

Influence of chemical potential on water transport in a hygroscopic soil

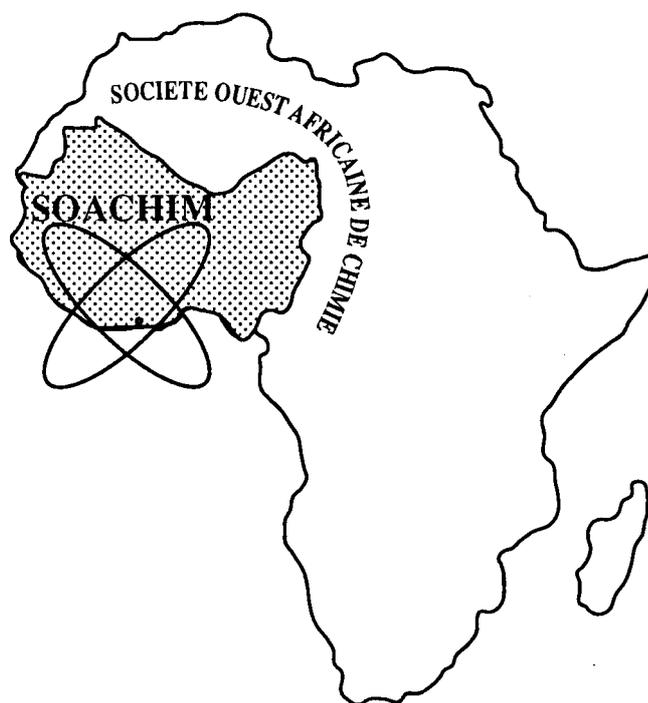
Samuel Ouoba , Fabien Cherblanc, Jean-Claude Bénéet,

Jean Kouliati

Journal de la Société Ouest-Africaine de Chimie

J. Soc. Ouest-Afr. Chim.(2015), 039 : 1 - 10

20^{ème} Année, Juin 2015



ISSN 0796-6687

Code Chemical Abstracts : JSOCF2

Cote INIST (CNRS France) : <27680>

Site Web: <http://www.soachim.org>

Influence of chemical potential on water transport in a hygroscopic soil

Samuel Ouoba^{1,*}, Fabien Cherblanc², Jean-Claude Béné², Jean Kouliadiati¹

¹*Laboratoire de Physique et de Chimie de l'Environnement, UFR-SEA, 03 BP 7021 Ouaga 03, Université de Ouagadougou, Burkina Faso*

²*Laboratoire de Mécanique et Génie Civil, UMR CNRS 5508, Université Montpellier 2, Cc 048, Place Eugène Bataillon, 34000 Montpellier, France*

(Reçu le 10/02/2014 – Accepté après corrections le 25/05/2015)

Abstract: Concerning the description of mass transport in a porous media, particularly in soil, the question is to know what are the main mechanisms to consider during transport phenomena for a best description of these transports. The answer to this question requires good understanding on thermodynamic law to include in the transport process for a good estimation of the flux of transport. The applications related to water transfer in soil are numerous: the remediation of pollution, the nutrition of plants, etc. The results of this paper show the importance of chemical potential on the mechanisms of transport of water in the soil. Our attention is mainly focused on hygroscopic soils with low water contents (<9%). Indeed, because of the small quantities in hygroscopic soils, water is strongly linked to solid matrix of soil and, its chemical potential is different to the one of water contained in saturated soils (free water). Thus, energy to extract one mole of water from the soil is higher and the migration of water becomes difficult. The apparatus used to determine the phenomenological parameters is called activity-meter. This device has been patented for the easiness of its exploitation and its reliability to determine water activity; not only in the soil but also in a wide range of other complex media such as coffee, mango, banana, etc. what is important for the conservation of food products in the domain of drying. The mechanisms of evaporation have been experimentally and numerically studied and the role of chemical potential of water has been highlighted during transport phenomena. The numerical models clearly established that the chemical potential allows describing water transport in hygroscopic soils. The experiments on the profiles of water content are in good agreement with the model which takes into account the chemical potential in the equations of water transport.

Keywords: Chemical Potential; Transport; Hygroscopic Soil; Water Content

Influence du potentiel chimique sur le transport d'eau dans un sol hygroscopique

Résumé : En ce qui concerne la description du transport de masse dans un milieu poreux, en particulier dans un sol, la question est de savoir quels sont les principaux mécanismes à prendre en compte lors des phénomènes de transport pour mieux décrire ces transports. La réponse à cette question nécessite une bonne compréhension des lois de la thermodynamique qu'il faut prendre en compte dans le processus de transport afin de pouvoir faire une bonne estimation du flux de transport du composé. Les applications liées au transfert d'eau dans le sol sont nombreuses : réhabilitation des sites pollués, nutrition des plantes, etc. Les résultats du présent travail montrent l'importance du potentiel chimique sur les mécanismes de transport d'eau dans le sol. Dans cet article, nous nous intéressons principalement aux sols hygroscopiques caractérisés par de faibles teneurs en eau (< 9%). En effet, en raison des faibles quantités dans les sols hygroscopiques, l'eau se retrouve fortement liée à la matrice solide du sol et par conséquent son potentiel chimique est différent de celui de l'eau contenue dans les sols saturés (eau libre). Ainsi, l'énergie d'extraction d'une mole d'eau dans le sol est plus élevée ce qui rend difficile la migration de l'eau. Le dispositif expérimental utilisé pour la détermination des paramètres phénoménologiques est appelé activimètre. Ce dispositif a fait l'objet d'un brevet pour sa facilité d'exploitation et sa précision sur la mesure de l'activité de l'eau non seulement dans le sol, mais aussi dans une large gamme d'autres milieux complexes tels que le café, la mangue, la banane, etc. ce qui est important pour la conservation des produits agroalimentaires surtout dans le domaine du séchage. Les mécanismes d'évaporation ont fait l'objet d'une étude expérimentale et des modèles de simulation prenant en compte ou non le potentiel chimique de l'eau dans les mécanismes de transport ont été élaborés. Ces modèles montrent que le potentiel chimique permet de bien décrire les mécanismes de transport d'eau dans les sols hygroscopiques. Les résultats expérimentaux sur les profils de teneur en eau sont en bon accord avec le modèle numérique qui prend en compte le potentiel chimique dans les équations de transport d'eau.

