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gebo Forschungsverbund Geothermie und Hochleistungsbohrtechnik

Heat Transfer in Borehole Heat Exchangers from Laminar to Turbulent Conditions

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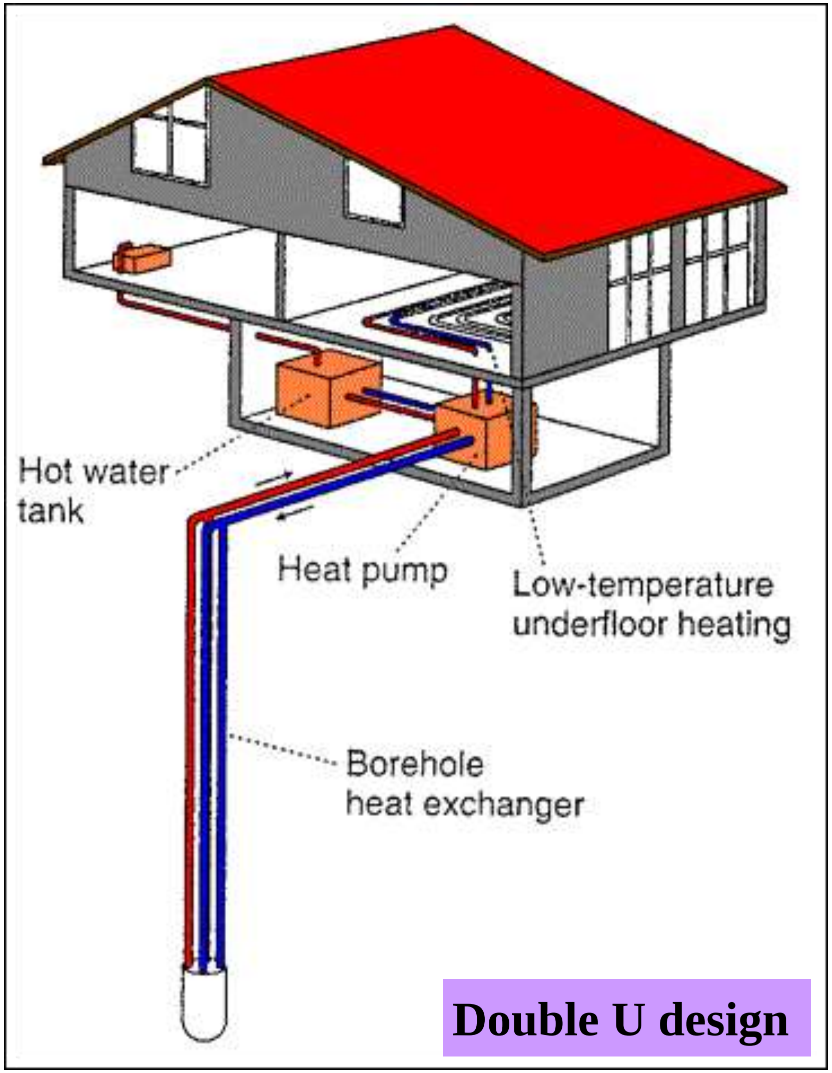
Borehole Heat Exchanger (BHE)



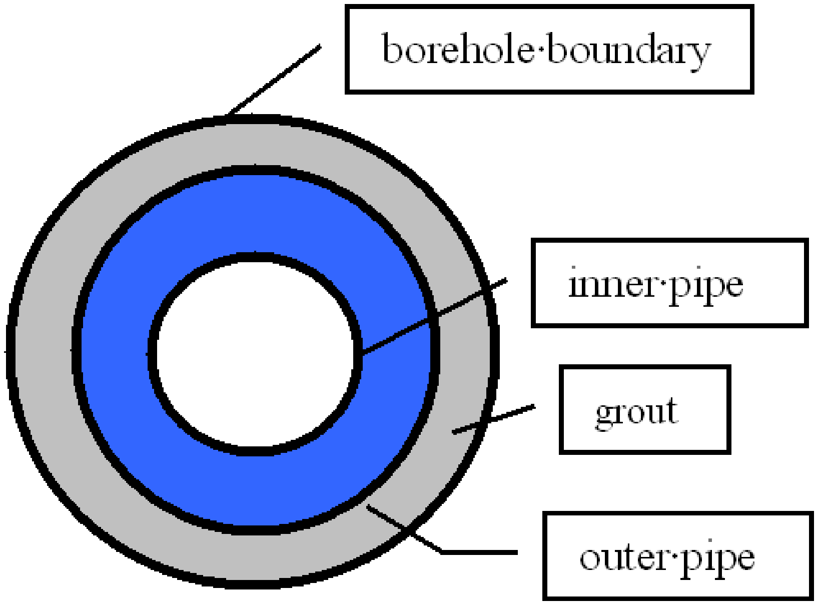
Borehole heat exchangers (BHE) in connection with heat pumps and floor heating in many countries are becoming an alternative to conventional heating or cooling systems using fossil resources. Geothermics is one building block within the suite of alternative low-carbon, sustainable and renewable energy technology.

