Study of the effect of wind speed on evaporation from soil through integrated modeling of atmospheric boundary layer and shallow subsurface

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ABSTRACT

Heat and mass flux in the form of soil evaporation across the land surface **couples the atmospheric boundary layer to the shallow subsurface**. The coupling between land and the atmosphere leads to **highly dynamic interactions** between the porous media properties, transport processes and boundary conditions, resulting in **dynamic evaporative behavior**. However, the **coupling** at the land-atmospheric interface is **rarely considered** in most current models and their validation for practical applications. This is due to the complexity of the problem in field scenarios and the scarcity of field or laboratory data capable of testing and refining coupled energy and mass transfer theories. In most efforts to compute evaporation from soil, only indirect coupling is provided to characterize the interaction between non-isothermal multiphase flows under realistic atmospheric conditions even though heat and mass flux are controlled by the coupled dynamics of the land and the atmospheric boundary layer. In earlier drying modeling concepts, imposing evaporation flux (kinetic of relative humidity) and temperature as surface boundary condition is often needed.

With the **goal of improving our understanding of the land/atmospheric coupling,** we developed a **model based on the coupling of Navier-Stokes free flow and Darcy flow in porous medium.** The model consists of the coupled equations of mass conservation for the liquid (water) and gas (water vapor and air) phases in porous medium with the gas phase in free flow domain under non-isothermal, non-equilibrium conditions. The boundary conditions at the porous medium-free flow medium interface include dynamical, thermal and solutal equilibriums, and using the Beavers-Joseph slip boundary condition. In order to experimentally validate the numerical results, we developed and used a unique two dimensional wind tunnel placed above a soil tank equipped with a network of different sensors. A series of experiments under varying boundary conditions, were performed. Precision data for soil moisture, soil and air temperature and relative humidity, and also wind velocity under well-controlled transient heat and wind boundary conditions was generated.

Results demonstrate that the **coupling concept can predict the different stages of the drying process** in porous media with good accuracy. Increasing the wind speed increases the first stage evaporation rate and decreases the transition time at low velocity values; then, at high values of wind speed the evaporation rate becomes less dependent of flow in free fluid. In the opposite, the impact of the wind speed on the second stage evaporation (diffusion dominant stage) is not significant. The proposed theoretical model can be used to predict the evaporation process where a porous medium flow is coupled to a free flow for different practical applications.

1. AIMS AND SCOPE

Modeling:

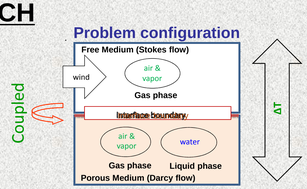
- ✓Develop and implement a numerical model based on the coupling of Navier-Stokes free flow and Darcy flow in porous medium to solve for liquid water and gas (water vapor and air) flux in the porous medium and gas flux in the free flow under non-isothermal, non-equilibrium phase change conditions
- ✓Study the effect of wind speed on evaporation by comparing numerical results with experimental data

Experiments:

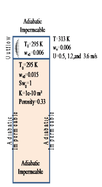
- ✓Develop and use a unique two dimensional wind tunnel/porous media apparatus equipped with a network of recent sensor technologies for automated and continuous monitoring of moisture/temperature behavior
- ✓Generate precision data under well-controlled transient wind boundary conditions at the soil surface

2. APPROACH

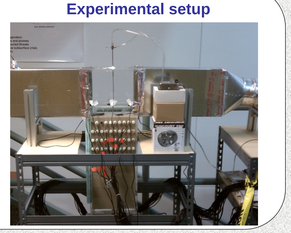
Problem configuration



Theoretical model



Experimental setup



3. NUMERICAL MODEL FORMULATION

Free flow equations

Momentum transport (Bird et al., 2002)

$$\rho_g\left(\frac{\partial \mathbf{v}_g}{\partial t}+\mathbf{v}_g.\nabla\mathbf{v}_g\right)=-\nabla p_g+\mu_g\nabla.\left(\nabla\mathbf{v}_g\right)+\rho_g\mathbf{g}$$

