Modeling Evaporation Using Coupled RANS/Darcy Models

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International Research Training Group nupus

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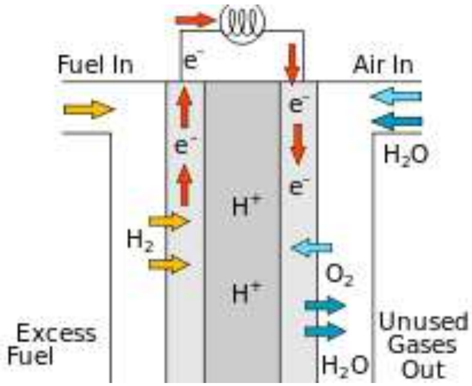
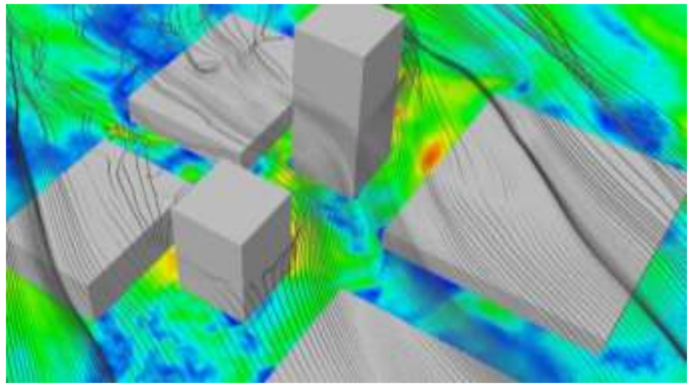
Introduction – Applications

- fuel cells



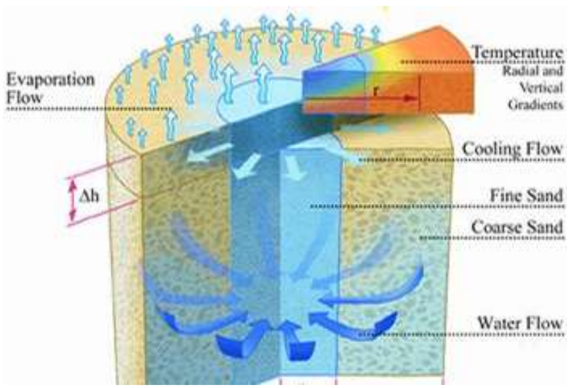
www.en.wikipedia.org

- buildings/urban areas



http://www.project-simba.eu

- evaporation



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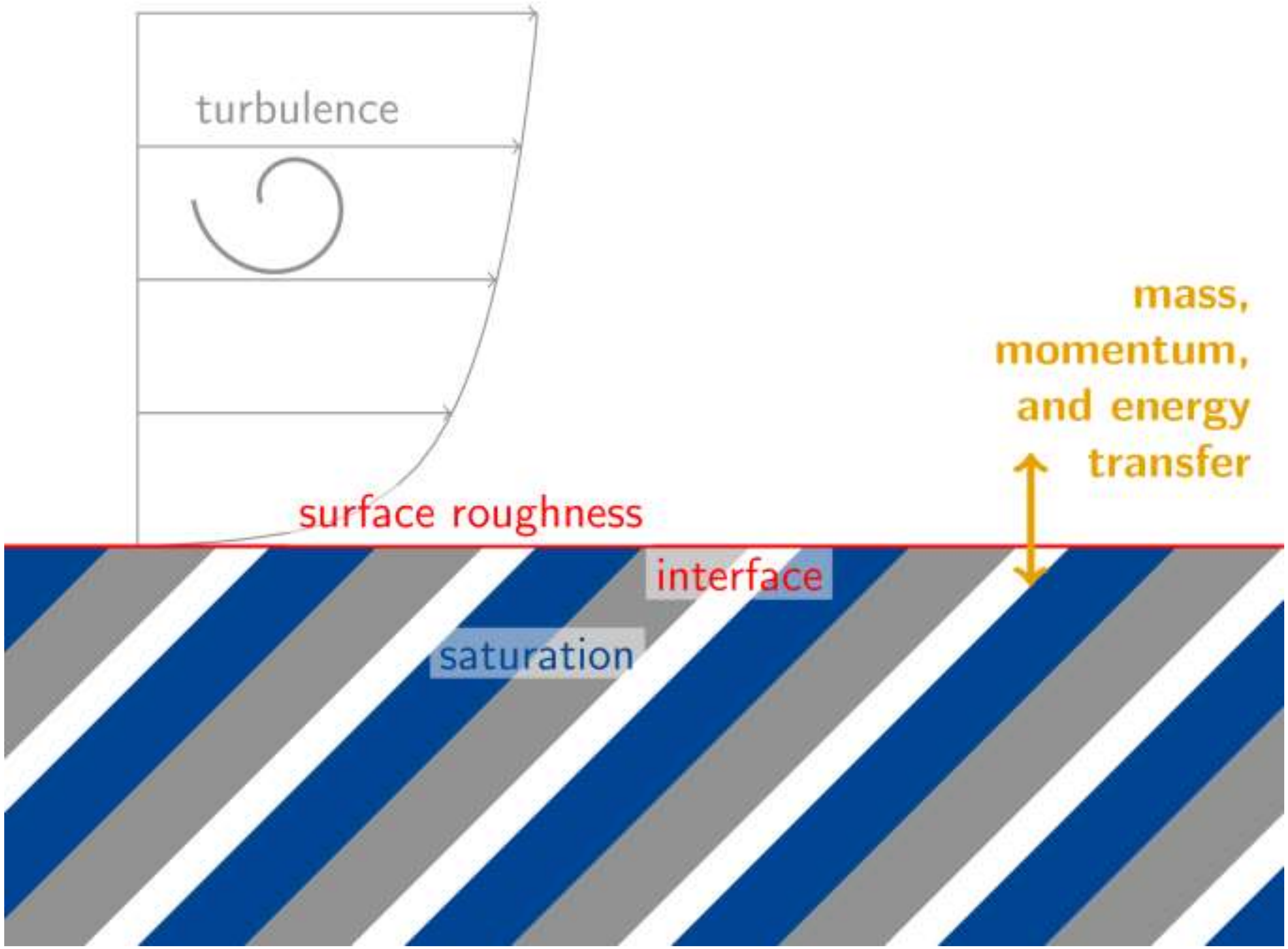
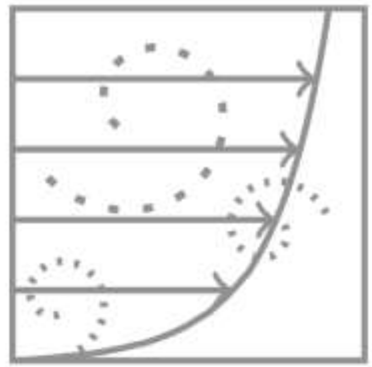
- …