BHE - Modeling

Co-axial design

Modeling is a convenient tool in order to understand and optimize the heat transfer between the technical system, consisting of borehole, pipes and grout, and the surrounding ground, which is crucial for the performance of the BHE.

1D model components for flow and heat transport in the technical part can be coupled with a 2D or 3D component for the ground. With appropriate borehole conductances the so coupled model is capable to cope with laminar, turbulent and transitory conditions in the pipes.



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Heat Transport & Flow

Differential Equations

in pipes (1D):

$$(\rho C)_f \frac{\partial T}{\partial t} + \frac{\partial}{\partial x}\left((\rho C)_f T v\right) = -\frac{\partial}{\partial x} \cdot \lambda_f \frac{\partial T}{\partial x} + j$$

in porous media:

$$(\rho C)\frac{\partial T}{\partial t} + \nabla \cdot \left((\rho C)_f T \mathbf{q}\right) = -\nabla \cdot \lambda \nabla T$$

$$S\frac{\partial h}{\partial t} = \nabla \mathbf{K} \nabla H + Q$$

groundwater flow:

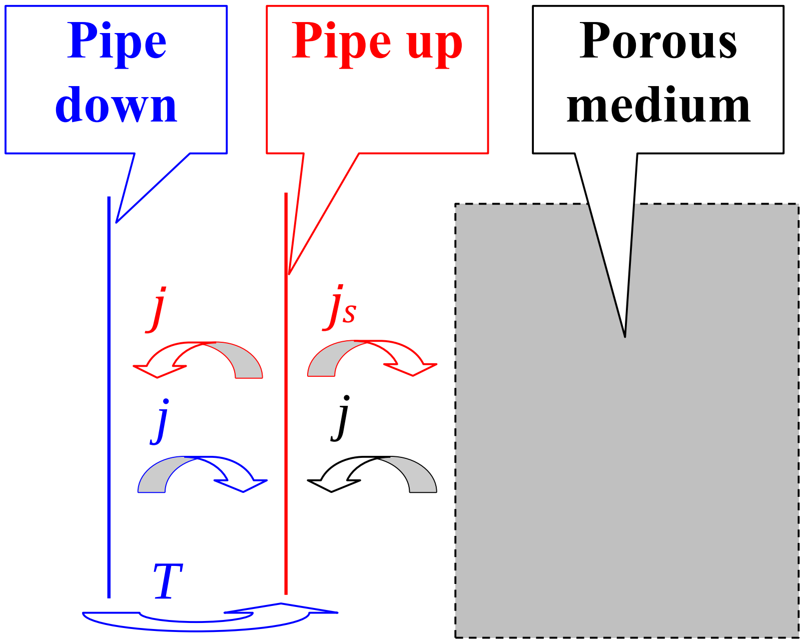
$$\mathbf{q} = -\mathbf{K} \cdot \nabla H$$

with

Temperature T, heat capacity of fluid $(\rho C)_f$, fluid thermal conductivity λ_f, flow velocity v and sinks/sources j, specific heat capacity of the fluid-solid system (ρC), its thermal conductivity λ, Darcy velocity **q**, piezometric head H, the tensor of hydraulic conductivities **K**, storage coefficient S and fluid sink/source term Q

Heat Flow & Transport

Couplings



Between pipes	$j = -h\Delta T$	source/sink
Pipe -> porous media	$j_s = -h\left(T - T_{ext}\right)$	boundary condition
Porous media -> pipe	$j = -h\Delta T$	source/sink

