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Simulation of Deep Geothermal Heat Production

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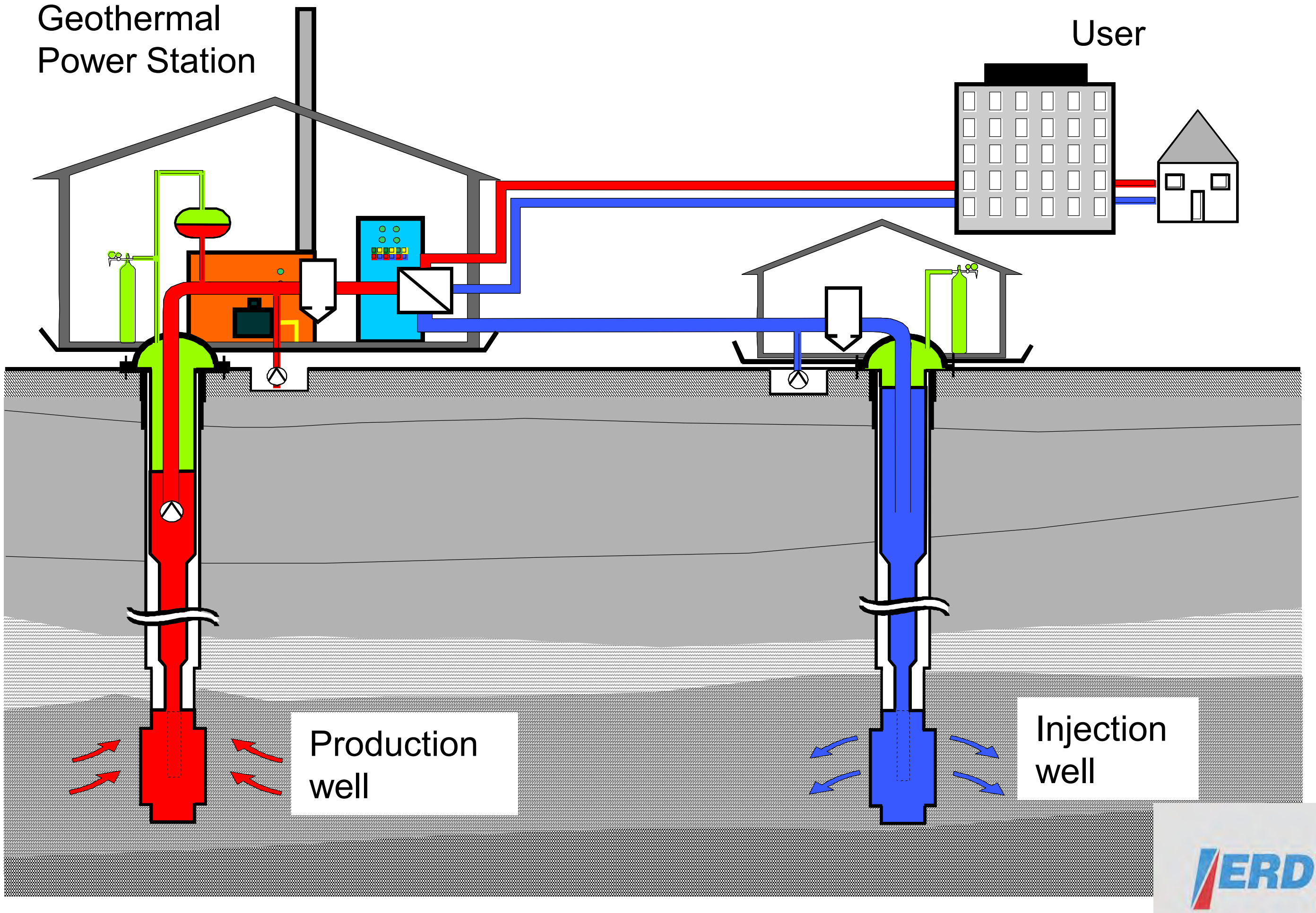
Geothermal Heat Production



