Modeling Brine Discharge into the Soil

Kais CHARFI[1] and ***M. J. Safi***[2]
[1]School Engineering of Tunis, B.P 37. 1002 Belvedere. TUNISIA
[2]School Engineering of Tunis, B.P 37. 1002 Belvedere. TUNISIA

ABSTRACT
To face the water shortage, many countries are recurring more and more to brackish water desalination. In the remote zones, R.O technique is usually used to desalt ground water at a salinity varying from 3 to 6 g/l. The desalt water is used to supply fresh water to the local population and to irrigate greenhouses, while the concentrated brine is released in the environment or injected into the ground without any "regulation". As a consequence the local agriculture will suffer and ground water quality will degrade. Therefore an efficient system is to find. As a first step towards the design of the system, a *numerical simulation* of brine discharge solutions are considered. The soil is simulated by *stratified porous layers* of different thickness and geological properties (porosity, permeability, etc…). The discharge is assumed to be at the surface in vertical direction (Fig.1). The transport phenomenon is described by *Navier-Stokes* and *concentration equations* including the *Darcy-Brinkman-Forcheimer* terms in the *streamline and vorticity* formulation (Ψ, Ω). The flow is considered two dimensional with an aspect ratio equal to 40. The set of coupling equations are solved using *Difference Finite Scheme* and A.D.I (*Alterning Direction Implicit*) technique. Numerical simulations were conducted for Reynolds number, Re = 5000, Sc = 770. The porosity and Darcy number values of the five porous layers are respectively (from top to bottom) equal to (ε_i; Da_i) = (0.8; 0.3210^{-7}), (0.7; 0.2810^{-7}), (0.6; 0.2410^{-7}), (0.5; 0.210^{-7}) and (0.4; 0.1610^{-7}) and (ε; Da) = (0.576; 0.230410^{-7}).

The results were presented in stream and iso-concentration lines. It was found that considering only one equivalent layer in steal of five ones allows good results.

INTRODUCTION
The mechanism of flow transport and concentration becomes strongly coupled and the prediction of its behavior can be obtained, often, only by numerical way. In this direction, Christophe Filder (2001) have been studied numerically the behaviour of a panache resulting from an injection located in a heterogeneous vertical porous medium made up of two superimposed layers of the same thickness and different permeabilities. This study shows that the propagation of the aqueous solution is characterized by the presence of two dissymetries convective cellular with a weak deformation of the panache in the direction of the initial ambient flow whatever the distribution of permeability and the type of injection. Our objective is to study flow and concentration transport through saturated soil including many stratified porous layers of different thickness and geological properties of various porosities and permeabilities by injection in concentration in top of the first porous layer and to assume that the bottom of the whole system is impermeable thus only vertical sides are permeable to the fluid.

PHYSICAL MODEL EQUATIONS
The system is represented by a stack of layers with different interface boundary layers. The flow in such a configuration is three dimensional and need parallel computers for real study.
As a first step, we make the following assumptions (which could in fact be realistic):
(1) The layers are homogenous but different each from the other (2) The soil is 20 times larger than the height (3) The bottom and the surface are non permeable (4) The brine at high

concentration is still considered as Newtonian fluid (5) Geological layers are represented by porous media that we assume isotropic. With these assumptions, the flow could be considered two dimensional and *Boussinesq approximation* is valid. Hence the transfer phenomenon is described by *Navier-Stokes* and concentration equations including the *Darcy-Brinkman-Forchheimer* formulation. To reduce the number of unknowns and overcome the resolution of the pressure equation, the streamline and vorticity formulation is used.
The consequent set of equations is:

$$\nabla^2 \Psi = \Omega \tag{1}$$

$$\frac{1}{\varepsilon}\frac{\partial \Omega}{\partial t}+\frac{1}{\varepsilon^2}\left(\frac{\partial u\Omega}{\partial x}+\frac{\partial v\Omega}{\partial y}\right)=-\underbrace{\frac{\Omega}{\mathrm{Re}\,Da}}_{\text{Darcy Term}}+\overbrace{\frac{(1+2.5\varepsilon)\nabla^2\Omega}{\mathrm{Re}}}^{\text{Brinkman term}}+\underbrace{\frac{b}{Da^{1/2}}\left(\frac{\partial |u| v}{\partial x}-\frac{\partial |u| u}{\partial y}\right)}_{\text{Forchheimer term}}-R_i\frac{\partial C}{\partial x} \tag{2}$$

$$\varepsilon\frac{\partial C}{\partial t}+\left(\frac{\partial uC}{\partial x}+\frac{\partial vC}{\partial y}\right)=\frac{\varepsilon\nabla^2 C}{\tau\,\mathrm{Re}\,Sc} \tag{3}$$