Pipe Flow Regimes

Laminar, turbulent or transitory

Conductances

$$h = \begin{cases} Nu \cdot \lambda \cdot \pi & \text{for cylinder flow} \\ Nu \cdot \lambda \cdot \pi \cdot r_i / d & \text{for inner boundary annular flow} \\ Nu \cdot \lambda \cdot \pi \cdot r_o / d & \text{for outer boundary annular flow} \end{cases}$$

Nusselt-numbers

laminar

$$Nu = \begin{cases} 4.364 & \text{for cylinder flow} \\ 3.66 + \left(4 - \dfrac{0.102}{0.02 + r_o / r_i}\right)\left(\dfrac{r_o}{r_i}\right)^{0.04} & \text{for annular flow} \end{cases}$$

turbulent

$$Nu = \begin{cases} \dfrac{(\xi / 8)\,\mathrm{Re} \cdot \mathrm{Pr}}{1 + 12.7\sqrt{\xi / 8}\left(\mathrm{Pr}^{2/3} - 1\right)}\left(1 + \left(\dfrac{2r}{L}\right)^{2/3}\right) & \text{for cylinder flow} \\ '' \square \; \dfrac{0.86\left(\dfrac{r_o}{r_i}\right)^{0.84} + \left[1 - 0.14\left(\dfrac{r_o}{r_i}\right)^{0.6}\right]}{1 + \left(\dfrac{r_o}{r_i}\right)} & \text{for annular flow} \end{cases}$$

with

Reynolds number Re

Prandtl number Pr

length L

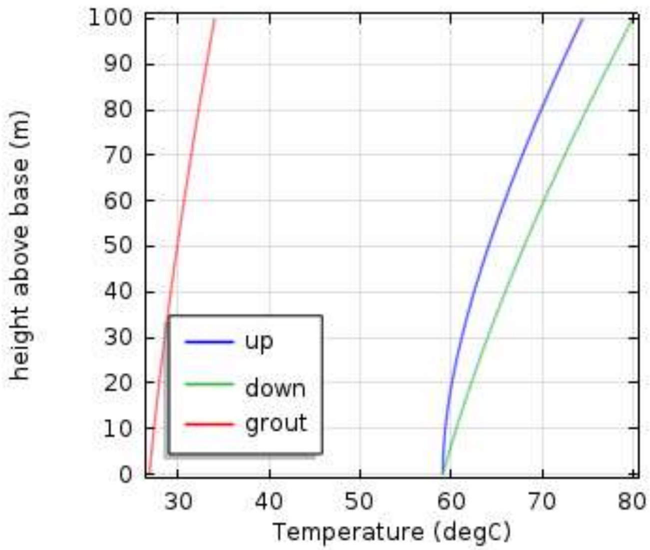
$$\xi = \left(1.8 \log_{10}(\mathrm{Re}) - 1.5\right)^{-2}$$

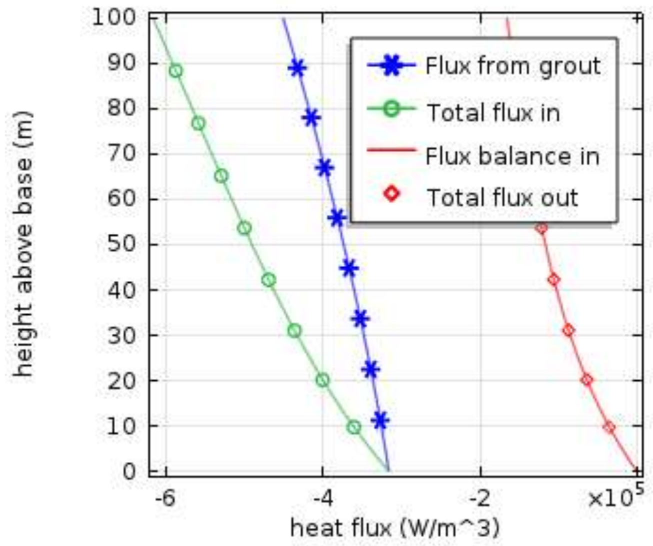
Verification Model

FEFLOW white paper

- model of pipes and grout
- fixed temperature at borehole wall
- transitory regime