Geothermal Power Station

User

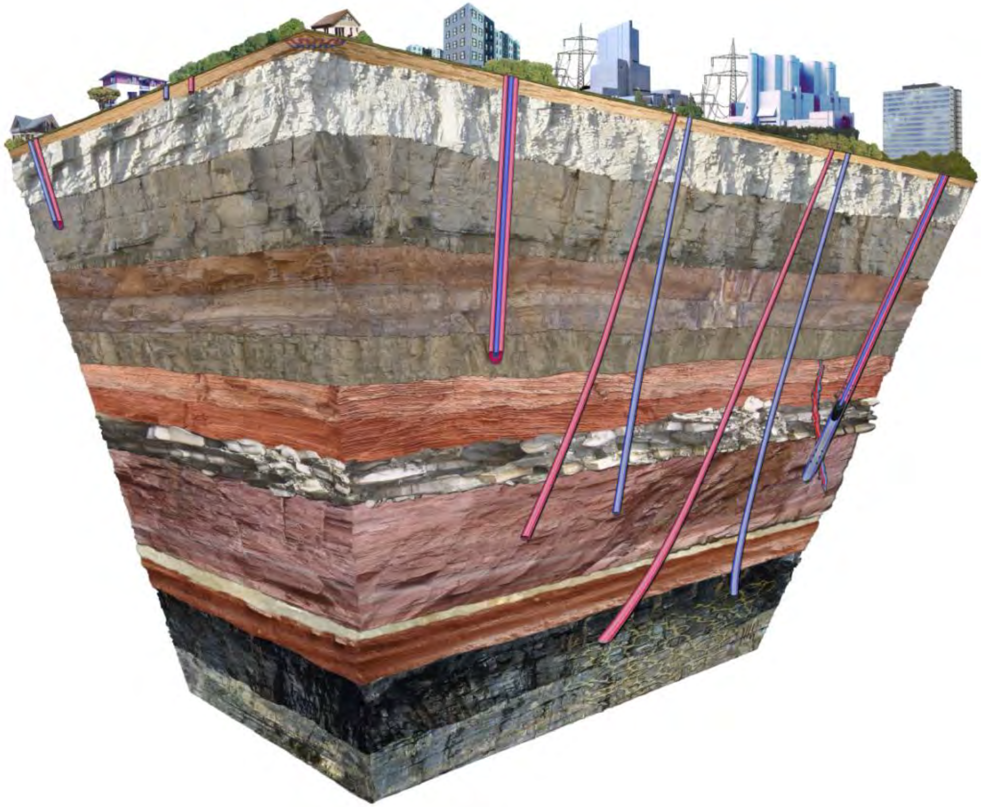
Production well

Injection well

ERDWÄRME Neustadt-Glewe GmbH

gebo

Challenges connected with geothermal heat production from deep reservoirs (5000-7000 m) are currently examined within the collaborative research program "Geothermal Energy and High-Performance Drilling" (gebo), funded by the Ministry of Science and Culture of Lower Saxony (Germany) and Baker Hughes.

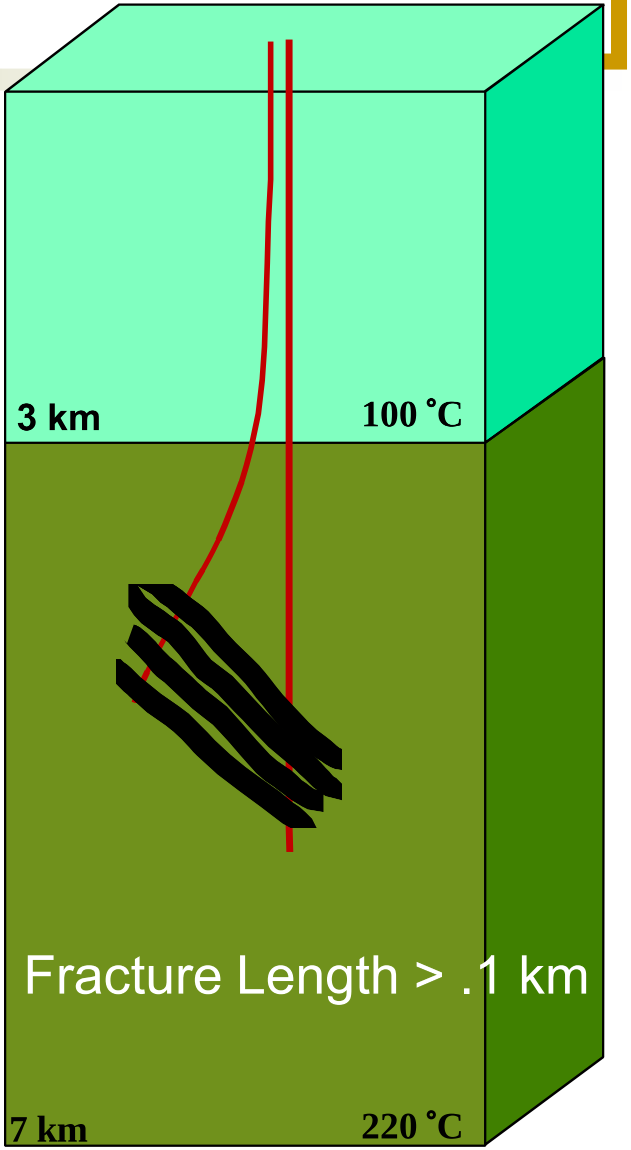


Leibniz Institute for Applied Geophysics (LIAG)

Deep Geothermal Heat Production

Temperature	**> 100 °C**
Depth	**< 7 km**
Flow	**> 50 m³/h**

(from: Jung, Orzol, Schellschmidt)