Mots-clés: Potentiel Chimique, Transport, Sol Hygroscopique; Teneur en Eau

* Corresponding author : Samuel Ouoba ; E-mail : samuel_ouoba@yahoo.fr

List of Symbols

\tilde{A}_v : Thermodynamic force responsible of state change of water
 a_w : Water activity
 D_{va} : Diffusion coefficient of the soil
 g : Intensity of gravitational force
 \vec{J}_v : Diffusion flux of vapor phase of water
 K_{ns} : Coefficient of permeability of soil
 K_{sat} : Saturated permeability of soil
 L : Evaporation coefficient of water
 M_e : Molar mass of water
 n_a : Moles number of air
 n_p : Total number of volume increments
 \vec{P}_e : Pressure in the liquid phase of water
 P_{geq}^i : Equilibrium vapor pressure of gas
 P_{veq} : Equilibrium vapor pressure of water
 P_{vsat} : Saturation vapor pressure of water
 P_v : Vapor pressure
 P^0 : Reference pressure
 T : Temperature
 R : Constant of ideal gas
 RH : Relative humidity
 \vec{v}_e : Water velocity
 V_0 : Initial volume of gaseous phase
 w : Water content
 w_r : Residual water content
 w_{sat} : Saturated water content
 λ : Characteristic parameter of soil
 ρ_s : Real density of soil
 ρ_s^* : Apparent density of soil
 ρ_v : Volumic density of vapor phase of water
 $\hat{\rho}_e$: Evaporation flux of liquid phase of water
 $\hat{\rho}_v$: Evaporation flux of vapor phase of water
 ΔV^i : Volume increments
 μ_v : Chemical potential of vapor phase of water
 μ_e : Chemical potential of liquid phase of water
 μ_v^0 : Reference value of the chemical potential depending of temperature

1. Introduction

In porous media, able to contain water in particular the soil, the chemical potential is an essential parameter which can be used to describe the effects of the medium on water ^[1]. This fundamental thermodynamic function is rarely used in soil mechanics because many other parameters directly related to the experience such as the capillary potential and the relative humidity are sometime preferred.

However, the chemical potential is a fundamental function directly deduced from the principles of thermodynamics such as temperature ^[2] and there are many advantages to use it in soil mechanics. Also, physical and mathematical approaches can be applied to establish a relation between physics and chemistry. The chemical potential can be compared to energy of chemical interactions of the species with the medium. It is deduced from the second principle of thermodynamic ^[3] saying that during a natural isotherm transformation, all the chemical species are moving from the regions of high chemical potential to low chemical potential. We can then consider the chemical potential as an important parameter to describe mass transport in a system such as temperature allows describing heat transfer ^[1]. The main problem to use the chemical potential is related to the difficulties for its experimental measurement. However it can be used in many domains such as water transport in soil, the remediation of soil pollution, the mineral nutrition of plants and the storage of carbon dioxide (CO₂) ^[1]. The chemical potential has been introduced for the first time by Gibbs in 1875 to study some systems with variable compositions ^[3]. This parameter will be successfully used by other searchers to describe the thermodynamic state of water in soil ^[4-7]. Results of previous works have compared the chemical potential as an energy to provide during an adiabatic reversible transformation to extract an unit mass of water from the soil ^[2,6]. Basing on this definition, the chemical potential can be used not only in the soil but also in many other complex media. A comparison of different values of chemical potential of water obtained by ^[8,9] on two different soils, a silty clay soil and a sandy soil, shows that chemical potential of sandy soil is lower than chemical potential of silty clay soil. These results indicate that extraction of water requires less energy for sandy soil than for silty clay soil. In other words, water is less retained in sandy soil than in silty clay soil.

In this manuscript we propose to highlight the importance of chemical potential in the description of water transport in soil. Considering its thermodynamic definition, the concept of chemical potential will be used for all the range of water content to characterize the thermodynamic state of water in the soil in relation with transport. Indeed, this thermodynamic quantity allows establishing a relation between transport phenomena and the evaporation coefficient deduced from the second principle of thermodynamic ^[1].

The theory we adopted in this work consider the gradient of chemical potential between liquid and vapor as responsible of state change of water. When the thermodynamic state tends to equilibrium, the law of change of state of water can be expressed by:

$$\hat{\rho}_e = L \frac{\mu_e - \mu_v}{T} \quad (1)$$

Considering that the vapor phase of water behaves as an ideal gas, its chemical potential is given by [10-12].

$$\mu_v = \mu_v^0(T) + \frac{RT}{M_e} \ln \left(\frac{P_v}{P^0} \right) \quad (2)$$

The phase change is endothermic phenomenon. It is accompanied by a temperature drop at the interface and therefore cannot be considered isothermal. Thus, we cannot consider (at equilibrium) that there is equality between the chemical potentials of the liquid and vapor. So, in order to assess the chemical potential of the liquid we consider here the method proposed by [2] establishing a relation between the chemical potential of the liquid and the internal variables ζ_i :

$$\mu_e = \mu_e(\zeta_i) \quad (3)$$

The variables ζ_i are mainly temperature and liquid composition.

