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Water, vapour and heat transport in concrete cells for storing radioactive waste

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ABSTRACT

Water is collected from a drain situated at the centre of a concrete cell that stores radioactive waste at 'El Cabril', which is the low and intermediate level radioactive waste disposal facility of Spain. This indicates flow of water within the cell. 2D numerical models have been made in order to reproduce and understand the processes that take place inside the cell. Temperature and relative humidity measured by sensors in the cells and thermo-hydraulic parameters from laboratory test have been used. Results show that this phenomenon is caused by capillary rise from the phreatic level, evaporation and condensation within the cell produced by temperature gradients caused by seasonal temperature fluctuations outside. At the centre of the cell, flow of gas and convection also play a role. Three remedial actions have been studied that may avoid the leakage of water from the drain.

1. Introduction

It is known that concrete in constructions and buildings, can be damaged by exposure to variations of temperature and relative humidity and its service life reduced by processes involving water flow, heat transport, evaporation and condensation. Several studies investigating these processes have been reported. Bažant and Najjar (1972) studied analytically the dependence of the diffusivity on pore humidity, degree of hydration and temperature in concrete. Andrade et al. (1999) studied experimentally the effects of daily and seasonal variations of external temperature and relative humidity on concrete columns. Häupl et al. (1997) studied the interaction between heat transfer, gas and humidity in materials used in construction by means of numerical models. Lü (2002) developed a numerical model to predict the heat transfer and humidity in buildings, which has been tested experimentally. Liu et al. (2004) developed a method to solve condensation problems using numerical models and experimental data.

In soils evaporation is an important process too. Hence, also an extensive amount of literature exists on the coupled transport of water vapour, liquid water and heat in this type of medium (e.g.; Banimahd and Zand-Parsa, 2013; Bittelli et al., 2008; Gawin et al., 1995; Gran-Esforzado, 2015; Grifoll et al., 2005; Sakai et al., 2009). The heat transfer in non saturated porous materials under temperature gradients has also been studied analytically by Philip and De Vries (1957). In unsaturated porous media temperature gradients can cause diffusion of vapour with evaporation at the hot and condensation at the cold side. In theory, this process could saturate parts of the cold side. However, to our knowledge, vapour diffusion, due to temperature gradients, through an unsaturated part of the porous medium followed by condensation and water leakage at the edge of a completely saturated part has not been found in porous media, neither in concrete nor in soils.

Our study was motivated by the transport of water and heat in the radioactive waste facility of 'El Cabril', located in the south of Spain, where water is collected inside concrete cells storing the waste. In 'El Cabril' the low and intermediate level activity radioactive waste are stored. Firstly, the waste, which is a solid material, is stored in metal drums. Secondly, it is placed in concrete containers. When the containers are full, they are filled with mortar. Thirdly, the containers are placed in a concrete cell. When the cell is completely full it is sealed with a concrete slab on top. Finally, the outside is painted with a waterproof paint. In the future, when all the cells are full, the whole facility will be protected with a multilayer cover (Gran-Esforzado, 2015).

The first cell was sealed in 1992. From 2003 on, water is collected from a drain installed at the centre of each cell indicating flow of water within the cell. This occurred every year in summer and winter. Several hypotheses were suggested to explain this phenomenon. One of them was related to rainwater. However, there

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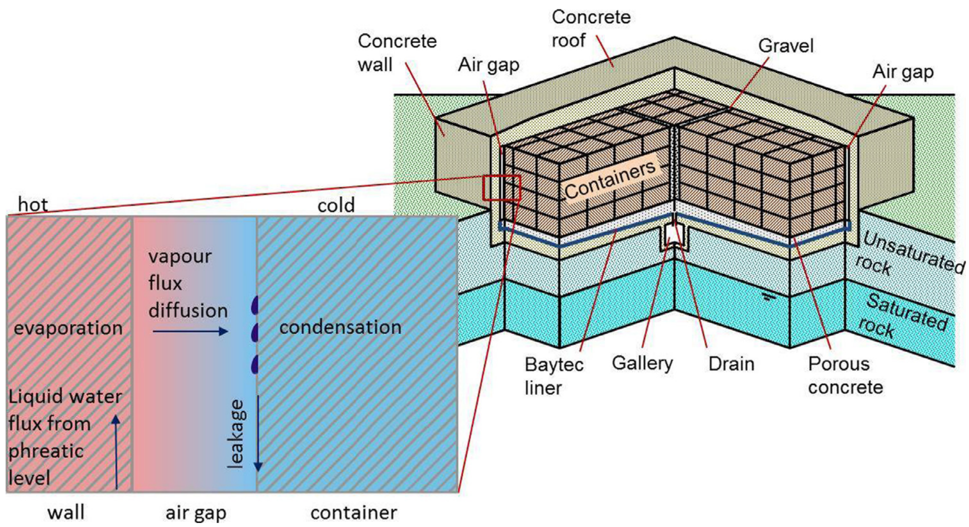

