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Modeling a Nozzle in a Borehole (2)

Ekkehard Holzbecher

German University of Technology in Oman

Fengchao Sun

Georg-August Universität Göttingen

GUtech RWTH AACHEN
الجامعة الألمانية للتكنولوجيا في عمان
German University of Technology in Oman

GEORG-AUGUST-UNIVERSITÄT
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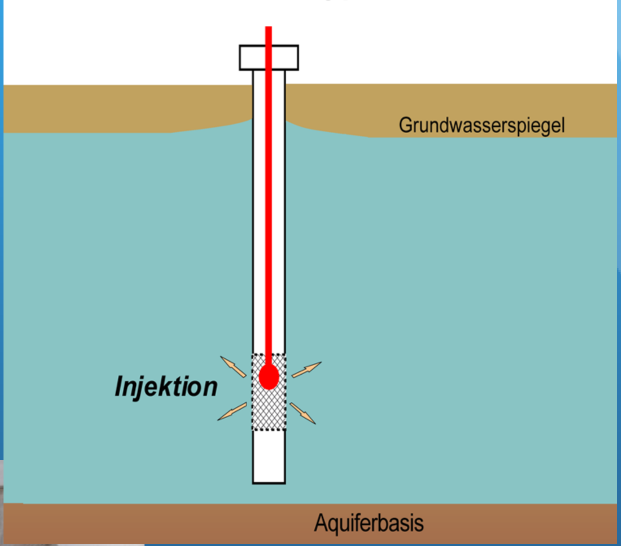
Water Injection into Aquifers



Introduction

Within boreholes nozzles have been found advantageous to increase the infiltration of water into the subsurface ground. Studies and practice in the field shows that the infiltration of water into permeable aquifers can be improved, if the flow in the borehole is modified: due to a nozzle the flow regime turns from laminar to turbulent. CFD studies help to understand the physics of the infiltration process. The transition of the flow regime within the borehole and its further effects on flow within the porous medium of the aquifer were examined using COMSOL Multiphysics.

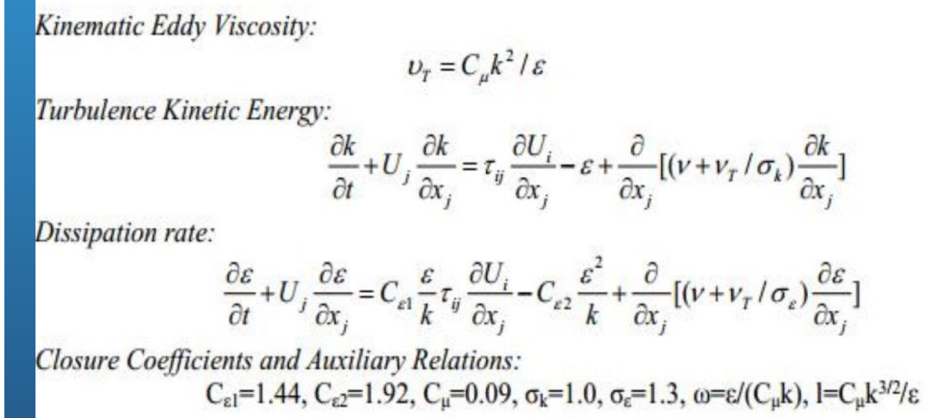
Overview

We report about numerical experiments with slightly turbulent flow, as observed in the nozzle. Two options of turbulent flow modeling, Navier-Stokes k-ω and k-ε, are tested. Mesh refinement and boundary layer options are studied in addition. From the experiences in a simplified geometry we draw conclusions about best modelling options.

Differential Equations

Alternatives

k-ε Mode



Kinematic Eddy Viscosity:

$$\upsilon_T = C_\mu k^2 / \varepsilon$$

Turbulence Kinetic Energy:

$$\frac{\partial k}{\partial t} + U_j \frac{\partial k}{\partial x_j} = \tau_{ij} \frac{\partial U_i}{\partial x_j} - \varepsilon + \frac{\partial}{\partial x_j}[(\nu + \nu_T / \sigma_k) \frac{\partial k}{\partial x_j}]$$

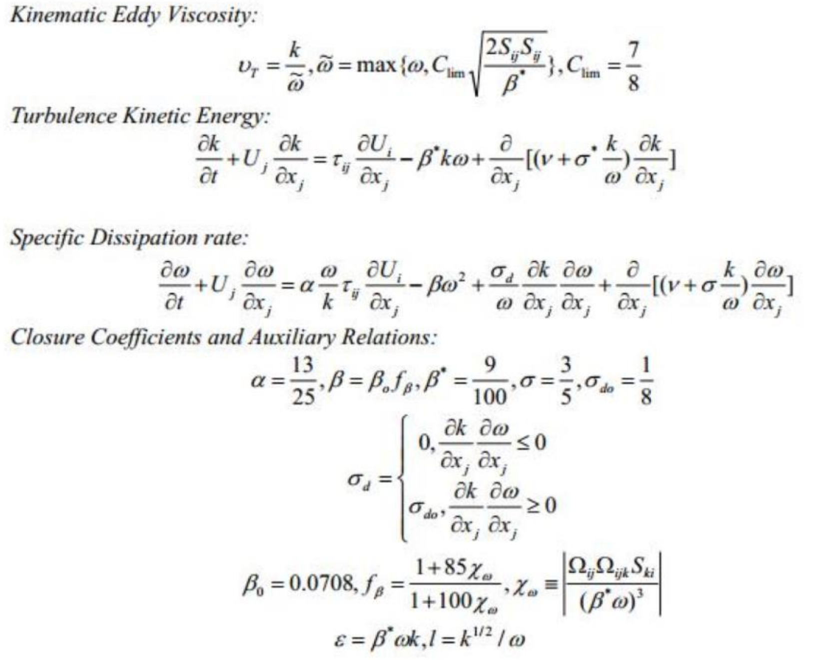
Dissipation rate:

$$\frac{\partial \varepsilon}{\partial t} + U_j \frac{\partial \varepsilon}{\partial x_j} = C_{\varepsilon 1} \frac{\varepsilon}{k} \tau_{ij} \frac{\partial U_i}{\partial x_j} - C_{\varepsilon 2} \frac{\varepsilon^2}{k} + \frac{\partial}{\partial x_j}[(\nu + \nu_T / \sigma_\varepsilon) \frac{\partial \varepsilon}{\partial x_j}]$$