Taking into account **Equations (2) and (3) Equation (1)** becomes:

$$\hat{\rho}_e = -L \left[\tilde{A}_v + \frac{R}{M_e} \ln \left(\frac{P_v}{P^0} \right) \right] \quad (4)$$

Where

$$\tilde{A}_v = \frac{1}{T} [\mu_v^0(T) - \mu_e(\zeta_i)] \quad (5)$$

And **Equation (4)** becomes:

$$\hat{\rho}_e = -L \frac{R}{M_e} \ln \left(\frac{P_v}{P_{veq}} \right) \quad (6)$$

In **Equations (6)**, L depends on the water content (w), temperature (T) and the vapor pressure (P_v).

When water content tends to zero, the saturation vapor pressure tends to zero and chemical potential tends to infinity. For porous media with a slightly deformable solid phase, water content does not exceed the saturation value w_{sat} . If for this value, the properties of water contained in the medium are the same that these of free water, the chemical potential of water tends to zero when water content tends to saturation value w_{sat} .

The desorption isotherm establishes the relation between water content of the medium and the relative humidity (RH) of air [13].

$$RH = \frac{P_{veq}}{P_{vsat}(T)} \quad (7)$$

2. Basic Equations for Water Transport in Soil

To establish the equations of water transport in soil, we adopt the approach used by [14] concerning transport of Volatile Organic Compounds (VOCs).

Transport equation of liquid

In soil, mechanism governing the transport of water in liquid phase is the filtration because there is no diffusion in a pure compound and the following equation is obtained for water in liquid phase:

$$\frac{\partial \rho_e}{\partial t} + \underbrace{\overrightarrow{grad}(\rho_e \vec{v}_e)}_{\text{term of diffusion}} = \underbrace{\hat{\rho}_e}_{\text{term source/well}} \quad (8)$$

Where

$$\rho_e \vec{v}_e = -\frac{K_{ns}}{g} \left(\overrightarrow{grad}(\vec{P}_e + \rho_e \vec{g}) \right) \quad (9)$$

With

$$K_{ns} = K_{sat} \left(\frac{w - w_r}{w_{sat} - w_r} \right)^\lambda \quad (10)$$

Where λ depends on soil characteristics. For the soil used in this paper $\lambda = 5$.

Transport equation of vapor

The permeability of soil to a gas phase is very high and the filtration of gas phase is almost instantaneously what leads to a zero pressure gradient in the gas phase. Therefore the only mechanism responsible to the transport of vapor is the diffusion and we can obtain:

$$\frac{\partial \rho_v}{\partial t} + \underbrace{\overrightarrow{grad}(\vec{J}_v)}_{\text{term of diffusion}} = \underbrace{\hat{\rho}_v}_{\text{term source/well}} \quad (11)$$

Where \vec{J}_v is given by:

$$\vec{J}_v = -D_{va} \frac{M_e}{RT} \overrightarrow{grad}(\vec{P}_v) \quad (12)$$

We can show that $\hat{\rho}_v = -\hat{\rho}_e$ because evaporated water becomes vapor phase while the condensed water vapor becomes liquid.

Assuming that temperature is constant and that no change is occurs in the composition of the liquid because of chemical reactions accordance to the experimental conditions considered in this study,

the evaporation flux of water is given by **Equation (6)**:

Many results of the literature about the evaporation coefficient are available ^[15-21] but the recent searches have provided more satisfactory results ^[1,6].

3. Experimental Device and Procedure

The experimental device called activity-meter is shown on **Figure 1**. It is designed in the Laboratory of Mechanics and Civil Engineering of the University of Montpellier II. This device and the associated method have been patented ^[22] and can be used in many domains of science. But, in this manuscript we use it to determine water activity in soil for the calculation of the evaporation coefficient of water.

The device is composed of three parts which are:

1. A base: The base has a cylindrical shape of 46 mm of inner diameter able to receive a sample holder. It is pierced with a hole of 13 mm diameter to receive a pressure sensor for the measurement of gas pressure inside the device;
2. A sample holder: It has two O-rings on each of its bases to ensure a perfect seal;
3. A cylinder: Inside the cylinder slides a piston. A threaded rod driven by a crank allows achievement of volume increments.

These three parts are connected together by rods using nuts. The pressure sensor is connected to a signal conditioner and all the system is controlled by a computer for recording the data via a computer program (LABVIEW). **Table I** presents the characteristic dimensions of the experimental device.