These equations have been non-dimensionnelized by defining:

$$(u,v)=\left(\frac{U^*}{V_0},\frac{V^*}{V_0}\right),\ (x,y)=\left(\frac{X^*}{H},\frac{Y^*}{H}\right),\ C=\frac{C^*-C_2^*}{\Delta C_{ref}},\ t=\frac{t^*}{t_0},\ t_0=\frac{H}{V_1^*}\ \text{and}\ u=-\frac{\partial\Psi}{\partial y},\ v=\frac{\partial\Psi}{\partial x},\ \Omega=\frac{\partial v}{\partial x}-\frac{\partial u}{\partial y}$$

It results that the flow depends on the *dimensionless parameters*:

Reynolds number: $\mathrm{Re}=\frac{V_0 H}{\upsilon}$; Grashof number: $Gr=\frac{g\alpha\Delta C^*_{ref}H^3}{\upsilon^2}$;

Richardson number: $R_i=\frac{Gr}{\mathrm{Re}^2}$; Schmidt number: $Sc=\frac{\upsilon}{D}$;

Darcy number: $Da=\frac{K}{H^2}$; $Rv=\frac{\upsilon_e}{\upsilon}$.

Each porous layer is characterized by its porosity ε and tortuosity $\tau = 1$. b is the Forchheimer coefficient given by the following expression: $0.55\sqrt{Da}$ (Hwa-Chong 1999). The solving domain is reduced to a rectangular cavity as shown in Fig 1. The boundary conditions are defined in the following way: all the walls are considered rigid and impermeable except at entry and exit where flow is considered parallel.

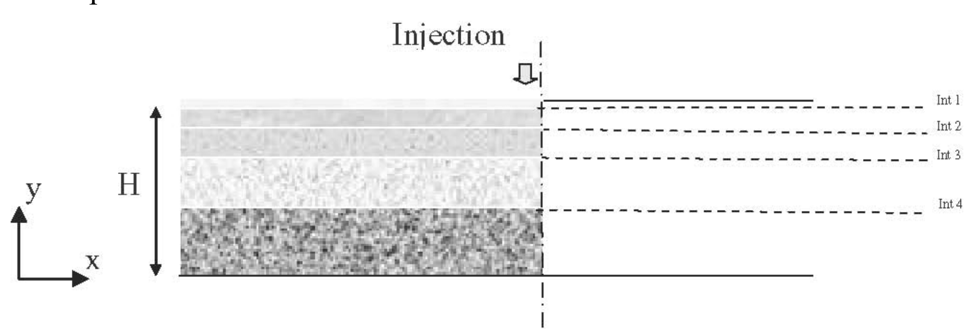

Fig.1 Physical Model

NUMERICAL METHOD

The set of coupling equations (1-3) are solved using a compact *Hermetian method* where the function and its first and second derivates are considered as unknowns. This method allows to reach a good accuracy: fourth order O (h^4) for Ψ and second order O (h^2) for, ω, T and C. The whole components of the system are represented by only one domain of resolution instead considering *multi-domain approach* but using *non regular discretization*. The A.D.I (*Alternate Direction Implicit*) technique is used to integrate the *parabolic equations* and is well described in the literature and has been widely used for *natural convection* and *recirculation zones* (M.J.SAFI 1994). This procedure has the advantage that the resulting *tridiagonal matrix* instead of a matrix with five occupied diagonals can easily be solved by *factorization algorithm*. The numerical study was carried out in a rectangular field with a grid of 1001x51 nodes. In order to achieve real time simulations to ensure *numerical stability* and good *convergence* and the set of equations was solved in *transient regime* using small time steps. The flow was simulated for 7 days, consequently time calculation using *Pentium 4 with 1 Go*, was very long. Two types of results are presented: quantitative information contour plots of concentration and steam function at different physical times.

RESULTS

Numerical simulations were investigated for a rectangular cavity with 5 m deep and 200 m large hence the aspect ratio is equal to 40. The five layers heights are respectively (from top to bottom): h_1 = 0.6 m, h_2 = 0.8 m, h_3 = 1 m, h_4 = 1.2 m, h_5 = 1.4 m. Due to the symmetry of the geometry only the mid-domain is considered so the injection brine is located at the top corner and the exit was set along the horizontal boundaries. A flow rate of brackish water equal to $1m^3/h$ and conversion rate of 40% was considered. The dimensionless parameters values are: Reynolds number Re = 5000, and Sc = 770.