Introduction – Challenges



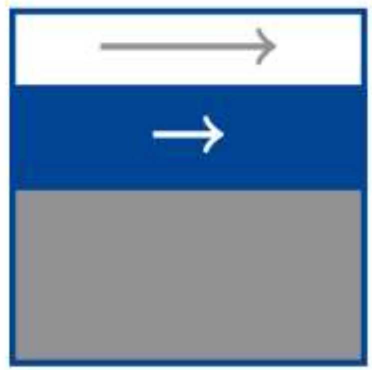
Model – Concept

free flow



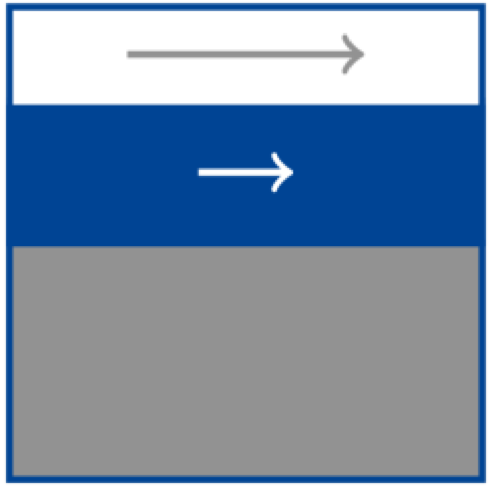
interface

porous medium flow



Model – Porous Medium Model

- REV concept, Darcy‘s law
- two fluid phases (gas, liquid)
- two components (air, water)
- non-isothermal
- equilibrium phase transitions
- p_g, S_l or X_g^w, T



Model – Porous Medium Equations

- momentum balance (Darcy)

$$\frac{k_{r,\alpha}}{\nu_\alpha \varrho_\alpha}\mathbf{K}\left(\nabla p_\alpha - \varrho_\alpha \mathbf{g}\right) + \mathbf{v}_\alpha = 0$$

pressure gravity

- component mass balance

$$\sum_{\alpha\in\{l,g\}} \left\{ \phi \frac{\partial\left(\varrho_\alpha S_\alpha X_\alpha^\kappa\right)}{\partial t} + \nabla\cdot\left(\varrho_\alpha X_\alpha^\kappa \mathbf{v}_\alpha\right) - \nabla\cdot\mathbf{j}_{\alpha,pm,diff}^\kappa - q_\alpha^\kappa \right\} = 0$$

storage advection diffusion source

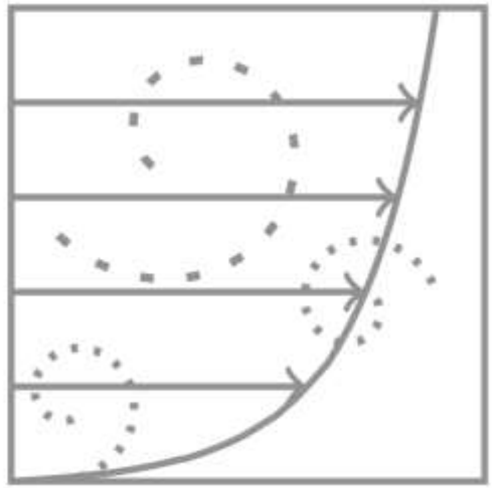
- energy balance

$$\sum_{\alpha\in\{l,g\}} \left\{ \phi \frac{\partial\left(\varrho_\alpha S_\alpha u_\alpha\right)}{\partial t} + \nabla\cdot\left(\varrho_\alpha h_\alpha \mathbf{v}_\alpha\right) \right\} + (1-\phi)\frac{(\partial \varrho_s c_s T)}{\partial t} - \nabla\cdot\left(\lambda_{pm}\nabla T\right) - q^T = 0$$

storage advection storage (solid) conduction source

Model – Free Flow

- laminar/turbulent (RANS)
- single phase (gas)
- two components (air/water)
- non-isothermal
- $p_\mathrm{g}, \mathbf{v}_\mathrm{g}, X_\mathrm{g}^\mathrm{w}, T$



Model – Free Flow Equations

- mass balance

$$\underbrace{\frac{\partial \varrho_g}{\partial t}}_{\text{storage}} + \underbrace{\nabla \cdot (\varrho_g \bar{\mathbf{v}}_g)}_{\text{advection}} = 0$$