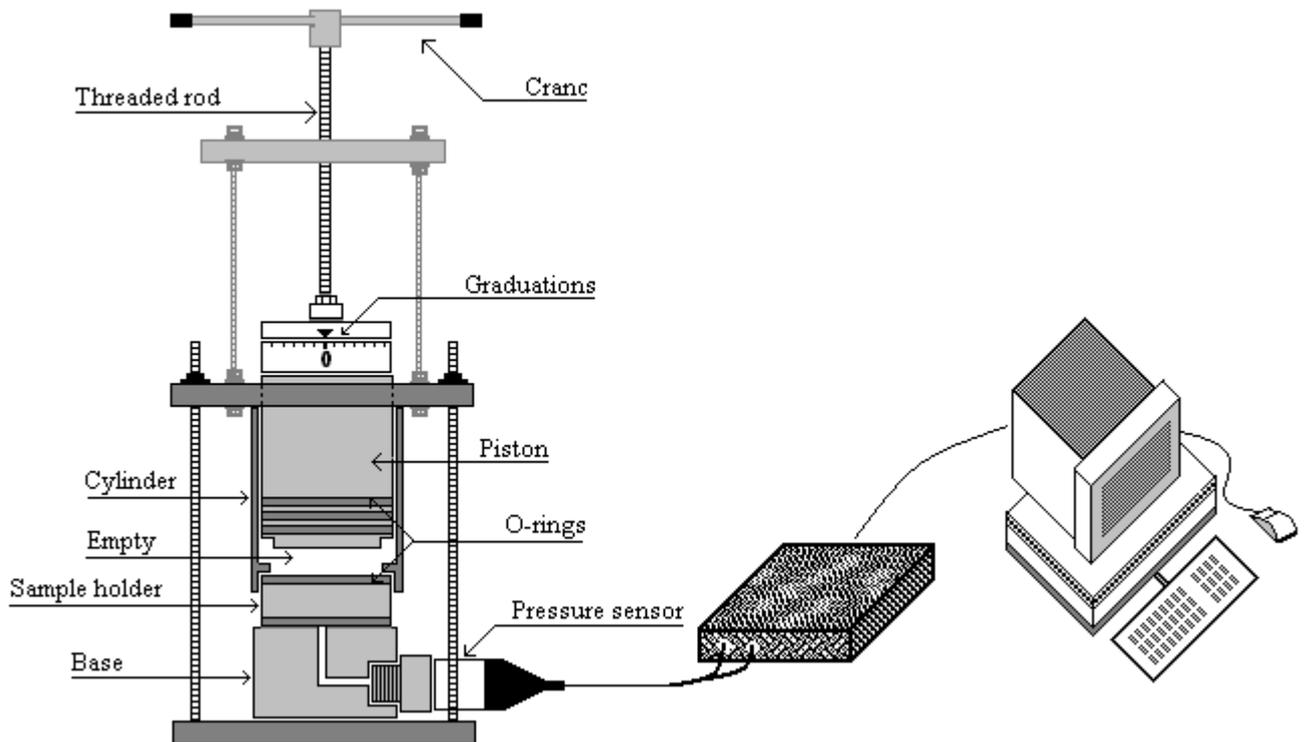


Figure 1: Schematic diagram of the activity-meter.

Table I: Dimensional Characteristics of the Experimental Device.

sample diameter /mm	32
sample height /mm	15
sample volume /cm ³	12.07
piston diameter /mm	44.5
piston displacement for one rotation /mm	1.75
volume increment for one rotation /cm ³	2.722

To determine water activity in soil i.e. the vapor pressure, the following procedure is required:

- Put the sample in the sample-holder of the device;
- Gather all the elements of the device (base, sample-holder and piston) using threaded rods and immerse all in a thermostated bath where the temperature is maintained at 30 °C;
- Achieve volume increments using the crank to create a disequilibrium as shown in **Figure 2**;
- Wait for the return of equilibrium and note the indication of the pressure sensor
- Apply the necessary volume increments to obtain the number of curves desired.

The variations of temperature and pressure in gas phase are recorded in **Figure 2**.

Exploitation of an experience

After an increment of volume, the pressure of the gas increases with time and stabilizes at an equilibrium value denoted P_{geq}^i given by the pressure sensor.

If we denote by ΔV^i the volume increments achieved during an experiment, and assuming that the ideal gas law can be applied to the air, the total pressure of the gas can be given by:

$$P_{\text{geq}}^i = P_{\text{veq}} + n_a \frac{RT}{V_0 + \sum_{i=1}^{n_p} \Delta V^i} \tag{13}$$

Where the moles number of air (n_a) is assumed to be constant because O-rings ensure a perfect seal. When the temperature is constant, P_{veq} only

depends on the water content and remains constant during the experiment ^[1, 23,24].

Analyzing **Equation (13)** and taking into account description above, the unknown parameters are P_{veq} , n_a and V_0 . To determine these three unknowns, three minimum equations are required i.e. three volume increments. But to improve experimental results, 6-8 volume increments are realized to obtain more equations than unknowns. A non-linear minimization program using the Levenberg-Marquardt method (Matlab) allows to determine the parameters ^[23,24].

The previous works ^[24] indicate that the total uncertainty of the device depends on two parameters according to the experimental procedure i.e. the number of volume increments (n_p) and the size of volume increments defined by the number of revolutions (n_r). However, the number of volume increments n_p allows increasing the precision of results more than the number of revolutions (n_r).

4. Results and Discussions

The experiments are realized on the columns of soil by constructing and compacting soil in PVC tubes using a hydraulic press. The columns of soil are then placed in a climatic chamber where temperature and relative humidity are controlled (**Figure 3**). The problem is one-dimensional and the initial data are defined by:

$$w(t = 0, z) = w_0$$

$$P_v(t = 0, z) = P_{\text{veq}}(w_0)$$

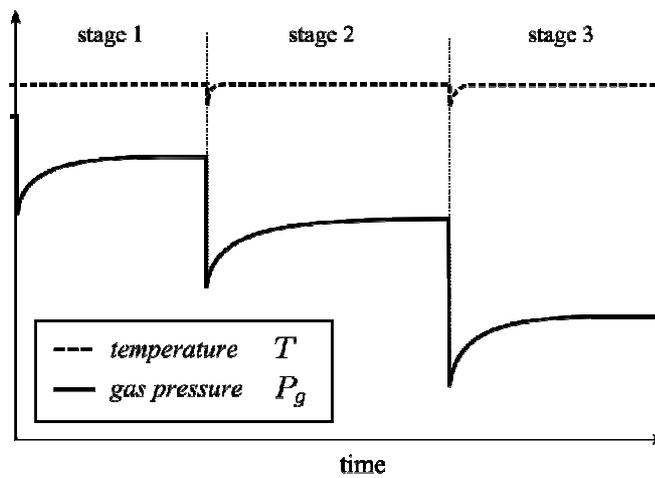


Figure 2: Schematic representation of temperature, T , and total gas pressure, P_g , evolutions during an experiment composed of 3 equilibrium stages.