FEFLOW, DHI-WASY Software, *Finite Element Subsurface Flow & Transport Simulation System*, White Papers, Vol 5





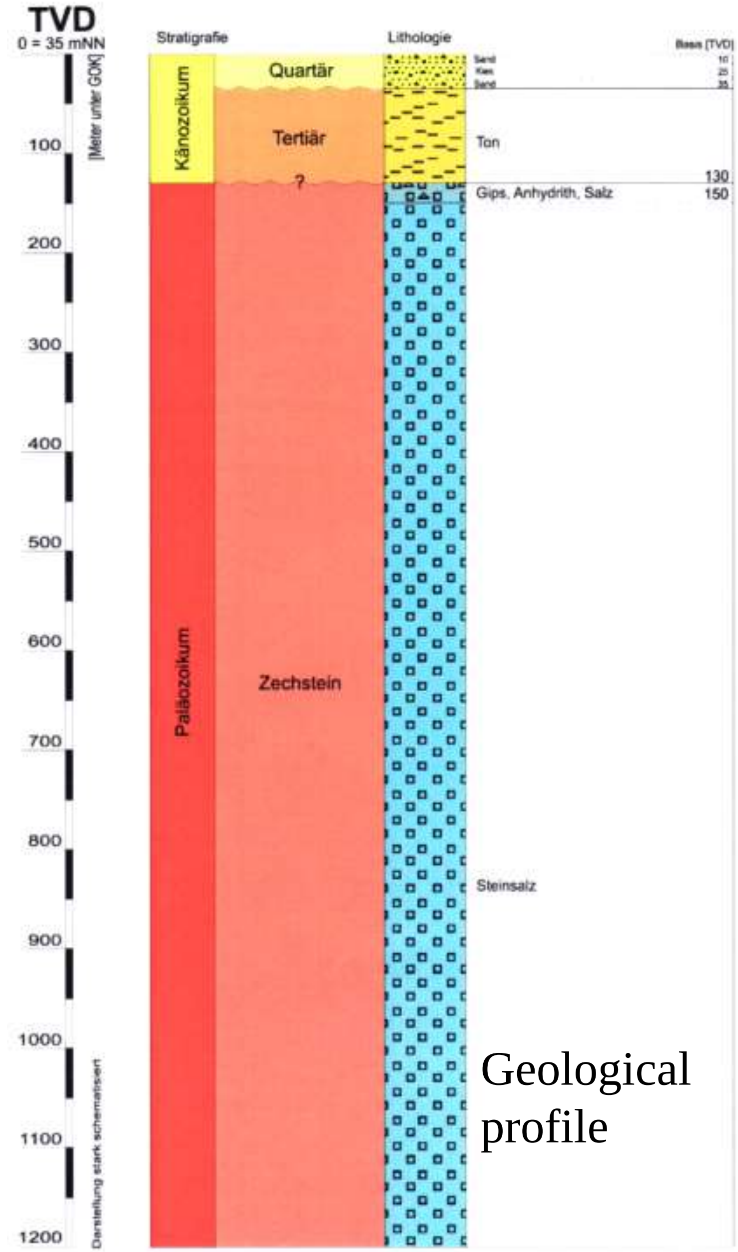
- Heat flux balance o.k.
- Temperature profiles significantly different from FEFLOW