- momentum balance (RANS)

$$\underbrace{\frac{\partial (\varrho_g \bar{\mathbf{v}}_g)}{\partial t}}_{\text{storage}} + \underbrace{\nabla \cdot (\varrho_g \bar{\mathbf{v}}_g \bar{\mathbf{v}}_g^{\mathsf{T}})}_{\text{inertia}} - \underbrace{\nabla \cdot ([\varrho_g \nu_g}_{\text{viscous}} + \underbrace{\varrho_g \nu_{g,t}}_{\text{eddy viscosity}}] \nabla (\bar{\mathbf{v}}_g + \bar{\mathbf{v}}_g^{\mathsf{T}}))) + \underbrace{\nabla \bar{p}_g}_{\text{pressure}} - \underbrace{\varrho_g \nabla g}_{\text{gravity}} = 0$$

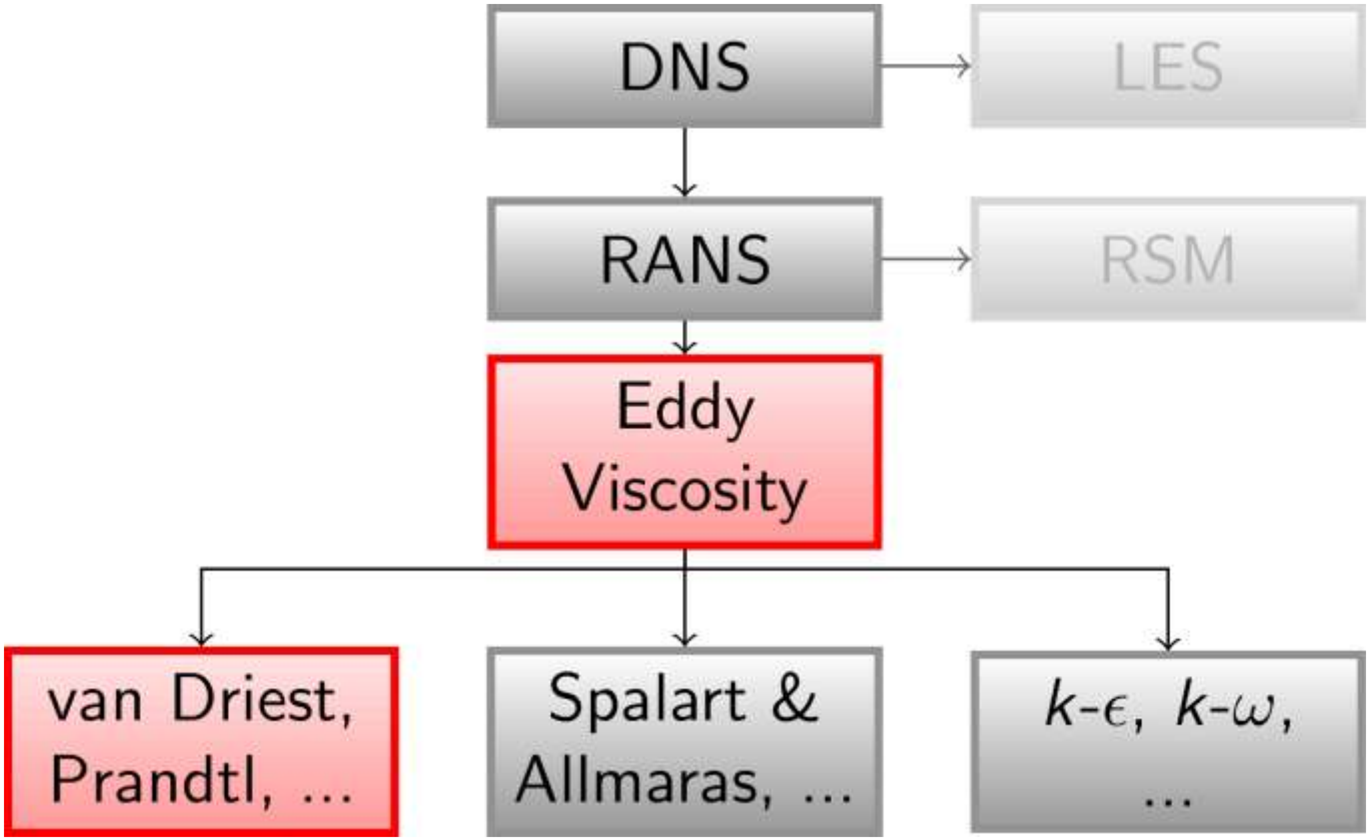
- component mass balance

$$\underbrace{\frac{\partial (\varrho_g \bar{X}_g^\kappa)}{\partial t}}_{\text{storage}} + \underbrace{\nabla \cdot (\varrho_g \bar{X}_g^\kappa \bar{\mathbf{v}}_g)}_{\text{advection}} - \underbrace{\nabla \cdot ([D_g^\kappa}_{\text{diffusion}} + \underbrace{D_{g,t}^\kappa}_{\text{eddy diffusion}}] \varrho_{g,\mathrm{mol}} M^\kappa \nabla \bar{x}_g^\kappa) - \underbrace{q_g^\kappa}_{\text{source}} = 0$$

