

THERMO-MECHANICAL BEHAVIOUR OF UNSATURATED GRANULAR POROUS MEDIA

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An interface of two immiscible fluids, e.g. air and water in an unsaturated soil, behaves as if it was in a state of uniform tension. There is a pressure difference across a curved interface which can be related to the surface tension and the radii of curvature in a flexible membrane. The characteristic profile of a liquid capillary bridge between solid spheres has served as a physical model in adsorption thermodynamics. Some of its applications include flow behaviour and tensile strength of granular materials, and moisture retention of soil systems¹. A physical model is proposed for the equilibrium of liquid bridge where the effect of particle contact is taken into account. The objective of the present work is to formulate a physical model for a theoretical study of the problem from the viewpoints of mass and heat transfer.

The expression of the pressure difference for a saddle-shaped surface, which is referred to as Laplace's equation, reads²

$$p = p_g - p_l = \sigma \left(\frac{1}{R_1} - \frac{1}{R_2} \right) \quad (1)$$

Where R_1 and R_2 are the radii of curvature of the liquid bridge located in the gas and the liquid respectively, σ is the surface tension, p is the pressure difference across the gas-liquid interface or capillary suction, while p_g is the pressure in the gas and p_l is the pressure in the liquid. The total capillary (or interparticle) force F is given by³

$$F = \frac{2\pi R \sigma}{1 + \tan\left(\frac{\beta}{2}\right)} \quad (2)$$

where R is the particle size and β is the half-filling angle of the liquid bridge between two spheres.

In the low saturation range of unsaturated granular porous media flow of liquid occurs mainly in the form of vapour, thus involving evaporation and condensation. The humidity of the pore air and its equilibrium relation to the pore liquid suction is therefore another main interaction component of unsaturated granular porous media. Kelvins' equation expresses the connection of the liquid and vapour systems based implicitly on the assumption that these systems are at thermodynamic equilibrium, i.e.⁴

$$h = \exp\left(\frac{p}{\rho_l R_v T}\right) \quad (3)$$

in which ρ_l is the density of liquid, R_v is the gas constant of vapour and T is the absolute temperature. It shows that for any particle size the capillary suction increases with decreasing relative humidity h .

In granular porous media, drying and wetting may be accompanied with temperature changes. These phenomena are slow processes. For example, in soil testing the majority of desaturation and saturation of soil is done by drainage and infiltration of water. However, if desaturation and

saturation are controlled through vapour flow the temperature change, if measurable, may be of interest possibly in non-isothermal moisture flow in wetting and drying of a soil sample.

The heat absorbed or released per unit volume of porous medium during phase change is written as⁵

$$q = \rho_l n L S_l \quad (4)$$

where q is the heat absorbed or released by the porous medium during the change of state, n is the porosity of the medium, L represents the latent heat of vaporization per unit mass of liquid, and S_l is the degree of saturation. By using Equation (4), the variations of latent heat per unit volume of a porous medium with the degree of saturation during saturation/desaturation for different structures can be determined. In the case of water, the latent heat of vaporization per unit mass at water surface can be estimated by⁶

$$L = 2500.78 - 2.37(T - 273) \quad (5)$$

in which T is the absolute temperature in K.

Equation (4) in a differential form can be written as

$$\delta q = \rho_l n L dS_l \quad (6)$$

in which δq is equivalent to the heat change in the medium, i.e.

$$\delta q = \rho_m C_{pm} dT \quad (7)$$

where ρ_m is the density of the porous medium and C_{pm} is the specific heat of the medium. The product $\rho_m C_{pm}$ expresses the heat capacity, per unit volume of the medium at reference temperature. So,

$$\rho_m C_{pm} dT = \rho_l n L dS_l \quad (8)$$

Volumetric specific heat capacity of a moist medium can be readily calculated from volume fractions of the solid, liquid, and gas phases. The contribution of gas phase to the heat capacity of the composite media, compared to liquid, is small and therefore can generally be neglected. Hence

$$[n S_l \rho_l C_{pl} + (1 - n) \rho_s C_{ps}] dT = \rho_l n L dS_l \quad (9)$$

where subscript s stands for solid phase.

The ratio of the change of temperature to the change of the degree of saturation, therefore, becomes

$$\frac{dT}{dS_l} = \frac{\rho_l n L}{n S_l \rho_l C_{pl} + (1 - n) \rho_s C_{ps}} \quad (10)$$

Using dT/dS_l and an incremental change of the degree of saturation, the change in temperature δT for different structures of porous media can be calculated.

CONCLUSION

Values of suction at the wetting and drying fronts during saturation and desaturation processes in different porous media are not the same. The temperature change of a thermally isolated unsaturated porous medium in the phase change due to the variation of the degree of saturation is calculatable but is not easily measurable.

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