Simulation of Water Movement in Rockwool Slabs Used as Growing Media

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Keywords: simulation, rockwool slabs, water movement, CFD, sweet pepper, closed systems, irrigation, greenhouse

Abstract
Determination of the dynamics of water and nutrients in substrates is important because it allows for adjustment of the nutrient and water supply to plant needs during successive crop cycles. In this study, we focus on the movement of water in rockwool slabs used as growing substrates. Utilising the transport equation, root absorption is described by an experimentally determined sink term. Commercial Computer Fluid Dynamics (CFD) software was used to solve numerically in two-dimensions the equations of water movement. However, as the Richard’s equation describing the water movements in the substrate is quite different from the Navier Stokes equations used by the CFD, significant modifications of the standard transport equations were required. The numerical results were compared with experimental results and a sensitivity analysis was performed with respect to various physical parameters of the substrate. Based on this study, an alternative substrate design better adapted to closed systems was proposed.

INTRODUCTION
Physical and chemical properties of artificial growing media have recently received particular attention because they greatly influence the water and nutrient balances at root level and affect recycling of the nutrient solution. Rockwool offers the opportunity to deliver water at low suction in a smaller volume, but its hydraulic properties must first be determined. The need to avoid ion accumulation in the root zone by using high drainage rates (>30%) causes pollution which can be reduced by recycling the nutrient solution. However, in order to avoid any change in the composition of this recycled solution, it is necessary to better match solution delivery with crop consumption, to avoid drying and saturation episodes which hinder root absorption. An accurate model of the system is therefore needed. 2D modelling of water without the same water uptake model has been carried out before (Heinen, 1997; Heinen and de Willigen, 1999). The water transfer in the substrate was simulated by applying the Richard’s equation to the substrate physics. Water transfers in two types of Grodan® rockwool (Floriculture and Expert) (Grodan®) were simulated for a sweet pepper crop and compared with experimental results. Once validated, the model was used for simulation studies aimed at improving substrate dynamics.

MATERIALS AND METHODS
The geometry of the growing medium, the position of the drippers and the drainage slit are shown in Figure 1. A slope about 2% is given to the substrate.

Theory
1. Water Movement. Water movement in a porous medium satisfies the conservation equation of matter and for an incompressible fluid in a rigid porous media, the combination of this equation and Darcy’s equation is described by the Richard’s equation for a porous unsaturated medium:

\[ C(h) \frac{\partial h}{\partial t} = \nabla \cdot [K(h) \nabla h] - \frac{\partial K(h)}{\partial z} - Sw \]  

(1)
Where \( h \) is the suction, the gravitational head \( z \) is assumed to be positive downward, \( \theta \) is the volumetric water content, \( S_{w} \) is the sink term corresponding to the water absorbed by the plants, \( K(h) \) is the hydraulic conductivity of the medium and \( C(h) \) its differential water capacity, given by:

\[
C(h) = \frac{d \theta}{dh}
\]

(2)

Solving this equation requires determination of the system boundary conditions, its initial conditions together with the values of the hydraulic conductivity, differential water capacity and sink terms. These various parameters were experimentally determined.

2. Boundary Conditions and Initial Condition for the Movement of Water. The Richards equation describing water movement was solved for the boundary and initial conditions described in figure 1. \( q_{y} \) was the vertical component of the volumetric flux density. The drain conditions used is that of a horizontal seepage face. In case the substrate was saturated (\( h = 0 \)) at the drain there will be outflow and as soon as the substrate at the drain location becomes unsaturated, the boundary condition will be that of no-flow (\( q_{y} = 0 \)).

3. Hydraulic Conductivity and Differential Water Capacity. Conductivity versus suction for both steady state and transient regimes in evaporation and humidification were experimentally determined for Floriculture and Expert rockwool slabs as illustrated by the conductivity of the two rockwool slab types versus suction shown in figures 2 and 3. The corresponding parameter values, fitted on the Mualem model (see Appendix 1) are given in table 1. These results were determined for regimes corresponding to different ranges of suction and they were compiled into a global curve with a wider validity domain (symbol M-VG total in Fig 2 & 3). The corresponding global parameters values are given in table 1. In the figures 2 and 3, no hysteresis can be shown, probably because it is hidden by a strong dispersion of the experimental data in the low suction range due to a high sensor sensibility (Tamari et al., 1993).

4. Sink Term. Root absorption by sweet pepper is considered as a sink for nutrient solution with the rate of absorption depending on both the root distribution and substrate suction (Brun et al., 2004). We have used formulas similar to that of Jinquan et al., (1999) to determine the rate of plant absorption. Knowing potential absorption (\( S_{\text{max}} \)), actual absorption is given by:

\[
S = \eta(h)S_{\text{max}} = \eta(h)\frac{T_{y}L_{\text{wd}}(z_{r})}{L_{r}}
\]

(3)

where the coefficient \( \eta(h) \) is experimentally determined (Longuenesse and Brun, 2004) according to substrate suction as shown in Figure 4:

\[
\eta(h) = \frac{S}{S_{\text{max}}}
\]

(4)

\( T_{y} \) is the atmospheric demand (experimentally determined) and \( L_{r} \) the height of the substrate. The term \( L_{\text{rd}}(z_{r}) = \frac{L_{r}(z_{r})}{\int L_{r}(z_{r})dz_{r}} \) represents the relative density of roots in the substrate determined from experiments (Longuenesse and Brun, 2004).
Numerical Analysis

Richard’s equation is a non-linear equation requiring the use of numerical methods to solve. This equation was implicitly solved using commercial Computer Dynamics software: CFD 2000®, based on a control volumes method.