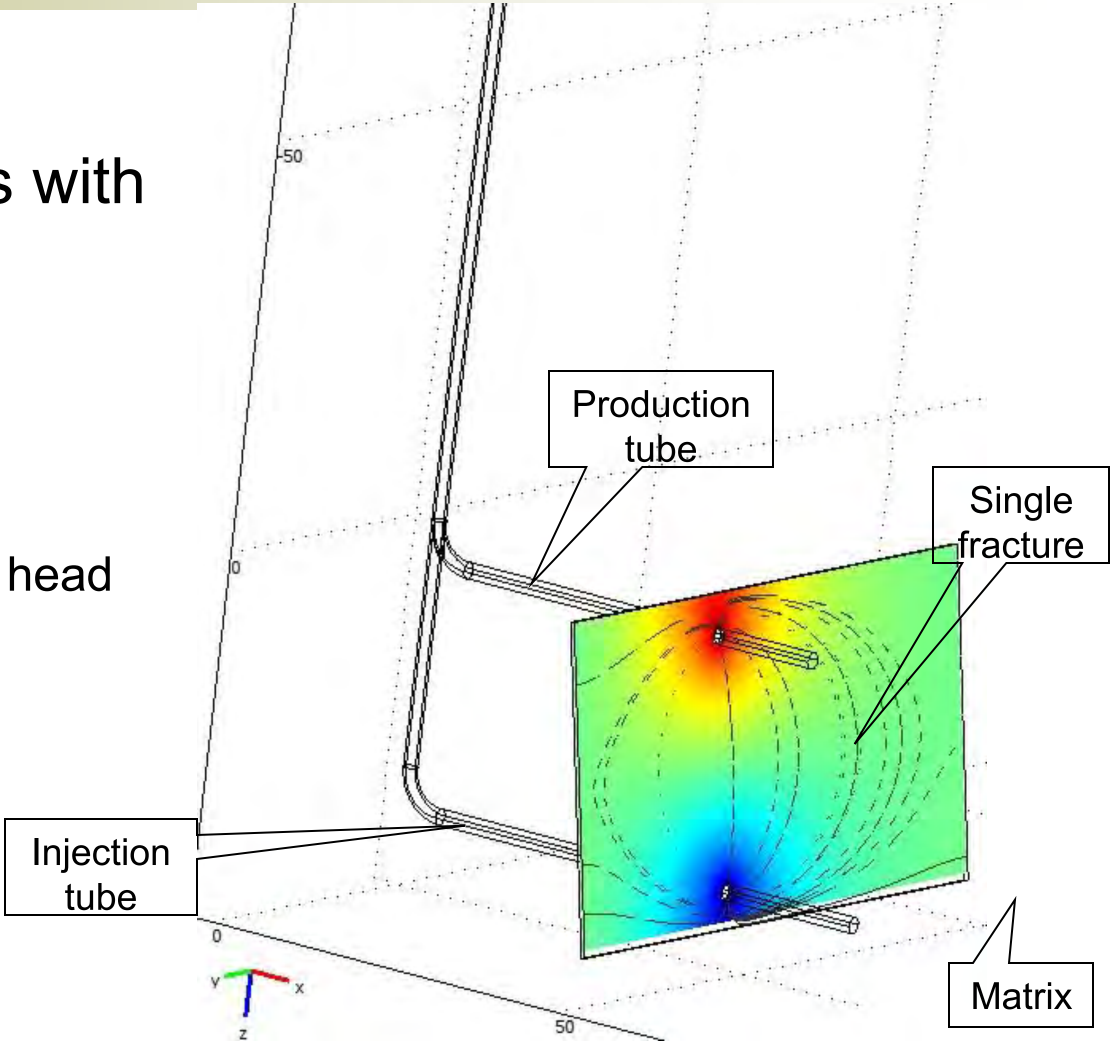
Fracture Model

Fracture connections with

- injection tube
- matrix
- production tube

Fracture flow:

- Surface map for hydraulic head
- Streamlines

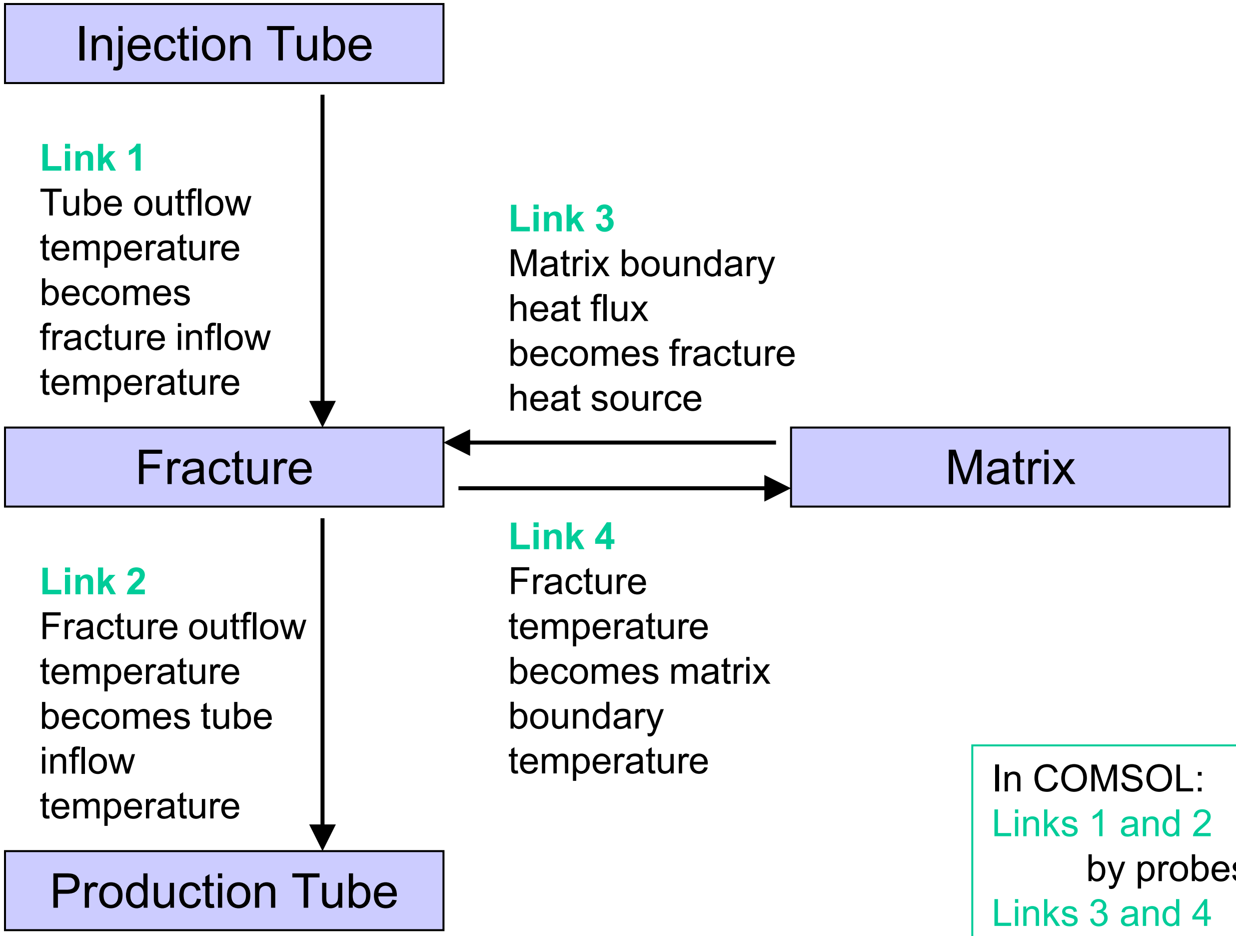


Model Set-up

Model	**Dim.**	**Flow**	**Cond./ Conv.**	Transvers. heat flux neglected	Convect. heat flux neglected
Injection tube	1	Free Fluid	both	x	
Fracture	2	Darcy / Free Fluid	both	x	
Matrix	3	no Flow	cond. only	*	x
Production tube	1	Free Fluid	both	x	

* In most conventional models, transversal heat in the matrix is neglected, (following Vinsome & Westerveld).

Couplings / Links



Injection Tube

Link 1
Tube outflow temperature becomes fracture inflow temperature

Link 3
Matrix boundary heat flux becomes fracture heat source

Fracture

Matrix

Link 4
Fracture temperature becomes matrix boundary temperature

Link 2
Fracture outflow temperature becomes tube inflow temperature

Production Tube

In COMSOL:
Links 1 and 2
  by probes, unidirectional
Links 3 and 4
  by extrusions

Further Dependencies & Couplings

Temperature dependency of

- fluid thermal conductivity
- fluid heat capacity

within heat
flow mode

- fluid density
- viscosity

between
flow and
transport

Not yet considered !

Pde - Flow Options

- Matrix
  - No-flow ✗
  - Darcy‘s Law
- Fracture
  - Darcy‘s Law
  - Potential flow ✗
  - Navier-Stokes equations
  - Brinkman equations
  - [Hagen-Poiseuille Law (for slices)]
- Tubes
  - 1D constant ✗
  - [Hagen-Poiseuille Law (for tubes)]
  - [Navier-Stokes equations]

Example: Brinkman equation (steady state)