- energy balance

$$\underbrace{\frac{\partial (\varrho_g \bar{u}_g)}{\partial t}}_{\text{storage}} + \underbrace{\nabla \cdot (\varrho_g \bar{h}_g \bar{\mathbf{v}}_g)}_{\text{advection}} - \sum_{\kappa \in \{a,w\}} \underbrace{\{\nabla \cdot (\bar{h}_g^\kappa \bar{j}_{g,\mathrm{ff,t,diff}}^\kappa)\}}_{\text{(eddy-)diffusion}} - \underbrace{\nabla \cdot ([\lambda_g}_{\text{conduction}} + \underbrace{\lambda_{g,t}}_{\text{eddy conduction}}] \nabla \bar{T}) - \underbrace{q_g^T}_{\text{source}} = 0$$

Model – Turbulence and Roughness

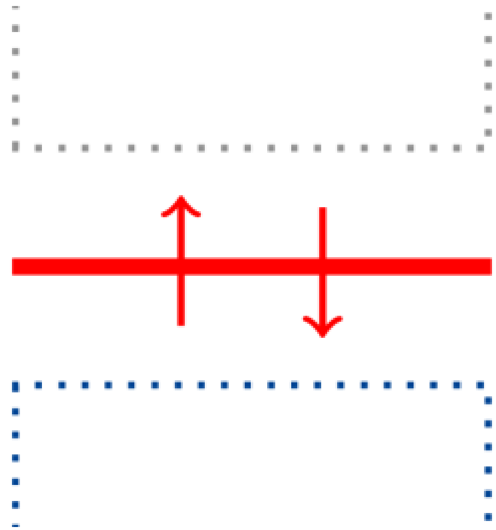


[Cebeci, T. 1978]

$\nu_{g,t} = f\left(\partial \bar{u} / \partial y, y, k_s\right)$

Model – Coupling Model

- [Mosthaf et al. 2011, Fetzer et al. 2015 (submitted)]
- local thermodynamic equilibrium
- continuity of fluxes
- continuity of primary variables