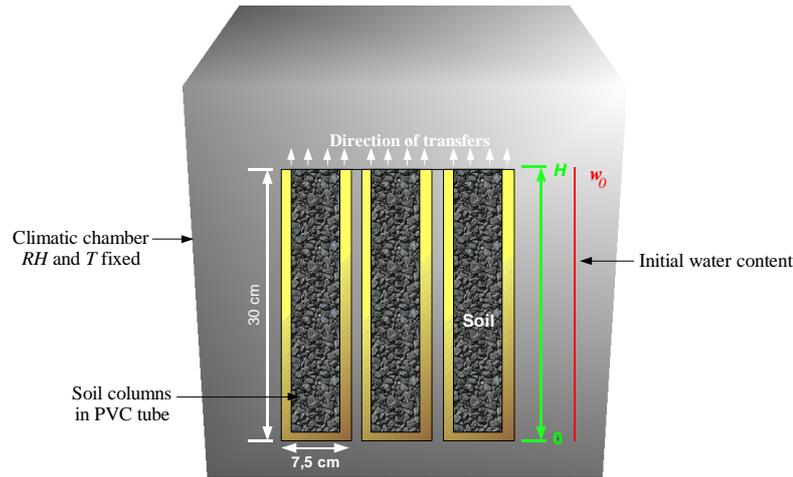


Figure 3: Climate chamber containing soil samples.

The physico-chemical properties of the soil are given in **Table II**. For each sample of soil, the initial water content, w_0 , is fixed and known. Therefore, the vapor pressure P_{veq} , is given by the following relation:

$$P_{veq} = a_w P_{vsat} \tag{14}$$

Where
$$a_w = 1 - \left[\ln \left(e + \left(\frac{w}{A} \right)^B \right) \right]^C$$

With $A = 2.8146 \cdot 10^{-3}$, $B = 2.8688$ and $C = -1.8906$.

The approach to determine the evaporation coefficient is based on the method established by [6] improved and used by [7,25].

This approach has allowed determining the evaporation coefficient of water as given by the following equation:

$$L = b_1 w^8 + b_2 w^7 + b_3 w^6 + b_4 w^5 + b_5 w^4 + b_6 w^3 + b_7 w^2 + b_8 w \tag{15}$$

Where

$$b_1 = -11274.38322; \quad b_2 = 5884.813541; \quad b_3 = -1147.817575; \quad b_4 = 109.5810347; \quad b_5 = -5.407196772; \\ b_6 = 0.1290527662; \quad b_7 = -0.12034229 \times 10^{-2}; \quad b_8 = 0.53366 \times 10^{-5}.$$

A numerical model has been developed using a decentered upstream method for discretization. This method previously used by [14] relies on the fact that the direction of water flow is a resultant of the

gravitational force and capillary force. The resolution of the nonlinear equations obtained after discretization uses an iterative method of Newton-Raphson.

A comparison between numerical model, taking into account chemical potential or not, and experiments for $w=6\%$ is shown on **Figures 4 to 9** where numerical curves are in full lines.

Figures 4, 5 and 6 are obtained for $RH=30\%$ and $T=30\text{ }^\circ\text{C}$. We can see on these Figures that chemical potential considered as a thermodynamic force allows a better description of water transport in the soil (red curve). This chemical potential is particularly important when water content of soil decreases as shown on **Figure 6**. **Figures 4, 5 and 6** are respectively obtained after 4 days, 23 days and 38 days. The experiments on the average water contents in the soil are respectively 4.29%, 2.85% and 1.77%. As we can see, the average water content in the soil decreases what increases the hygroscopic effects of soil which become more important for the low water contents. Under these conditions, the chemical potential of water adsorbed on soil particles is different than the chemical potential of free water contained in a saturated soil. This difference on chemical potential can cause the transport of water. Thus, all transport model which does not take into account the chemical potential could overestimate the transport by overestimating the flux of transport.

Table II : Physico-chemical properties of the Soil.

Parameters	$\rho_s \text{ (kg m}^3\text{)}$	$\rho_s^* \text{ (kg m}^3\text{)}$	$K_{sat} \text{ (m s}^{-1}\text{)}$	$w_{sat} \text{ (\%)}$	$w_r \text{ (\%)}$	Organic matter (%)	Organic carbon (%)	Total nitrogen (‰)	C/N
Values	1500	2600	$3 \cdot 10^{-5}$	28.9	1	0.28	0.16	0.10	16.83

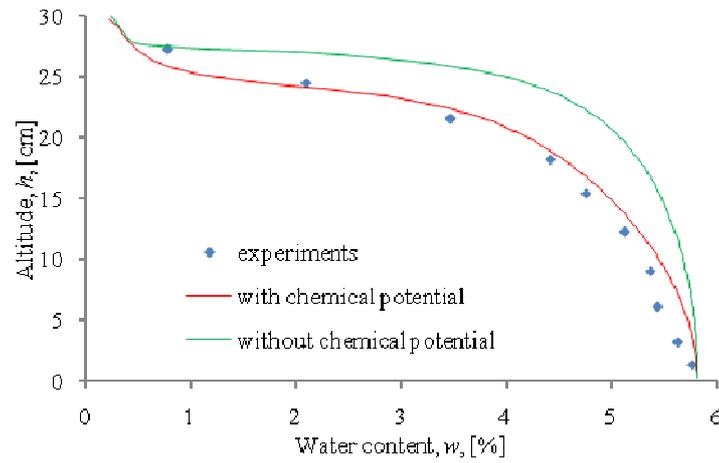


Figure 4: Water content profiles for $w_0=6\%$, $RH=30\%$, $T=30\text{ °C}$ and $t=4$ days.

