND FREEZING APPLICATIONS SUBJECT TO WATER SEEPAGE

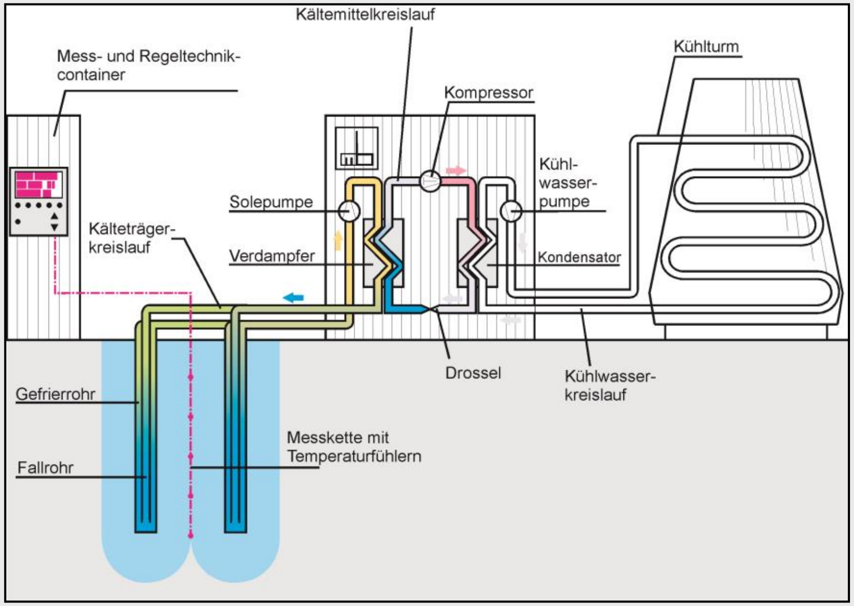
Univ.-Prof. Dr.-Ing. Martin Ziegler
Geotechnical Engineering, RWTH Aachen University



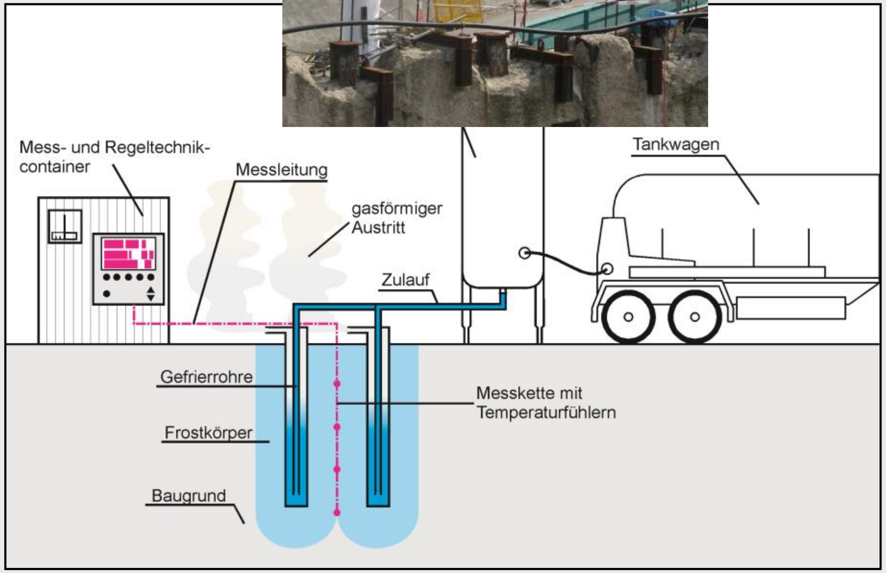


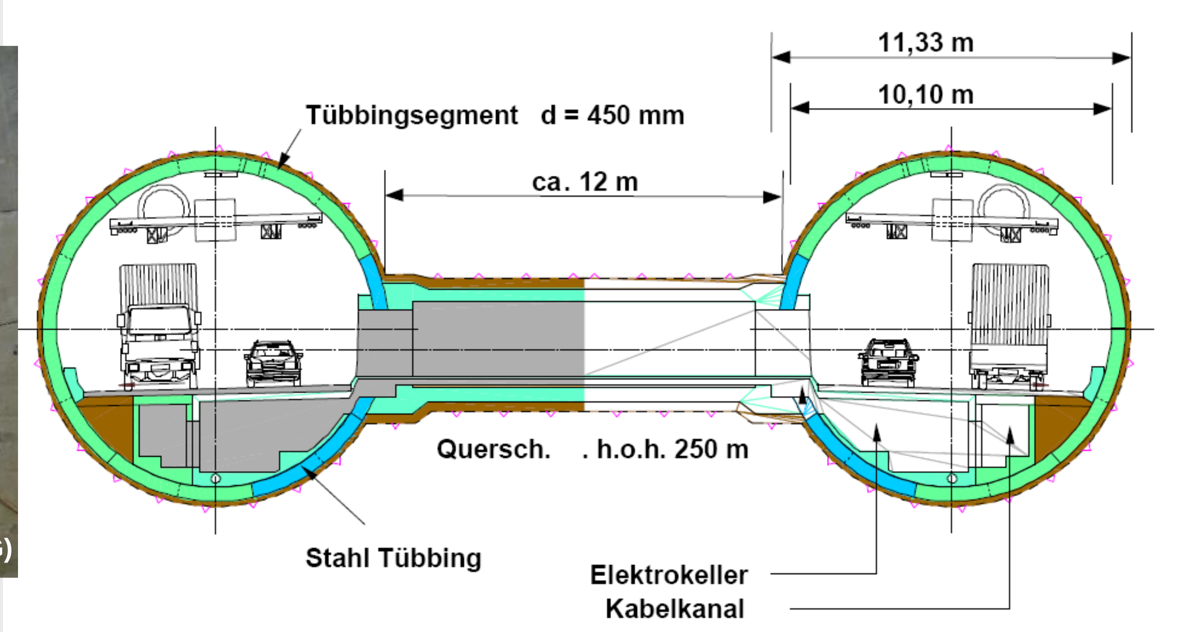


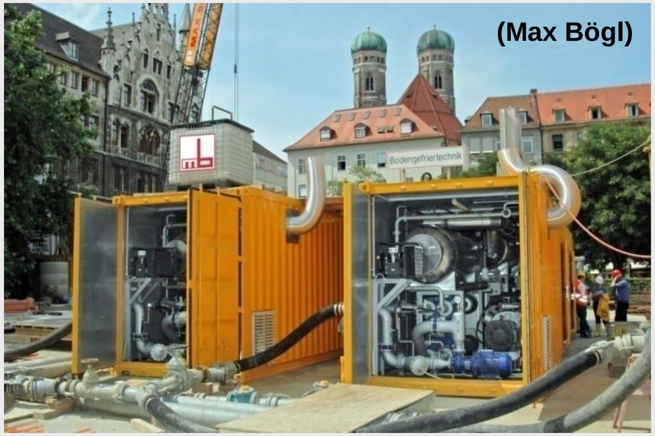
Brine freezing



Liquid nitrogen freezing

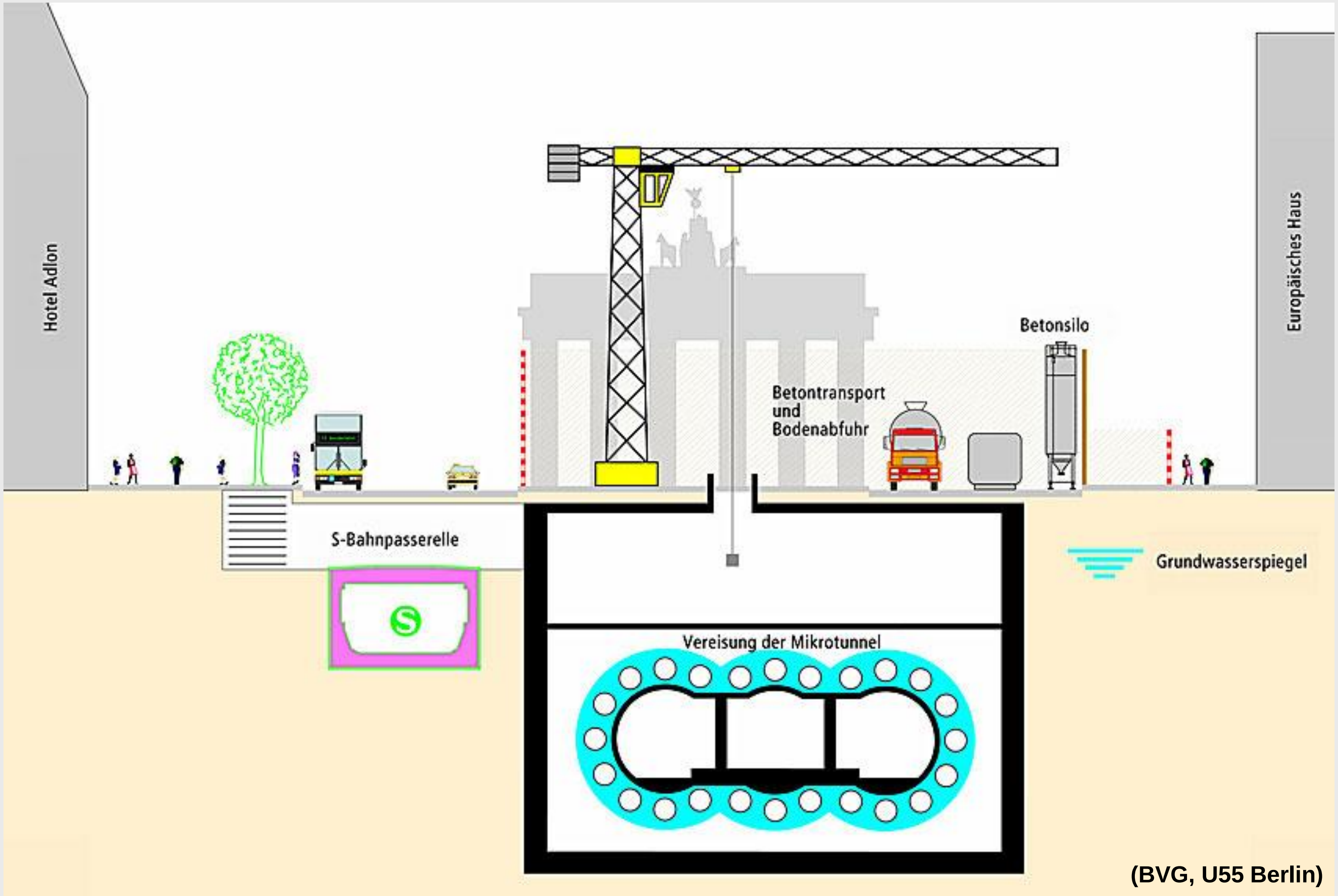






Mobile freezing unit

Freezing of a cross passage



(BVG, U55 Berlin)

Widening of underground station for TBM driven tunnels

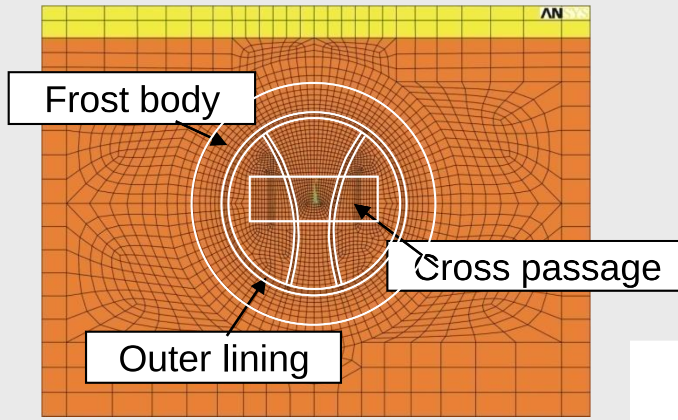
Freezing of an excavation pit wall

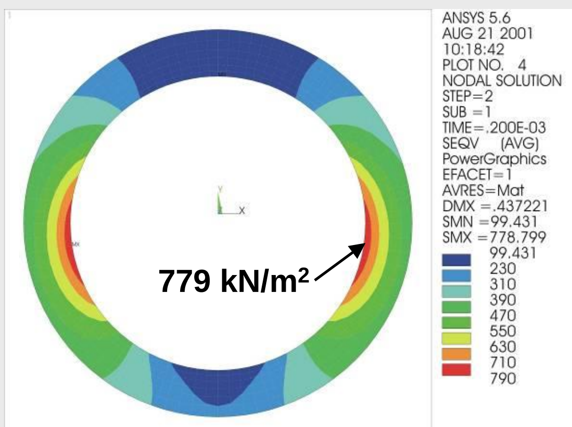
Common practice:

Decoupled calculations

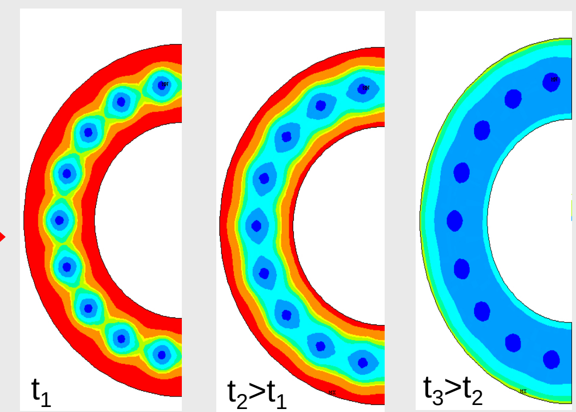
Statics of frost body

Freezing phase without flow

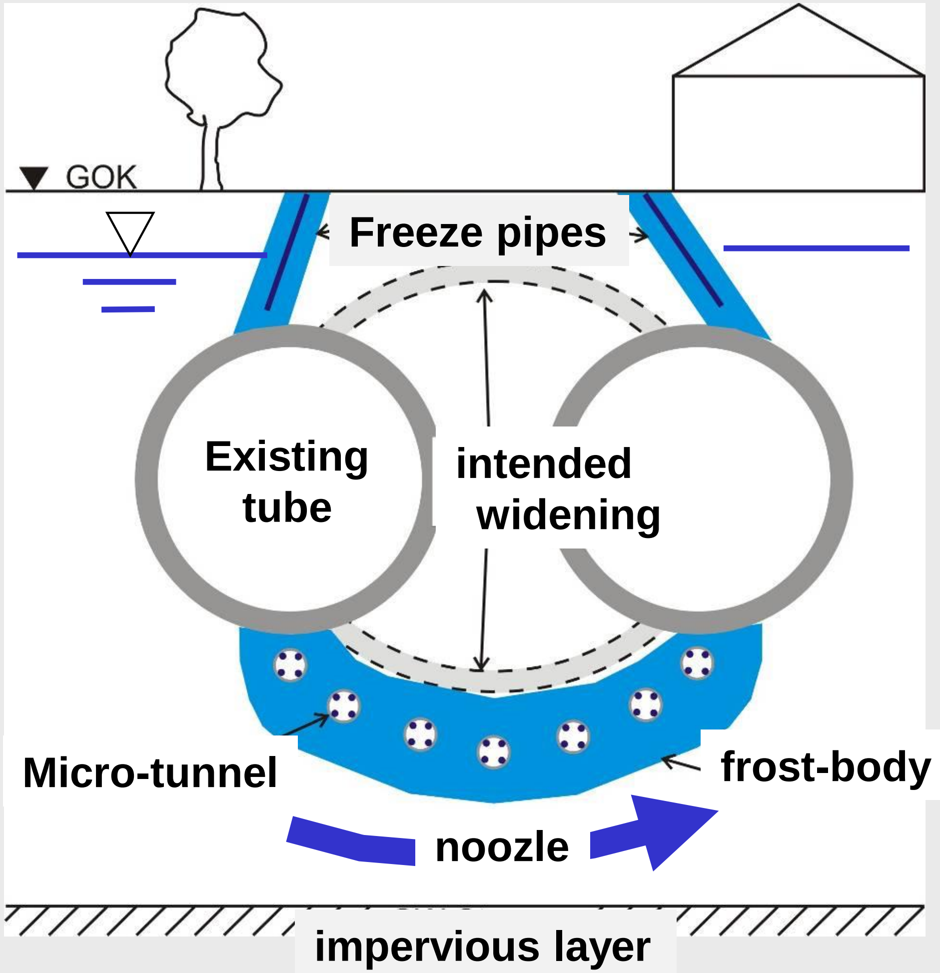




Structural mechanics (after freezing phase)



Temperature development (freezing phase)



Advantages

- sealing and statically effective
- applicable in almost all types of soil
- always controllable
- non-polluting
- almost completely reversible

Disadvantages

- costly
- Heave during freezing
- high energy consumption
- Restriction of the method in the case of high groúndwater velocity

