Heat and mass transfer coefficient analysis during rock convective drying

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ABSTRACT. This paper presents some experimental investigations about convective drying of rocks. Cylindrical samples made of limestone are dried from one their bases submitted to an air flow, while the other surfaces are hermetically covered. All other factors being equal, the influence of two parameters is looked after: the cylinder height, equivalent to the volume/surface ratio of the samples, and the direction of the air flow. The tests are interpreted both from the drying curves and from the values of water and heat transfer coefficients.
Results first highlight that air flow incidence on the dried surface changes the kinetics and the transfer coefficient values. It can thus be supposed that the air flow direction would modify the thickness of the transfer limit layer at the surface and/or would make invalid the hypothesis of such a limit layer model for some flow configurations.
Besides, the volume/surface ratio is shown to be correlated to the evaporation flux on the constant drying phase, and thus to the transfer coefficients. Nonetheless, this link tends to disappear from sufficiently high values of the volume/surface ratio since, in this case, the transfer coefficients reach constant values. This effect, in addition to other observations made on the drying curves, well fits with the hypothesis of a hydraulically connected layer below the drying surface, which would maintain during the constant drying rate phase. In the present case, this layer would have a thickness of around 20 to 30 mm.

KEYWORDS: Convective drying, mass and heat transfer, rocks, kinetics

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1 Introduction

Hydric change in rocks affects their hydro-mechanical behaviour in many situations. For example, in the context of nuclear waste storage into deep and impermeable formations, it has been highlighted that clay rocks saturation is a guarantee of hermetic confinement since it prevents shrinkage cracks and makes possible self-sealing of fissures caused by stress redistribution around the underground gallery (Blümling 2007). In another way, the drying-imbibition cycles on building stones can lead to a severe alteration of the rock (Alves 1996). In both examples, rocks are submitted to a convective air flow, either natural one or artificial one (ventilation of the galleries). The well-known limit layer model can thus be used to interpret experimental results of drying and quantify the water and heat transfers (Fig.1).

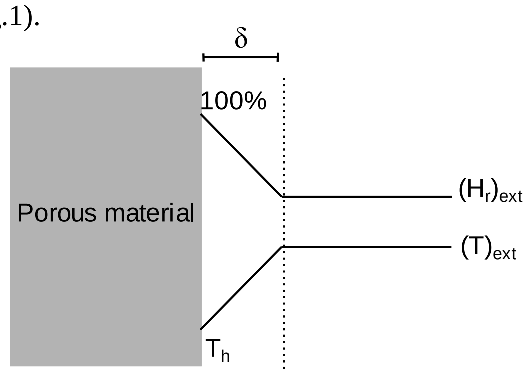

Fig. 1. Limit layer model of transfers for convective drying

This model expresses that, at the drying onset, the transfers take place on a thin layer around the surface, supposed to be initially covered by a water film, by a diffusional mechanism which depends on the external conditions. Heat transfer thus depends on the temperature difference between external temperature T_{ext} and humid temperature at the surface T_h, while vapour transfer is expressed as a function of either a relative humidity difference (Anagnostou 1995), a vapour pressure one (Zhongxuan et al. 2004) or a vapour density potential (Ben Nasrallah and Pere, 1988). The coefficients of proportionality between the transferred quantity and the driving potential are called transfer coefficients and a good estimation of them particularly matters for any numerical model. Although they are theoretically supposed to be constant for stationary phases of transfer (Luikov 1965), they are indeed observed to depend, even for the initial constant flow period, on various internal parameters such as the nature of the porous material (Van Braken 1980; Tournier 2001), or external ones as the velocity of the air flow (Anagnostou 1995, Gérard 2011). Actually, the variability of these parameters is not already fully understood.

In this context, the aim of this contribution is to experimentally determine, during rock convective drying, the influence of two factors on these coefficients. After a first section to present the material studied (a limestone) as well as the experimental campaign, the influence of a first factor is investigated: the volume/surface ratio of the dried samples. This ratio being somehow linked to the ratio between internal and external resistances for the transfers during the drying, a preliminary hypothesis can be that the transfer coefficients, theoretically independent from internal resistances, do not depend either on this parameter. In a second time, the configuration of the air flow related to the sample surface is investigated since, as said previously, the flow has a significant effect on the drying kinetics.

2 Materials and Methods

2.1 Limestone samples

The rock used in all experiments is a Campanian limestone from Lixhe (Belgium) characterized by a porosity between 42 and 44 %, a permeability of about 5.10^{-9} m/s and a global isotropy. 13 samples are bored in this material with a diameter *D*=18 mm and a variable height *H* between 7 and 40 mm. Samples are saturated between 87 and 92 % of the void volume by mean of a mere stay into a water bath during 3-4 days. This saturation corresponds to a water content *w* between 22 and 25% [kg/kg].

