Coupling porous-medium and free flow under turbulent and rough conditions

International Research Training Group nupus

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Motivation

This project focuses on understanding and modeling the relevant processes of evaporation. Evaporation is strongly influenced by the interaction of different physical processes:

- in the free flow
- at the interface
- inside the porous medium

The main goal is to describe these processes and to simulate porous-medium flow with an adjacent free flow. The developed concept can be used for improving soil salinization simulations, analyzing water balance relations or technical applications, like fuel cells or drying and cooling processes.

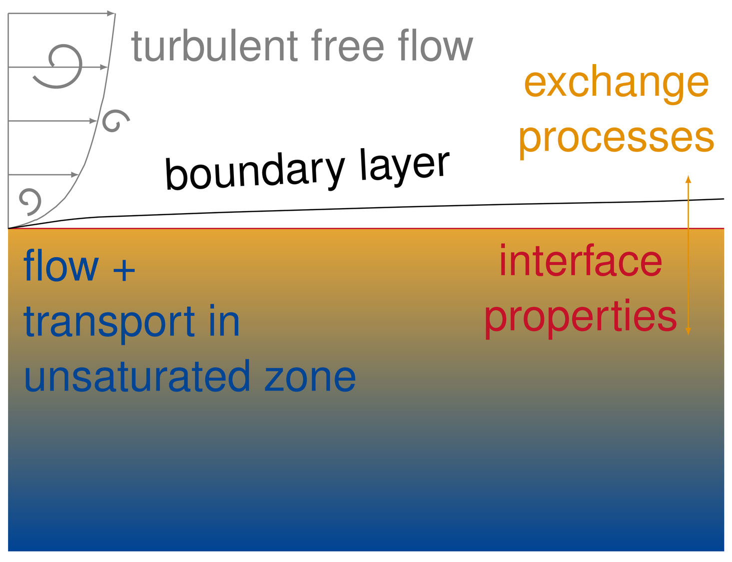

Figure 1: *Relevant processes for modeling evaporation from bare soil.*

Model concept

It is aimed for a numerically stable model. Simulation and analysis focus on the exchange of mass, momentum, and energy between the two flow domains.

Porous Medium Model

The porous medium is modeled by the Darcy equation. Based on the assumption of local thermodynamic equilibrium a two-phase (gas, liquid), two-component (air, water), non-isothermal model is used.

Free Flow Model

The one-phase (gas), two-component (air, water), non-isothermal free flow uses the Reynolds-averaged Navier-Stokes equation:

$$\frac{\partial(\varrho\bar{\mathbf{v}})}{\partial t} + \nabla\cdot(\varrho\bar{\mathbf{v}}\bar{\mathbf{v}}^{\mathsf{T}}) - \nabla\cdot((\varrho\nu+\varrho\nu_t)\nabla(\bar{\mathbf{v}}+\bar{\mathbf{v}}^{\mathsf{T}})) + \nabla p - \varrho\mathbf{g} = 0$$

and turbulence models, like k-ε:

$$\frac{\partial\varepsilon}{\partial t} + \nabla\cdot(\varepsilon\bar{\mathbf{v}}) - \nabla\cdot\left(\left(\nu+\frac{\nu_t}{\sigma_\varepsilon}\right)\nabla\varepsilon\right) - C_{1\varepsilon}\frac{\varepsilon}{k}2\nu_t\bar{\mathbf{S}}_{ij}\cdot\bar{\mathbf{S}}_{ij} + C_{2\varepsilon}\frac{\varepsilon^2}{k} = 0$$

$$\frac{\partial k}{\partial t} + \nabla\cdot(k\bar{\mathbf{v}}) - \nabla\cdot\left(\left(\nu+\frac{\nu_t}{\sigma_k}\right)\nabla k\right) - 2\nu_t\bar{\mathbf{S}}_{ij}\cdot\bar{\mathbf{S}}_{ij} + \varepsilon = 0$$

with the eddy viscosity: $\nu_t = C_\mu k^2/\varepsilon$

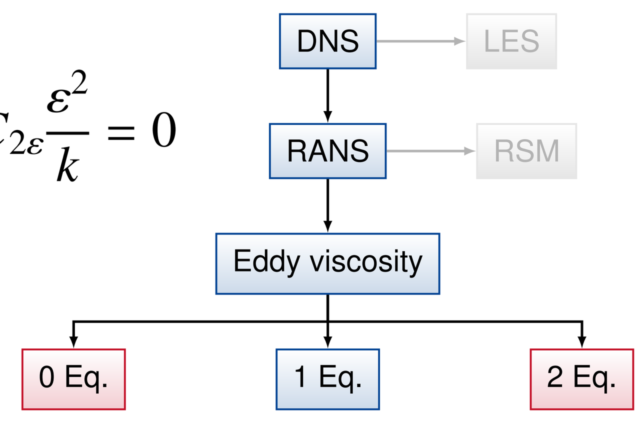

Figure 2: *Turbulence model hierarchy.*

Near the wall or the porous surface, inside the so called viscous sublayer, a special treatment of the k-ε equations is necessary and analytic wall functions will be applied as extended boundary conditions [4, 3].