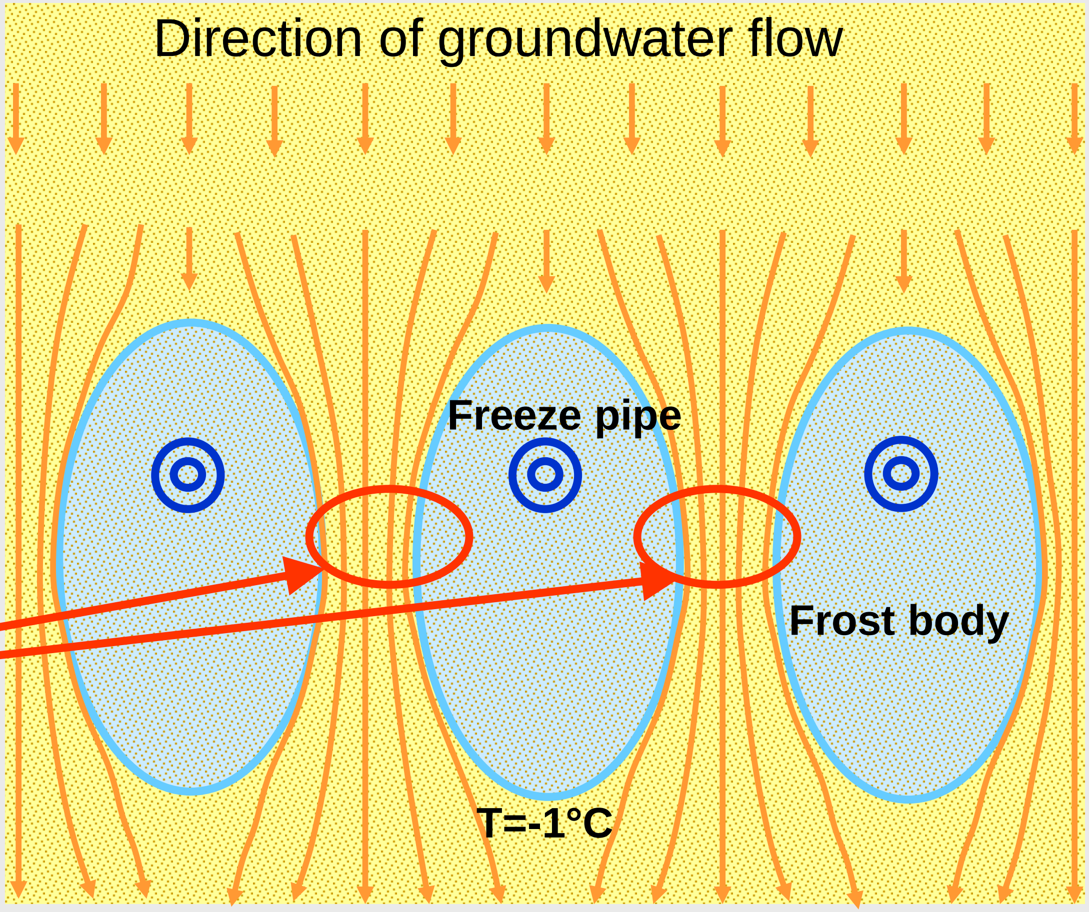
Advantages and disadvantages of the ground freezing method

- GW-Flow =

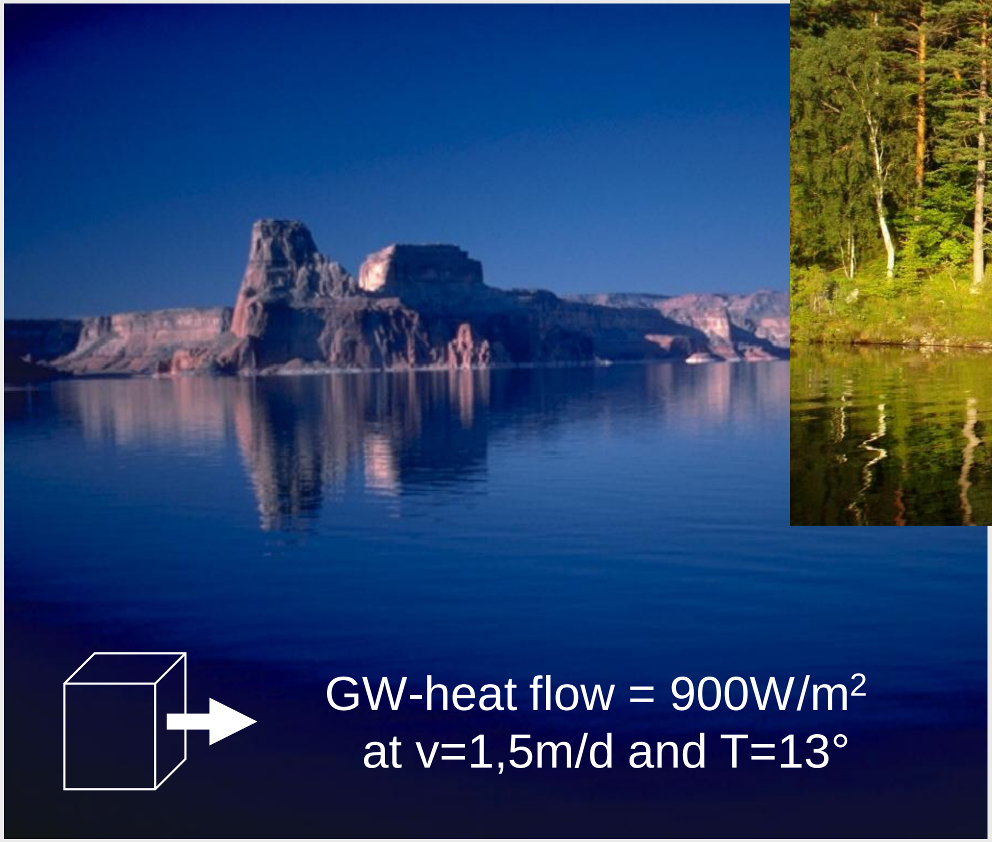
 Convective thermal impact

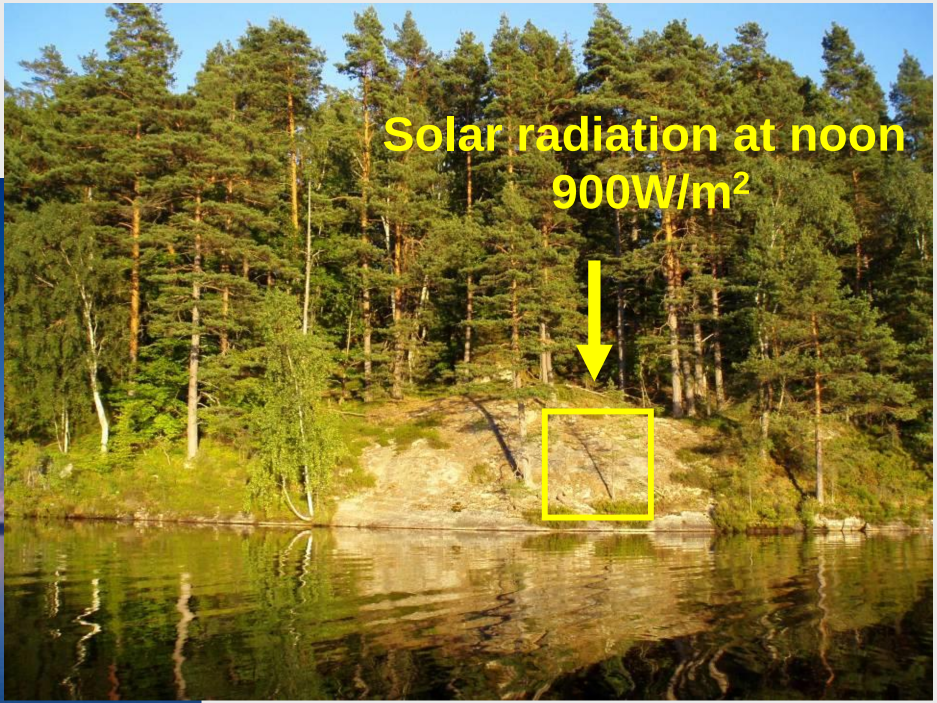
- Delay of frost propagation

- Hindrance of frost body closure possible



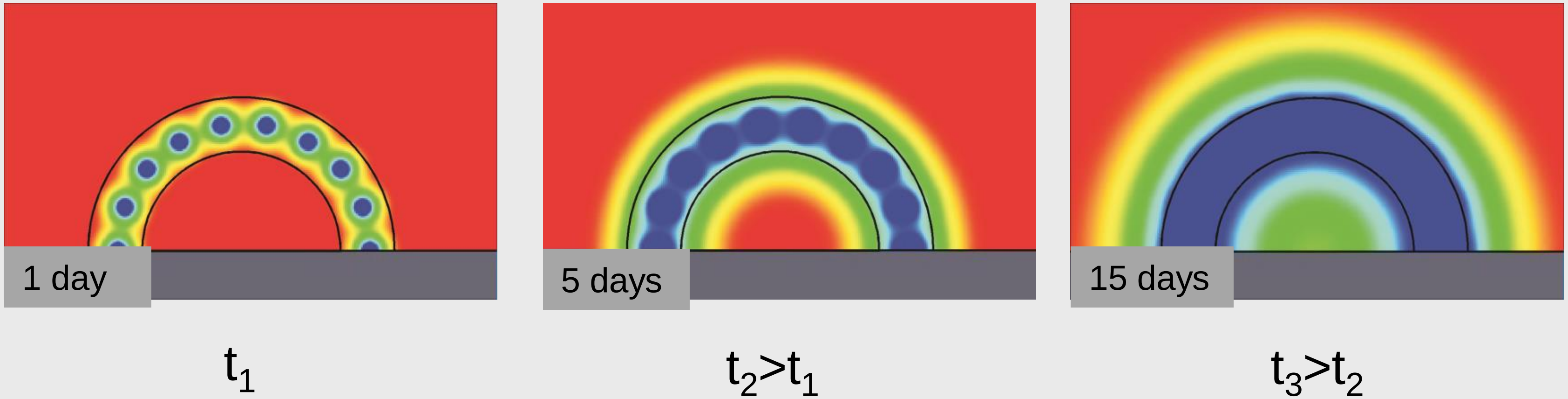
Frost body formation under influence of groundwater flow





Effect of groundwater flow

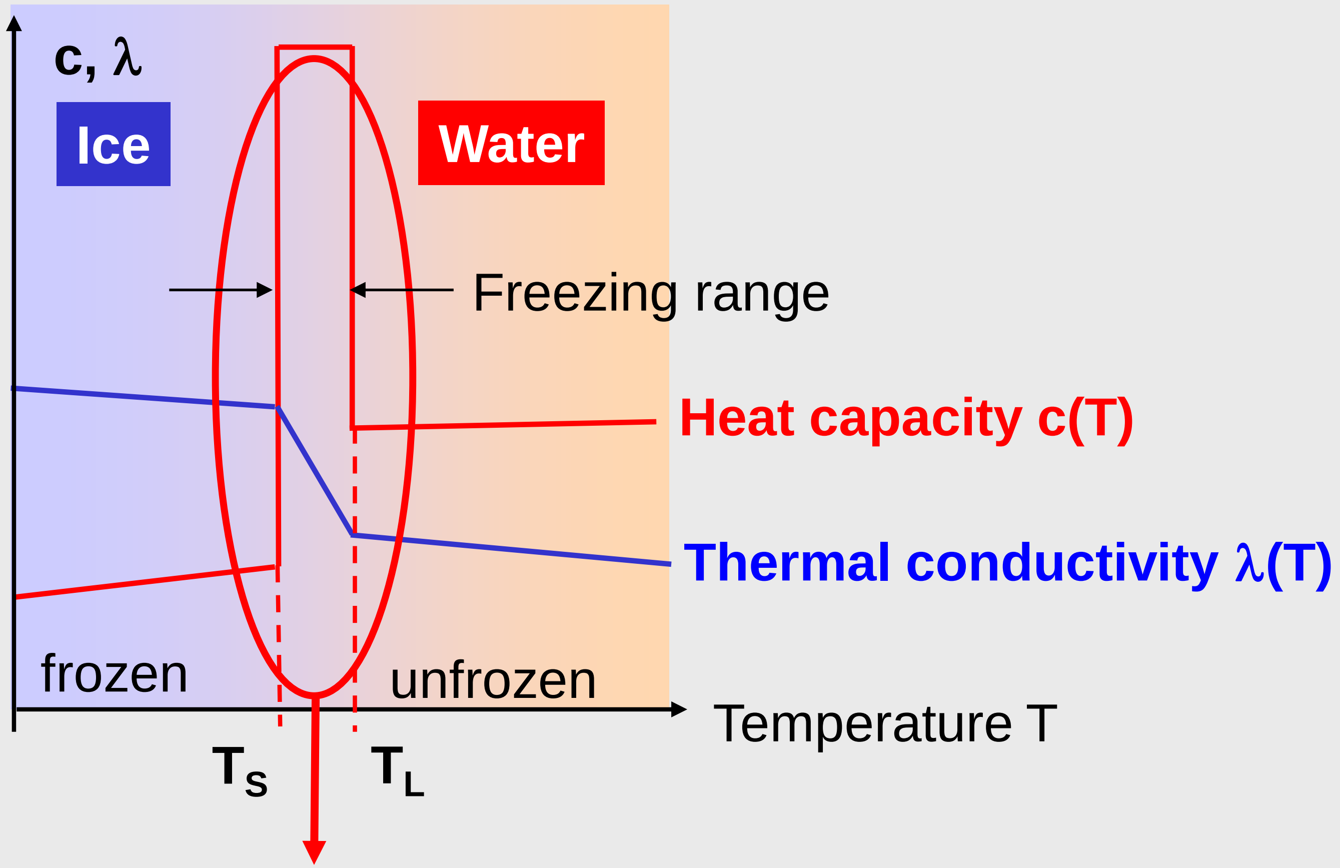
Temperature development during freezing phase



- Time-dependent temperature field $\Rightarrow$ transient calculations

Features of thermal freezing simulations

- Thermal properties are temperature-dependent $\Rightarrow$ nonlinear calculation



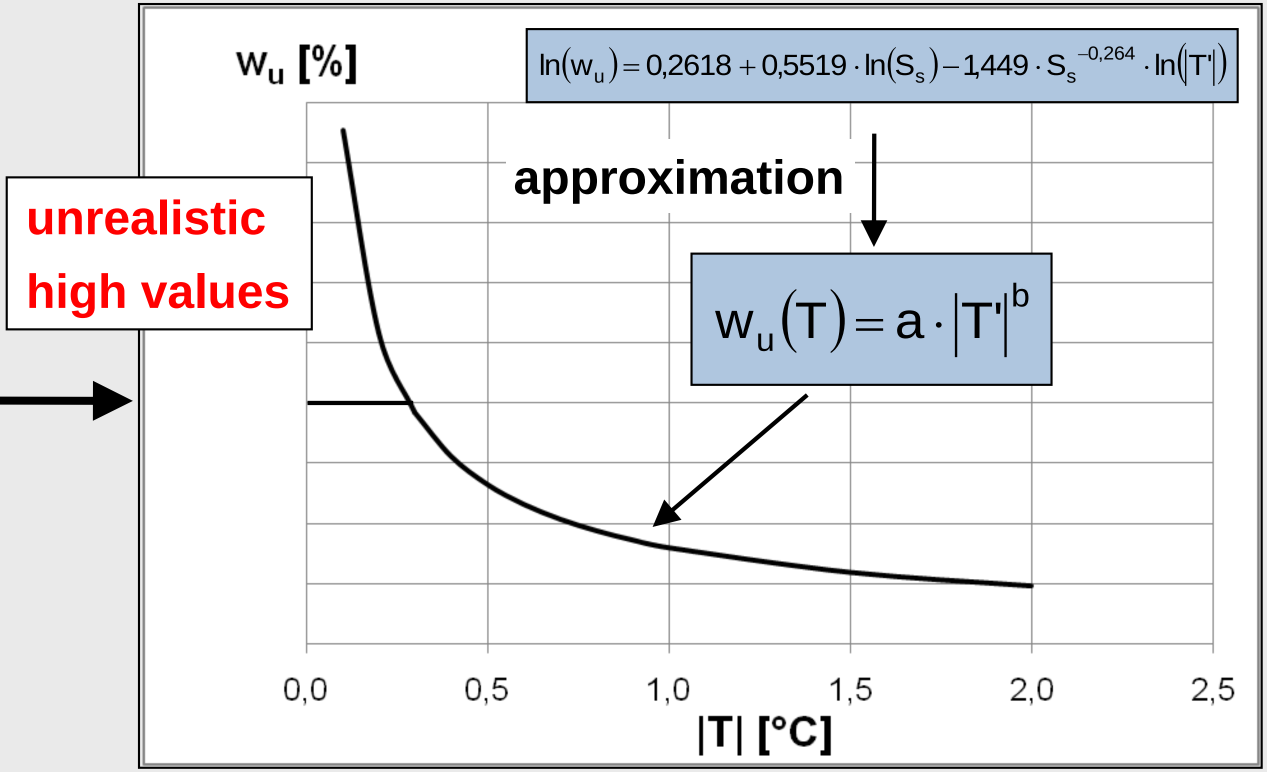
- Release of latent heat during phase change