2.2 Convective microdryer

A convective microdryer is used, specially designed for small samples (from 0.5 to 5 g) under air flow. The scheme of this tool is presented in Fig. 2 (more details about it are presented in (Leonard 2002)). One part of the system makes possible to control the air flow thanks to a pneumatic valve connected to a mass flowmeter (n°1 to 4 in Fig.2). The other part is able to heat the air up to the chosen temperature with a regulated heat tube (n°5 and 6 in Fig.2). Humidity is not controlled in the present experiments. Finally, air flows into a 4x4cm section drying chamber (n°9 in Fig.2) where temperature and relative humidity are measured (n°7). The studied sample is put in this cell and is regularly weighted with a precision of about 1 mg (n°8).

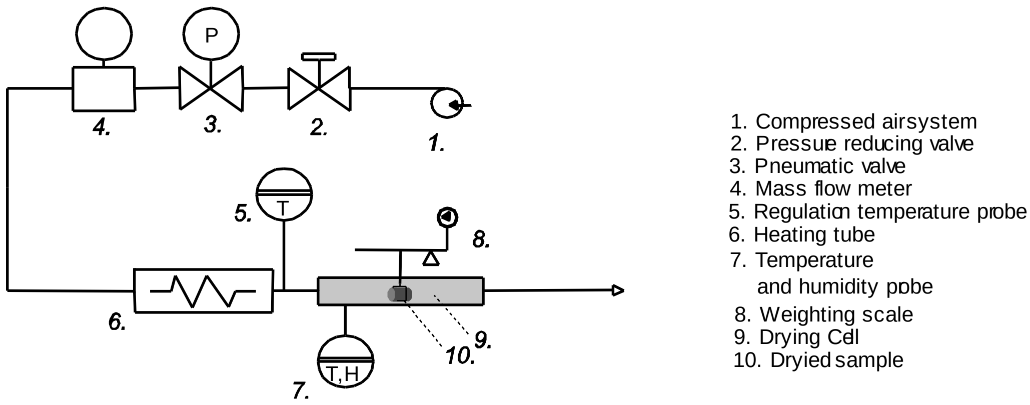

Fig. 2. Scheme of the microdryer system

2.3 Experimental protocol

Once a sample is almost saturated, its lateral and bottom surfaces are laterally covered with a latex sheath, in order to impose a single drying surface (Fig.3). Therefore, the height of a cylinder (*H*) is equal to the ratio between the sample volume and the evaporation surface (*V/S*) and it corresponds also to the maximum distance to be covered by water. Besides, it ensures that the water transfer is globally unidirectional, which simplifies the analysis of the results.

In order to study the influence of the air flow incidence on the drying surface, two positions of the cylindrical samples are considered into the drying chamber: parallel to the air flow (it means a frontal incidence of the flow, as in Fig.3) and perpendicular to it (it means a tangential incidence of the flow).

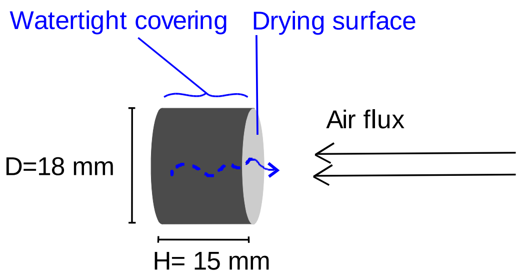

Fig. 3. Geometry of samples for the case H=15 mm and principle of the drying

The summary of the configurations studied is presented in table 1. The shortest height of 7 mm has been tested twice in both directions because of the little rotation of the sample on its reduced base observed during the test. Higher length than 33 mm is not possible in the perpendicular direction because of the limited width of the drying chamber (40 mm).

Table 1. Summary of the different configurations tested

	V/S=H (mm)							
	7	10	15	20	25	33	40	50
Number of tests with a frontal incidence of the air flow	2	1	1	1		1	1	1
Number of tests with a tangential incidence of the air flow	2		1		1	1		

A temperature of 50°C and a low air velocity of 0.8 m/s are chosen. Such a velocity is indeed, quite representative of a common natural wind or of the ventilation inside underground works. The samples are weighted every 30 seconds as well as the temperature and the relative humidity in the drying chamber.