Hambühren

Feasability study

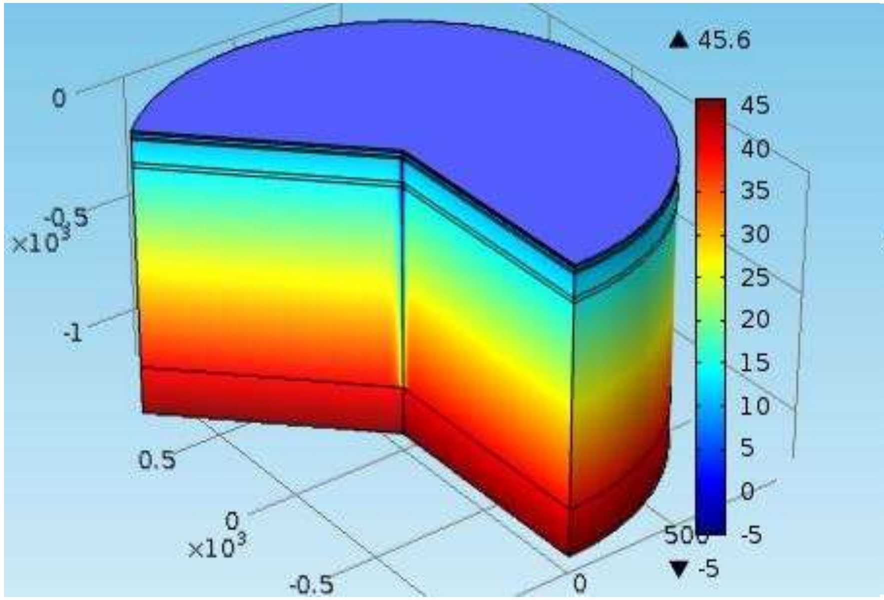
Major parameters:

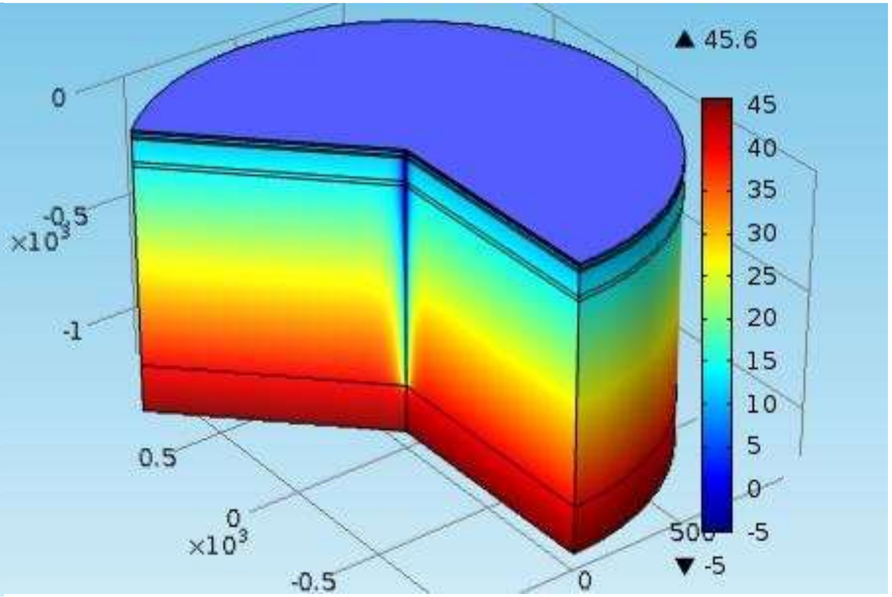
- BHE length: 1000 [m]
- Top layer thickness: 130 [m]
- Borehole radius: 10.8 [cm]
- Model extension: 360 [m]
- Production rate: 4[l/s]
- Fluid density: 1000 [kg/m^3]
- Fluid viscosity: 1.8 10^{-3} [kg/m/s]
- Operating period: 211 [d/a]
- Thermal gradient: 0.03 [°K/m]
- Salt thermal conductivity: 4 [W/m/K]
- Maximum surface temperature: 18.7 [°C]
- Minimum surface temperature: 1.4 [°C]
- Prandtl number: 12.8
- Inflow Reynolds number: 12482
- Outflow Reynolds number: 28095
- Heat pump temperature difference: 6 [°K]