Features of thermal freezing simulations

- Course of unfrozen water content $\Rightarrow$ approximation

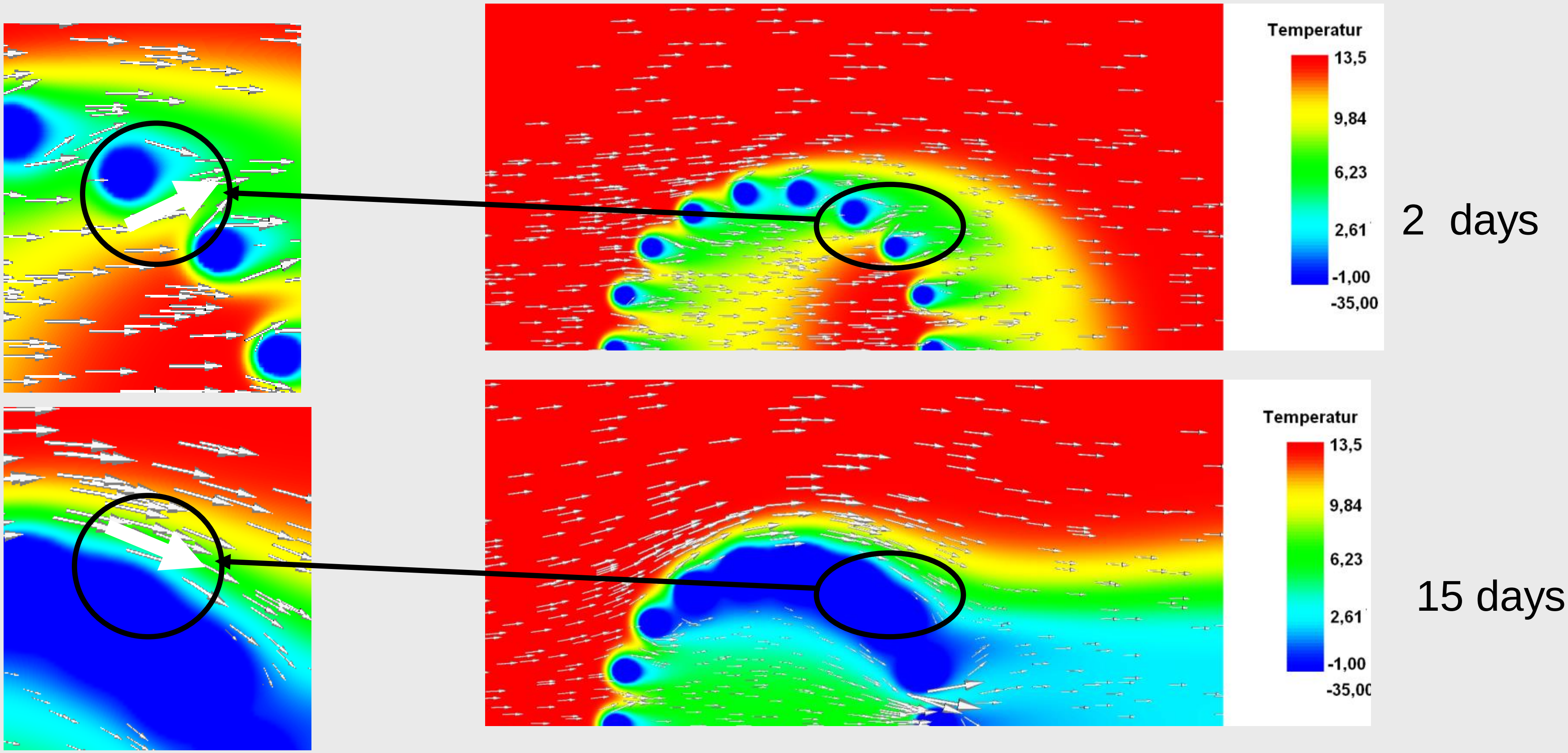
Specific surface

$$S_s = \sum_{i=1}^{n} \frac{6}{d_i \cdot \rho_s} \cdot \varphi_{m,i}$$



Simulation of freezing process

- Frost front is a „moving boundary“ for the flow field



- Coupled calculations of heat transfer and groundwater flow necessary

Features of thermal freezing simulations

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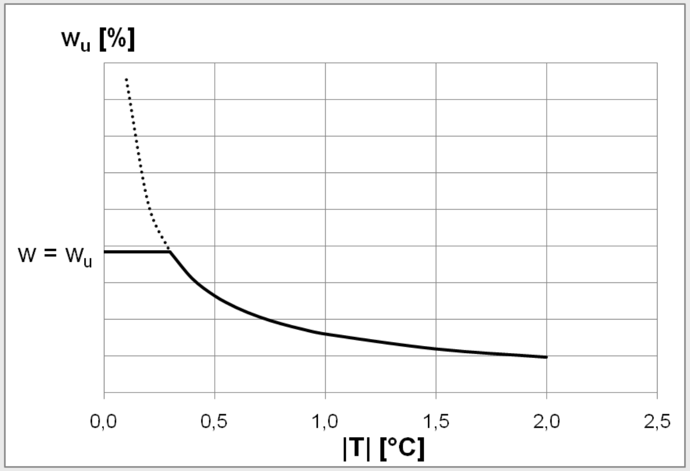
SHEMAT (Simulator for Heat and Mass Transport)

- solution of thermodynamical problems with finite difference method

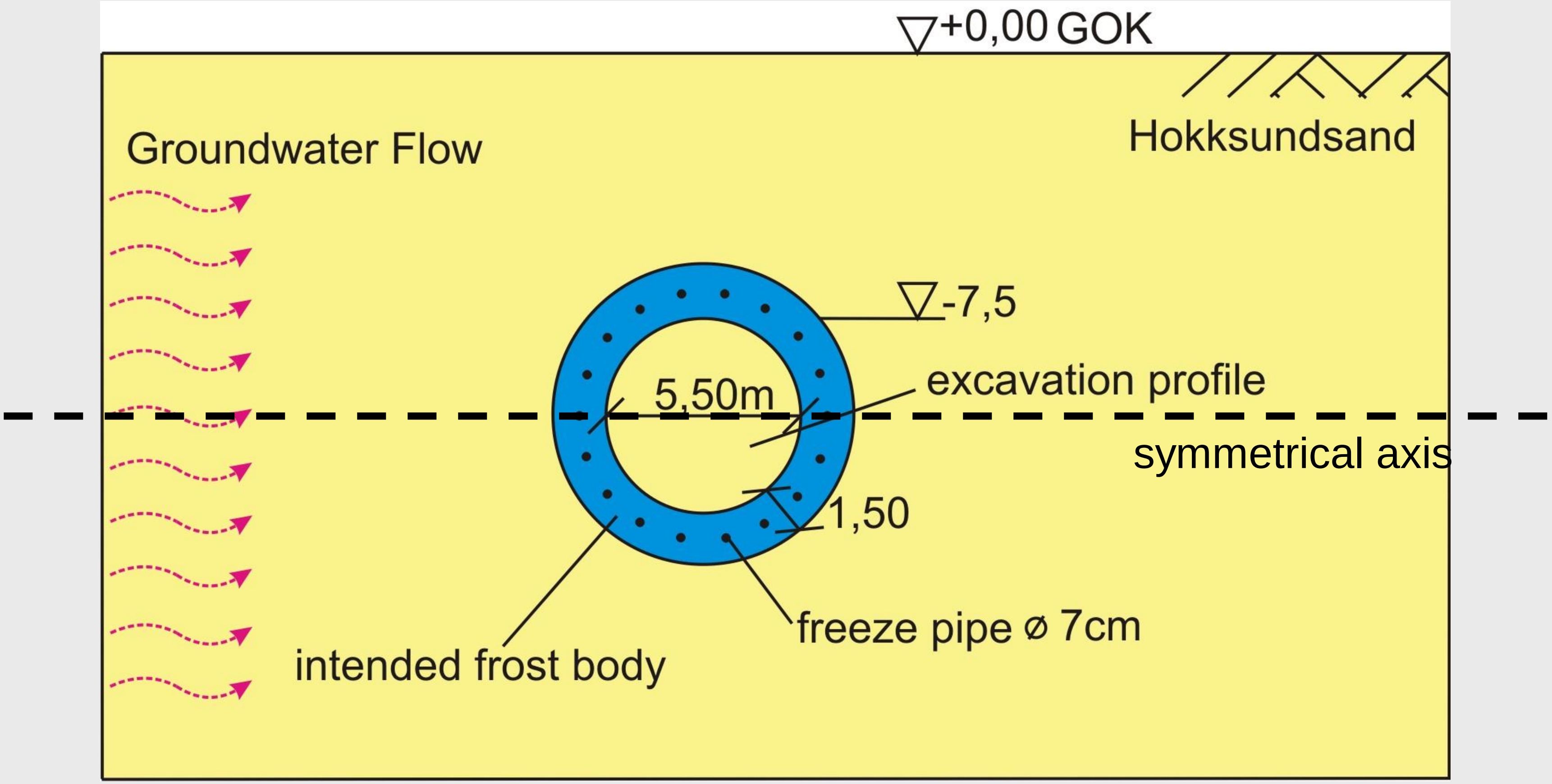
$$C_v(T) * \frac{\partial T}{\partial t} = \frac{\partial}{\partial x_i} * \left(\frac{\partial T}{\partial x_i} * \lambda_i\right) - C_{v,w} * \left(\frac{\partial T}{\partial x_i} * v_{f,i}\right) + q$$

- modular structure → possibility of activation / deactivation
- originally: solution of geophysical problems (Prof. Clauser)
- advancement: moving boundary for groundwater flow (Prof. Clauser, Dr. Mottaghy, Dr. Rath)

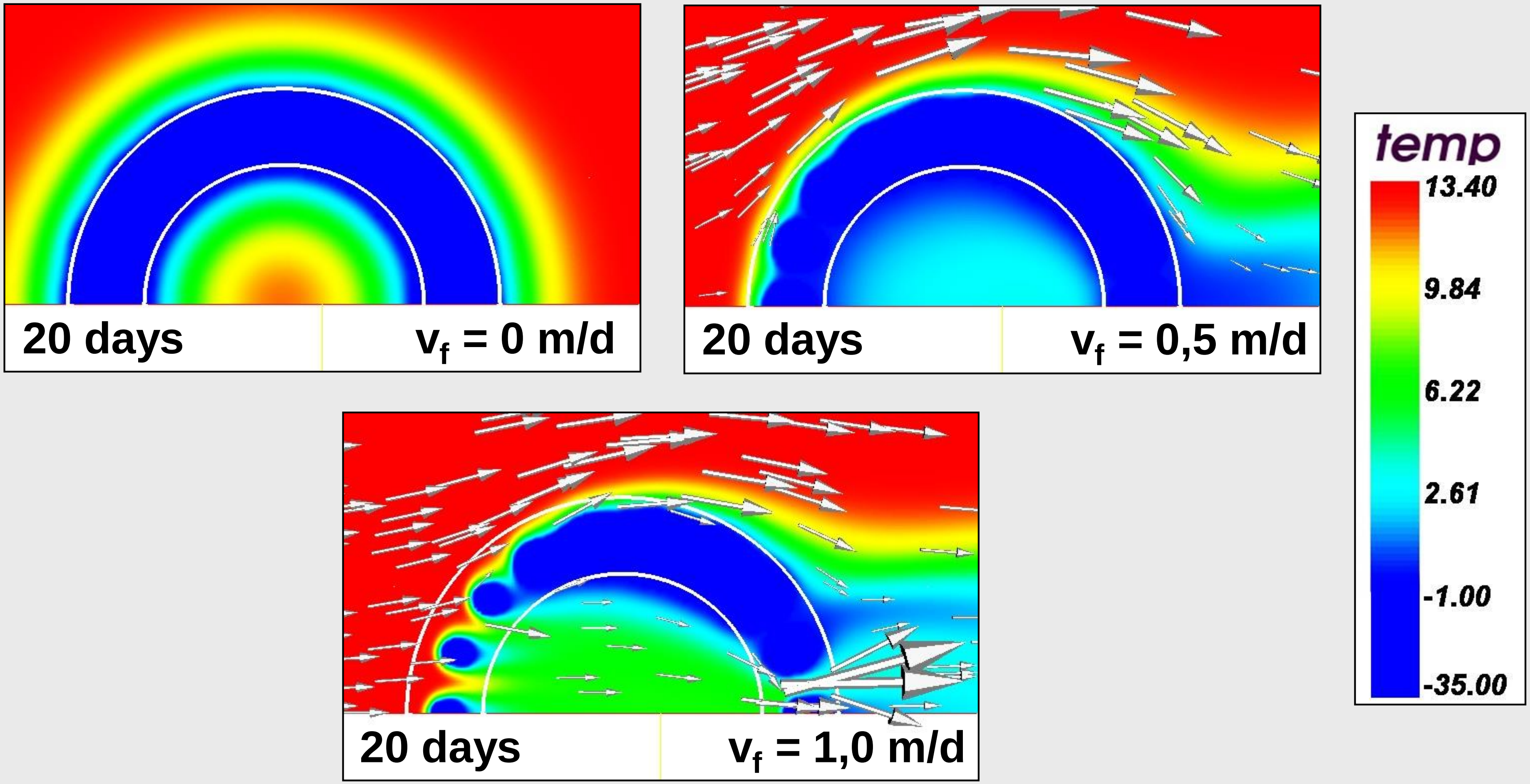
- „freezing"-modul (Dr. Baier)
  - phase change model / unfrozen water content
  - temperature dependent soil parameters λ, c, k
  - time-dependent boundary conditions



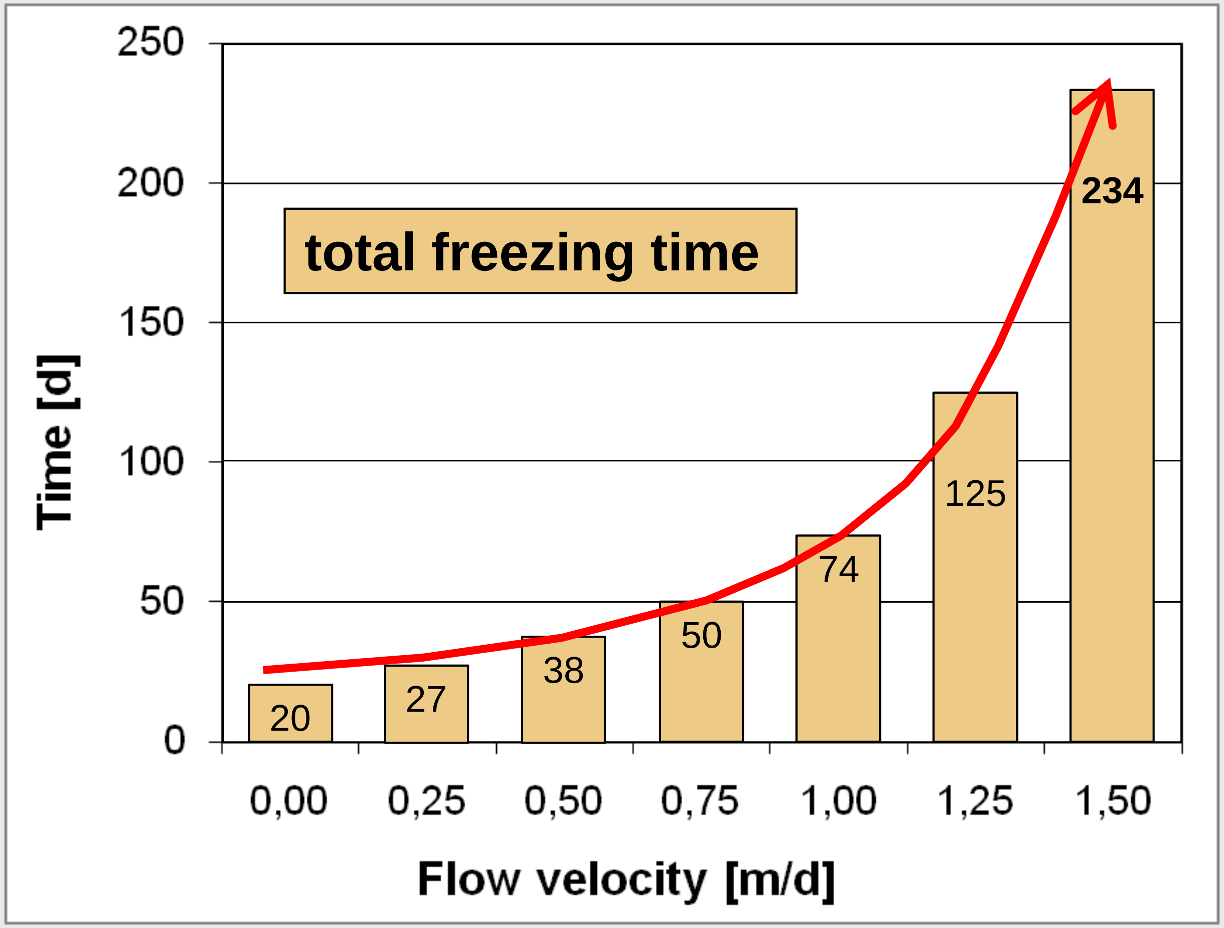
Example: Freezing of a cross passage

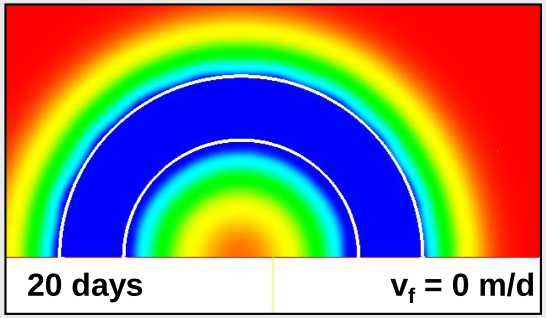


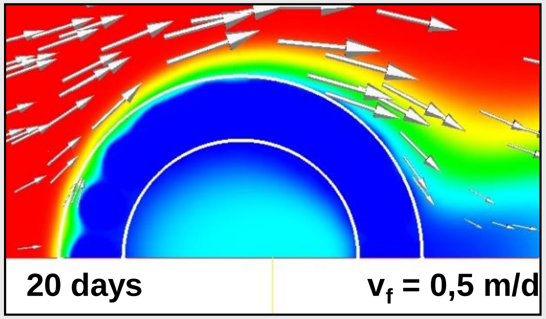
Geometry, elevation and freeze pipe arrangement