3 Results and discussion

3.1 Drying curves

For each sample, three curves have been plotted. The first one shows the mass loss along time, without presenting the initial saturated value (varying between 3.72 and 25.84 g) to better compare the different tests. The second one plots the surface water flux along time, processed with a Lanczos filter to attenuate the irregularity of the derivative. The last one plots this same flux but in function of the water content (Krischer curve). The results for the seven dimensions considered with the frontal incidence of the flow are gathered in Fig.4 and those for the three dimensions considered with the tangential indidence of the flow are presented in Fig. 5.

Various observations can be made for the frontal flux graph, where the classical distinction between constant and decreasing drying rates is clear for all tests (Fig.4b-c). First, it appears that, contrary to the preliminary hypothesis made in introduction, the more *V/S* ratio is, the higher the constant drying rate is. Besides, the more *V/S*, the longer the plateau region lasts. This effect is more significantly observed for *V/H* ratio less than around 20 to 30 mm.

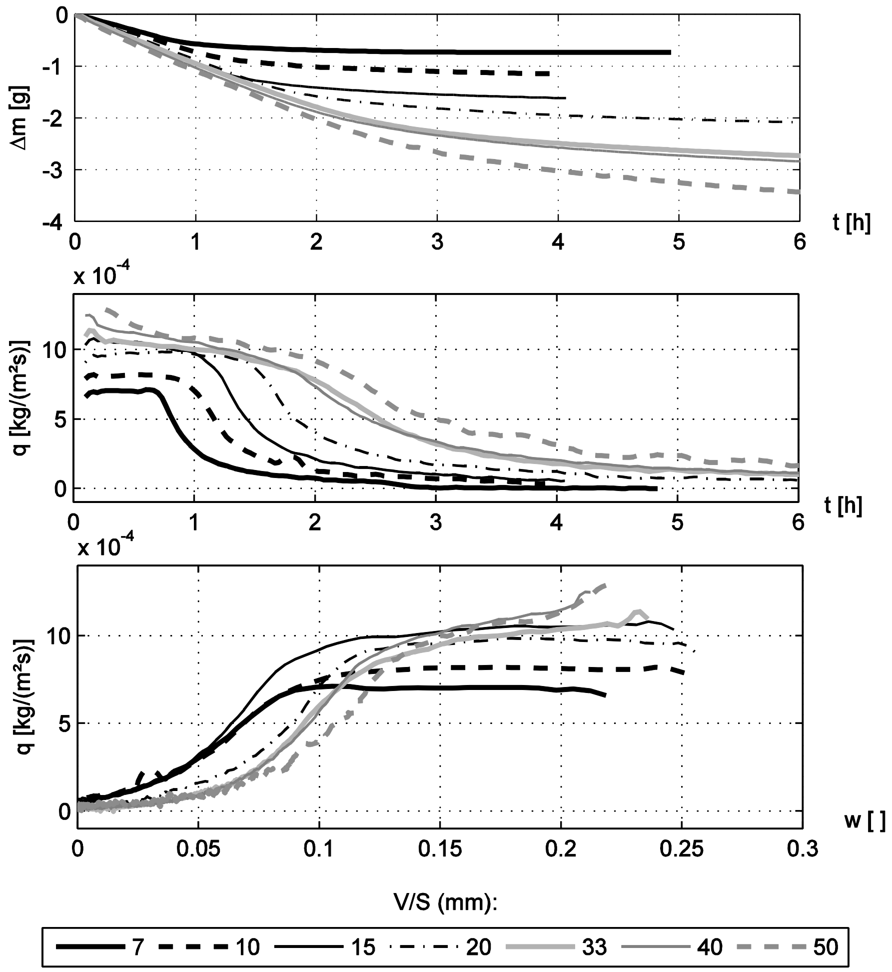

Fig. 4. Drying curves for frontal incidence of the air flow

It means that the water mass reaching the evaporation surface increases with the porous volume. This is probably not due to a modification of the flow configuration upon the drying surface because, even if the streamlines are certainly affected by the geometry change in the drying cell, this effect may take place downstream of the evaporation surface. Hence, this drying rate rise can be due to an increase of the available water with *V/S* ratio. This hypothesis involves that, for *H* smaller than around 20 to 30 mm, the drying surface would be connected to the whole sample volume, which goes in the direction of the theory developed by Lehmann et al. (2008) about a hydraulically connected layer below the drying surface. On the contrary, beyond this threshold of 20 - 30 mm, variation of *H* seems to have very little effect on the constant drying rate. This could mean that the pore water situated beyond this critical distance –with respect to the drying surface– does not contribute to the constant flow phase.