"Customisation" of the CFD 2000 Software

For a given specie $\phi$, the standard fluids mechanics transport equation solved by the CFD software (CFD 2000) is:

$$\frac{\partial}{\partial t} (\rho \phi) + \frac{\partial}{\partial x} (\rho \phi v) = \frac{\partial}{\partial x} \left( r \frac{\partial \phi}{\partial x} \right) + S$$  \hspace{1cm} (5)

Where the terms I, II, III, and IV respectively represent the non stationary term, the convection term, the diffusion and the source terms. $\rho$ is the density and, in our case, its value is equal to unity, $r$ is the coefficient of diffusion and $S$ is the term source. For water movement described by the suction variable $h$, significant modification of Eq.1 are needed to correspond with the standard transport equation used by the software CFD 2000 (Eq.5). Equation (1) was therefore rewritten according to the form given below (Eq. 6) with a non stationary term, diffusion and source terms, the convective term being null:

$$\frac{\partial h}{\partial t} = \nabla [K(h) \nabla h] - \frac{\partial (k(h) \frac{\partial h}{\partial z})}{\partial z} - C(h) \frac{\partial h}{\partial t} + \frac{\partial h}{\partial t} - Sw$$  \hspace{1cm} (6)

RESULTS

After rearrangement of the basic equation, water movement in the substrate was determined by the numerical solution of the Richard’s equation using the CFD software. We have used the hydraulic properties (hydraulic conductivity: $K(h)$ and water content $\theta(h)$) determined for the two substrate types (respectively Expert® & Floriculture® of Grodan) and irrigation rate was set to 2 l/h (dripper value) on the surface equivalent of the cube of the planting surface (100 cm$^2$).

Validation

Numerical calculation was carried out with two rockwool types (Floriculture® and Expert®) for two irrigation frequencies: a high (every 0.3 mm) and a lower frequency (every 0.6 mm). Water dynamics in the substrate was simulated for one day in July (07/2002), characterised by 12 irrigations events for the high frequency regime and 7 irrigations events for the lower one. Iso suction areas of the slabs are represented with the same colours (saturated zones in red and dry zones in blue) for both the numerical and experimental results (Fig. 5). Similar computational and experimental results, with the same dynamic after watering, were obtained for both substrate types and the two irrigation regimes. We can also note that, after each daytime watering, we can observe a similar periodic moisture variation in the substrate.

Focusing on the distribution of water in the substrate at the end of an irrigation cycle for the Expert slab with low and high frequency and for the Floriculture slab with low frequency (Fig. 5), one can make the following remarks:
- for all treatments, the zone located at the top of the drainage slit is always very dry, with suction values higher than –10 cm. This zone is independent of the substrate physical properties, but depends mainly on the position of the drippers;
- the saturated zones (yellow and red colours in Fig. 5) are always situated in the lower part of the substrate and under the drippers;
- comparing the two rockwool slab types (Fig. 5), the saturated zones are much more important for Floriculture® (high density rockwool slab) than for Expert® (lower density);
- high frequency irrigation rate induces higher saturation conditions (see Expert in Fig. 5).

It was difficult to compare the computed and measured values of water content in the slab because the measured values correspond to an average based on the width of the
slab whereas the computed values correspond to the actual values in the plane of the slab section passing by the drainage slit. Experimentally and by simulation, however, similar dynamic tendencies in the behaviour of the slabs were observed including:

- an higher saturation for Floriculture® than for Expert® and,
- an higher saturation for the higher frequency irrigation rate.

**Optimisation of the Substrate Based on Simulation Studies**

The simulation and experimental results show that the zones with high water content (>90%) represent about the half of the entire slab volume for the Floriculture® slab, but only one third for the Expert® slab. This suggests the substrate could be improved by utilising two types of rockwool with different densities, so the density of each type has a direct effect on hydraulic conductivity of the composite and on the whole slab humidity. This “optimal” slab would be composed of high density rockwool (Floriculture® type) located in the upper quarter part and of lower density rockwool (Expert® type) in the bottom three-quarters of the slab.

The performance of this “optimal” composite slab type was simulated and after computation, we note (Fig. 6) that for the same conditions and irrigation regime as the Expert® slab type, the dry zone domain decreased and that the humid zones (>90%) occupied about 2/3 of the whole volume of the substrate compared to less than ¼ for the Expert® slab. The increase in the volume of the humid zone is particularly important by the end of the day because it allows for a better exploitation of the slab volume by the roots of the plant. However this situation must not be constant because the saturated zones must be periodically dried in order to prevent anoxia. This can be achieved at night time, when irrigation is stopped and substrate has dried before the first irrigation of the day.