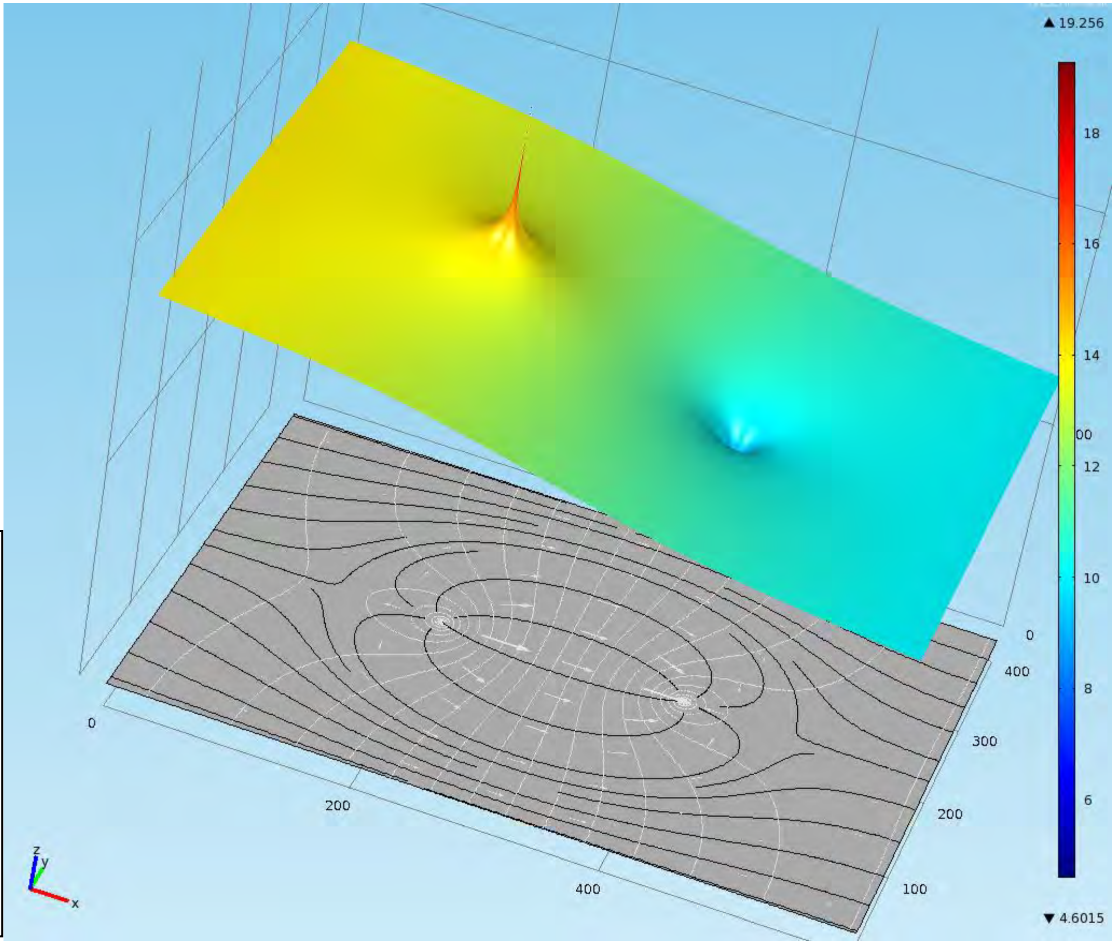
$$\frac{\eta}{\mathbf{k}}\mathbf{u} + \nabla p - \frac{\eta}{\theta}\nabla\left(\nabla\mathbf{u} + (\nabla\mathbf{u})^T\right) = 0$$

$$\nabla \cdot \mathbf{u} = 0$$

with symbols

$\mathbf{u}$	Darcy velocity
$\mathbf{k}$	permeability tensor
η	dynamic viscosity
p	pressure
θ	porosity

Doublet: Analytical Solution



For potential flow

- potential surface
- streamlines (black)
- potential contours (white)
- velocity vector field

Pde – Heat Flow Options

- Matrix
  - Heat Transfer in Solids
  - Heat Transfer in Porous Media
  - pde - mode X
- Fracture
  - Heat Transfer in Fluids X
  - Heat Transfer in Porous Media
  - pde - mode
- Tubes
  - Heat Transfer in Fluids X
  - pde - mode

Example:

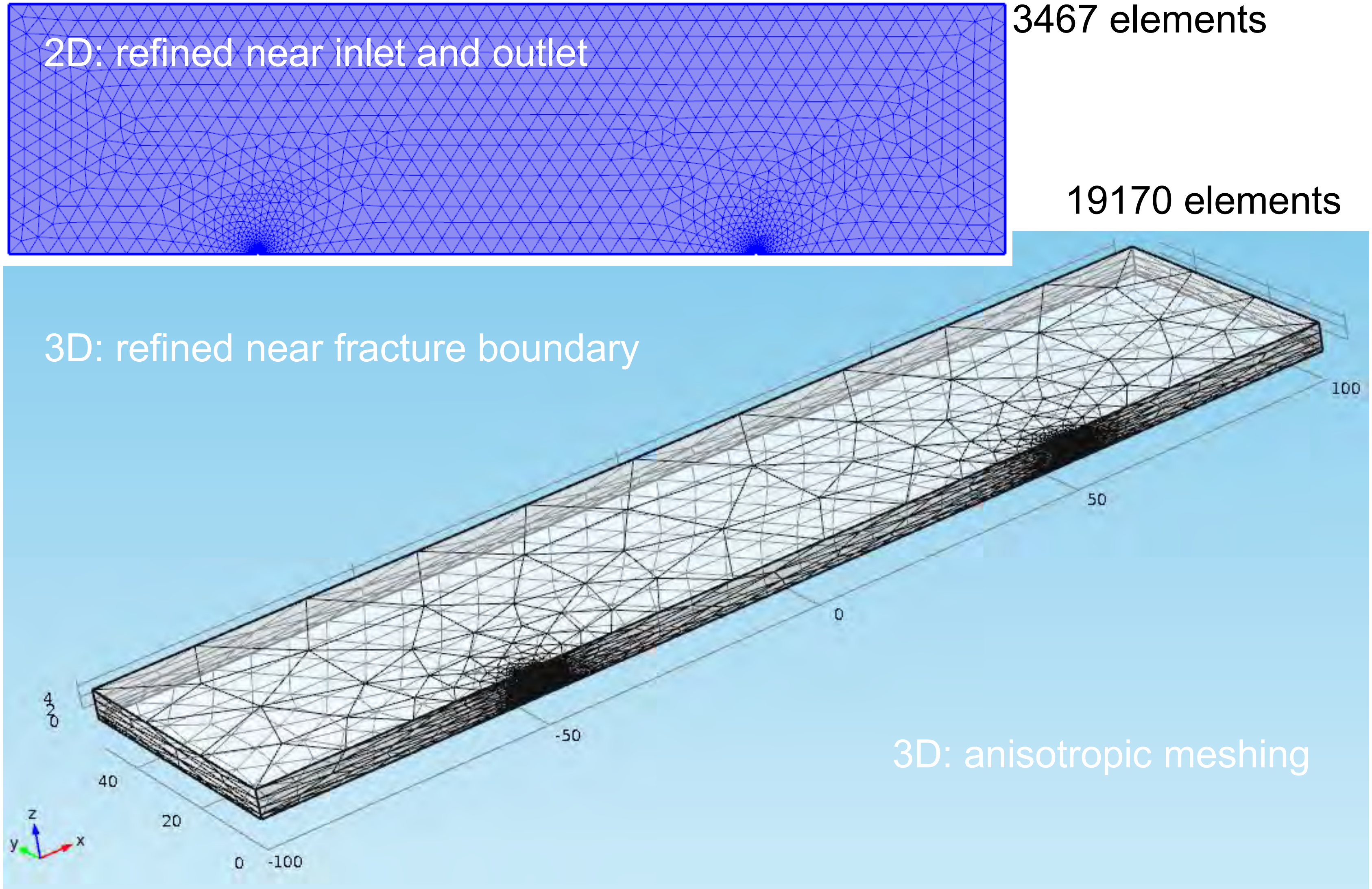
Heat transfer in porous media

$$(\rho C)^* \frac{\partial T}{\partial t} = \nabla k \nabla T - (\rho C)_f \mathbf{u} + Q = 0$$

with symbols

$\mathbf{u}$	Darcy velocity
k	thermal conductivity
$(\rho C)^*$	heat capacity of solid/fluid
$(\rho C)_f$	fluid heat capacity
Q	heat source / sink