Secondly, in the Krischer curves (Fig.4c) it can be observed that the 7, 10 and 15 mm height samples reaches the end of the constant flux phase at the same water content w=0.08 (which corresponds to a saturation degree of 26%). The hypothesis can thus be made that, since this critical saturation is independent from the sample length, the water repartition in the sample during the constant drying rate would be homogeneous. On the contrary, when *H* overcomes 20 mm, it can be noticed that the critical value of *w* tends to increase (from 0.11 to 0.14).

Finally, it must be pointed out that the plateau region of the Krischer curve becomes less horizontal when *H* increases, inducing that the distinction between the constant and the decreasing flow phases is less and less clear. For *V/S* < 20 mm, no internal resistance to the water transfer seems to limit the evaporation flux during the constant drying rate phase, since that flux stays constant whatever the saturation degree. However, a larger sample volume, in addition to make available to the drying surface a larger amount of water as seen previously, induces increasing internal resistances to the water transfer. These resistances can be due to a permeability reduction, to a capillary pressure rising with the desaturation or simply to the increase of the distance to be covered by water.

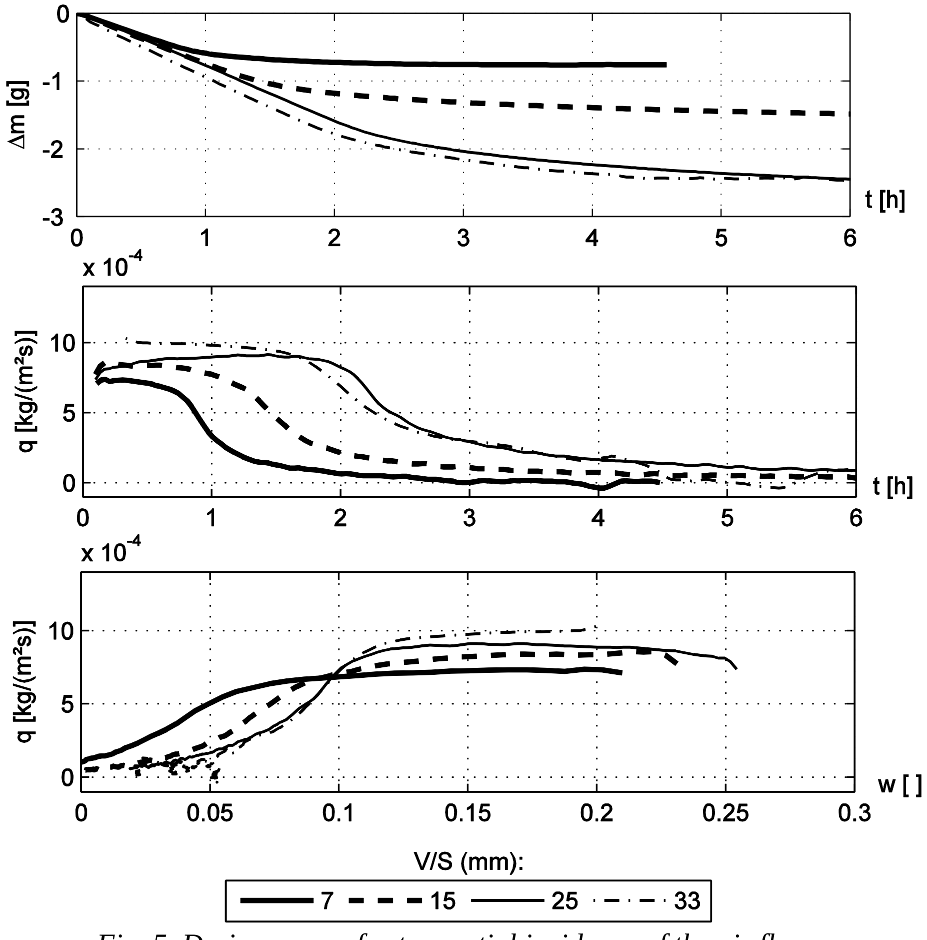

Fig. 5. Drying curves for tangential incidence of the air flow

In Fig.5, less observations can be made, due to the fewer number of tests made with the tangential incidence of the flow. In particular, no tests have been made with a length greater than 33 mm, which seems to be here a critical dimension according to the previous results. Nevertheless, the constant flow phase still appears clearly in the graphs, and there is still a correlation between the Volume/Surface ratio and the constant drying rate. However, contrary to the previous case, the water content at the end of the constant flux period seems not to be the same for the different length tested. This is to be further investigated.