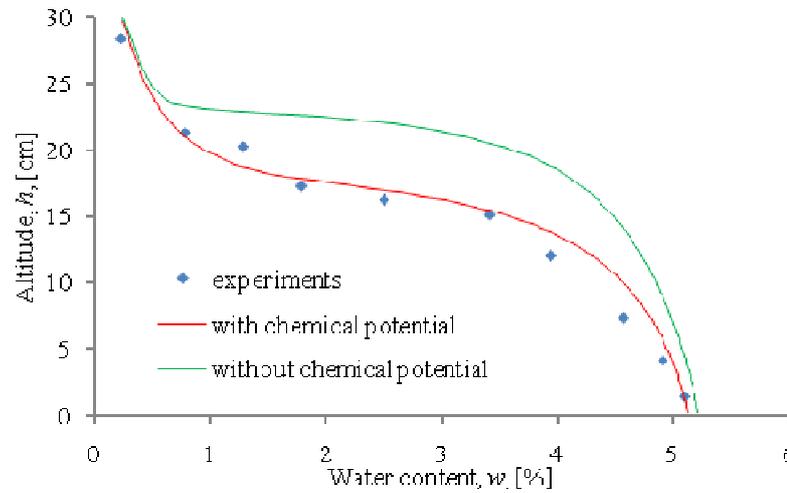


Figure 5: Water content profiles for $w_0=6\%$, $RH=30\%$, $T=30\text{ °C}$ and $t=23$ days.

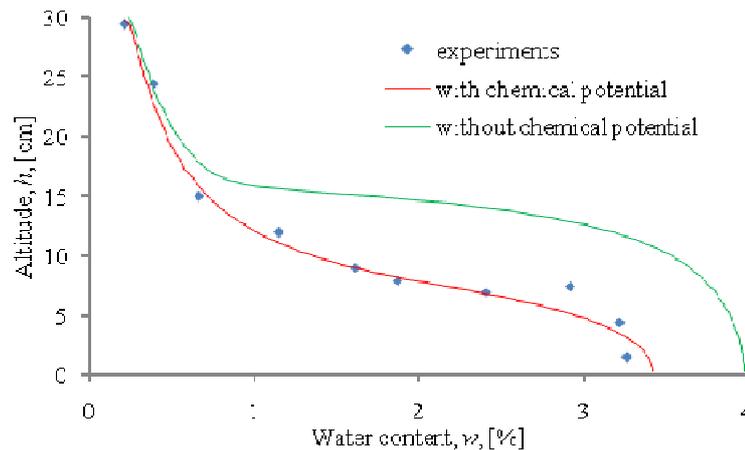


Figure 6: Water content profiles for $w_0=6\%$, $RH=30\%$, $T=30\text{ °C}$ and $t=38$ days.

The analyze of **Figures 7, 8 and 9** respectively obtained after 4 days, 16 days and 40 days for $RH=50\%$ and $T=30\text{ °C}$ allow to make the same conclusions than these done on **Figures 4, 5 and 6**. The gap increases with drying time between

experiments and numeric models which do not take into account the chemical potential. All these results highlight the importance of chemical potential as a parameter to allowing describing the mechanisms of transport of water in a hygroscopic soil.

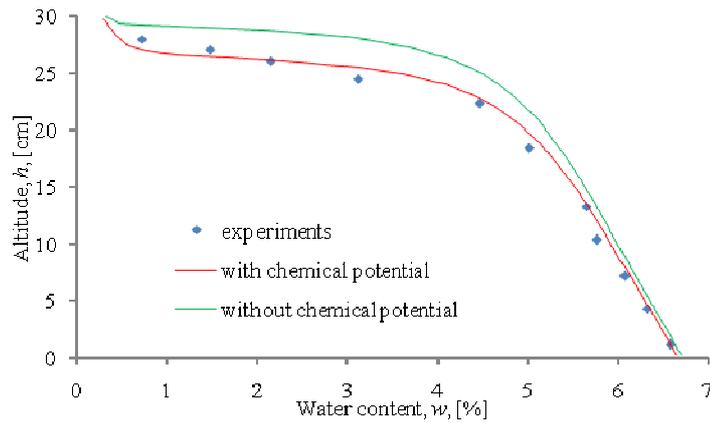


Figure 7: Water content profiles for $w_0=6\%$, $RH=50\%$, $T=30\text{ °C}$ and $t=4$ days.

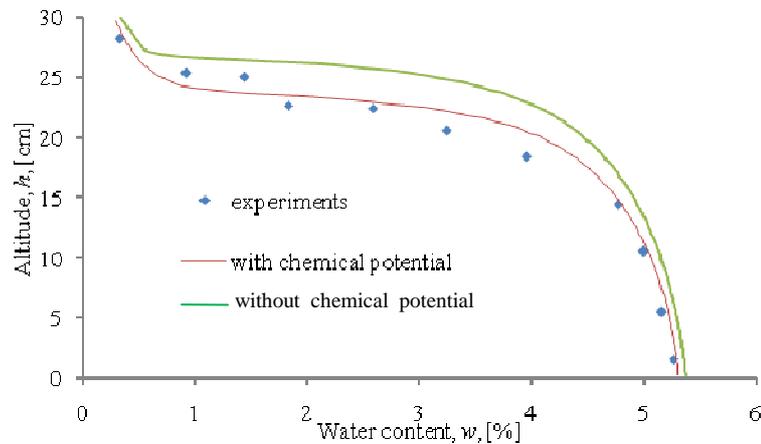


Figure 8: Water content profiles for $w_0=6\%$, $RH=50\%$, $T=30\text{ °C}$ and $t=16$ days.