Closure Coefficients and Auxiliary Relations:

$$C_{\varepsilon 1}=1.44,\ C_{\varepsilon 2}=1.92,\ C_\mu=0.09,\ \sigma_k=1.0,\ \sigma_\varepsilon=1.3,\ \omega=\varepsilon/(C_\mu k),\ l=C_\mu k^{3/2}/\varepsilon$$

k-ω Model



Kinematic Eddy Viscosity:

$$\upsilon_T = \frac{k}{\tilde{\omega}}, \tilde{\omega} = \max\{\omega, C_{\lim} \sqrt{\frac{2S_{ij}S_{ij}}{\beta^*}}\}, C_{\lim} = \frac{7}{8}$$

Turbulence Kinetic Energy:

$$\frac{\partial k}{\partial t} + U_j \frac{\partial k}{\partial x_j} = \tau_{ij} \frac{\partial U_i}{\partial x_j} - \beta^* k \omega + \frac{\partial}{\partial x_j}[(\nu + \sigma^* \frac{k}{\omega}) \frac{\partial k}{\partial x_j}]$$

Specific Dissipation rate:

$$\frac{\partial \omega}{\partial t} + U_j \frac{\partial \omega}{\partial x_j} = \alpha \frac{\omega}{k} \tau_{ij} \frac{\partial U_i}{\partial x_j} - \beta \omega^2 + \frac{\sigma_d}{\omega} \frac{\partial k}{\partial x_j} \frac{\partial \omega}{\partial x_j} + \frac{\partial}{\partial x_j}[(\nu + \sigma \frac{k}{\omega}) \frac{\partial \omega}{\partial x_j}]$$

Closure Coefficients and Auxiliary Relations:

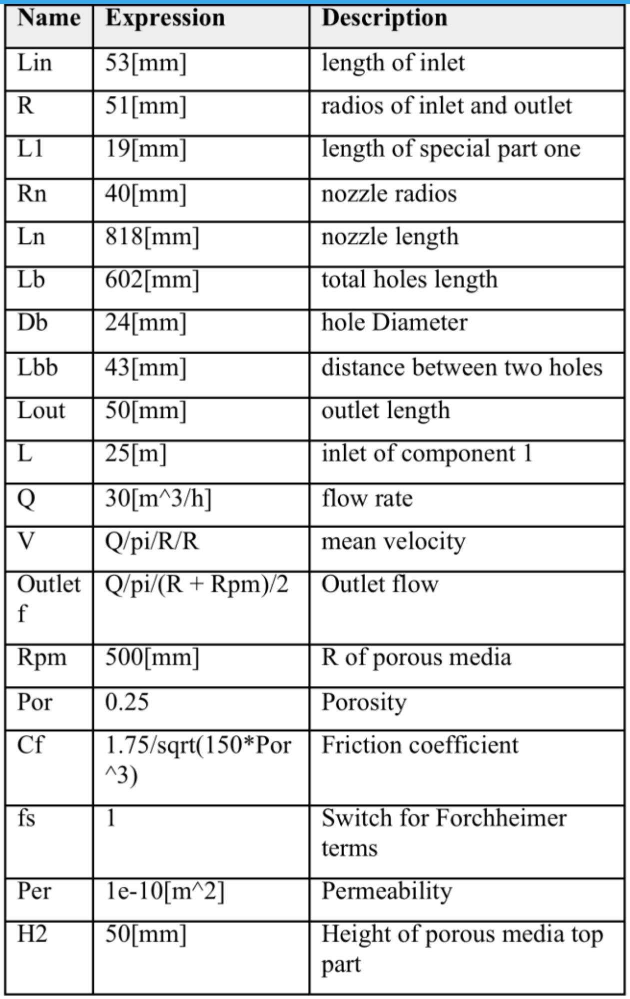
$$\alpha = \frac{13}{25}, \beta = \beta_o f_\beta, \beta^* = \frac{9}{100}, \sigma = \frac{3}{5}, \sigma_{do} = \frac{1}{8}$$

$$\sigma_d = \begin{cases} 0, \frac{\partial k}{\partial x_j} \frac{\partial \omega}{\partial x_j} \le 0 \\ \sigma_{do}, \frac{\partial k}{\partial x_j} \frac{\partial \omega}{\partial x_j} \ge 0 \end{cases}$$