3.2 Transfer coefficients computation

According to the limit layer model and considering temperature and vapour density driving potentials, the vapour and heat surface flux can be defined as follows:

$$q_w = \alpha(\rho_{v,ext} - \rho_{v,surf}) \qquad (kg/m^2/s)$$
$$q_h = L.q_w - \beta(T_{ext} - T_{surf}) \qquad (W/m^2/K),$$

with α and β respectively the vapour and heat transfer coefficients, L the latent heat of water, $\rho_{v,ext}$ and $\rho_{v,surf}$ respectively the vapour density in the surrounding air and directly above the limestone surface, T_{ext} and T_{surf} respectively the temperature of the air flow and of the surface. During the constant flux period, it is usually supposed that the drying surface is saturated which implies that upon it the relative humidity is 100% and the temperature is equal to the wet bulb temperature T_h. It means that all the heat supplies to the system is only consumed to evaporate the water film. In other words, no heat is transferred to the sample itself. α and β can thus be obtained as follows:

$$\alpha = \frac{q_w}{\rho_{v,ext} - \rho_{v,surf}} \qquad and \qquad \beta = \frac{L.q_w}{T_{ext} - T_h}$$

The wet bulb temperature T_h is calculated thanks to its relation with ambient vapour pressure P_v, saturated vapour pressure $P_{v,sat}$ and T_{ext} (see Nadeau 1995). $P_{v,sat}$ can be determined thanks to Garrel&Christ empirical expression (Garrel et al. 1965) for temperature between 273 and 303°K and P_v thanks to the relative humidity H_r given that: $P_v = H_r.P_{v,sat}$. α and β are thus computed for the 13 tests and the results are gathered in Fig.6 which illustrates the variation of the coefficients with both *V/S* ratio and the orientation of the air flow.

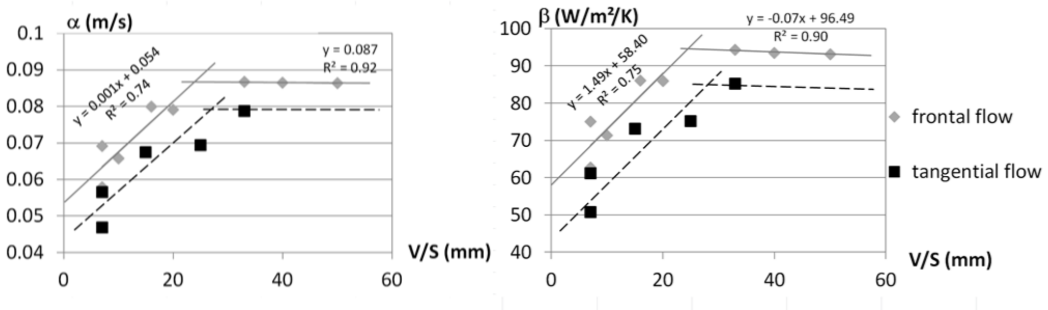

Fig. 6. Summary of the transfer coefficients according to the air flux direction and V/S

The first observation to make is that, in the same way as for the drying rate, α and β values increase with *V/S* up to approximately *V/S* =30 mm but, and this appears clearly for the frontal flux, they stabilize beyond this length. The second point to underline is that the frontal incidence of the air flow induces a more intense drying during the constant flux phase. Thus, it confirms that aerodynamics may have an effect on kinetics, probably because, on one hand, it may modify the thickness of the limit layer (see Fig.1) and, on the other hand, because this limit layer model may not be valid anymore for a highly turbulent flow.

4 Conclusions

In conclusion, it has been highlighted that α and β depend both on the air flux incidence with respect to the evaporation surface, and on the Volume/Surface ratio which was given here by the sample height.

Frontal air flow increases the water and heat transfer, probably because of a thickening of the limit layer and/or of some turbulence effects. Besides, the parametric study on *V/S* ratio leads to diverse effects. It has been shown that there is, for this limestone, a critical internal length, at which the kinetics changes. The results make appear that below this distance all the pore water seems to be connected to the drying surface contrary to the water beyond it. Furthermore, a homogeneous desaturation during the constant flow phase can be supposed for short samples with a frontal air flux (otherwise the water content at the end of this phase increases with *H*). All these results cannot miss to recall the film region model, presented by Yiotis et al. (2006) and Lehmann et al. (2008) for whom the constant drying rate period lasts as long as a liquid connection between the evaporating surface and a depth drying front is maintained. The thickness of this capillary zone depends on the porosity size and distribution.

Various questions arise from these results: can a depth drying front be actually observed experimentally for porous medium? Does this critical length exist for different material, and, in case yes, what is its link with the porosity? And finally what is the reason of internal resistances to the water transfer for sufficiently high *V/S* ratio? Further experiments are currently driven in order to find answers to these key points, notably with X-ray tomography investigations.

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