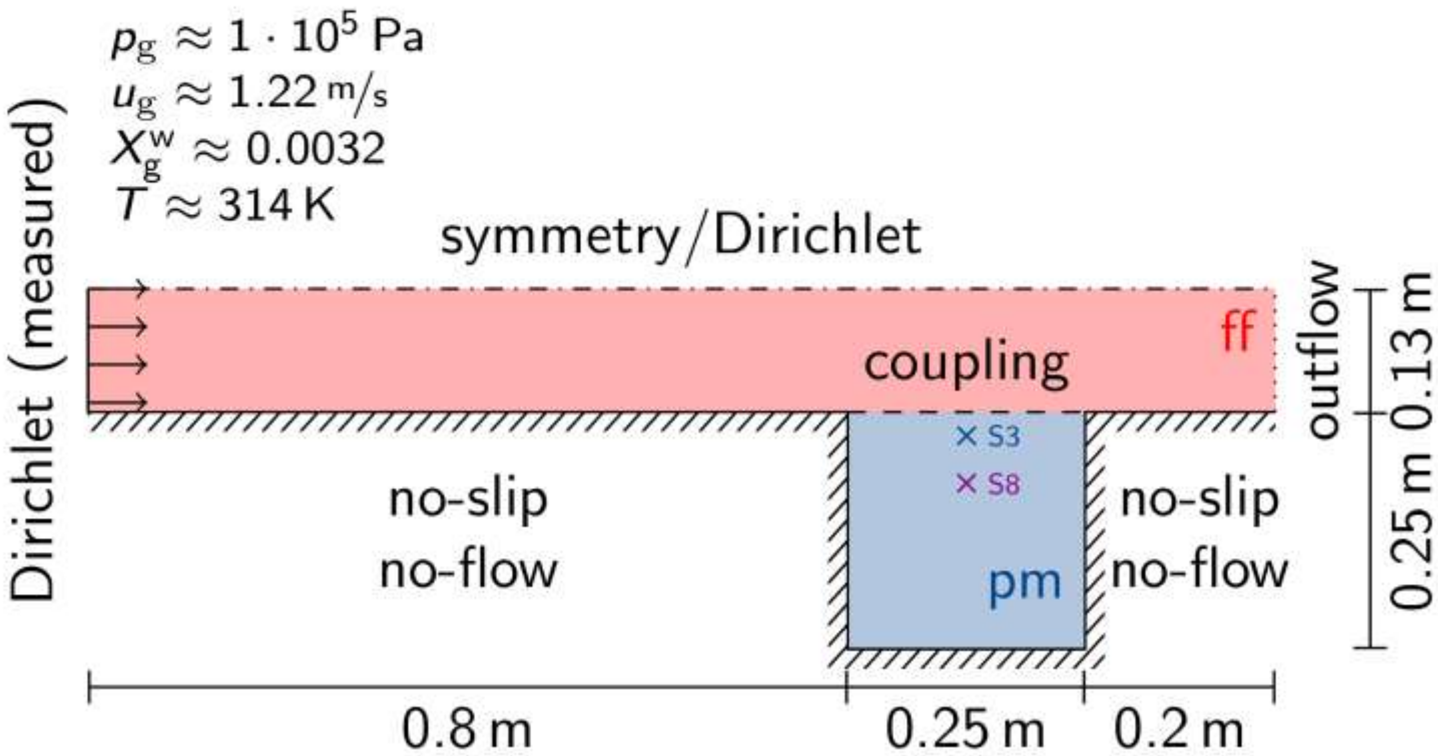


Model – Coupling Equations

- mass $$[(\varrho_g \bar{\mathbf{v}}_g) \cdot \mathbf{n}]^{ff} = -[(\varrho_g \mathbf{v}_g + \varrho_l \mathbf{v}_l) \cdot \mathbf{n}]^{pm}$$
- momentum (tangential) $$\left[\left(\bar{\mathbf{v}}_g + \frac{\sqrt{(\mathbf{K}\mathbf{t}_i) \cdot \mathbf{t}_i}}{\alpha_{BJ} \varrho_g \nu_g} \bar{\boldsymbol{\tau}}_{g,t} \mathbf{n}\right) \cdot \mathbf{t}_i\right]^{ff} = 0$$
- momentum (normal) $$[(\{\varrho_g \bar{\mathbf{v}}_g \bar{\mathbf{v}}_g^T - \bar{\boldsymbol{\tau}}_{g,t} + \bar{p}_g \mathbf{I}\} \mathbf{n}) \cdot \mathbf{n}]^{ff} = p_g^{pm}$$
- component
  - continuity of mass fractions
  - continuity of fluxes
- energy
  - continuity of temperature
  - continuity of fluxes

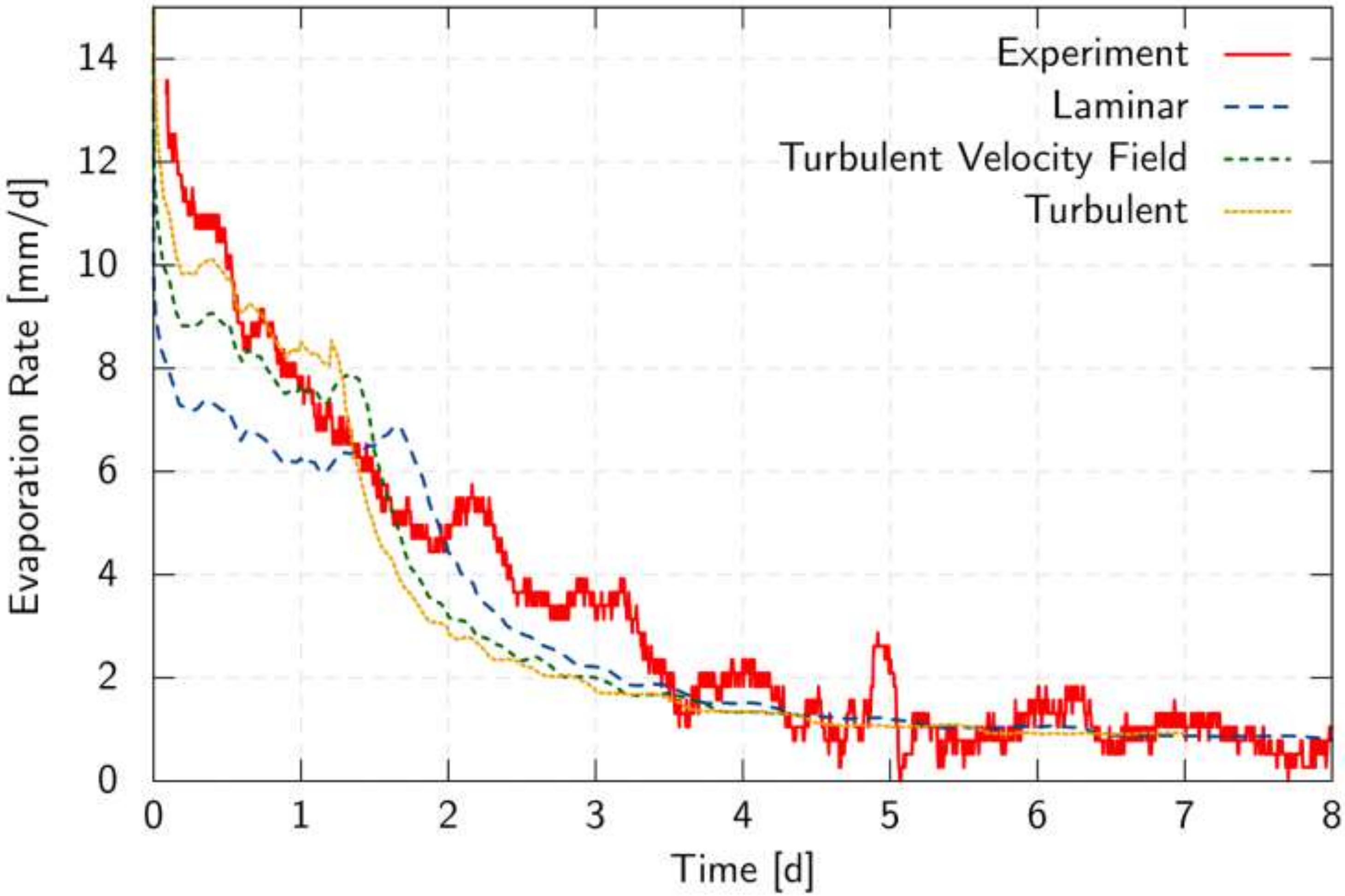
Results – Setup

- implementation: 2D, box, fully implicit
- experiments: [Davarzani et al. 2014]