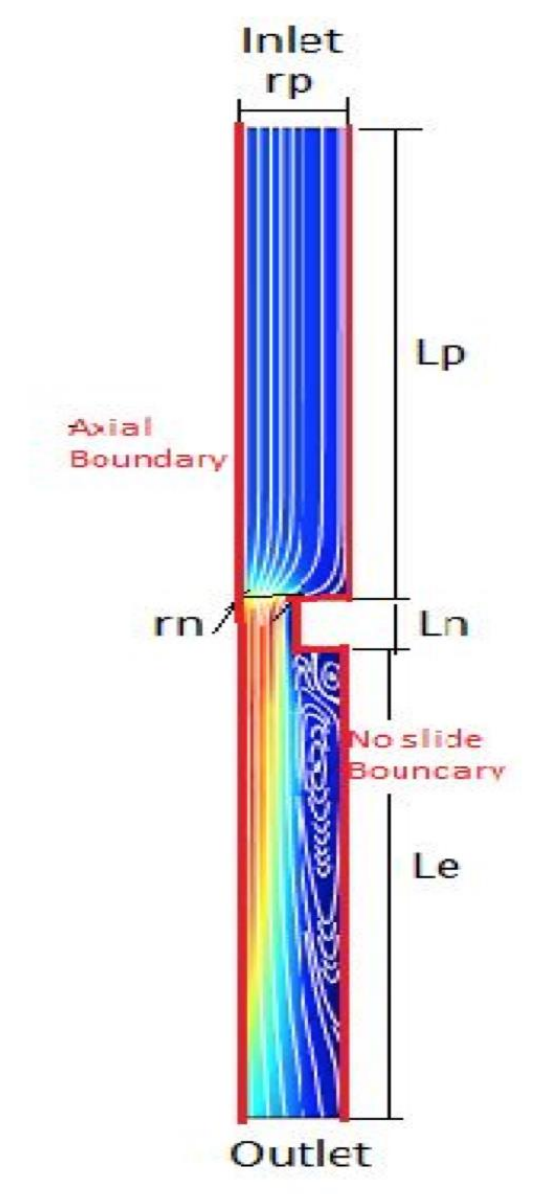
$$\beta_0 = 0.0708, f_\beta = \frac{1 + 85\chi_\omega}{1 + 100\chi_\omega}, \chi_\omega \equiv \left| \frac{\Omega_{ij}\Omega_{ijk}S_{ki}}{(\beta^* \omega)^3} \right|$$

$$\varepsilon = \beta^* \omega k, l = k^{1/2} / \omega$$

Simple Nozzle Model

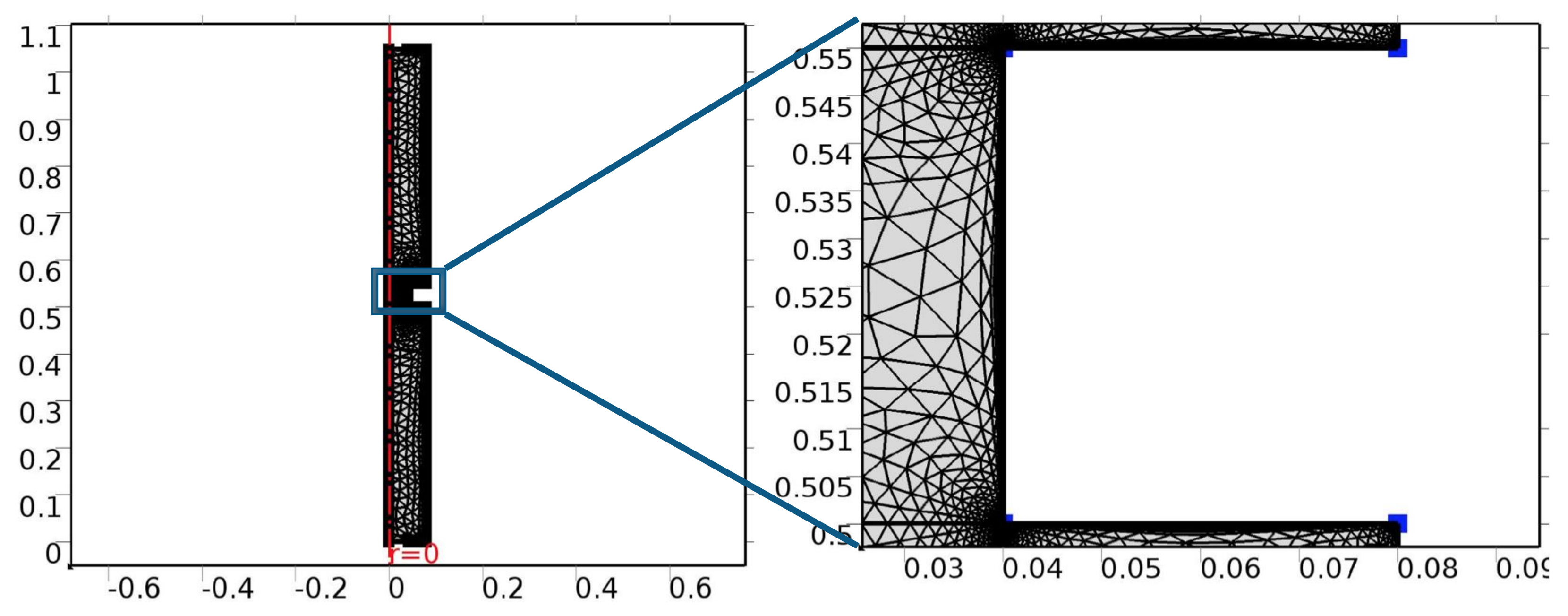


Name	Expression	Description
Lin	53[mm]	length of inlet
R	51[mm]	radios of inlet and outlet
L1	19[mm]	length of special part one
Rn	40[mm]	nozzle radios
Ln	818[mm]	nozzle length
Lb	602[mm]	total holes length
Db	24[mm]	hole Diameter
Lbb	43[mm]	distance between two holes
Lout	50[mm]	outlet length
L	25[m]	inlet of component 1
Q	30[m^3/h]	flow rate
V	Q/pi/R/R	mean velocity
Outlet f	Q/pi/(R + Rpm)/2	Outlet flow
Rpm	500[mm]	R of porous media
Por	0.25	Porosity
Cf	1.75/sqrt(150*Por ^3)	Friction coefficient
fs	1	Switch for Forchheimer terms
Per	1e-10[m^2]	Permeability
H2	50[mm]	Height of porous media top part