Five Stratified layers

The characteristics of the five porous layers are respectively taken as follows (from top to bottom): Layer 1: 6 meshes, $\varepsilon_1 = 0.8$, $Da_1 = 0.3210^{-7}$, Layer 2: 8 meshes, $\varepsilon_2 = 0.7$, $Da_2 = 0.2810^{-7}$, Layer 3: 10 meshes, $\varepsilon_3 = 0.6$, $Da_3 = 0.2410^{-7}$, Layer 4: 12 meshes, $\varepsilon_3 = 0.5$, $Da_3 = 0.210^{-7}$, Layer 5: 16 meshes, $\varepsilon_3 = 0.4$, $Da_3 = 0.1610^{-7}$. The results of simulation (Fig.2) show that:

- At the beginning of calculation, a *vortex* appears at the entry. The *flow* seems to be *laminar* in the rest of the cavity. *Diffusion of the concentration* is also limited to the vicinity to the entry. At the first step, only the entry influences the flow.

- Later, only one cell occupies the whole medium, with a maximum at the exit. Consequently the concentration is realised in the whole cavity. *Iso-concentration lines* are vertical segments. This indicates that the *diffusion* is dominating with to respect the *convection*. During this second step, the flow is strongly influenced by the exit. In this study the *interfaces* have no influence on the containing of C.

Only one equivalent layer

Here, we consider only one layer whose thickness is the sum of 5 layers thicknesses and whose thermo-physical propertiesis defined as:

$$\Phi = \frac{1}{N}\sum_{l=1} \eta \Phi_l \qquad (4)$$

With η: number of nodes in layer l, l: A number of layers, N: Numbers of total nodes in the medium. Thus this equivalent layer will have as properties: $\varepsilon = 0.576$ and $Da = 0.230410^{-7}$. Figure 3, illustrates the results obtained with only one equivalent layer. The flow is characterized by a *recirculation zone* which evolves in the x direction. This is due to the fact the only exit region was fitted at the end of x direction (boundary condition). The comparison of the two results at the same time indicates: (a) At the beginning of the injection, the phenomena are similar but the equivalent layer presents a perceptible *dephasing time* in the *streamlines* and the *Iso-concentrations* which are still located near the injection. (b) After a sufficiently long time (7days) *the recirculation zones* are very comparable with a maximum close to the exit.

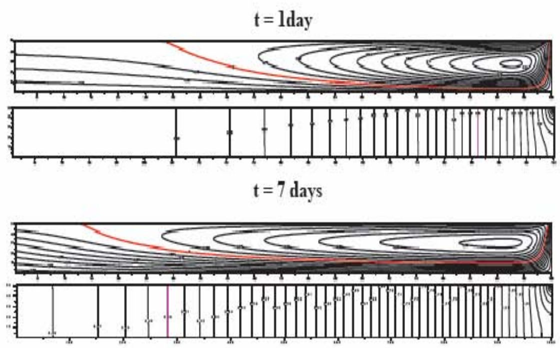

Fig.2 Temporal evolution of the Streamlines and the Iso-concentrations (Five stratified layers)

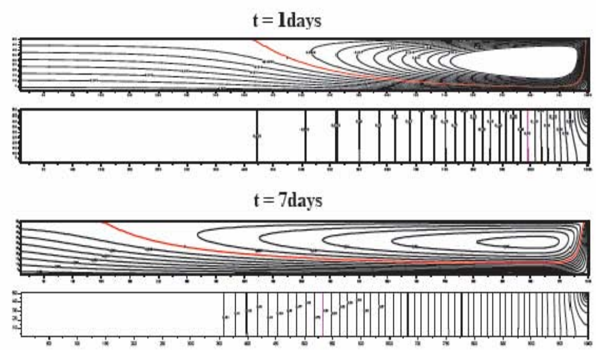

Fig. 3 Temporal evolution of the Streamlines and the Iso-concentrations (Only one equivalent layer)

The *numerical simulation* of the transport of concentration and momentum in five saturated porous layers has been investigated numerically with a new approach which consists of taking the whole components like only one field. This has the advantage to overcome the conditions at interfaces which are generally unknown. *The numerical simulation*, allowed us to calculate the temporal evolution of *concentration* and *streamlines fields*. In this study for Re up to 5000, the recirculation zone made only accelerate the *diffusion* without bringing the flow to be governed by *convection*. The simulation of five layers by only one equivalent layer proved to be acceptable from the *dynamic* point of view but an improvement of *thermal modelling* is desirable.

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Contact Information: M. J. Safi, School Engineering of Tunis, B.P 37. 1002 Belvedere. TUNISIA,
Phone: 21697661554 ; Fax: 216872729, Email: Mohamed.safi@enit.rnu.tn