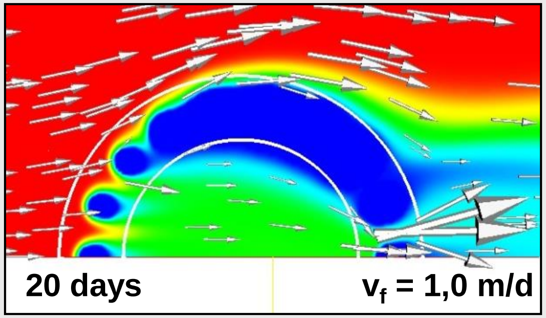


Influence of GW-flow on freezing process

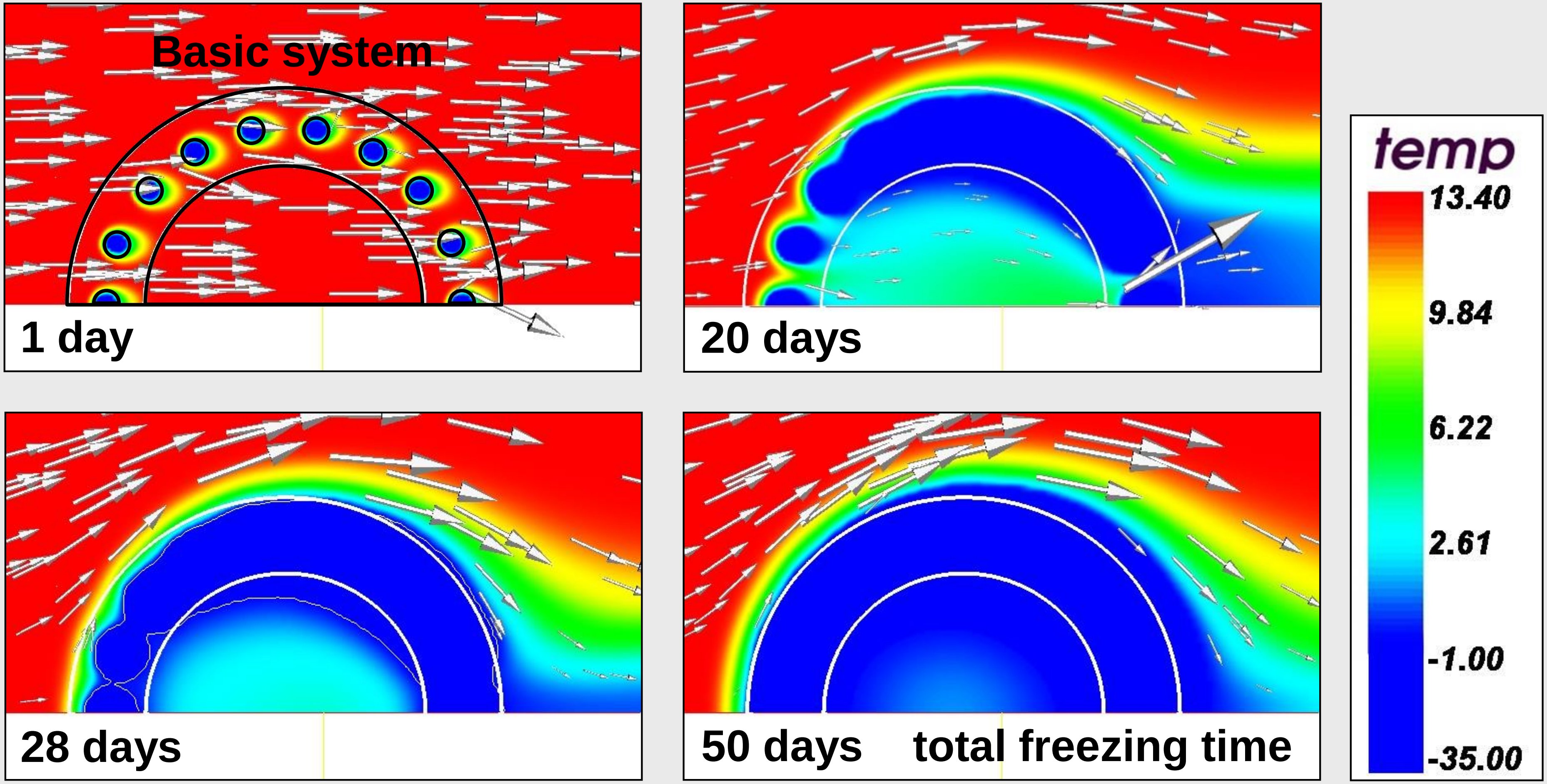




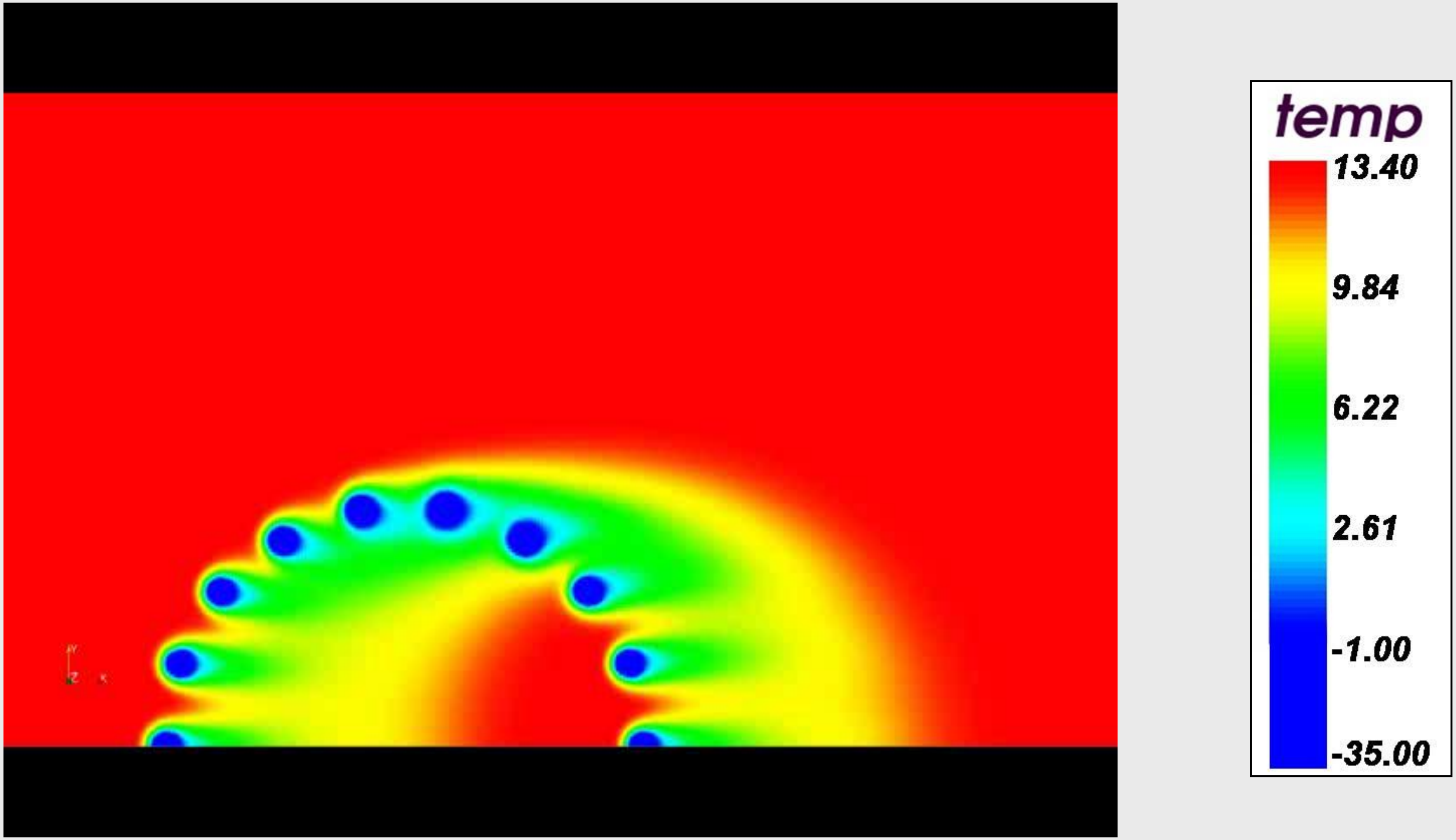




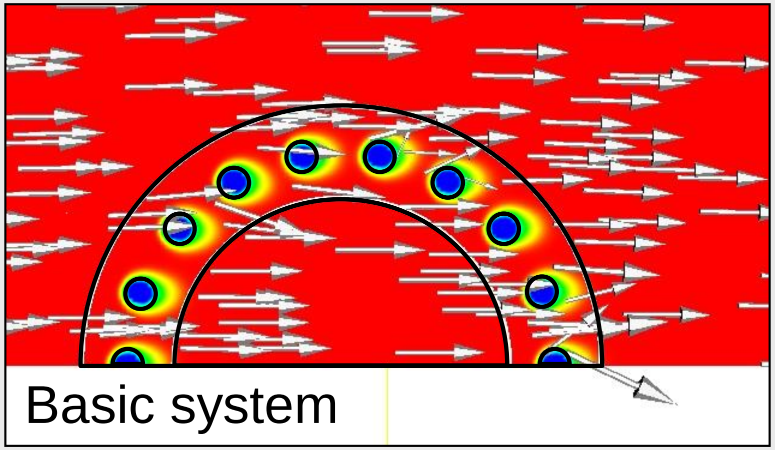
Influence of flow velocity on freezing process

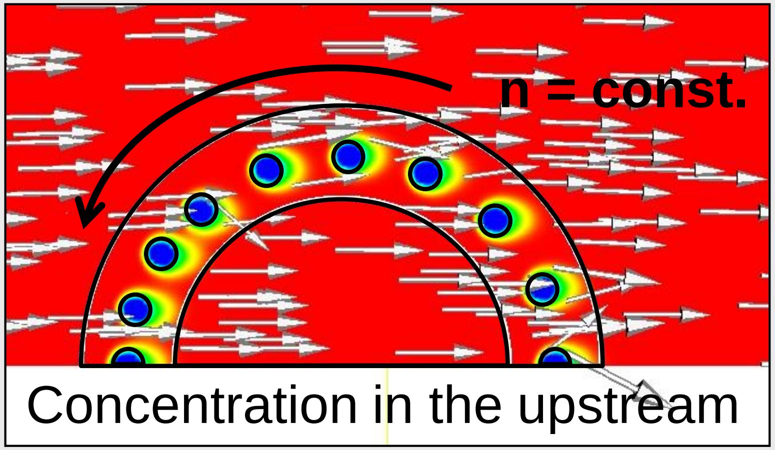


Freezing process for basic system (v = 0.75 m/d)

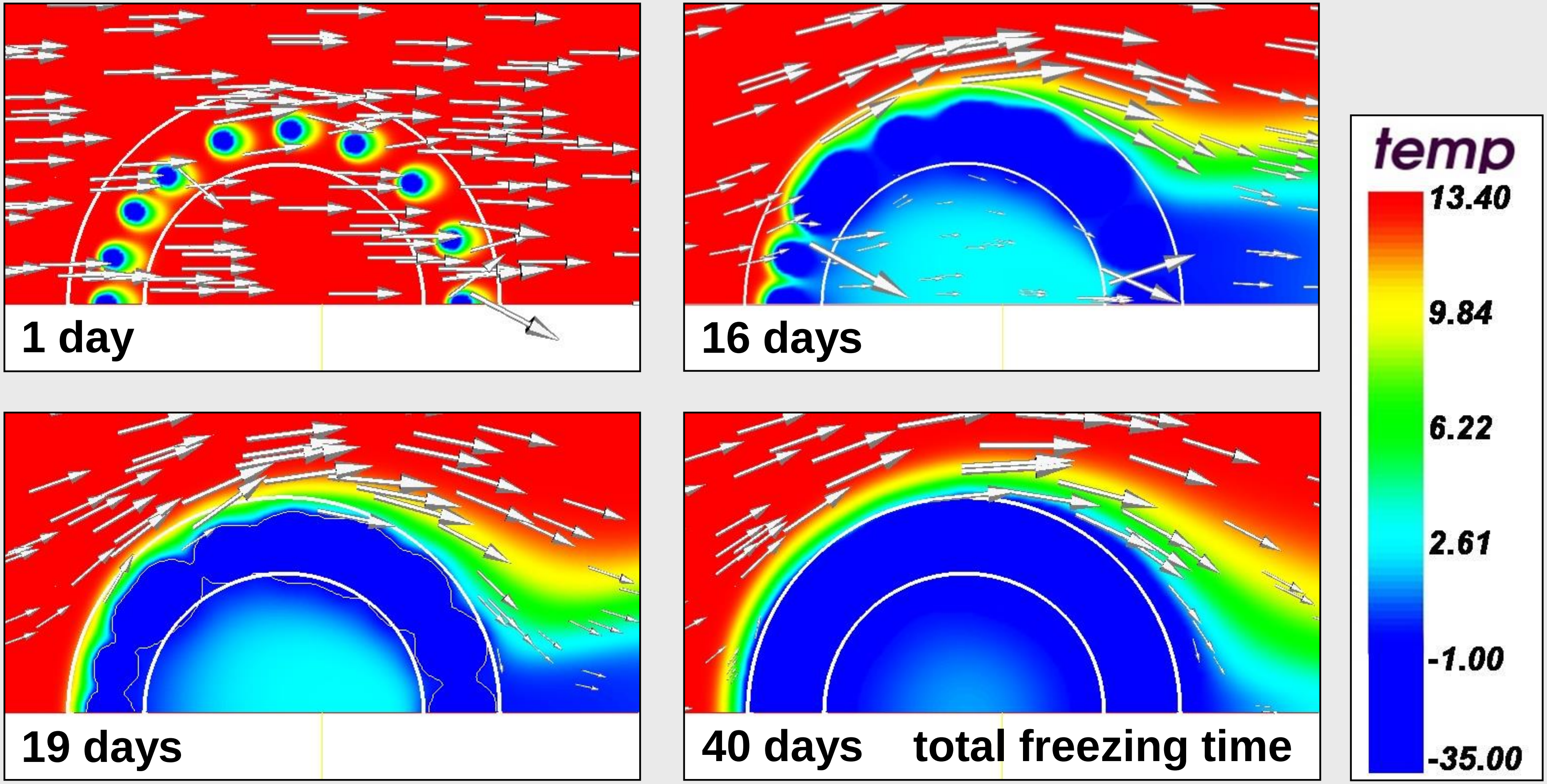


Freezing process for basic system (v = 0.75 m/d)