Meshing



2D: refined near inlet and outlet

3467 elements

19170 elements

3D: refined near fracture boundary

3D: anisotropic meshing

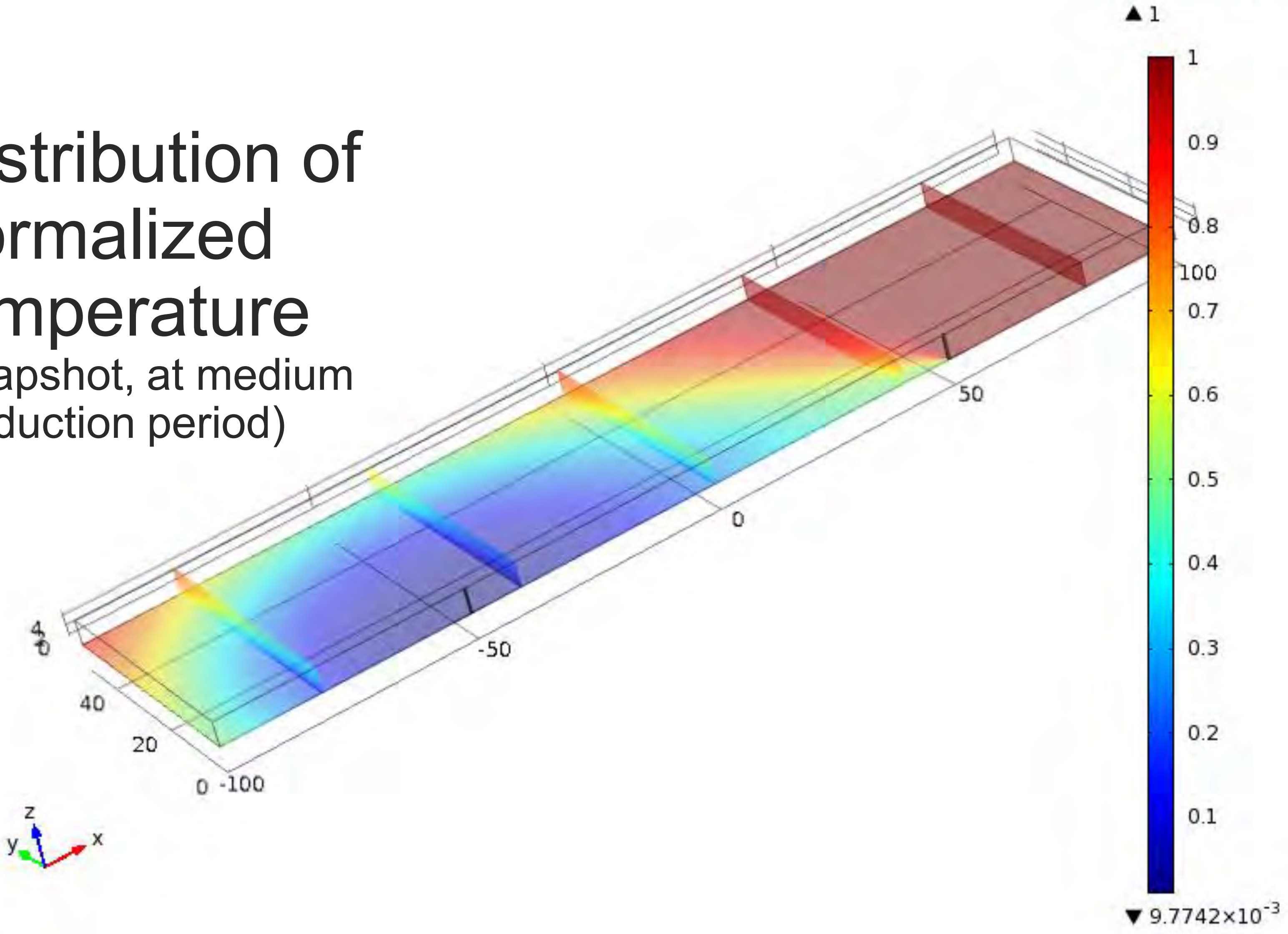
Input Data

Name	***Value***	***Unit***	***Name***	***Value***	***Unit***
Inlet temperature	70	˚C	Fracture porosity	0.6	-
Reservoir temperature	200	˚C	Fracture hydraulic conductivity	1.5 10^{-2}	m/s
Reservoir depth	5000	m	Fracture heat capacity	1000	J/kg/˚C
Geothermal gradient	0.038	˚C/m	Fracture thickness	0.002	M
Doublet distance	100	m	Longitudinal dispersivity	1	m
Borehole diameters	9 5/8, 7	inch	Transversal dispersivity	0.1	m
Total pumping/ Injection rate	0.115	m^3/s	Matrix thickness	5	m
Velocities in boreholes	0.62, 1.16	m/s	Matrix thermal conductivity	2	W/m/˚C
Fracture length	250	m	Time period	1.5 10^6	s
Fracture density	2000	kg/m^3			

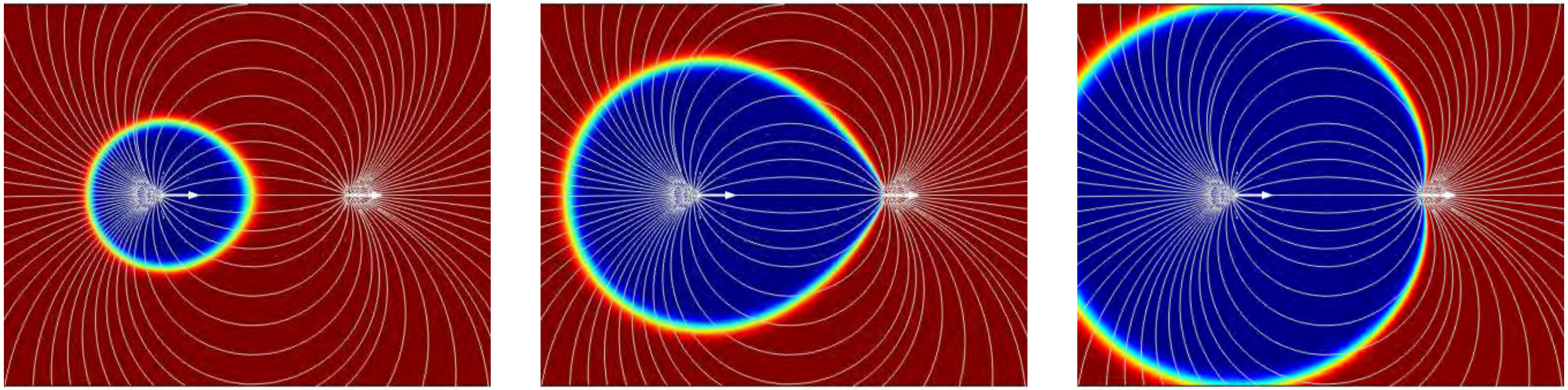
Results: Matrix Heat Transfer

Distribution of normalized temperature

(snapshot, at medium production period)

