Modeling interactions between turbulent free flow and porous-medium flow

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.

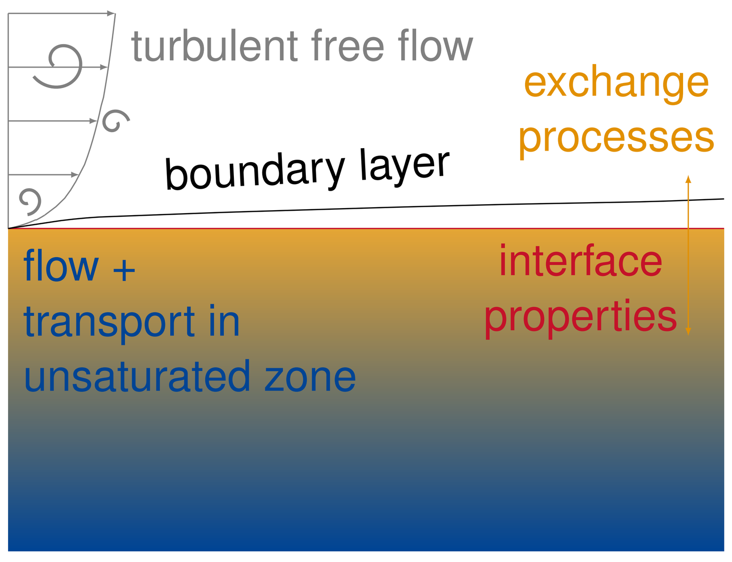


Figure 1: *Relevant processes for modeling evaporation from bare soil.*

Model concept

It is aimed to develop a numerically stable model, which is able to simulate the exchange processes 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 compositional non-isothermal free flow uses the Reynolds-averaged Navier-Stokes equation:

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

and turbulence models, like k-ε:

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

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

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

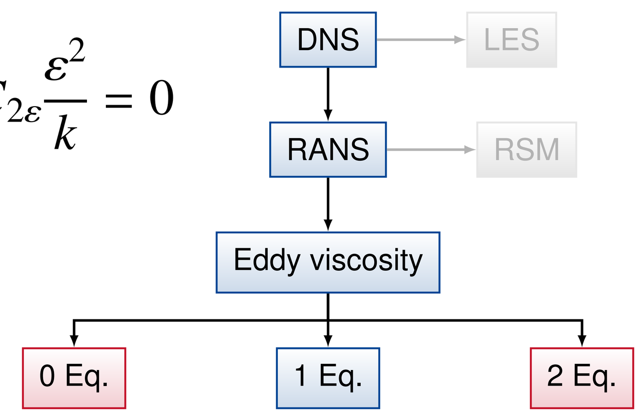


Figure 2: *Turbulence model hierarchy.*

Near the wall or the porous surface a special treatment of the k-ε equations is necessary and so called wall functions will be applied [5, 4].

Free Flow Discretization

Discretizing the free flow equations with a box or cell centered finite volume scheme leads to oscillations in pressure and therefore a staggered grid is used.