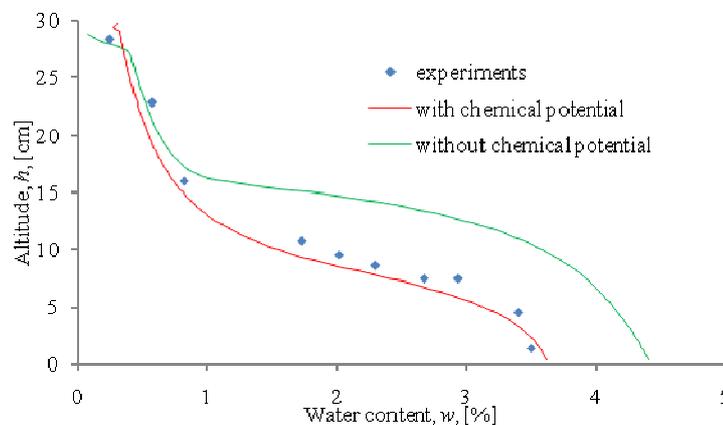


Figure 9: Water content profiles for $w_0=6\%$, $RH=50\%$, $T=30\text{ °C}$ and $t=40$ days.

Some supplementary experiments have been realized for $w=8\%$ and $RH=30\%$ and have been compared to numerical results. **Figure 10** is obtained after 6 days of drying and the average water content is 5.18%. Both the models allow obtaining satisfactory results. The role of the chemical potential on water transport is less important. However, after 49 days of drying as shown in **Figure 11**, the average water content is 1.17% and tends to the residual water content ($w_r=1\%$) for what hygroscopic effects are more

important. Only the model taking into account the chemical potential is appropriate to describe water transport even the uncertainties are more important than these of **Figures 6** and **9**. When water content of soil tends to residual value, no capillarity or filtration mechanisms of water is possible. In this part of soil, other forces such as Van Der Waals forces can appear. The competition between these forces and the thermodynamic forces resulting of the chemical potential can modify the mechanisms of transport of water.

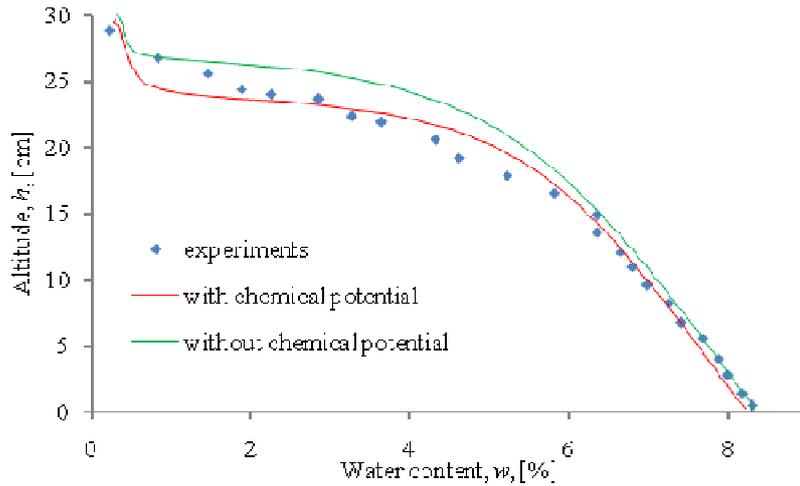


Figure 10 : Water content profiles for $w_0=8\%$, $RH=30\%$, $T=30\text{ °C}$ and $t=6$ days.

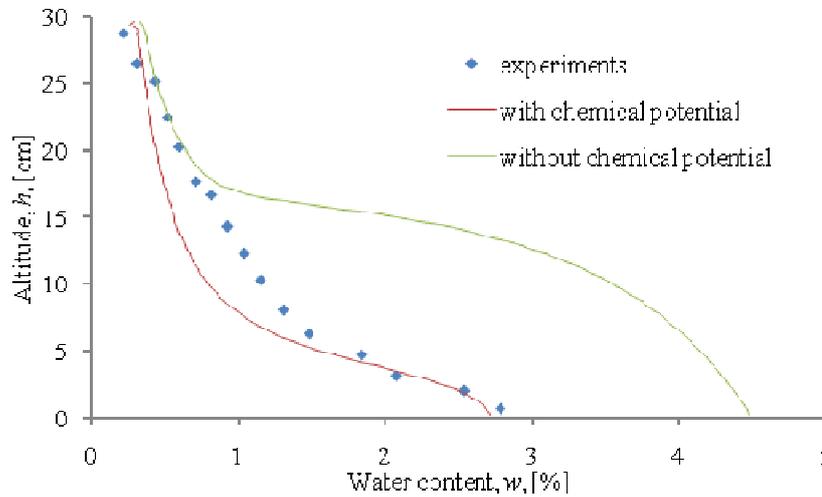


Figure 11: Water content profiles for $w_0=8\%$, $RH=30\%$, $T=30\text{ °C}$ and $t=49$ days.

5. Conclusion

The present work has allowed highlighting the importance of the chemical potential during the transport of water in soil. Experiments have been conducted on soil columns in a climatic chamber where temperature and relative humidity are fixed and known. A comparison between experiments and numerical results shows that in soil with low water content, any attempt to predict the mechanisms of water transport must take into account the chemical potential. Indeed, when water content tends to residual water content (1%), the discrepancy between experiments and the model which does not take into account the chemical potential can be very important. The relative error can reach or exceed 20 % and under these conditions the prediction model of water transport in a soil ignoring the

chemical potential of water cannot provide any satisfactory results. In a hygroscopic soil, water is strongly linked to the particles of soil so that its chemical potential tends to infinity making its extraction energy very high and the transport phenomena by evaporation become very slow.

However, the results show good agreement for the prediction model of water transport in the soil which takes into account the chemical potential. The errors on the overall results are less than 5% except in the soil where the average water content is 1.17. These errors may be due to the imperfection of the model or the experimental errors related to the process of the destruction of soil sample for the determination of water content.

The contribution of this work has enabled to highlight the importance of the chemical potential

on water transport in hygroscopic soil. Additional studies need to be extended on other soils having different physic-chemical characteristics in order to confirm the results of this work.