Mass transport (Bird et al., 2002)

$$\frac{\partial w_v}{\partial t}+\nabla.\left(\rho_g w_v\mathbf{v}_g\right)=\nabla.\left(\mathrm{D}_v\nabla\left(\rho_g w_v\right)\right)$$

Energy transfer (Kaviany, 2001)

$$\left(\rho c_p\right)_g\frac{\partial T_g}{\partial t}+\left(\rho c_p\right)_g\nabla.\left(T_g\mathbf{v}_g\right)=\nabla.\left(\Lambda_g\nabla T_g\right)$$

Interface boundary condition

Slip boundary condition (Beavers & Joseph, 1967; Staffman, 1971)

$$\mathbf{v}_g.\mathbf{t}_j=\frac{\sqrt{\mathrm{K}}}{\alpha_{BJ}}\mathbf{t}_j.\nabla\mathbf{v}_g$$

Continuity of normal mass flux for gas phase (Nield and Bejan, 2006)

$$\left[\left(\rho_g\mathbf{v}_g\right).\mathbf{n}\right]_{ff}=-\left[\left(\rho_g\mathbf{v}_g\right).\mathbf{n}\right]_{pm}$$

Continuity of temperature and concentration (Nield and Bejan, 2006)

$$\left[T\right]_{ff}=\left[T\right]_{pm}$$

$$\left[w_v\right]_{ff}=\left[w_v\right]_{pm}$$

Porous medium equations

Mass balance (Bear, 1972)

$$\phi\frac{dS_w}{dp_c}\frac{\partial\rho_w\left(p_g-p_w\right)}{\partial t}+\nabla.\left(\rho_w\mathbf{v}_w\right)=-\dot{m}$$

$$\phi\frac{dS_g}{dp_c}\frac{\partial\rho_g\left(p_g-p_w\right)}{\partial t}+\nabla.\left(\rho_g\mathbf{v}_g\right)=0$$

Mass transport in the gas phase (Bear, 1972)

$$\frac{\partial\left(\rho_g S_g w_v\right)}{\partial t}+\nabla.\left(\rho_g w_v\mathbf{v}_g-\mathrm{D}_v^*\nabla\left(\rho_g w_v\right)\right)=\dot{m}$$

Water-vapor phase change rate

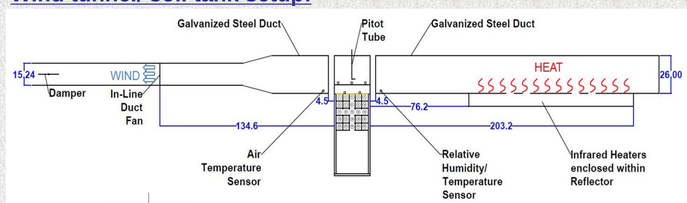
$$\dot{m}=\frac{\left(S_w-S_{wr}\right)\phi}{t_{eq}}\left(\rho_{veq}-\rho_v\right)$$

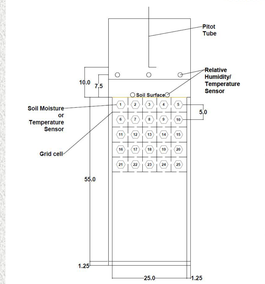
Energy transfer (Whitaker, 1977)

$$\left(\rho c_p\right)^*\frac{\partial}{\partial t}T+\nabla.\left(\left(\rho c_p\right)_w\mathbf{v}_w T+\left(\rho c_p\right)_g\mathbf{v}_g T\right)-\nabla.\left(\Lambda^*\nabla T\right)=-L\dot{m}-Q_s$$

4. EXPERIMENTAL METHODS

Wind tunnel/ soil tank setup:





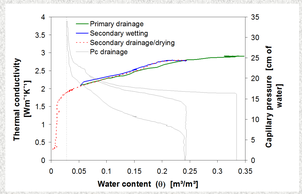
Continuously monitor:

- ✧Soil Moisture
- ✧Temperature (soil and air)
- ✧ Relative Humidity (soil and air)
- ✧ Tank Weight
- ✧ Wind speed

Test sand:

Accusand #30/40

- ✧ 99.8% quartz
- ✧ d_{50} = 0.53 mm
- ✧ Porosity = 0.334
- ✧ K_s = 0.104 cm/s
- ✧ρ bulk = 1.76 g/cm^3



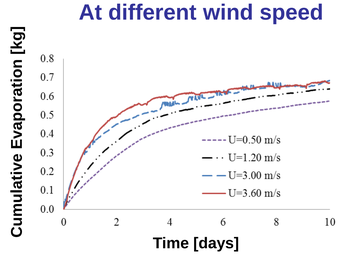
Smits et al., 2010

Procedure:

- ✓ Water table initially at top surface of column
- ✓ Bottom boundary did not allow for water flow
- ✓ Uniform temperature distribution established at upper boundary using an infrared heater
- ✓ Evaporation induced at soil surface (Drying) upper boundary open
- ✓ 8 test cases under varying wind conditions from 0.5 m/s to 3.5 m/s wind speed

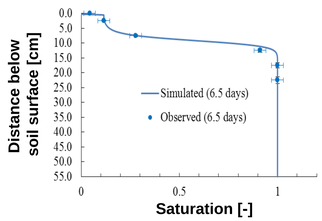
5. COMPARISON OF MODEL RESULTS WITH EXPERIMENTAL DATA

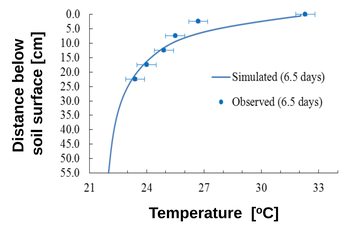
Observed evaporation At different wind speed



RESULT: Evaporation less dependent on flow in free fluid at high wind speeds

Simulated and observed saturation and temperature profiles at tank center, t=6.5 days, U_w=1.2m/s

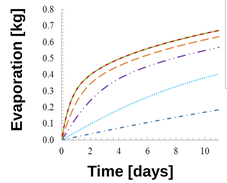




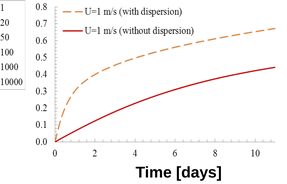
RESULT: Good comparison between observed and simulated results

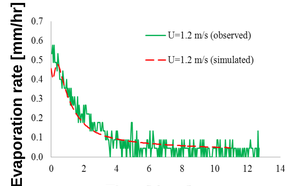
5. COMPARISON OF EXPERIMENTAL AND MODEL RESULTS

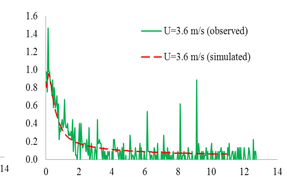
Impact of solutal Péclet number on wind speed



Impact of solutal and thermal dispersion in free flow domain on evaporation







RESULTS:

- ➢ Increase in evaporation is significant for low Péclet numbers. The influence becomes small for very high Péclet numbers.
- ➢ Demonstrates the importance of including atmospheric system dispersion in evaporation modeling efforts.

6. CONCLUSIONS

- ➢ Good agreement between theoretical predictions and experimental results suggest the relevancy of coupling approach to describe heat, water and water vapor transport (without needing soil surface humidity and temperature)
- ➢ Coupled model captures the dependence of evaporation on wind speed: at high wind speeds, evaporation is less dependent on flow in free fluid
- ➢ Increase wind speed, increase 1st stage evaporation rate and decrease transition time from stage I to stage II evaporation
- ➢ Additional consideration of turbulent conditions is necessary

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