Geological profile

Results
Temperature Fields





after 5 years of operation

after 30 years of operation

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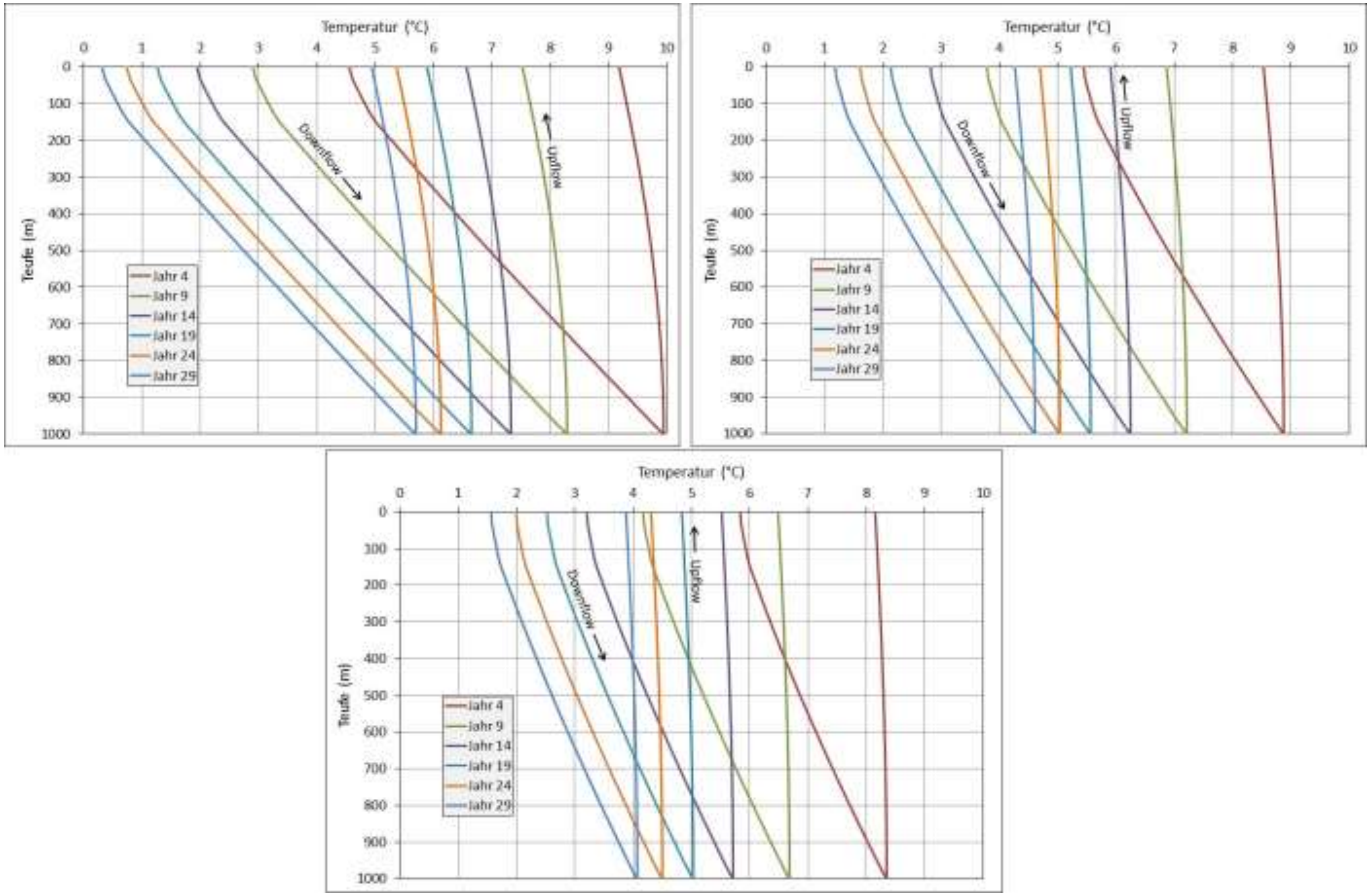
Results

Temperature Profiles in Pipes



for pumping rates of 4, 6 and 8 l/s

Conclusions

- The 1D pipe concept can be applied within 2D or 3D porous medium domains in cartesian or axisymmetric coordinates, for steady-state as well as for transient problems.
- Advective processes resulting from groundwater or seepage flow can be included (not shown here), using 3D domains.
- It is even possible to treat high temperature gradients, when changes of fluid properties, density and viscosity, have to be taken into account; thus using a two-way coupled TH-model.
- Geological layers, complex geometries, inhomogeneities, anisotropies of the porous medium can be accounted for.
- It is possible to use the here presented concept for heat exchangers of different design (U-pipe, double U-pipe).
- For rough pipes these should be altered accordingly.
- The transient response of the system due to varying pumping regimes can be simulated. Finally it is possible to take different conditions at the boundaries into account.

Acknowledgements

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Thank you very much for your attention!

Questions?