REFERENCES

- [1] A. Lozano, F. Cherblanc, B. Cousin and J.-C. Bénét, "Experimental study and modelling of the water phase change kinetics in soils," *European Journal of Soil Science*, Vol. 59, 2008, pp. 939–949.
- [2] J.-C. Bénét and P. Jouanna, "Non équilibre thermodynamique dans les milieux poreux non saturés avec changement de phase," *International Journal of Heat and Mass Transfer*, Vol. 26, 1983, pp 1585–1595, 1983.
- [3] E.A. Guggenheim, "Thermodynamique," *Dunod*, Paris, 1965.
- [4] T. Ruiz and J.-C. Bénét, "Phase Change in a Heterogeneous Medium: Comparison Between the Vaporisation of Water and Heptane in an Unsaturated Soil at Two Temperatures," *Transport in Porous Media*, Vol. 44, 2001, pp. 337–353.
- [5] A. Chamhari, "Transfert d'eau en sol aride avec changement de phase : water transport with phase change at low water content," *Comptes Rendus Mécanique*, Vol. 331, 2003, pp. 759–765.
- [6] J.-C. Bénét, A.-L. Lozano, F. Cherblanc and B. Cousin, "Phase Change of Water in a Hygroscopic Porous Medium. Phenomenological Relation and Experimental Analysis for Water in soil," *Journal of Non-Equilibrium Thermodynamic*, Vol. 34, 2009, pp. 97-117
- [7] F. Ouedraogo, F. Cherblanc, B. Naon and J.-C. Bénét, "Water transfer in soil at low water content. Is the local equilibrium assumption still appropriate?," *Journal of Hydrology*, Vol. 492, 2013, pp. 117 – 127.
- [8] A Lozano, "Etude expérimentale du changement de phase liquide/gaz dans un sol hygroscopique," Thèse de doctorat, Université Montpellier 2, 2007.
- [9] F. Ouedraogo, "Etude des transferts d'eau à l'interface sol-atmosphère : cas d'un sol du Burkina Faso à faible teneur en eau," Thèse de doctorat, Université Montpellier 2, 2008.
- [10] M. Hulin, N. Hulin and M. Veyssié, "Thermodynamique, cours et problèmes résolus," *Dunod*, Paris, 1994.
- [11] J.-C. Bénét and I. Mrani, "Utilisation des potentiels chimiques en mécanique des milieux complexes. Cas du transport de matière sous contrainte en milieu biphasique, élastique, hygroscopique," *Bulletin du Groupe Français de Mécanique des Matériaux*, Vol. 28, 2002, pp. 33–43.
- [12] M. Bond and M. Struchtrup, "Mean evaporation and condensation coefficients bond on energy dependent condensation probability," *Physical Review*, Vol. 70, 2004, pp. 061 – 605.
- [13] S. Salager, F. Jamin, M.S. El Youssefi and C. Saix, "Influence de la température sur la courbe de rétention d'eau de milieux poreux," *Comptes Rendus de Mécanique*, Vol. 334, 2006, pp. 393–398.
- [14] S. Ouoba, "Adsorption et transport d'un Composé Organique Volatile (COV) dans un sol hygroscopique : cas du trichloréthylène dans un sol aride," Thèse de doctorat, Université Montpellier 2, 2009.
- [15] T. Alty, "The maximum rate of evaporation of water," *Philosophical Magazine*, Vol. 15, 1933, pp. 82–103.
- [16] K.C.D. Hickman, "Maximum evaporation coefficient of water. Industrial and Engineering," *Chemistry Research*, Vol. 46, 1954, pp. 1442–1446.
- [17] H.K. Cammenga, "Evaporation mechanisms of liquids," Dans Kaldis Ed., éditeur, *Current Topics in Materials Science*. North-Holland Publishing Company, Amsterdam, 1980.
- [18] I.W. Eames, "The evaporation coefficient of water : a review," *International Journal of Heat and Mass Transfer*, Vol. 42, 1997, pp. 2963–2973.
- [19] D. Bedeaux and S. Kjelstrup, "Transfer coefficients for evaporation," *Physica A*, Vol. 270, 1999, pp. 413–426.
- [20] R. Marek and J. Straub, "Analysis of the evaporation coefficient and the condensation coefficient of water," *International Journal of Heat and Mass Transfer*, Vol. 44, 2001, pp. 39–53.
- [21] D. Bedeaux and S. Kjelstrup, "Irreversible thermodynamics. a tool to describe phase transitions far from global equilibrium," *Chemical Engineering Science*, Vol. 59, 2004, pp. 109–118.
- [22] J.-C. Bénét, B. Cousin, F. Cherblanc and S. Ouoba, "Device for measuring the activity of a liquid in a complex medium and associated method," United States Patent Application Publication, Pub. n° US 20120266663A1 (Oct. 25, 2012).
- [23] S. Ouoba, B. Cousin, F. Cherblanc and J.-C. Bénét, "Une méthode mécanique pour mesurer la pression de vapeur d'équilibre de l'eau dans un milieu complexe," *Comptes Rendus de Mécanique*, Vol. 338, 2010, pp. 113-119.
- [24] S. Ouoba, F. Cherblanc, B. Cousin and J.-C. Bénét, "A New Experimental Method to Determine the Sorption Isotherm of a Liquid in a Porous Medium," *Environmental Science & Technology*, Vol. 44, 2010, pp. 5915-5919.
- [25] S. Ouoba, T. Daho, F. Cherblanc, J. Kouliadiati and J.-C. Bénét, "A New Experimental Method to Determine the Evaporation Coefficient of Trichloroethylene (TCE) in an arid soil," *Transport in Porous Media*, 2014, DOI: 10.1007/s11242-014-0404-6