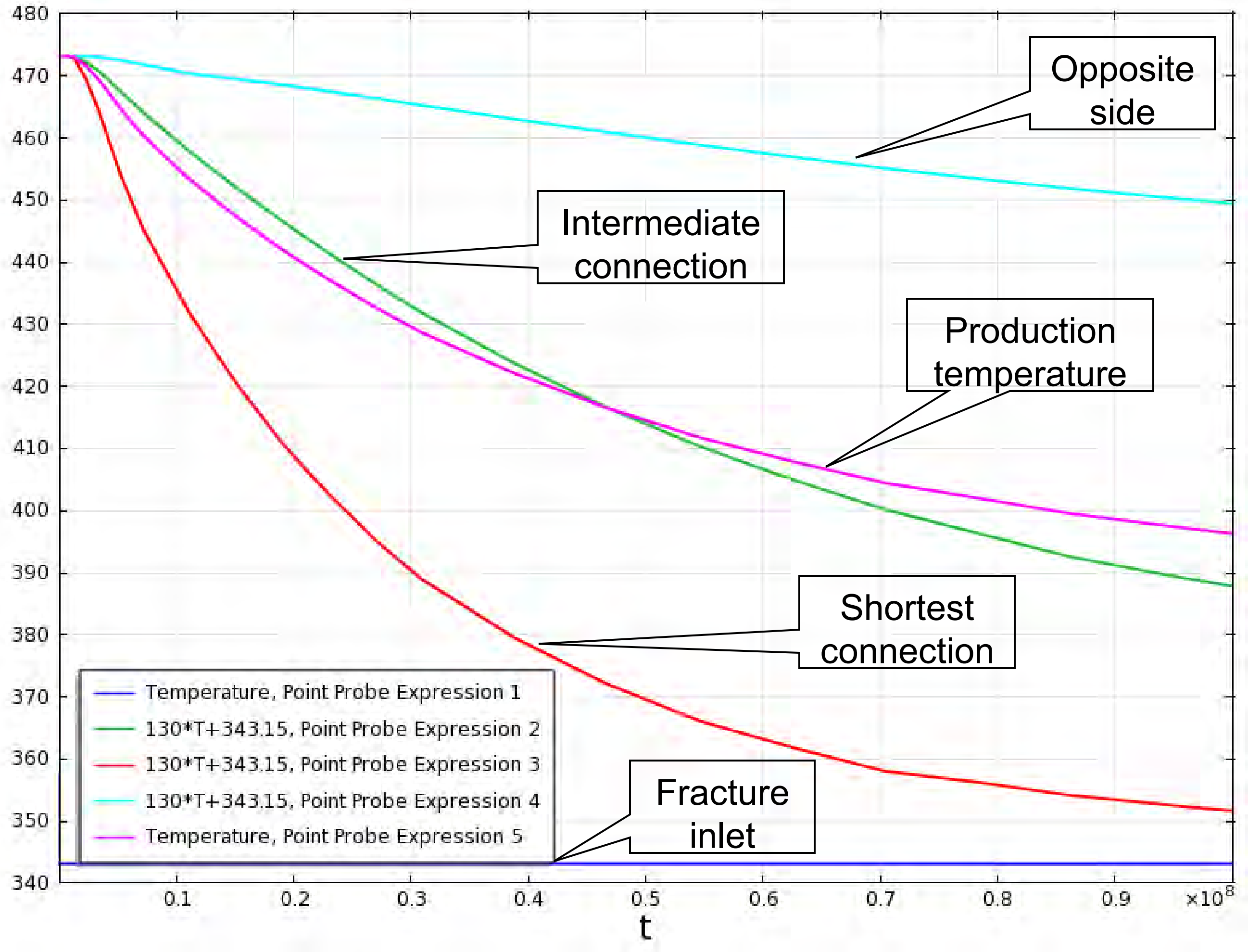


Results: Fracture Heat Flux



Cold water plume at three different stages of geothermal production

Results: Breakthrough Curves



Temperatures [°K] at sub-model couplings and final production, in dependence of time [s]

Conclusions

- The model approach is superior to the conventional method, in which transversal heat transfer in the matrix is neglected

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- Using COMSOL Multiphysics, models of different dimensionality can be coupled easily
- Couplings can be uni-directional or two-directional
- Couplings can be realized by
    - extrusions, if the same geometry is shared by both models
    - Probes, if only single valued functions have to be transfered

Lookout

We intend a comparison

- concerning the different pde-approaches in COMSOL
- with results from a similar study using the cellular automata approach (performed at Techn. Univ. Braunschweig)

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