Coupling Concept

The coupling of turbulent free and porous-medium flow is based on continuity of mass, momentum, and energy and continuity of fluxes across the interface [2]. The coupling is based on the assumption of local thermodynamic equilibrium and includes the slip-velocity concepts of Beavers and Joseph [1].

Discretization

cell centered finite volume (porous medium)

staggered grid (free flow)

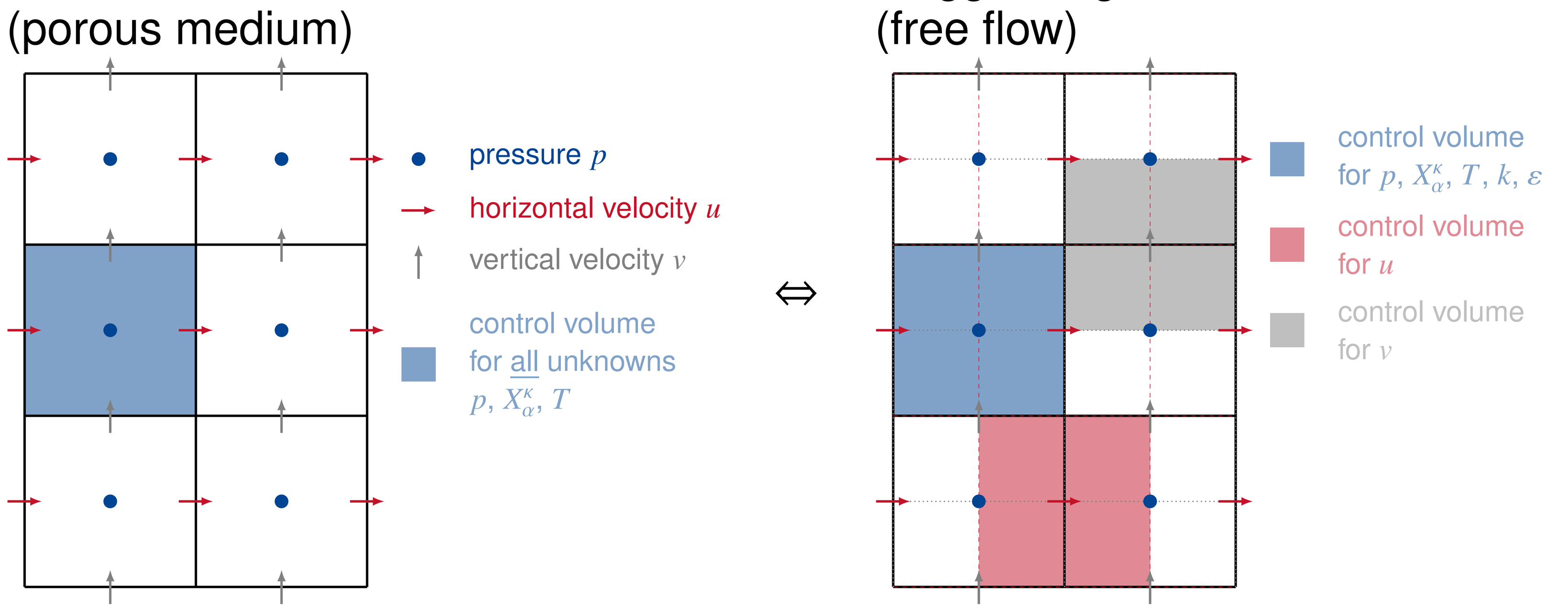

Figure 3: *Discretization scheme for modeling coupled porous-medium and free flow.*

Simulations are performed using the open-source simulator DuMu^x.