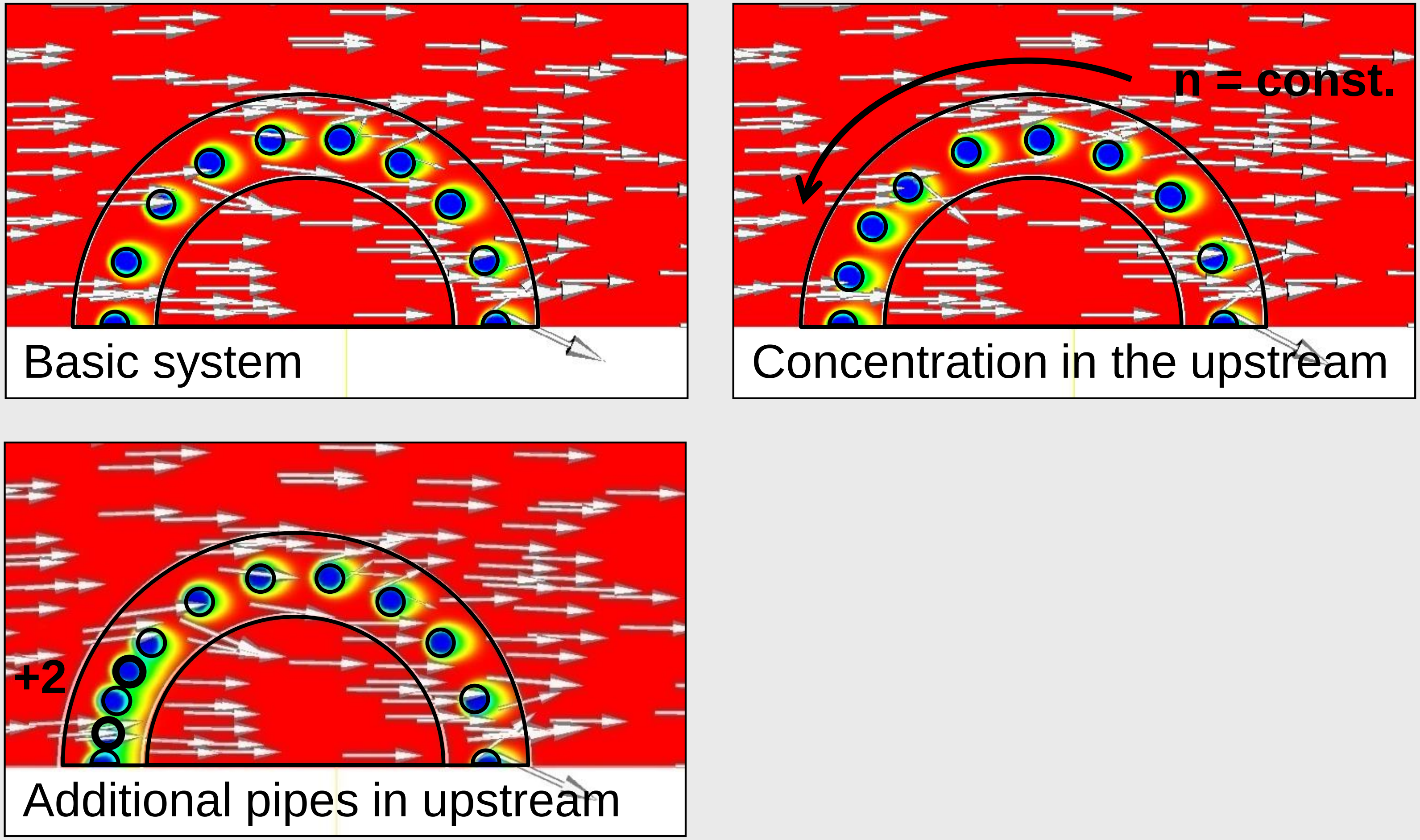




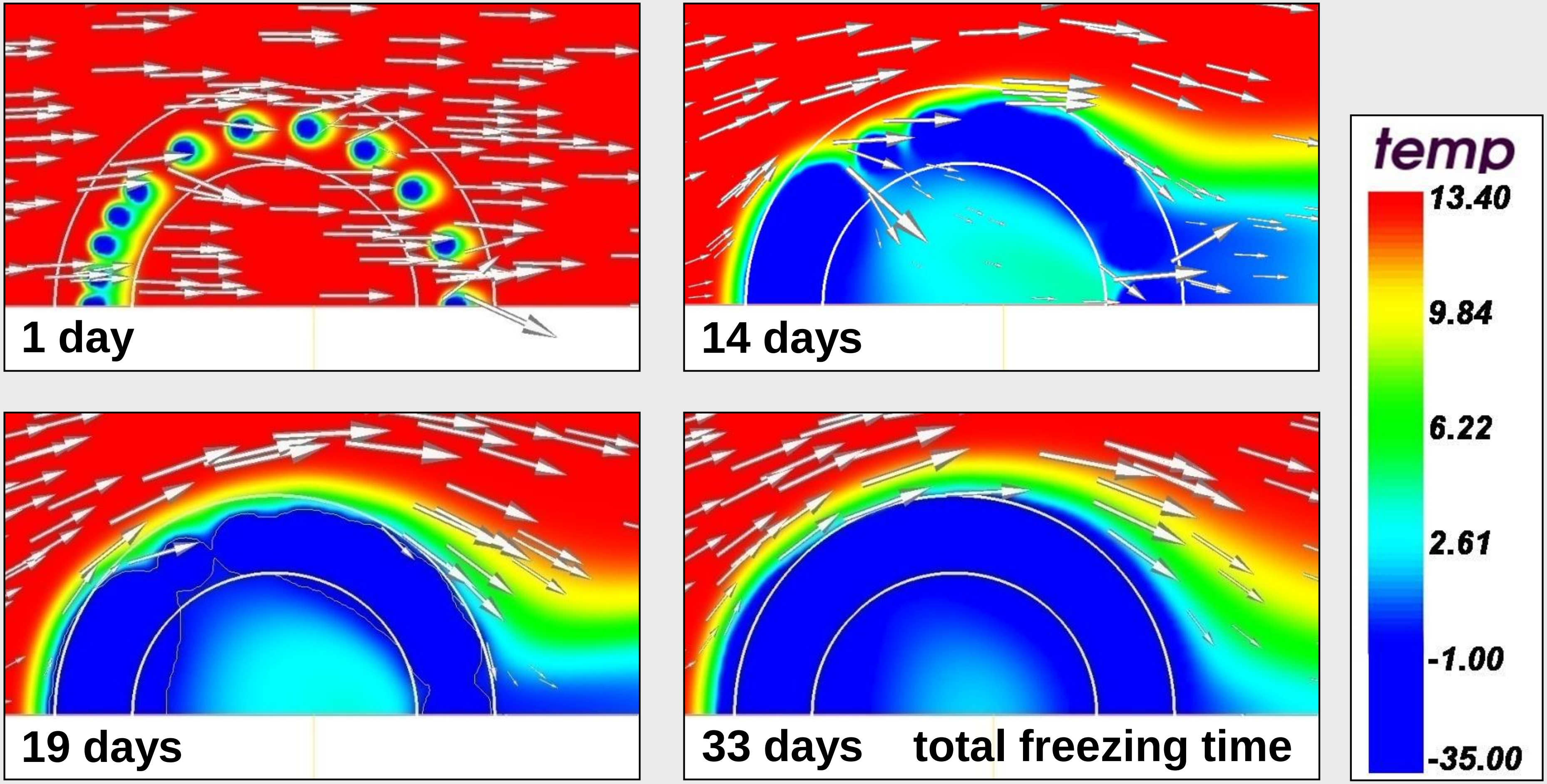
Concentration in the upstream



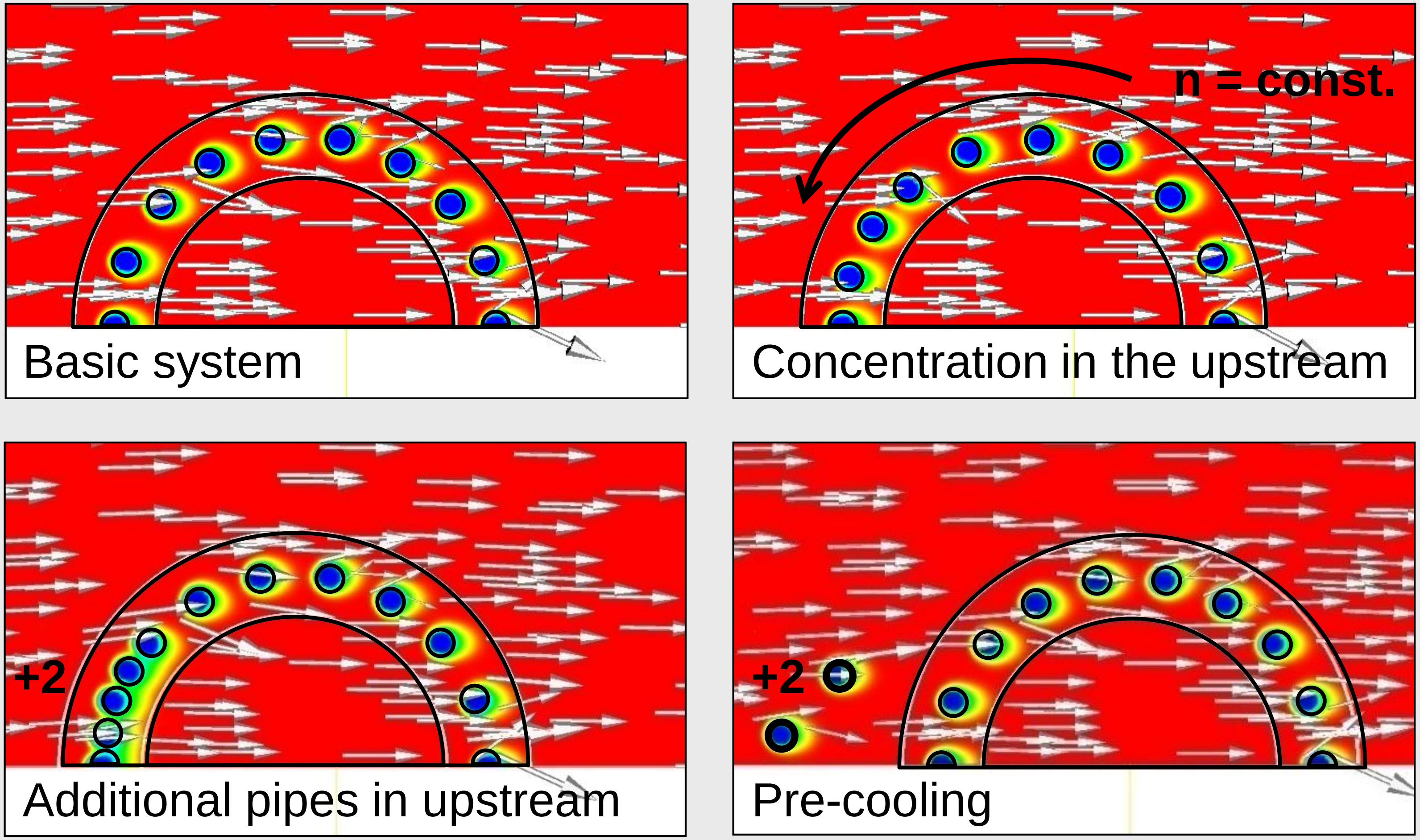
Concentration in the upstream (v = 0.75 m/d)



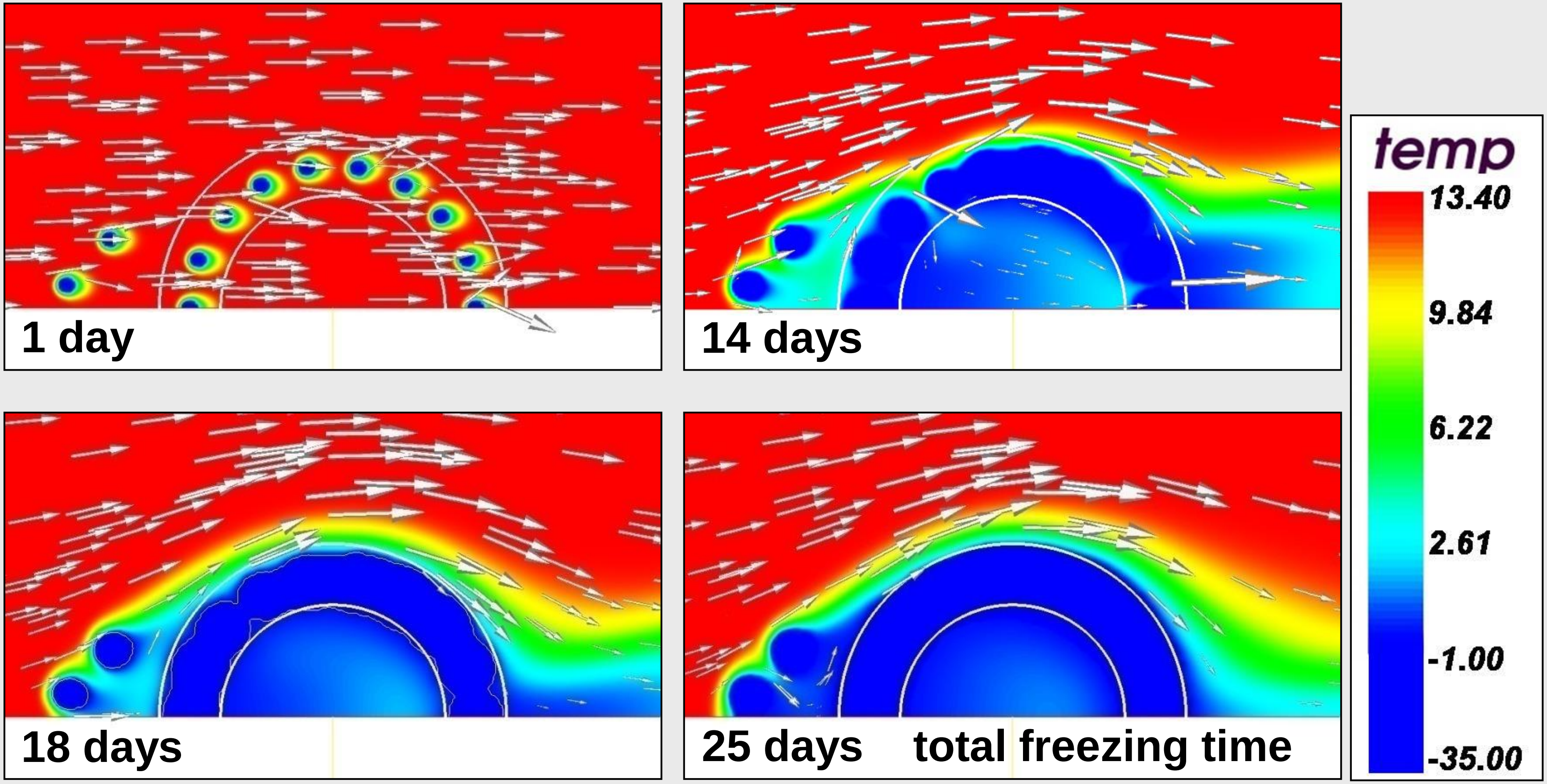
Additional pipes in the upstream



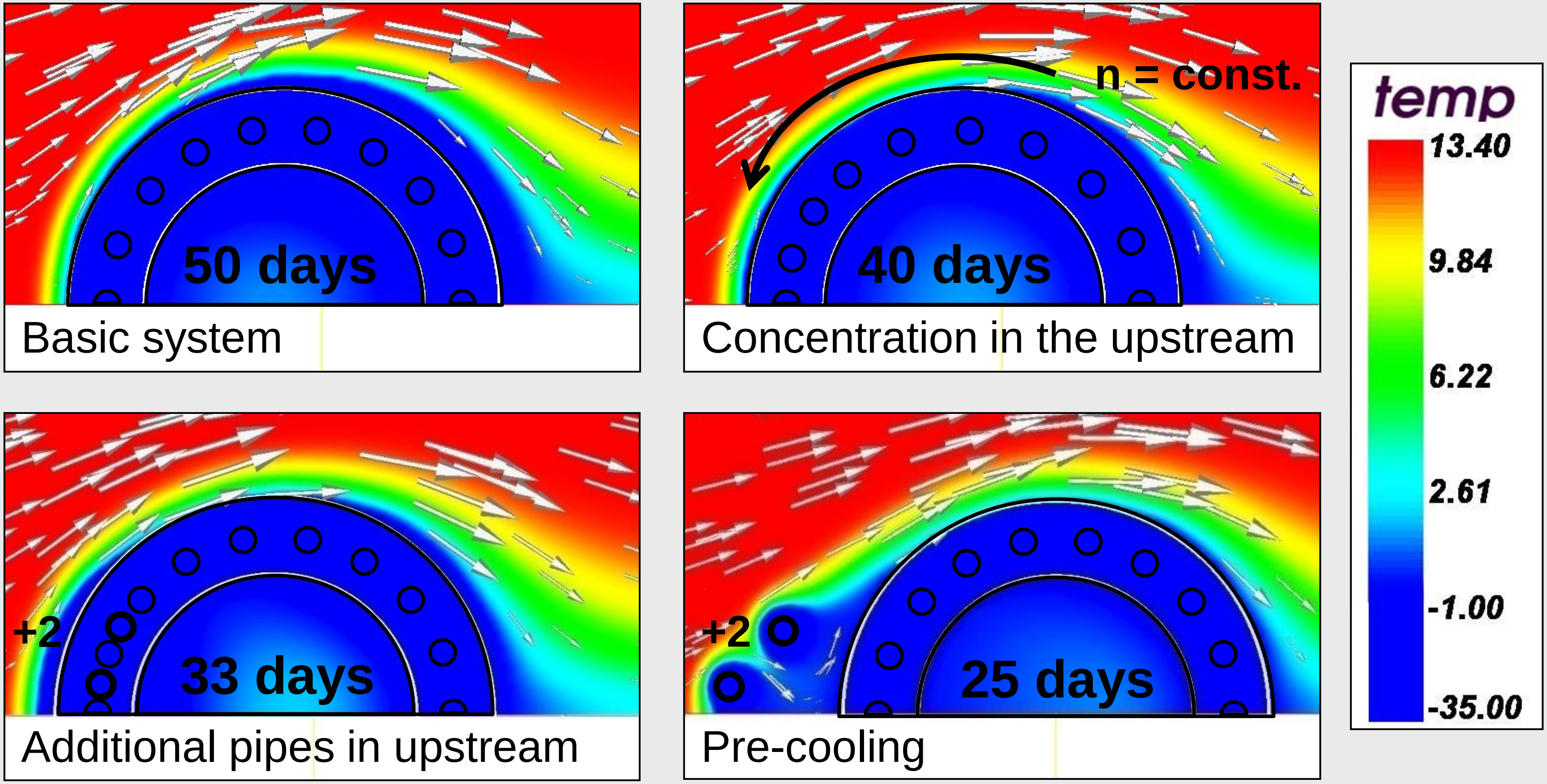
Additional pipes in the upstream (v = 0.75 m/d)


n = const.
+2
+2
Basic system
Concentration in the upstream
Additional pipes in upstream
Pre-cooling