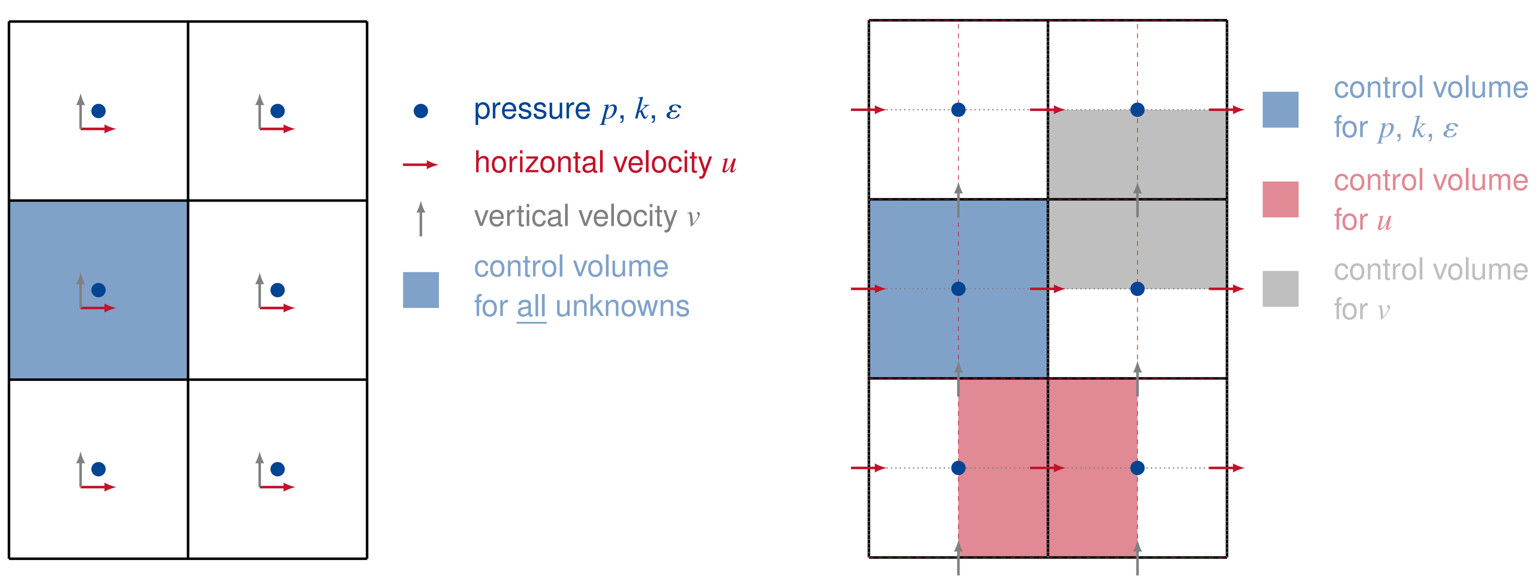


Figure 3: *Discretization schemes for modeling free flow cell centered (left) and staggered grid (right).*

Coupling

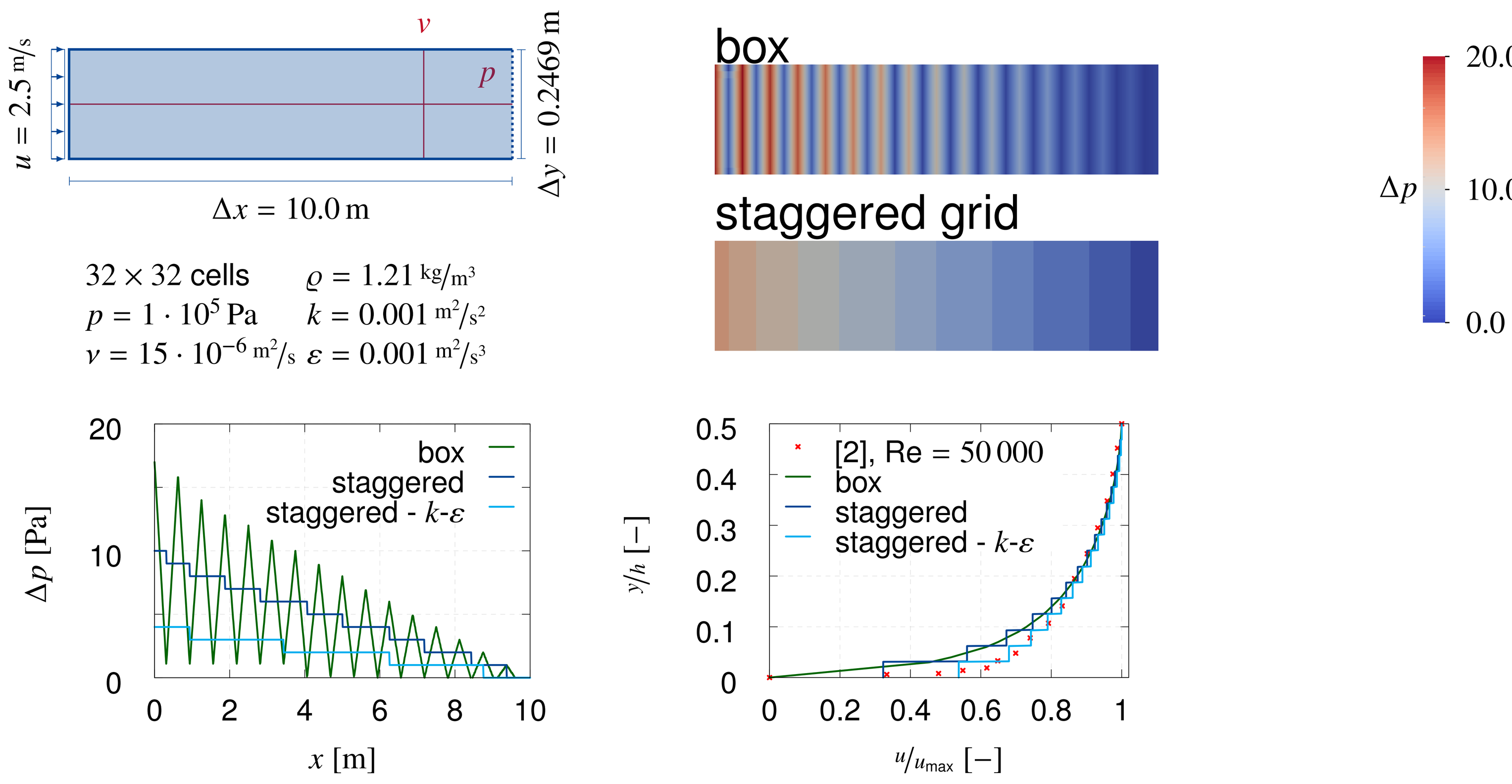
The coupling conditions of Mosthaf et al. [3] are extended to a turbulent free flow. Conditions for mass transfer, momentum transfer, and heat transfer have to be given. Transfer of tangential momentum between the free and porous-medium flow is accounted for by the Beavers and Joseph slip-velocity condition [1].