Fig. 1. Scheme of a concrete cell and conceptual model. Situation in summer: water ascends from the phreatic surface, evaporates at the hot side (wall of the cell), vapour diffuses through the air gap and water condensates at the cold side (wall of container).

is no correlation between rainfall and the periods of the collected water in the drain. Another one was the fact that water could infiltrate into the cell through the junctions of the concrete. However, this hypothesis cannot explain the quantity of collected water. Finally, the hypothesis proposed to explain this phenomenon consists of capillary rise from groundwater, evaporation and condensation within the cell, produced by temperature gradients caused by seasonal temperature fluctuations outside. A sum of several factors contributes to the phenomenon taking place. The aquifer is approximately 3 m below the base of the cell and is hydraulically connected to the walls of the cell, allowing a capillary rise. The concrete used to build the cells has a low intrinsic permeability and high capacity of retention. So it contains water available for evaporation. A gap of air exists between the wall of the cell and the containers, causing a sufficient temperature difference for vapour diffusion to occur.

A study has been reported where the phenomenon that takes place in ‘El Cabril’ is explained supported by numerical models (Zuloaga et al., 2006). Nevertheless, it did not take into account the real data of temperature and relative humidity measured in the cells. Moreover, it used thermo-hydraulic parameters from literature instead of parameters of the concrete to build the cells. Furthermore, results were also qualitative because it only considered the roof and one wall of the cell instead of simulating the temperature gradients in the whole cell.

The objective of this work is to study the processes that are taking place inside the cell by means of numerical models. To do so, we take into account the temperature and relative humidity measured by sensors placed inside and outside the cells. Also we used thermo-hydraulic parameters of the concrete used to build the cells. These parameters have been obtained from laboratory tests of the concrete (Villar et al., 2009) and thermo-hydraulic multiphase flow models of evaporation experiments (Chaparro et al., 2015). Moreover, we give some possible scenarios in order to remediable and avoid this problem.

2. Conceptual model

Fig. 1 displays a scheme of a concrete cell where the radioactive waste is stored, and the conceptual model that explains why water is collected in the drain. ’El Cabril’ has 28 cells, each one measuring 19.3 m by 23.8 m and can storing 1000 m^3 of waste. The cells are filled with concrete containers, of 2.20 m by 2.25 m. Each contains the drums with the radioactive waste. The cells have 4 zones with containers, each zone has 80 containers. The 4 zones are separated with gravel. The wall of the cell and the containers do not fit perfectly. Between them a small gap of air exists. At the base of the containers there is porous concrete underlain by a layer of baytec. Each cell has a drain at its center, which can be accessed through a gallery. This gallery connects all the cells in the platform. The cell is partly buried (3 m) into the underlying rock. The rest of it is exposed to the atmosphere with its temperature oscillations. The temperature outside the cell oscillates between 40 °C in summer and 5 °C in winter. The water table is about 4 m below the base of the cell.

The conceptual model considers that water can ascend from the phreatic level to the wall of the cell due to capillary rise through the unsaturated rock. In summer, the wall of the cell is hotter and the wall of the container is colder because the air gap acts as a thermal insulation. Thus, water can evaporate from the wall of the cell. Vapour diffuses through the air gap due to the temperature gradient between the wall of the cell and the wall of the container. Water condensates at the wall of the container because of its lower temperature. Consequently, condensed water runs off to the drain. In winter, the wall is colder and the container is hotter. Hence, water evaporates at the container and condenses at the wall. So, again water runs off to the drain. This only occurs in summer and winter because only then the temperature difference across the air gap is large enough to produce this phenomenon.

To understand and quantify these processes it is worthwhile to remember some basic psychrometric properties and relations. The saturated vapour pressure as a function of temperature can be expressed as:

$$P^{w}_{g,sat} = a \exp\left(\frac{-b}{T}\right) \tag{1}$$

Where T is the temperature in K, a and b are parameters which have values of 1.36075 × 10^{11} Pa and 5.2397 × 10^3 K, respectively (Olivella et al., 1996a). Suction can be related to the saturated and actual vapour pressure through Kelvin’s law.

$$RH = \frac{P^{w}_{g}}{P^{w}_{g,sat}} = \exp\left(\frac{-\psi M^{w}}{R\rho_l T}\right) \tag{2}$$

Where RH is relative humidity, P^{w}_{g} is the actual vapour pressure, ψ is the suction pressure ρ_l is the density of liquid water (1000 kg m^{-3}), R is the gas constant (8.314 J mol^{-1} K^{-1}) and M^{w} is the