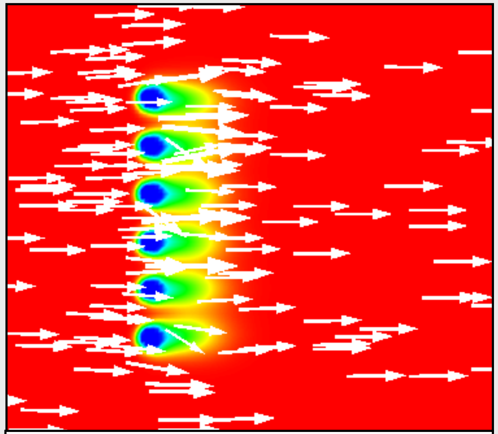
Pre-cooling



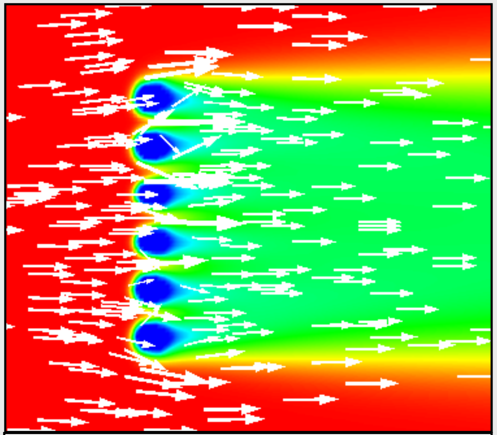
Pre-cooling (v = 0.75 m/d)



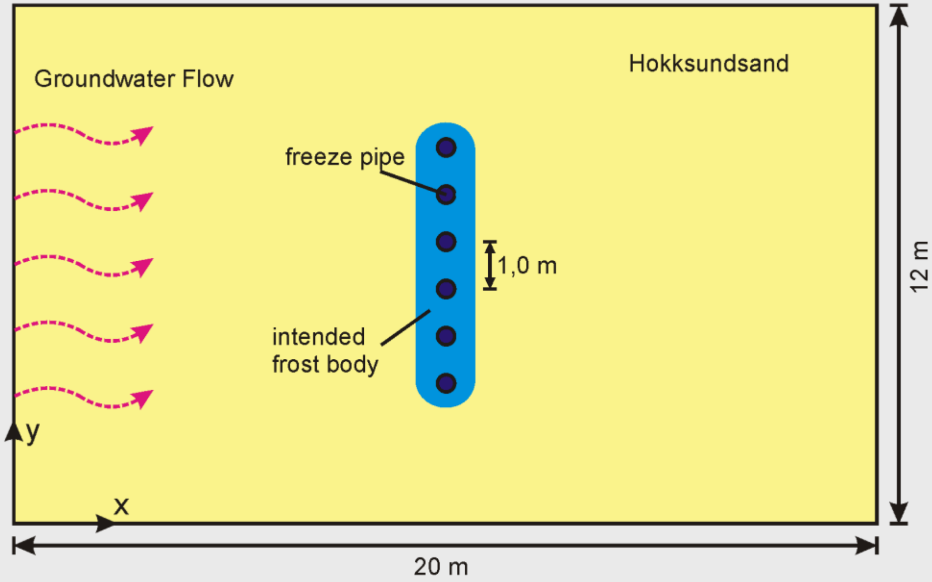
Total freezing time for optimization systems



1 day

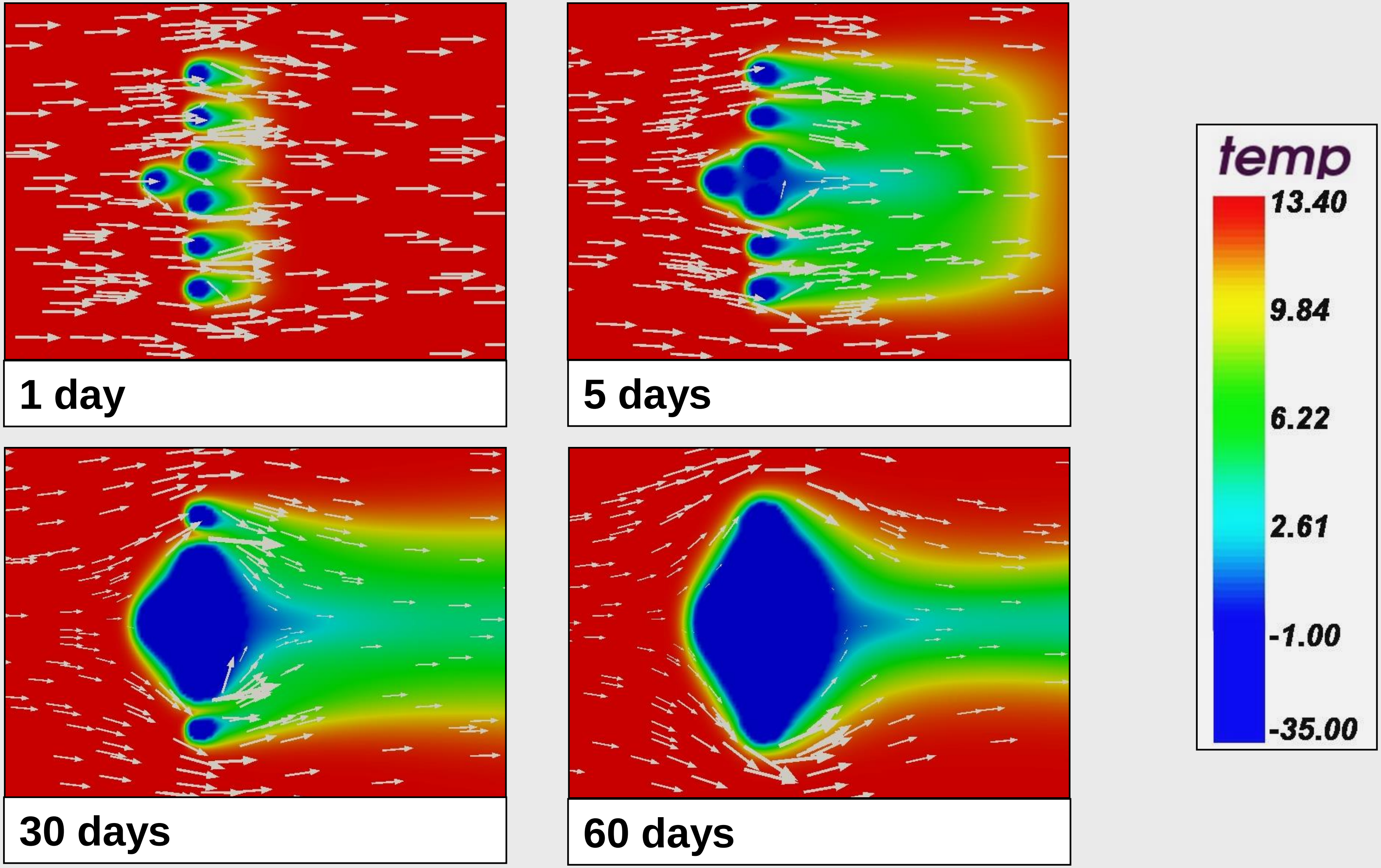


70 days

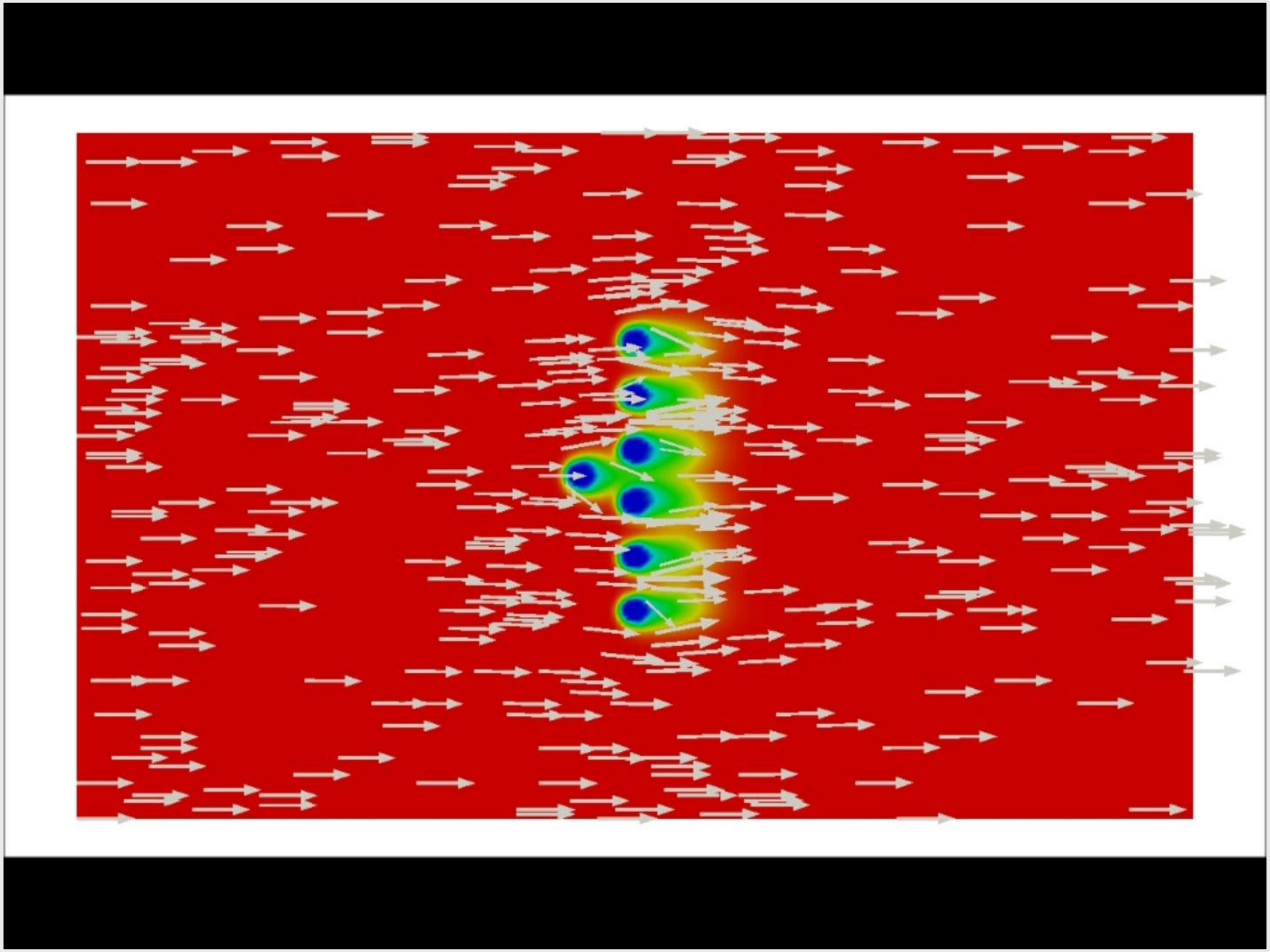


→ **steady - state**

excavation pit wall



Pre-cooling of an excavation pit wall – v = 1,0 m/d



Pre-cooling of an excavation pit wall – v = 1,0 m/d

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Further investigations:

Optimization of artificial ground freezing applications with respect to

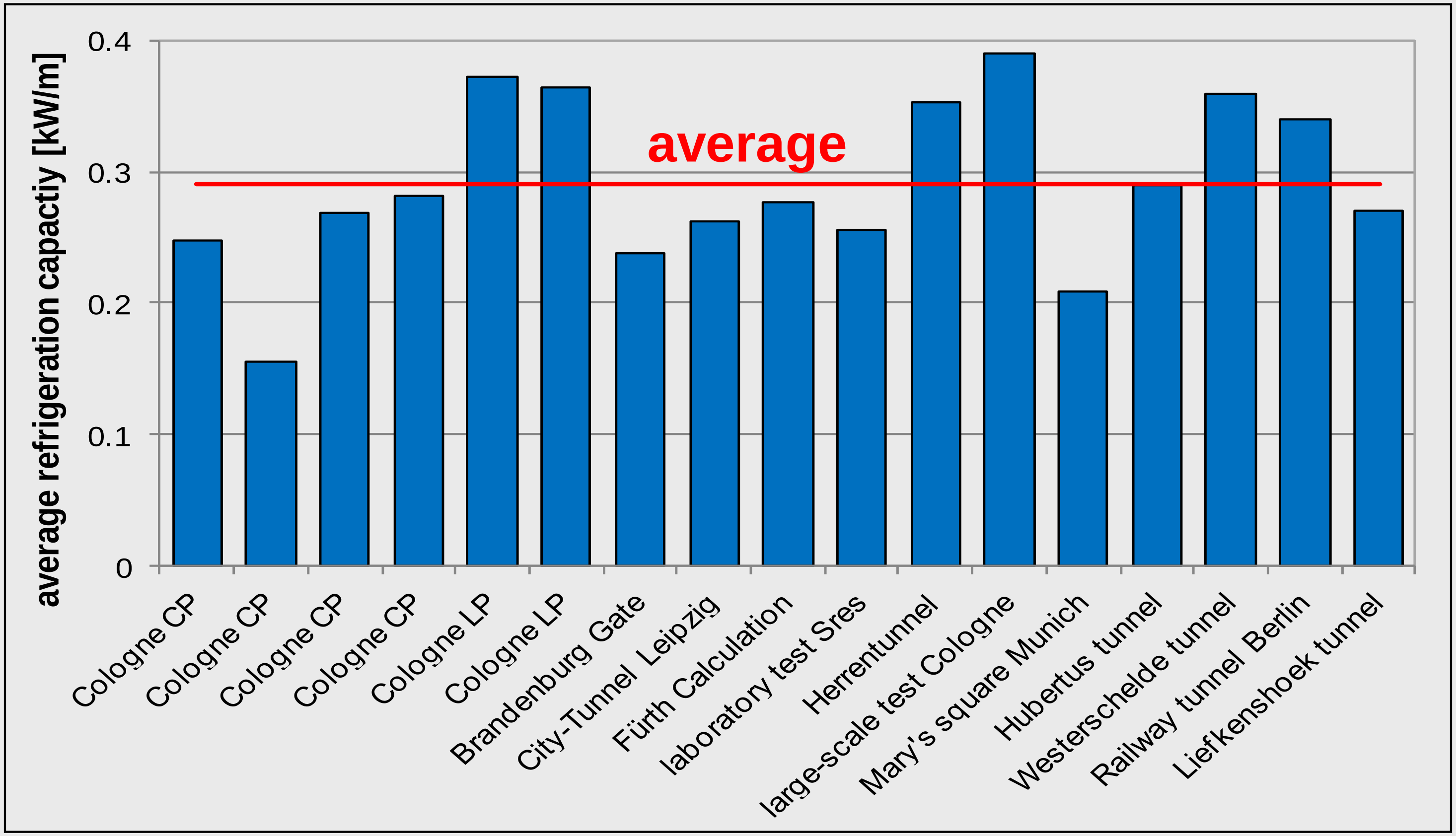
- **freezing time**
- **energy consumption**

→ **determination of refrigeration capacity**

(Max Bögl)