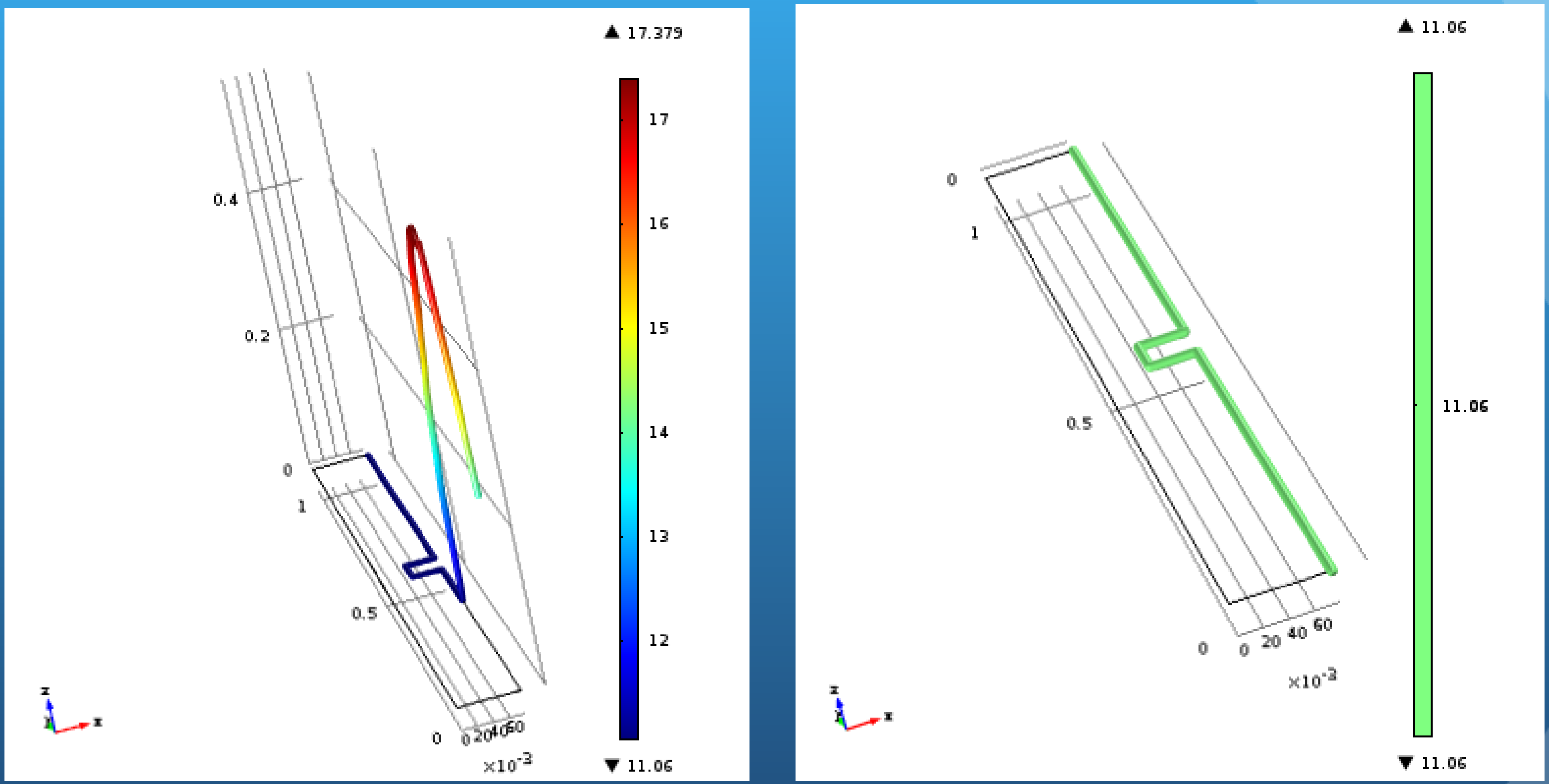
Meshing

Mesh Refinement



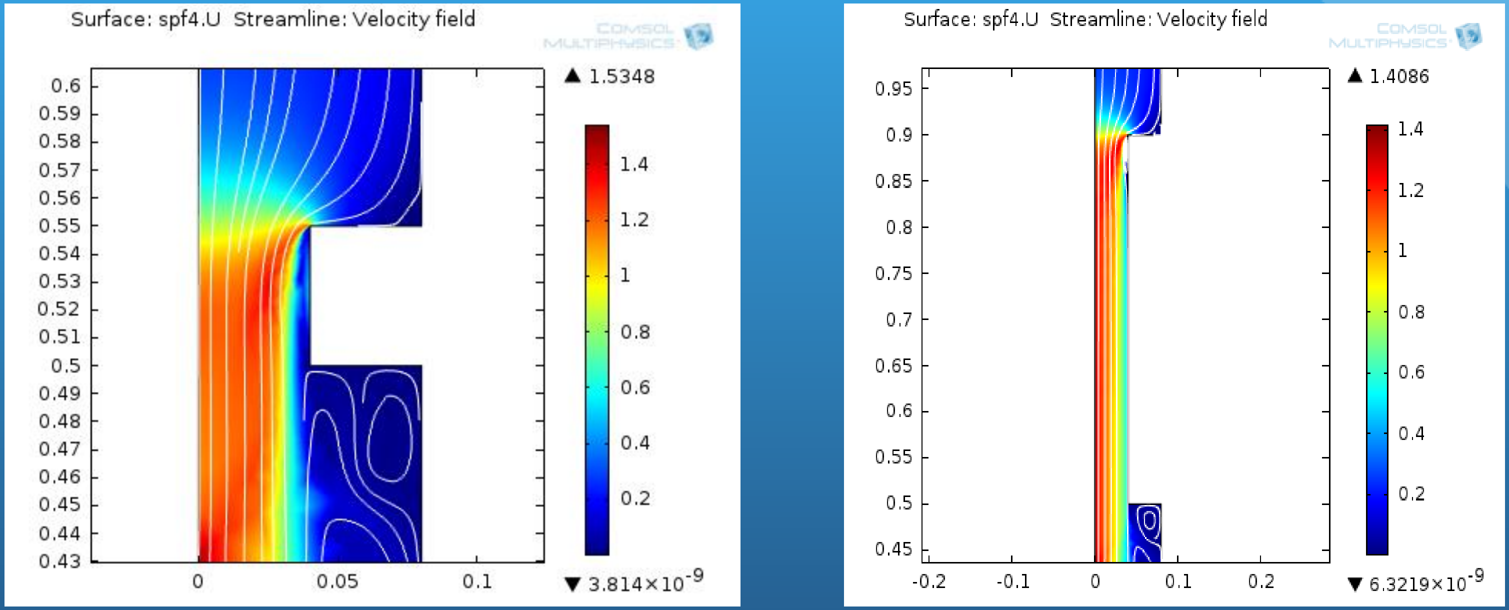
Refinement at corners, boundary elements for boundary layer

Wall Lift-Off Effects



Wall lift-off, depending on turbulent closure; left: *k*-*ε*, right: *k*-*ω*

Variation of Nozzle Length



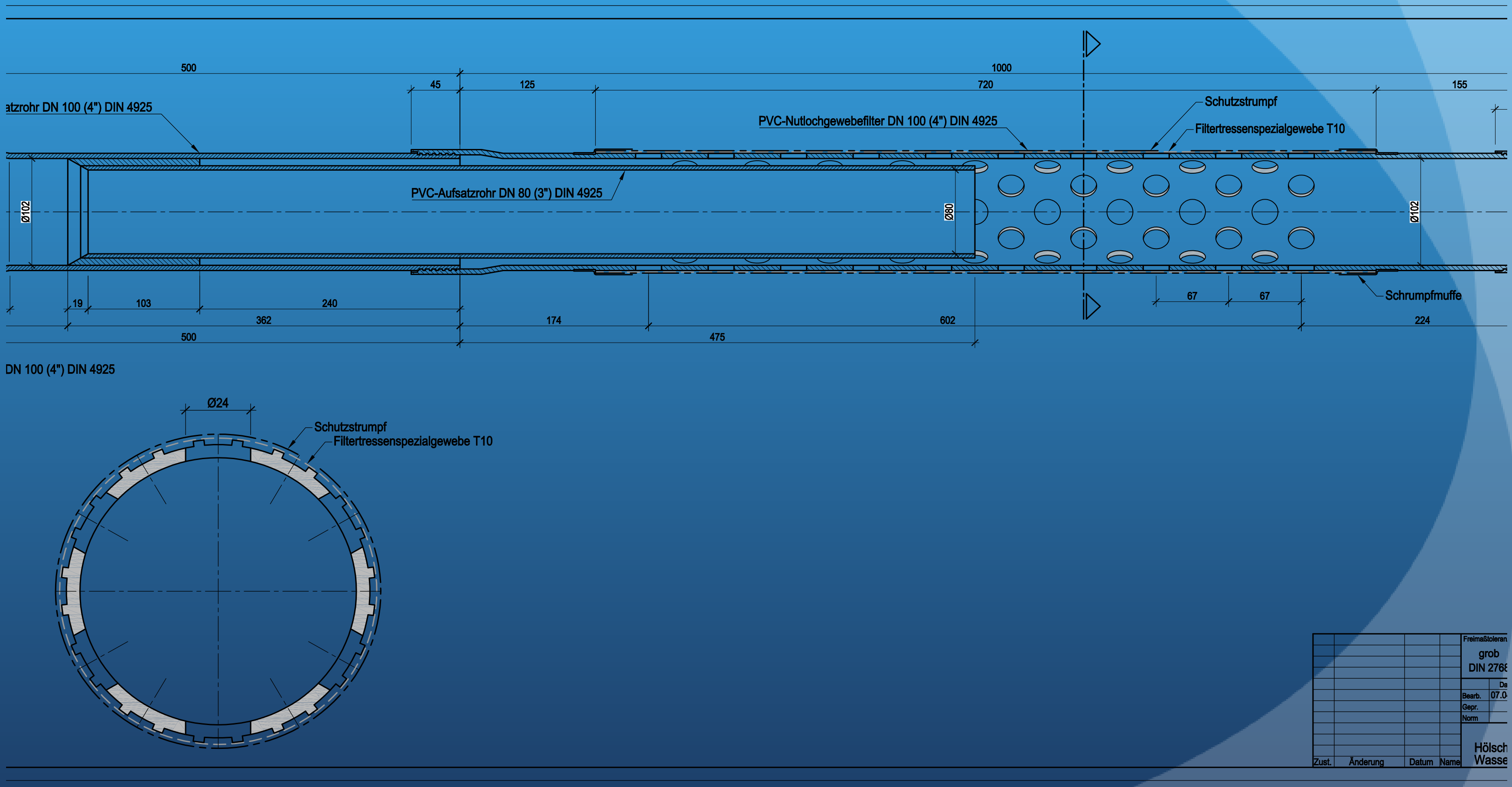
Velocity field in different nozzle length model
(left-nozzle=0.05 m, right-nozzle length=0.4 m

Real Nozzle

The major work is about a nozzle design that is currently used in practical field work. Parametric model runs were used to examine the effect of the nozzle design (length, radius, shape), placement within the borehole and in relation to the filter screen. Moreover we studied the influence of the pumping-rate as operational parameter on the flow regime within the borehole.