DuMux

Simulations are performed using the open-source simulator DuMux.

Support of the German Research Foundation is gratefully acknowledged.

Simulations



Experiments

To get a better understanding of the influence of interface properties and porous medium processes, wind tunnel experiments will be performed at the CESEP, Colorado School of Mines.
Additionally, Lattice Boltzmann simulations for small soil samples are performed in collaboration with the TU Braunschweig.
The focus herein lies on analyzing the influence of ...

Surface Roughness
1. smooth plate
2. impermeable + rough
3. permeable + rough

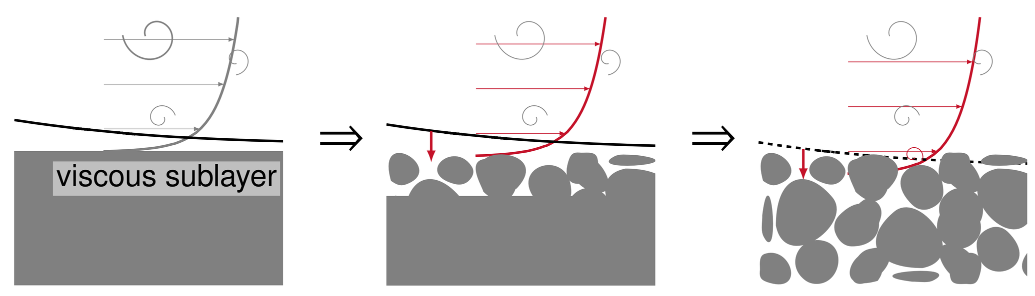


Figure 4: *Surface roughness effects on free flow velocity profile.*

Saturation
1. fully saturated
2. step-wise decreasing saturation

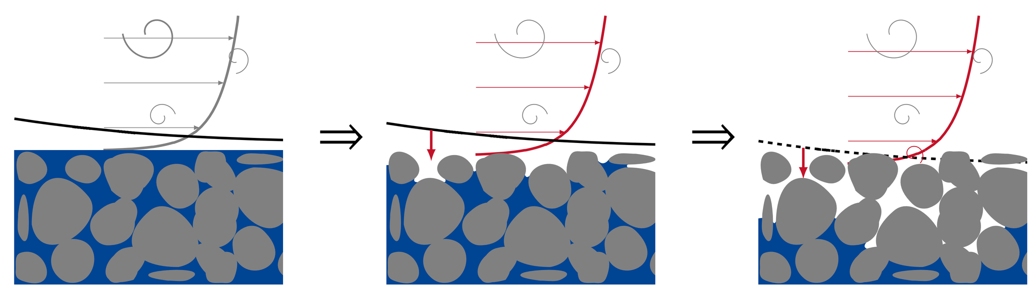


Figure 5: *Influence of saturation changes.*

... 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

- coupling staggered grid free flow with porous medium
- wall functions + low-Re implementation
- roughness with permeable medium
- gravity + compositional + non-isothermal free flow on staggered grid

Long-Term

- pore scale effects
- structure of the porous medium
- influence of saturation
- reduction of model complexity

Literature

[1] G. S. Beavers and D. D. Joseph. Boundary conditions at a naturally permeable wall. *Journal of Fluid Mechanics*, 30(1):197–207, 1967.
[2] J. Laufer. The structure of turbulence in fully developed pipe flow. *NACA Report*, 1174:417–434, 1954.
[3] K. Mosthaf, K. Baber, B. Flemisch, R. Helmig, A. Leijnse, I. Rybak, and B. Wohlmuth. A coupling concept for two-phase compositional porous-medium and single-phase compositional free flow. *Water Resources Research*, 47, 2011.
[4] S. B. Pope. *Turbulent flows.* Cambridge University Press, Cambridge, 4. edition, 2006.
[5] D. C. Wilcox. *Turbulence Modeling for CFD.* DCW Industries, La Cañada, California, 2. edition, 1998.