Estimation of refrigeration capacity with actual construction projects

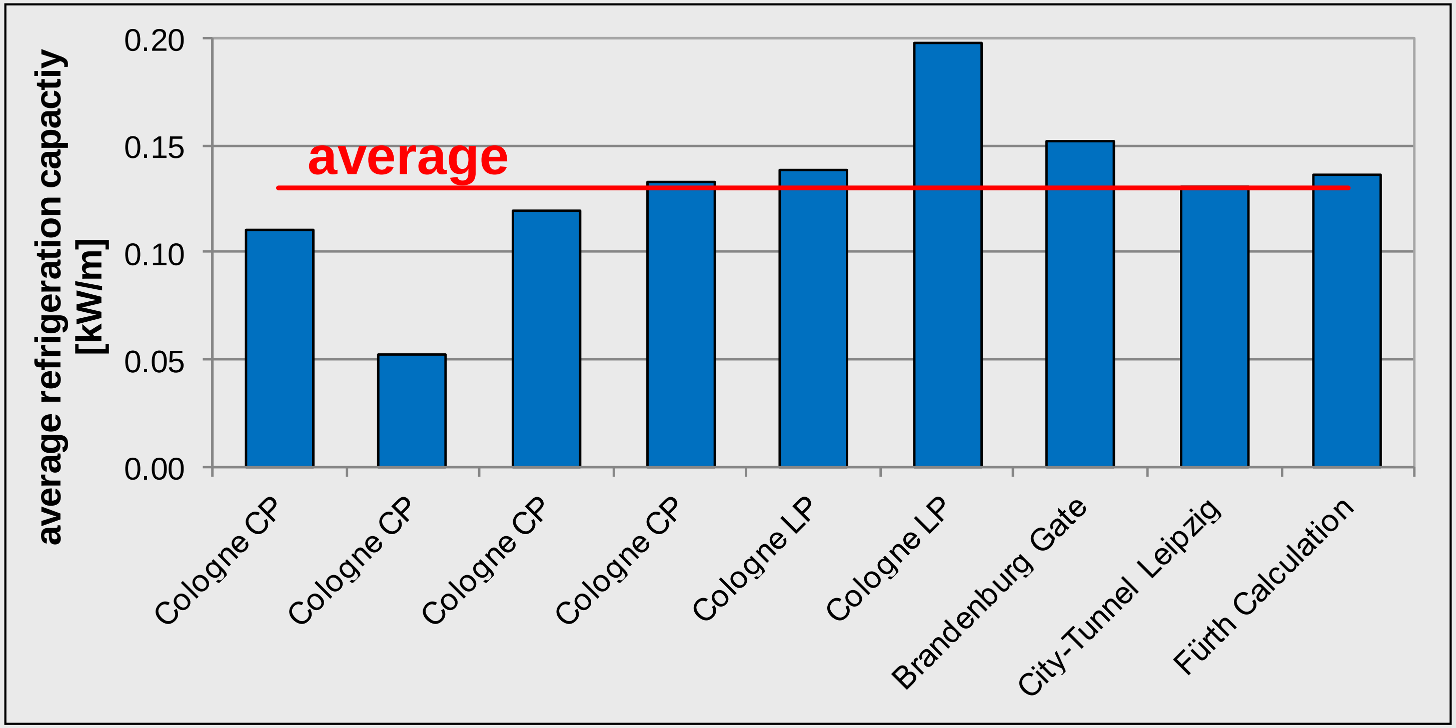
freezing phase



average refrigeration capacity approx. 0,29 kW/m

Estimation of refrigeration capacity with actual construction projects

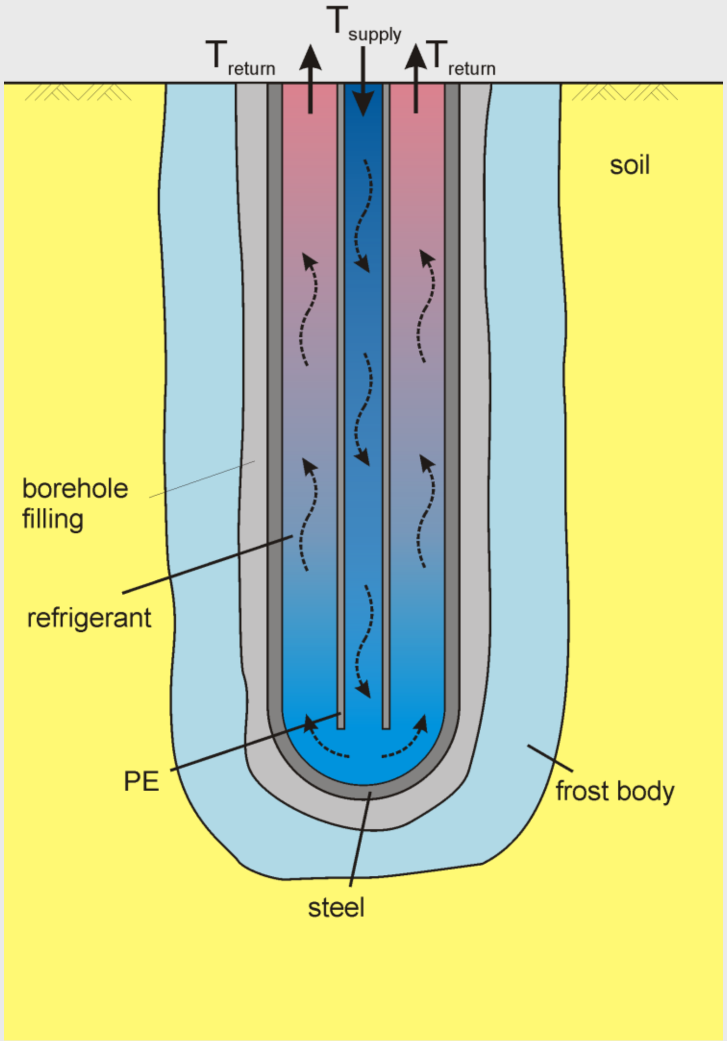
operating phase

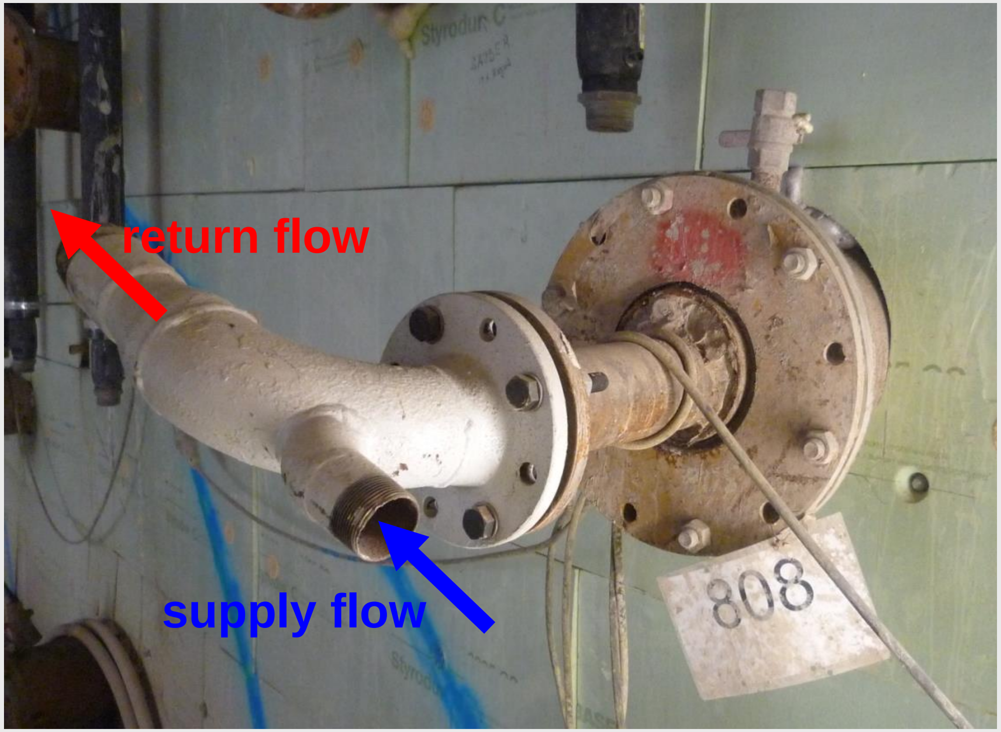


average refrigeration capacity approx. 0,13 kW/m

45 % of freezing phase

Freeze-pipe structure

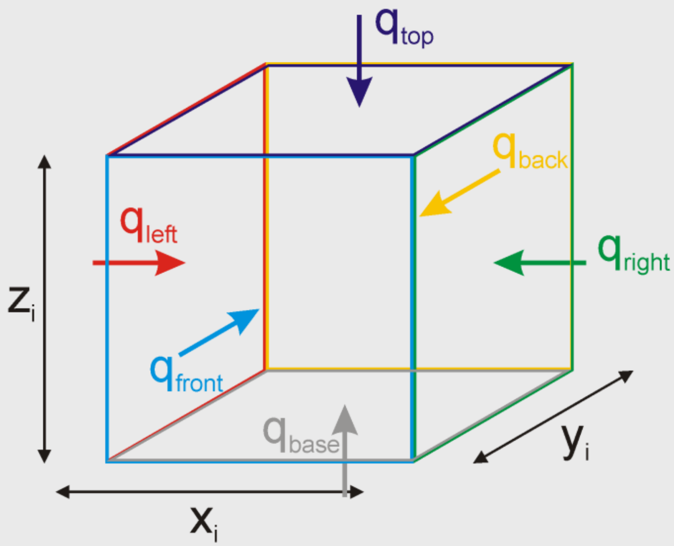




SHEMAT - „freezing“-module

simplified calculation approach for refrigeration capacity

- freeze-pipe temperature as Dirichlet boundary condition
- sum of heat flow

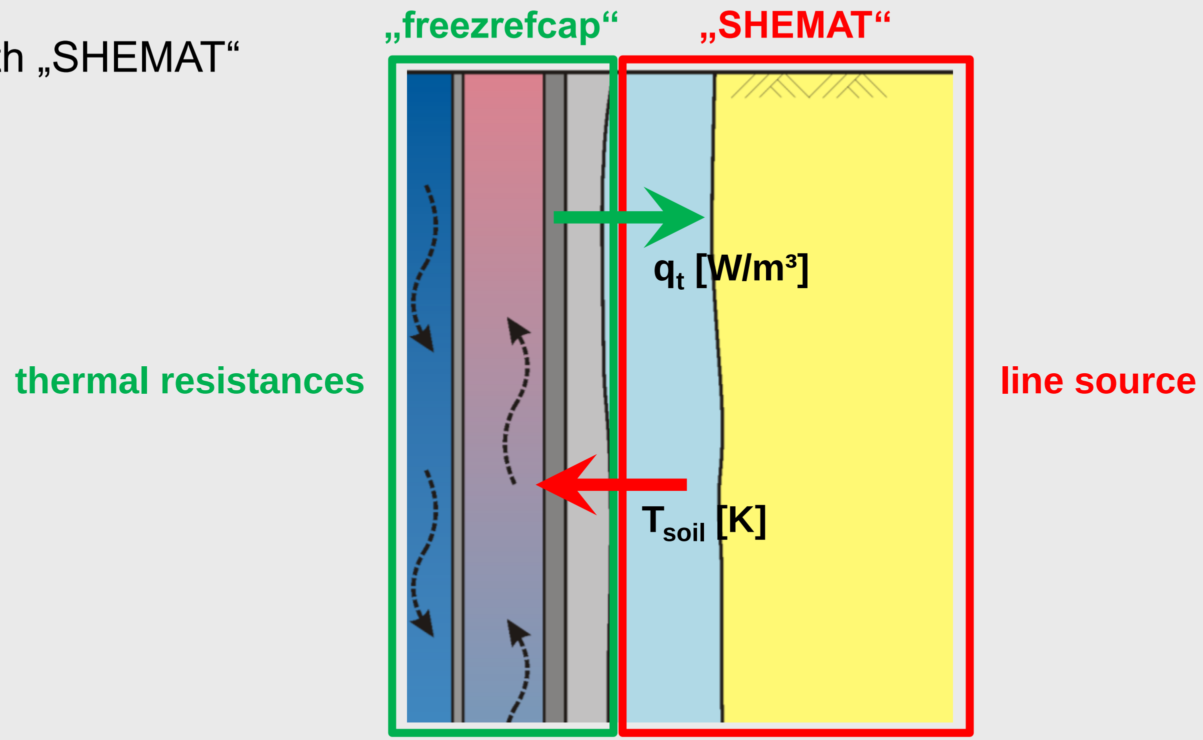


$$P = \sum_{i=1}^{6} q_i \cdot A_i$$

$$\begin{aligned} P = \; & (q_{left} + q_{right}) \cdot y_i \cdot z_i \\ & + (q_{front} + q_{back}) \cdot x_i \cdot z_i \\ & + (q_{top} + q_{base}) \cdot x_i \cdot y_i \end{aligned}$$

SHEMAT - „freezrefcap“-module

- separate module for determining heat transfer processes inside the freeze-pipe
- detailed input parameters:
  - radial & thermal conductivity of down pipe, riser pipe and borehole, freeze-pipe length
  - pump, supply temperature, refrigerant
- coupling with „SHEMAT“



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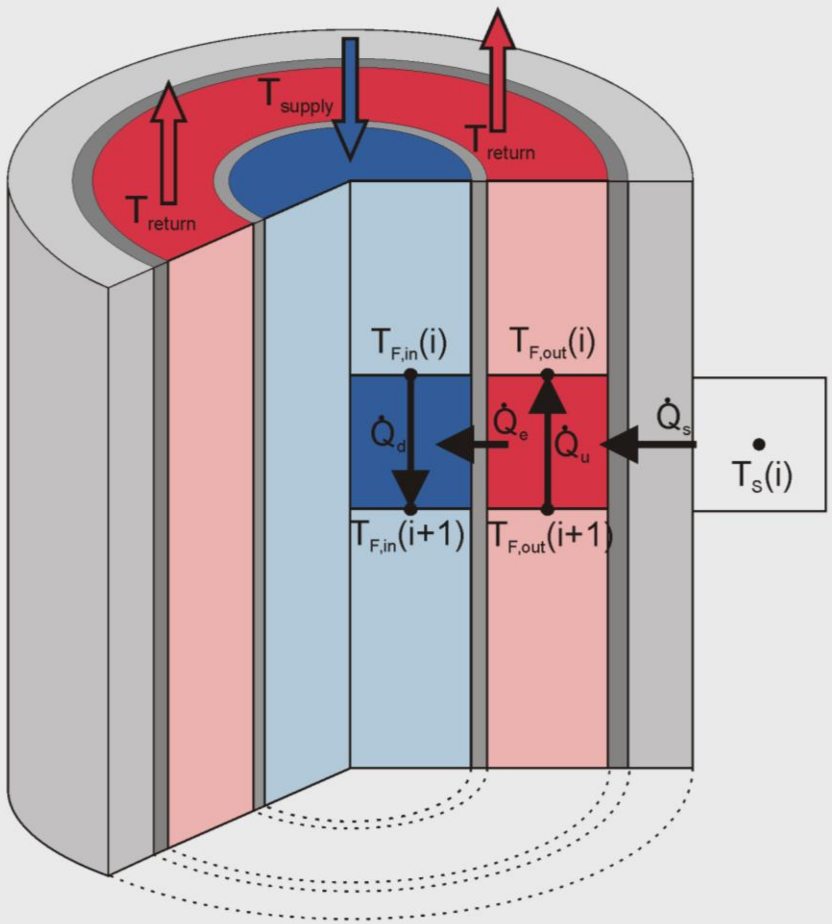
SHEMAT - „freezrefcap“-module



thermal resistances of freeze-pipe components

R_{outer} / R_{inner}

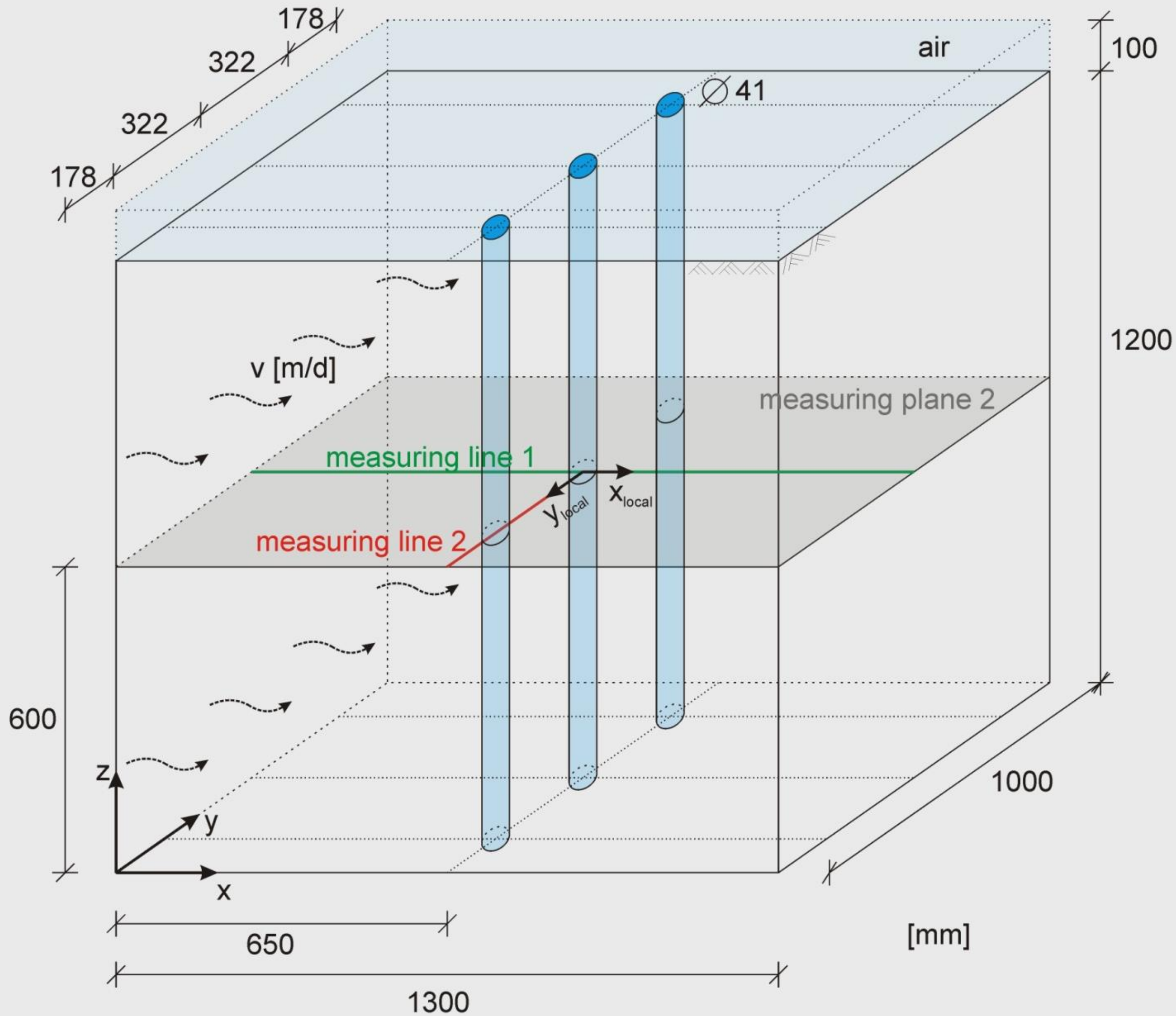
- conductive resistance
  - → depending on $\lambda_{\text{freeze-pipe component}}$
- convective resistance
  - → depending on $\alpha_{\text{refrigerant}}$
    - → depending on Nu

input Q [m³/s] and T_{supply} [°C]

results:

- temperatur distribution in freeze-pipe (down/up)
  - → refrigeration capacity
- heat flow Q_s to soil
  - → coupling with SHEMAT (q_t)

Laboratory test of ETH Zurich



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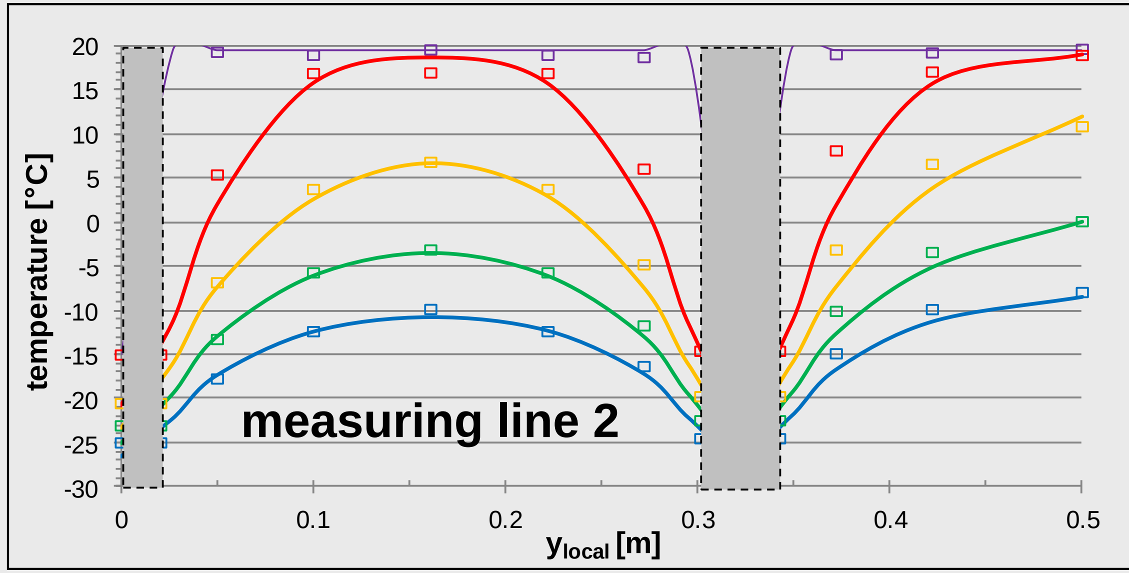
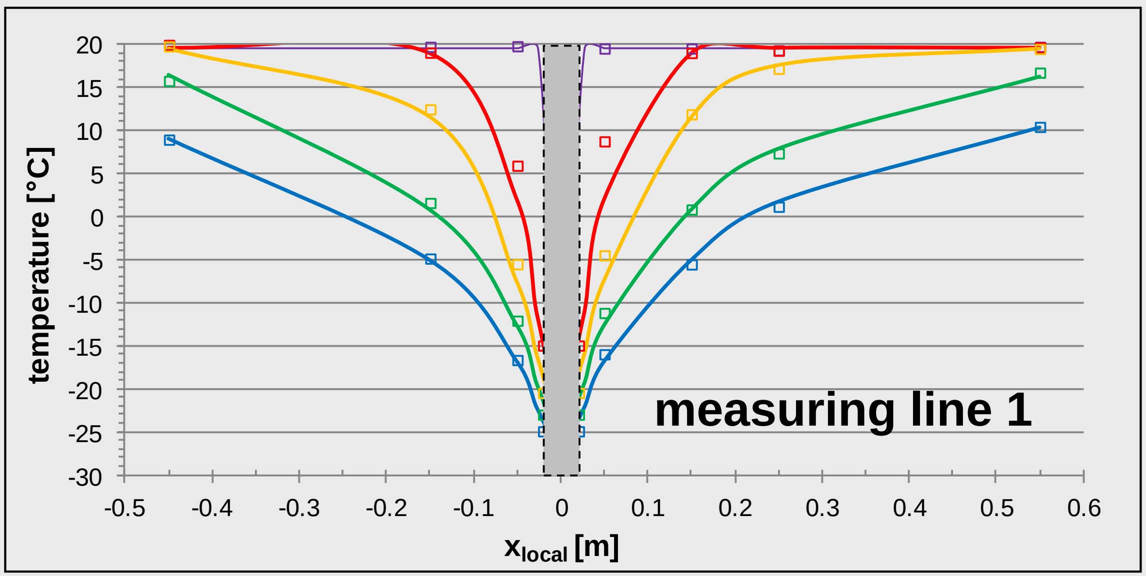
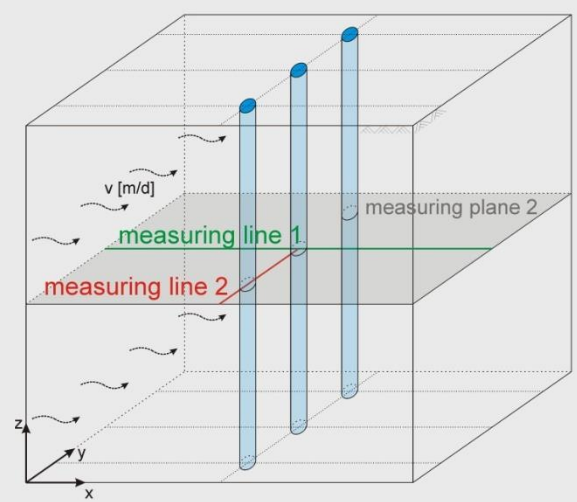
simulation results
„freezrefcap“ - v = 0 m/d

measured data
t = 1h
t = 5h
t = 20h
t = 40h







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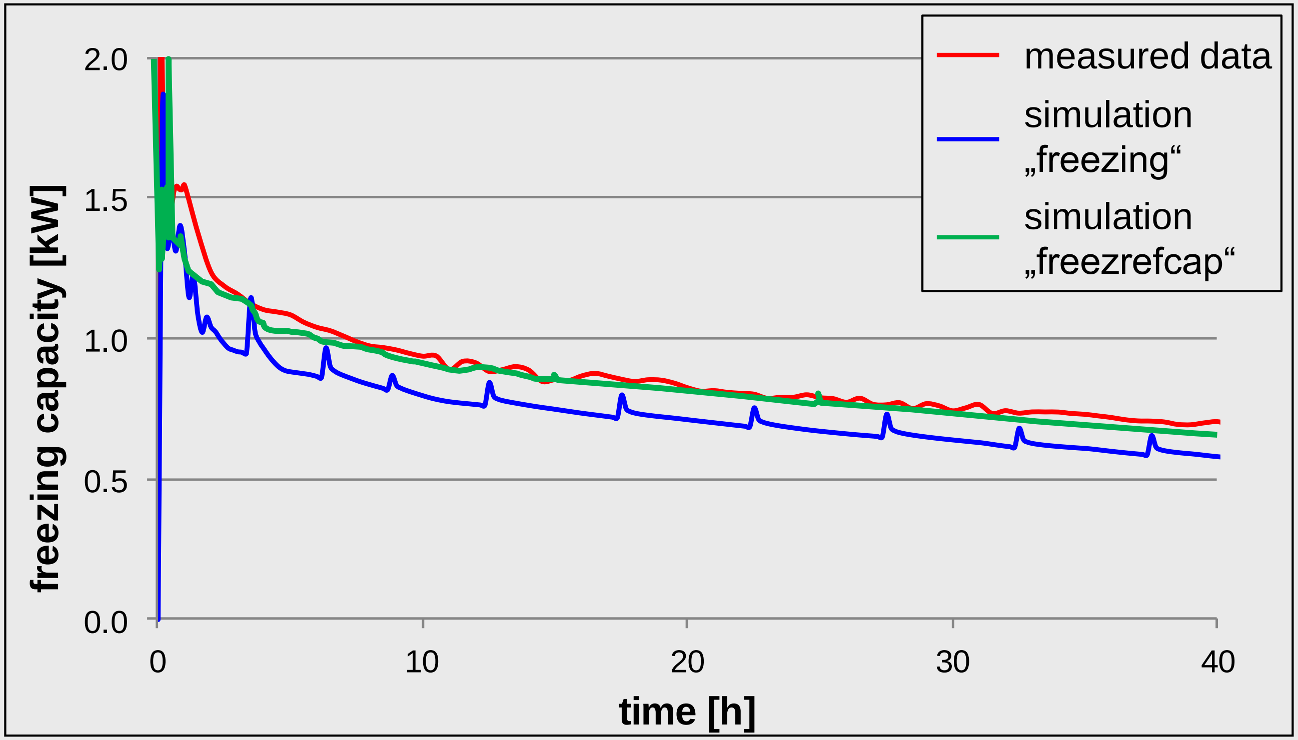
simulation results

„freezrefcap“ - v = 0 m/d



➡ clear difference between „freezing“ and „freezrefcap“

➡ bad heat transfer due to the laminar flow

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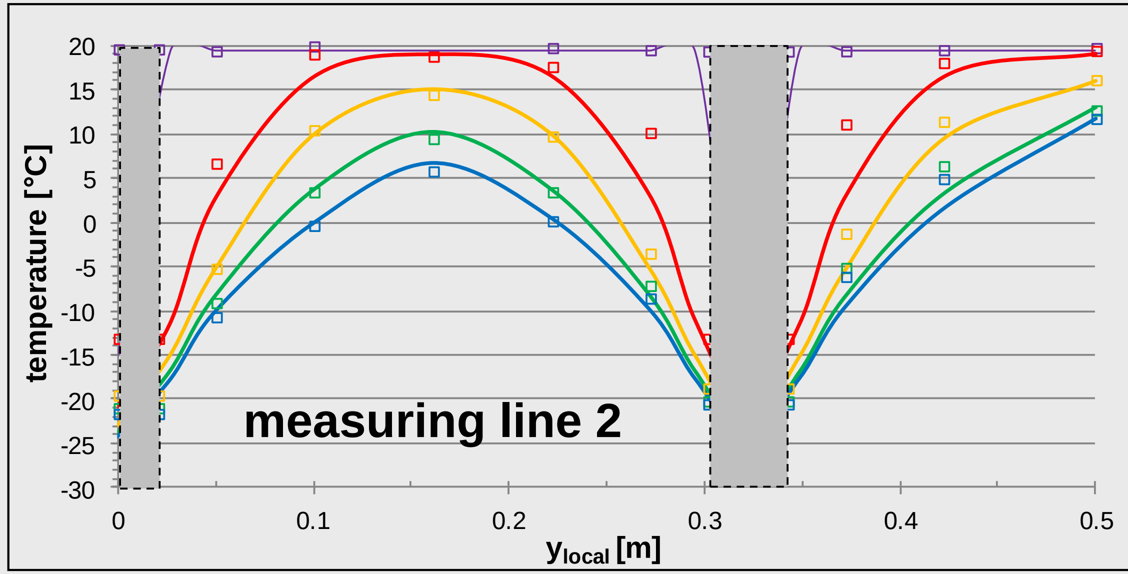
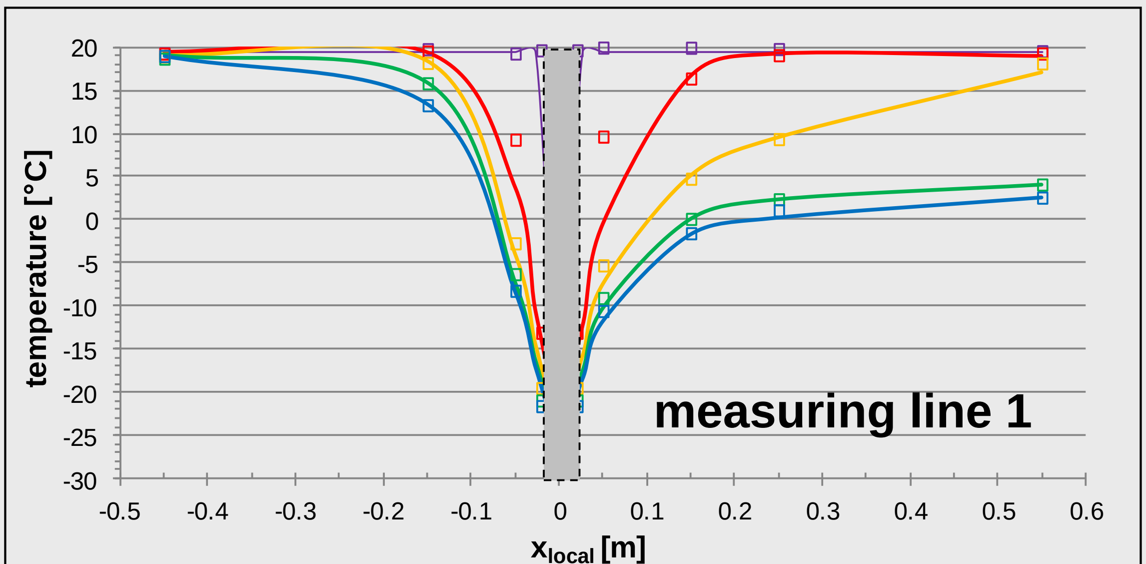
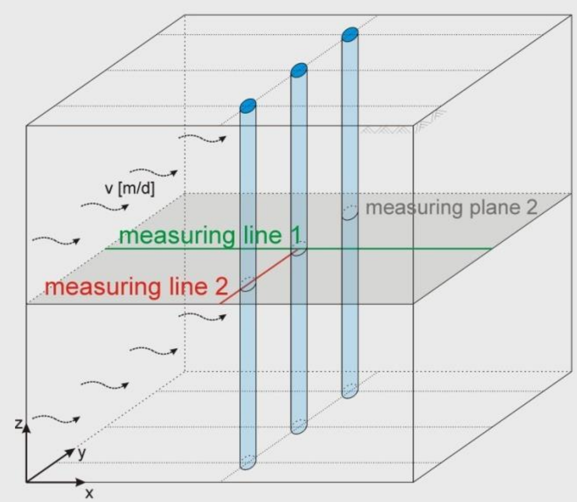
simulation results

„freezrefcap“ - v = 1,5 m/d

- measured data
- t = 1h
- t = 5h
- t = 20h
- t = 40h







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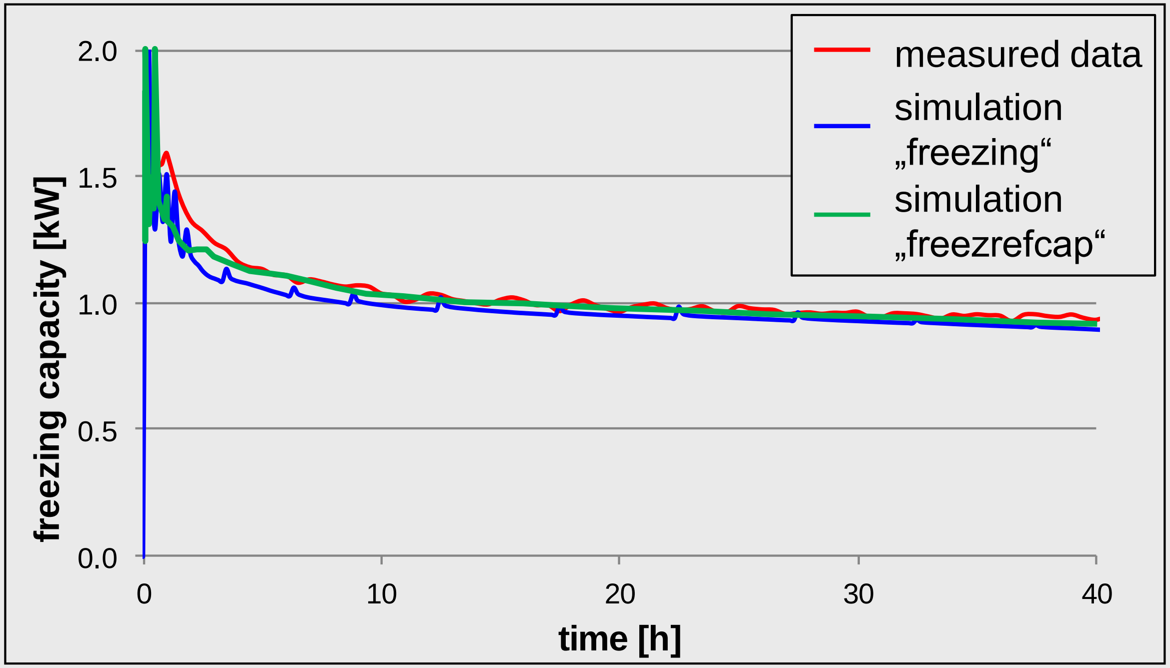
simulation results

„freezrefcap" - v = 1,5 m/d



➡ good representation of freezing prozess with „freezing"- and „freezrefcap"-module

- ➡ small underestimation of refrigeration capacity with „freezing"-module
- ➡ good representation of refrigeration capacity with „freezrefcap"-module

- **Groundwater flow may not be neglected, particularly if barriers in the underground create a nozzle effect, leading to an increased velocity of the groundwater.**

- **Realistic assessment of ground freezing subject to groundwater flow requires numerical methods.**

- **Considerable cost saving potentials can be achieved by flow-optimized design and operating options**

- **Realistic determination of refrigeration capacity allows an energetic optimization including the operating phase**

Thank you for your attention!