Nozzle with Filter

(4“, horizontal)



Simplified Model Approach

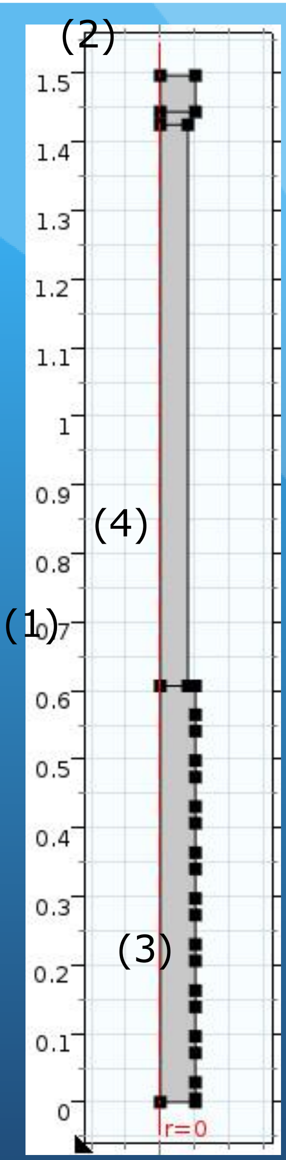
Real Nozzle is 3D.

We use a 2D approach, converting the filter holes into filter slices.

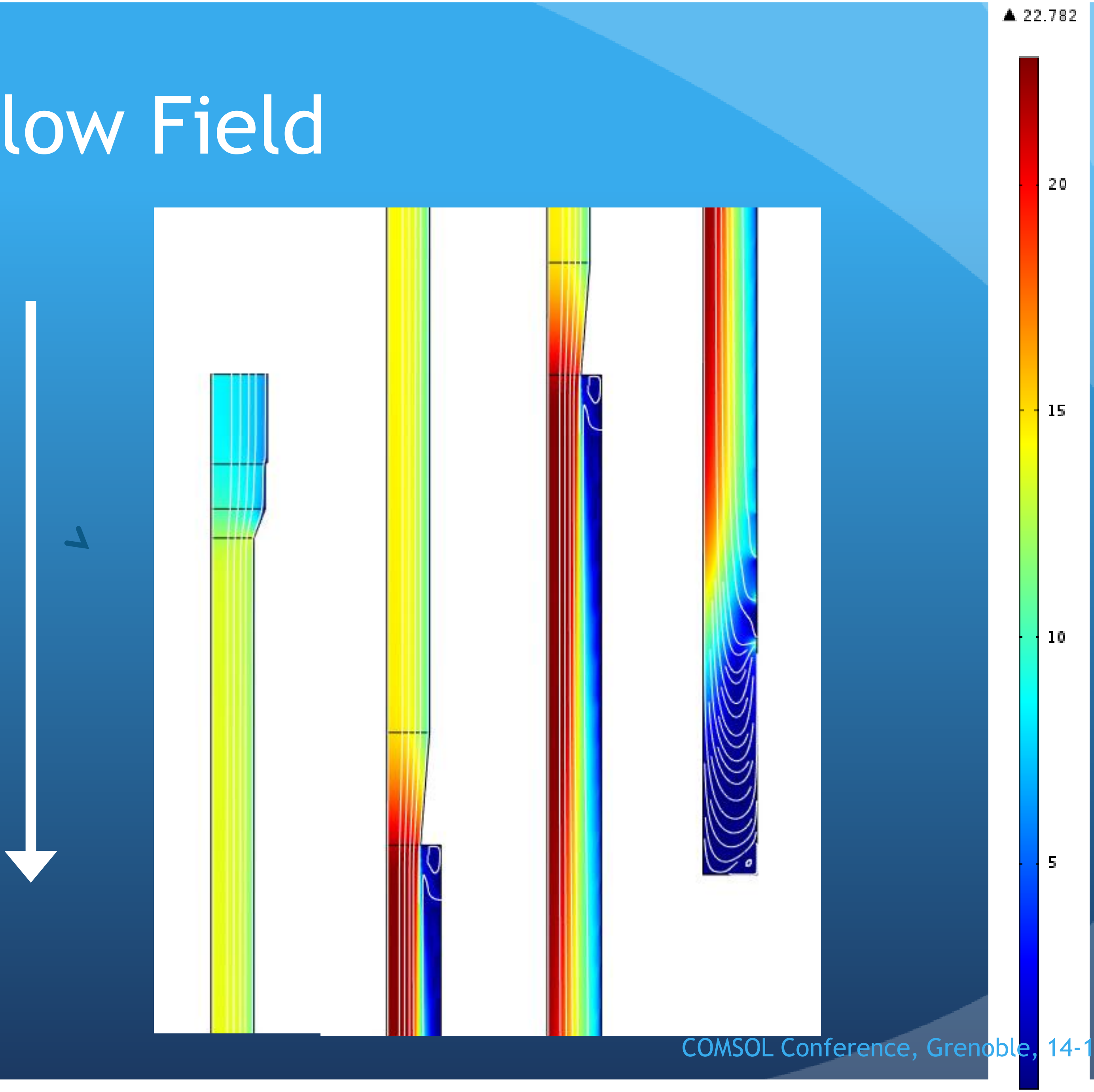
The filter consists of 9 slices in the modelled design