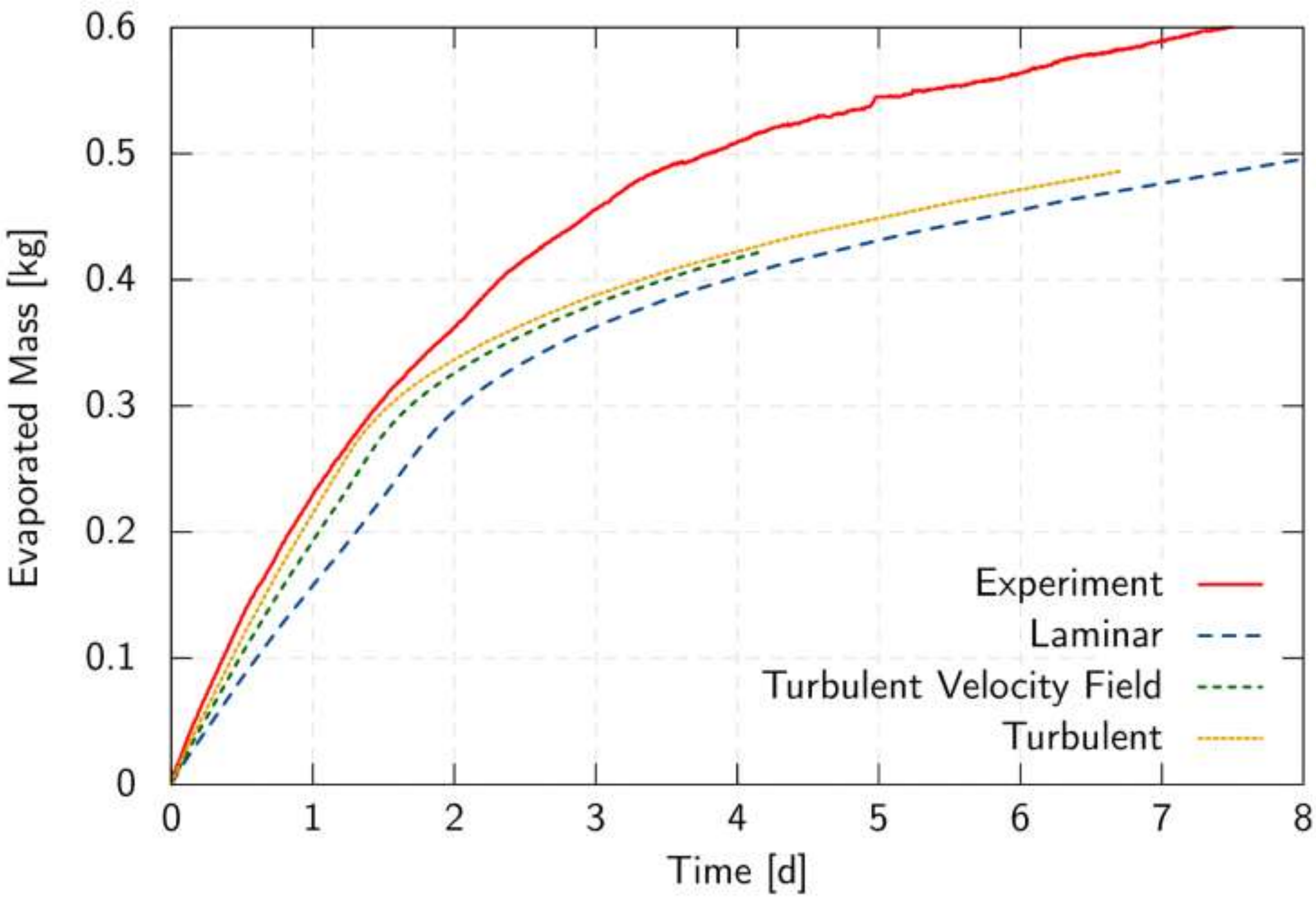


www.hydrosys.uni-stuttgart.de

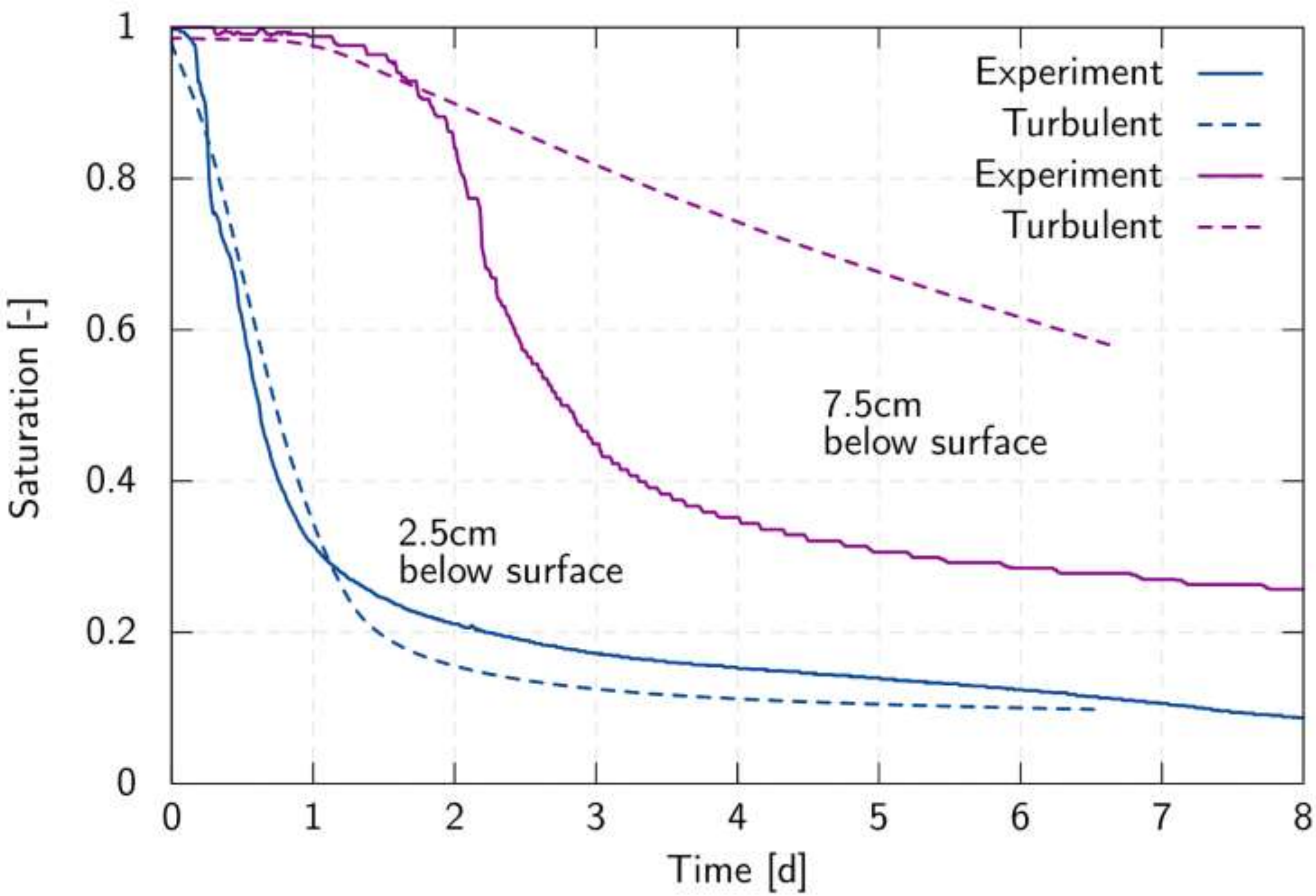
Results – Evaporation Rate

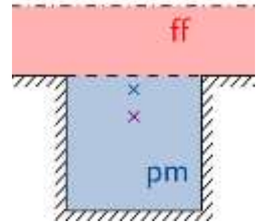


Results – Cumulative Mass Loss

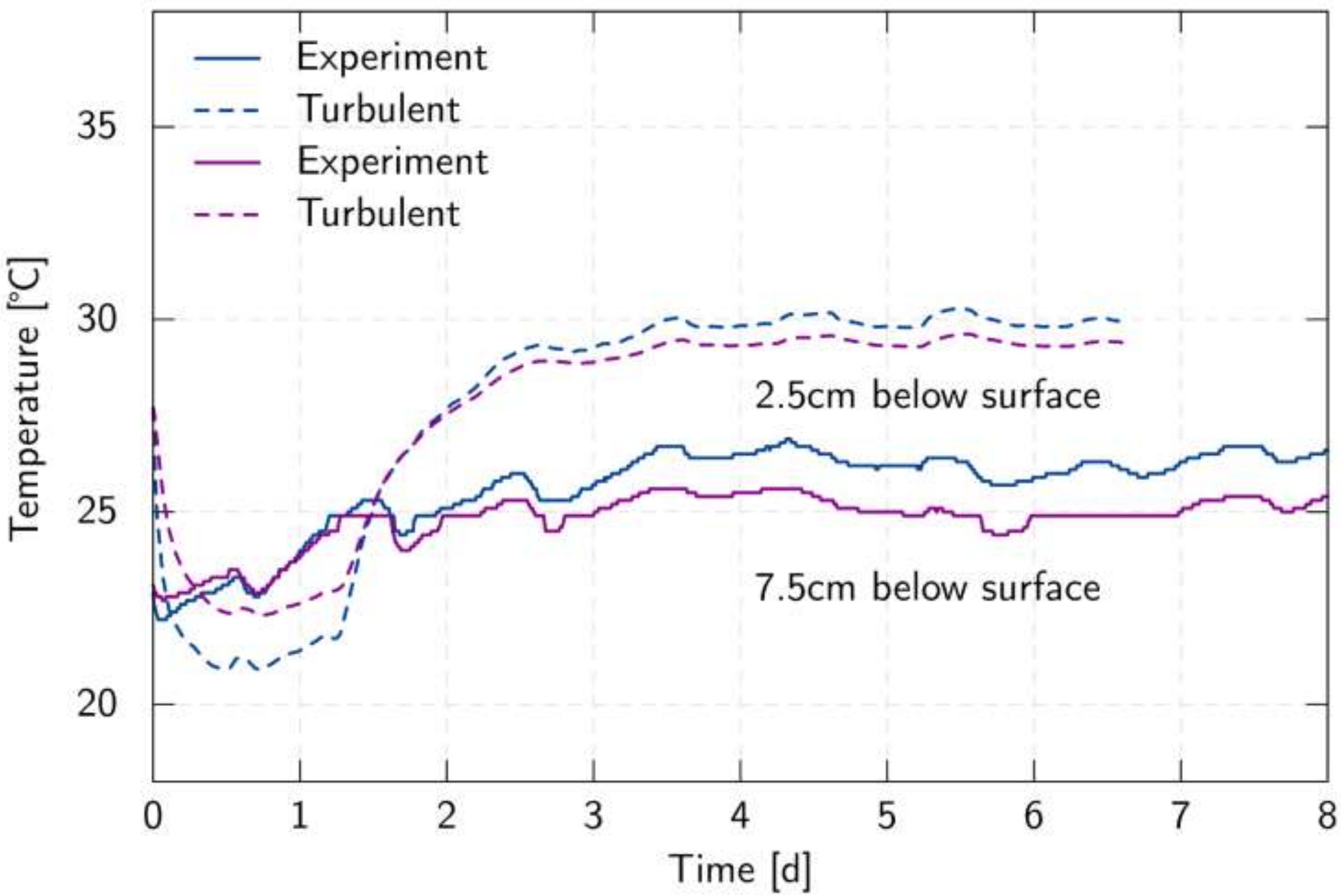


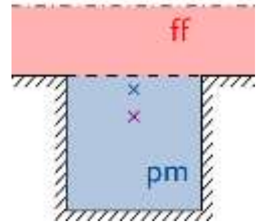
Results – Porous Medium Saturation



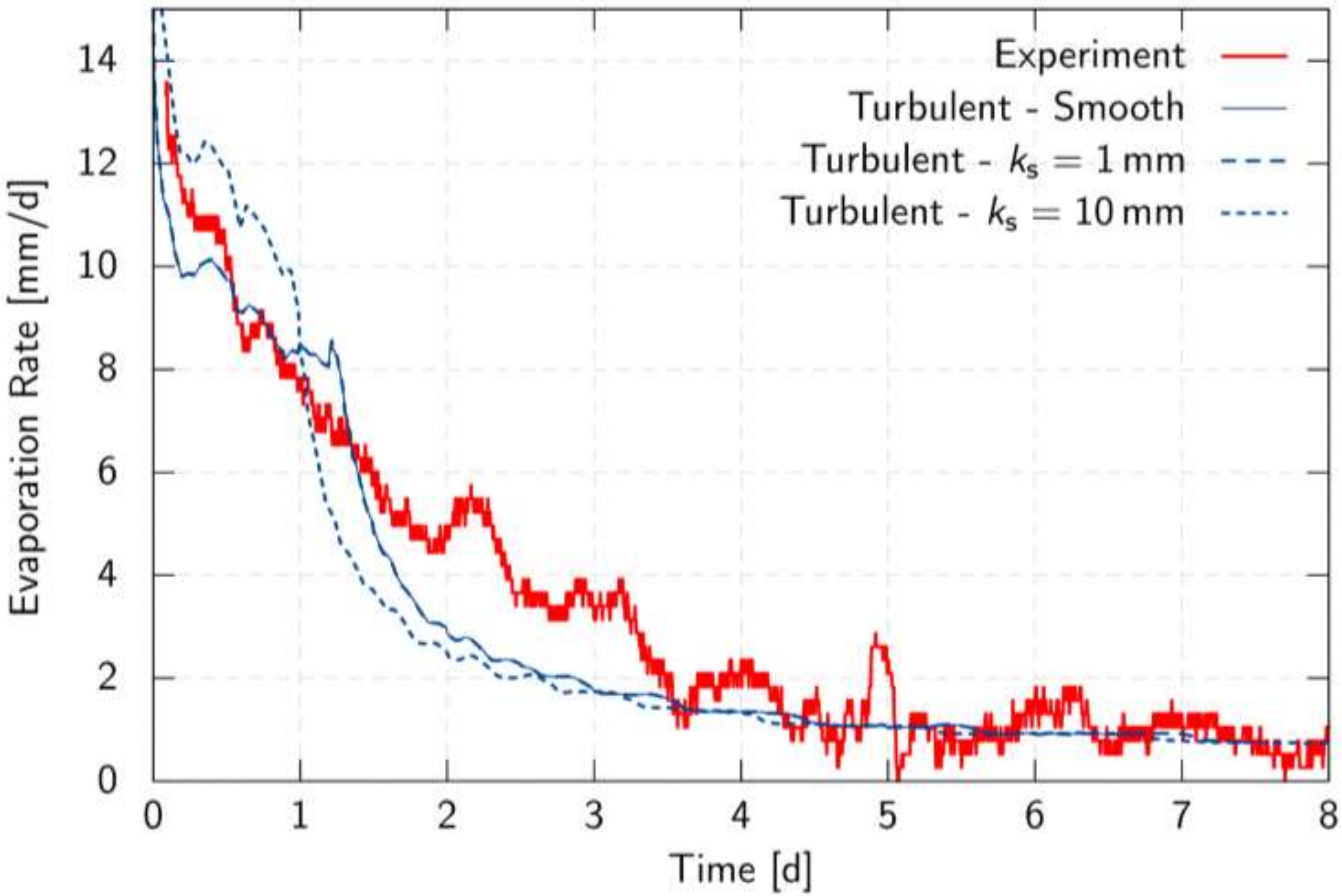


Results – Porous Medium Temperature





Results – Roughness



Summary and Outlook

- test case
  - turbulence – improves prediction of evaporation rates
  - roughness – minor role
- model
  - improve discretization of numerical free flow model
  - advanced turbulence models
  - include gravity
- model + experiments
  - heterogeneities
  - discrete roughness elements

Thank you for your attention!

- [Mosthaf et al. 2011] - A coupling concept for two-phase compositional porous-medium and single-phase compositional free flow
  Water Resources Research, **2011**, *47*, W10522
- [Fetzer et al. 2015 (submitted)] - Effect of Turbulence and Roughness on Coupled Porous-Medium/Free Flow Exchange Processes
  Transport in Porous Media, **2015**, *submitted*
- [Davarzani et al. 2014] - Study of the effect of wind speed on evaporation from soil through integrated modeling of the atmospheric boundary layer and shallow subsurface
  Water Resources Research, **2014**, *50*, 1-20
- [Beavers, G. S. & Joseph, D. D. 1967] - Boundary conditions at a naturally permeable wall
  Journal of Fluid Mechanics, **1967**, *30*, 197-207
- [Cebeci, T. 1978] - Calculation of Incompressible Rough-Wall Boundary Layer Flows
  AIAA Journal, **1978**, *16*, 730-735

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