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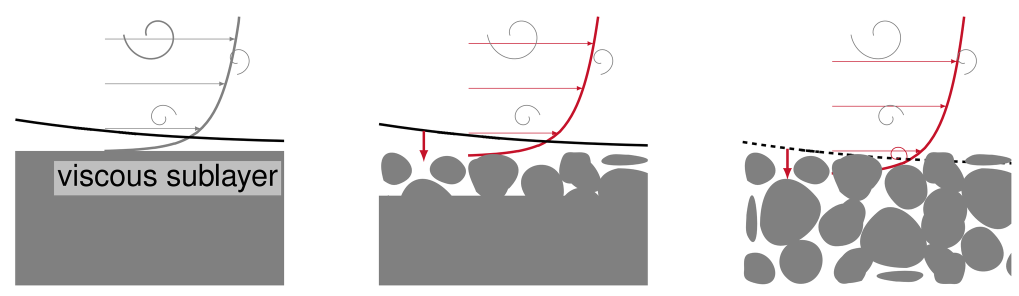
Link to poster.

Experiments

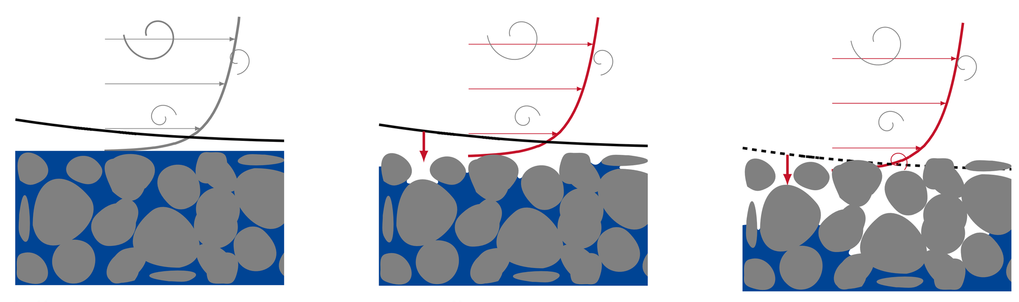
To get a better understanding of the influence of interface properties and porous medium processes, wind tunnel experiments have been performed at CESEP, Colorado School of Mines. Two different type of soils have been used for the experiments. Additionally, Lattice Boltzmann simulations for small soil samples will be performed at the TU Braunschweig.
The focus herein lies on analyzing the influence of ...

Roughness
- velocity boundary layer
- flow in porous medium



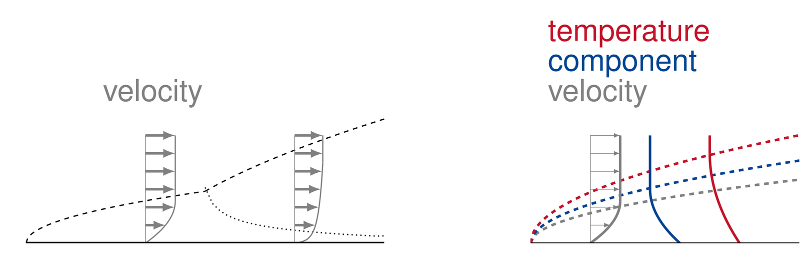
smooth plate sand plate porous medium

Saturation
- roughness as $f(S_w)$
- effect of S_w on mass/heat transfer



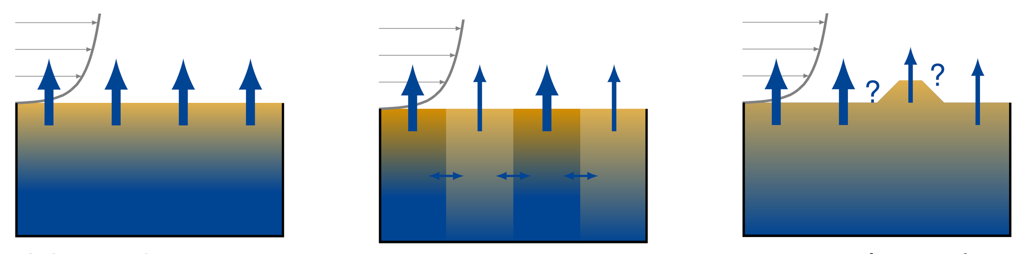
fully saturated partially saturated dried out interface

Boundary Layers
- effects of evaporation on velocity boundary layer
- interactions between different boundary layers



boundary layer development boundary layers

Soil Structures
- evaporation
- upscaling
- atmospheric influences



plain sand vertical structures macroscale roughness

... and on integrating the results as boundary conditions for the k-ε wall functions and on the validation of the numerical model.

Outlook

Short-Term

- evaluation of experimental results
- DNS experiments
- implementation of low-Re models
- implementation of coupling concept

Long-Term

- compositional/non-isothermal flow
- gravitation
- analysis of pore scale effects
- reduction of model complexity

Literature

[1] Beavers, G. S. and Joseph, D. D. (1967). Boundary conditions at a naturally permeable wall. *Journal of Fluid Mechanics*, 30(1):197–207.

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