Model Set-up

- **Parameters:**
- L 15[m] length comp1
- rp 0.08[m] pipe radius
- Qp 15[m^3/h] flow rate
- vp Qp/pi/rp/rp mean velocity
- Lp 0.5[m] pipe length before nozzle
- Ln 0.05[m] nozzle length
- rn 0.04[m] nozzle radius
- Le 0.5[m] length behind nozzle
- Lout 0.05[m] length below outlets
-
- **2D Radial Geometry**
- **k-epsilon, k-omega Modes**
- **Components Comp1:**
- Geometry: Rectangle, length L, radius rp
- Material: Water
- Fluid properties: from material (20°C)
- Initial values: p=0, v=w=0, kinit, epinit
- Boundary conditions:
- Axial symmetry (1)
- Wall (4): wall functions
- Inlet (2): velocity vp, turbulent intensity 0.05, turbulent length scale 0.01 m
- Outlet (3): p=0, suppress backflow



Flow Field



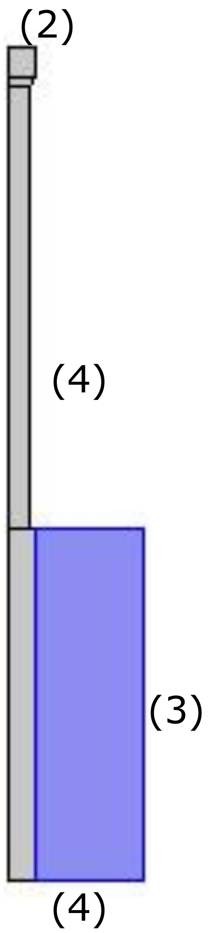
Extension for Porous Medium

In a further extension we included the porous ground surrounding the borehole in the model. Using parametric runs again, we examined the influence of the porous medium properties (porosity, permeability) on the coupled flow regime. Also the position of the well screen in relation to the boundaries of the aquifer layer was examined.

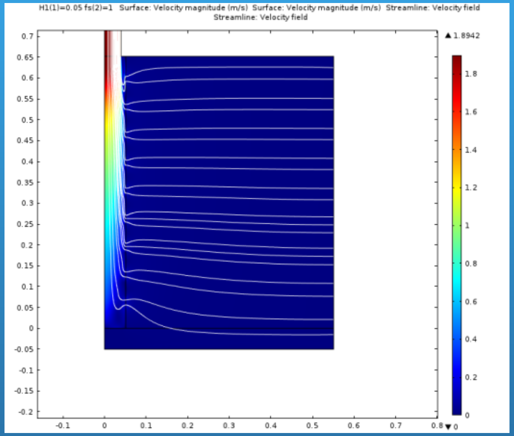
Coupling with Porous Medium

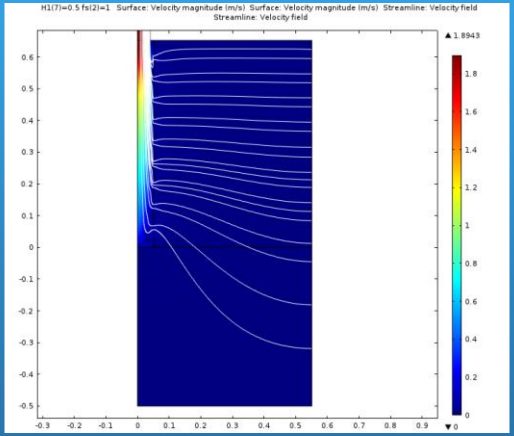
Parameters:
Lt 0.65[m] thickness
rpm 0.20[m] horizontal extension

2D Radial Geometry
Free and Porous Media Mode
Components Comp1:
Geometry: rectangle, length Lt, extension rpm
Material: Water
Fluid properties: from material (20°C)
Porosity: 0.25
Permeability: 10^{-10} m^2
Forchheimer drag: with/without
Initial values: p=0, v=w=0
Boundary conditions:
Wall (4): no slip
Inlet (2): velocity from free fluid model
Outlet (3): p=0