Substrate water content distribution was therefore investigated at the end of the night, and just before the first irrigation, for both Floriculture rockwool slabs (low frequency irrigation), Expert rockwool slabs (low frequency irrigation), and also for the composite substrate (low and high frequency irrigation). For the three substrate types, simulation results (Fig. 7) highlight an absence of water stagnation (and of the consecutive risks of anoxia) in the lower parts of the substrate. Thanks to the different hydraulic properties of the rockwool used in the composite substrate, it allows maintenance of a greater substrate volume with high moisture content but without anoxia. Dynamics of water in the substrate, particularly drainage and water absorption by the roots of the plants are therefore improved.

**CONCLUSIONS**

Simulation of solution transfers in a rockwool slab with plant roots can be satisfactorily performed using the numerical methods of CFD software. This experimental and simulation study shows that both the physical substrate characteristics (particularly hydraulic conductivity) and watering frequency are crucial parameters, however root distribution is also a key factor, which needs further research. Simulation results allow sensitivity studies and testing optimised substrates which may be better adapted than conventional ones to recirculation of nutrients solutions. A composite slab was designed, which can keep higher water content in the upper part of the slab and a higher hydraulic conductivity in its lower part to get a more even distribution of solution and humidity along slab height, while keeping a higher drainage rate of the whole slab.

**ACKNOWLEDGMENTS**

"This project was carried out with financial support from the European Commission under the RTD programme "Quality of life and management of living resources" (project QLRT-1999-31301). It does not necessarily reflect the Commission's views and in no way anticipates its future policy in this area."
Literature Cited
CFD2000/STORM v 3.45, 1999. CFD systems. Pacific Sierra Corp., USA

APPENDIX 1

Hydraulic conductivity, water content and water capacity modelling.

The model of Mualem (Mualem, 1976) used to determine the hydraulic conductivity is:

\[ K(h) = K_s \left( \frac{(1 - (a|h|)^m)^{-1/m}}{(1 + (a|h|)^m)^{1 + 1/m}} \right), \quad h \leq 0 \]

\[ K_s \text{ is the conductivity at saturation and } m = 1 - 1/n. \]

The function of retention of water \( \theta(h) \) is given by van Genuchten (1980) as follows:

\[ S_r(h) = \frac{\theta(h) - \theta_r}{\theta_s - \theta_r} = \begin{cases} 1, & h \leq 0 \\ \left( \frac{1}{n} \right)^{1/m}, & h > 0 \end{cases} \]

The differential water capacity \( C(h) = d\theta / dh \) is deduced from the characteristic curve of water retention. It is given by the following equation (Heinen, 1997):

\[ C(h) = \begin{cases} \frac{(\theta_s - \theta_r)nmc}{(1 + (a|h|)^m)^{1 + 1/m}} \left( \frac{1}{n} \right)^{1/m}, & h \leq 0 \\ \theta_s - \theta_r, & h > 0 \end{cases} \]
Tables

Table 1. Parameters adjusted of hydraulic conductivity and water content.

<table>
<thead>
<tr>
<th>Adjustment parameters for the Conductivity: Floriculture</th>
<th>Adjustment parameters for the conductivity: Expert</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{sat}$ ( (m \ s^{-1}) )</td>
<td>$n$</td>
</tr>
<tr>
<td>Wind-Evaporation</td>
<td>0.00212</td>
</tr>
<tr>
<td>Wind Infiltration</td>
<td>0.00212</td>
</tr>
<tr>
<td>Drip Infiltrometer</td>
<td>0.00212</td>
</tr>
<tr>
<td>All data</td>
<td>0.00212</td>
</tr>
</tbody>
</table>

Adjustment parameters of the water content:  
- Floriculture
  - Sorption: $\theta_s$ = 0.7288, $\theta_r$ = 0.026, $Sorption$ = 0.5712, $Drying$ = 0.0192
  - Drying: $\theta_s$ = 0.975, $\theta_r$ = 0.0103, $Sorption$ = 0.983, $Drying$ = 0.0037

Figures

Fig. 1. Geometry of the growing media.
Fig. 2. Hydraulic conductivity of Floriculture.

Fig. 3. Hydraulic conductivity of Expert.
Fig. 4. Variation of the coefficient $\alpha(h)$ according to the suction value.

\[ \eta = 1 \text{ for } -0.05m \leq h \leq 0m \]
\[ \eta = 18h + 1.09 \text{ for } -0.10m \leq h \leq -0.05m \]
\[ \eta = 27.5h + 3.66 \text{ for } -0.12m \leq h \leq -0.10m \]
\[ \eta = 8h + 1.32 \text{ for } -0.15m \leq h \leq -0.12m \]
\[ \eta = 2.4h + 0.48 \text{ for } -0.20m \leq h \leq -0.15m \]
\[ \eta = 0 \text{ for } h < -0.20m \]

Fig. 5. Scenarios of distribution of water after an irrigation.
Fig. 6. Scenarios of simulation for wetting conditions and re-wetting.

Fig. 7. Variation of moisture for the two types of substrate at the end of the night.