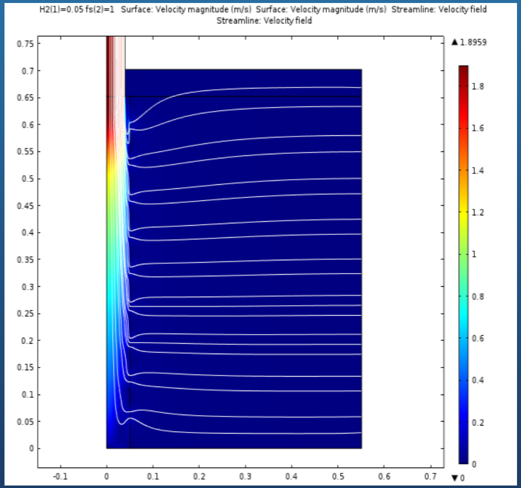


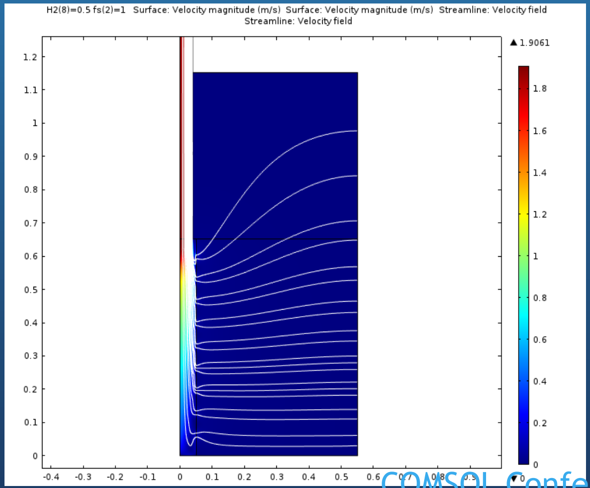
Variation of Bottom Partition





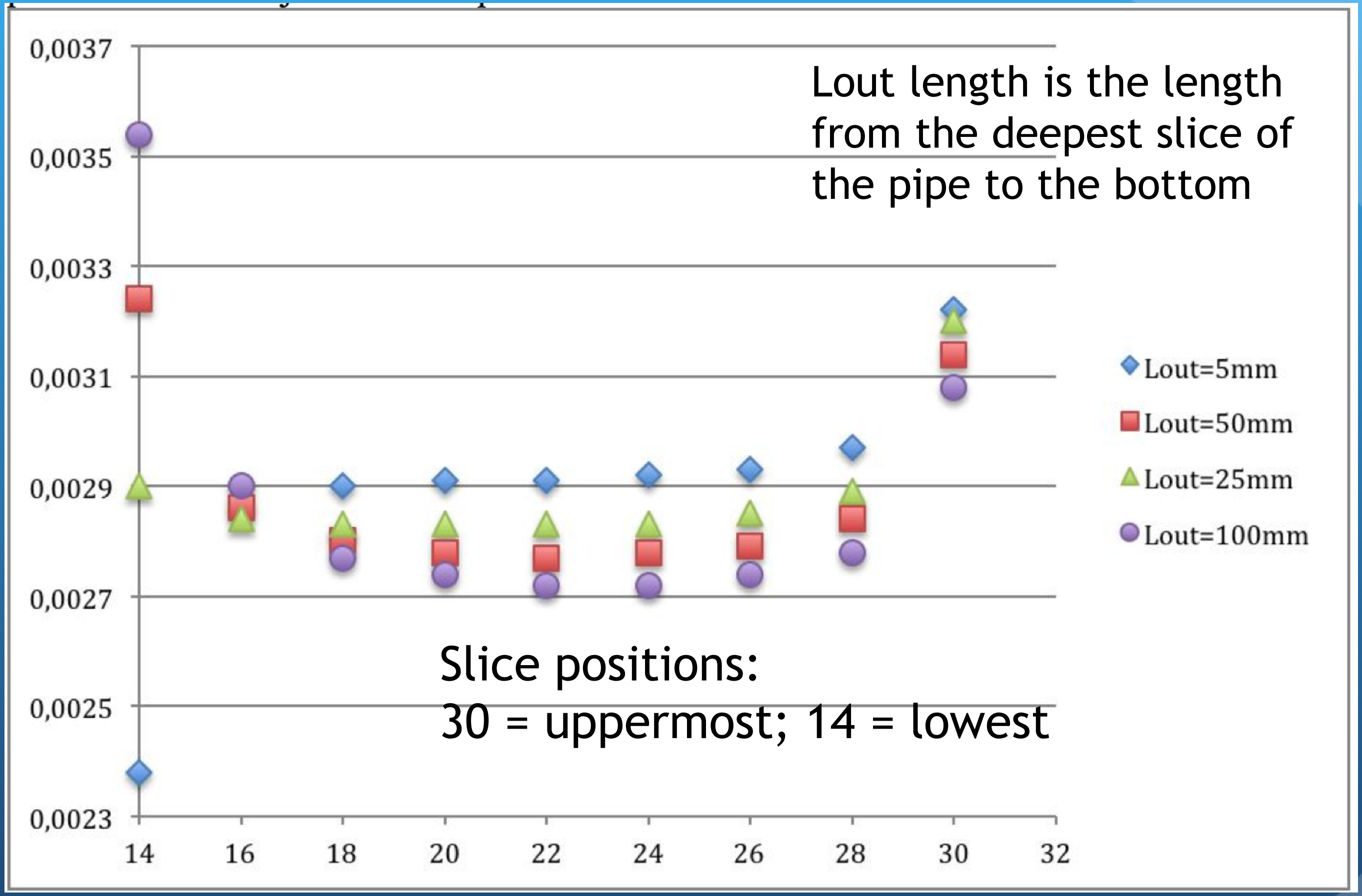
Head colormap and streamlines





Outlet Characteristics

Flux
[m^3/s]



Lout length is the length from the deepest slice of the pipe to the bottom

Slice positions:
30 = uppermost; 14 = lowest

Observation

Change from S-Shape to U-Shape:

For very low distances between deepest slice and pipe bottom there is very low outflux at the lowest slice, and outflow is increasing with decreasing depth: upper slices show more flux.

For longer distances between deepest slice and pipe the curve gets an (irregular) U-shape: the lowest outlet has the highest flux, and the uppermost the second highest, with smaller fluxes in between.

Obviously there is a strong influence from the no-slip boundary at the pipe bottom

Conclusions

- Free laminar or turbulent flow in one sub-domain can be coupled with porous media flow in a connected sub-domain
- Turbulence closure using k-$\boldsymbol{\omega}$ models wall lift off effects better than k-$\boldsymbol{\varepsilon}$ closure
- The outflux through different outlets of the screen depends very much on the pipe/nozzle design:
  - the length of the pipe below the lowest outlet
  - the position of the filter screen in relation to over- and underlying lower permeable layers

Concerning Modeling

COMSOL Multiphysics turned out to be very convenient for CFD simulations models in which flow of free fluids (laminar or turbulent) is coupled with porous medium (Darcy) flow

Thanks

for your attention.

Q?/A!

In case of interest and for more information:

E-mail: Ekkehard.holzbecher@gutech.edu.om

https://www.researchgate.net/profile/Ekkehard_Holzbecher