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DEVELOPMENT OF A PROCEDURE FOR THE DETERMINATION OF MOISTURE PROFILES IN POROUS BEDS BASED ON MEASUREMENTS OF ELECTRICAL CAPACITANCE

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ABSTRACT

A methodology was developed for non destructive determination of moisture profiles in porous capillary bodies during drying in non isothermal conditions. A fixed bed dryer with rectangular transversal section 0.02 m thickness x 0.145 m height and 0.25 m length was built. Along the length of the dryer 19 thermocouples and 18 equally spaced pairs of metallic plates (0.003 m x 0.145 m each, frontally spaced by 0.02 m) were installed. Each pair of plates acts as a local electric capacitor in the bed. Calibration equations of the electrical capacitance with moisture and temperature for each capacitor were developed. Drying tests for the determination of moisture profiles along the bed length were accomplished. The local instantaneous moisture content of the bed was obtained by means of the local electrical capacitance measurements. The moisture profile at the end of a drying test is compared with moisture determinations by dry mass presenting satisfactory results.

INTRODUCTION

When drying capillary porous bodies, mass transfer always occurs simultaneously to heat transfer. For the study of such coupling it is necessary to know both the moisture and temperature profiles in transient conditions. In this work a methodology is proposed for obtaining moisture profiles through the use of an equipment that allows the on-line determination of the local water content of the porous bed by means of non destructive measurements.

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The standard method more thoroughly used for the determination of moisture content in porous capillary bodies is the difference among its moist and dry masses after drying in stove. It is a simple and reliable method but very tedious when it is necessary to establish the moisture profile during transient drying test. There is also the serious inconvenience of the need to collect periodic samples or even to destroy the body studied.

Others methods are the determination of the moisture content through measurements of electrical resistance or capacitance of bodies conditioned between metallic sensors (capacitors). Such measurements are non-destructive, rapid and accurate but they need a previous development of calibration equations of the moisture of each material studied with the electrical resistance or capacitance and with temperature. The use of the capacitance method for determination of water contents in samples of moist materials is quite sensible because the dielectric constant of the sample is strongly affected by the presence of water. The dielectric constant of the water ($k_w = 78$) HALLIDAY (1973) is several times greater than the one of the dry fluorapatite ($k_s \sim 5$).

There are some commercial instruments for the determination of moisture in samples of soils or cereals, for instance the one manufactured by Gehaka Company (model Geole 400). Those instruments normally make use of capacitors in the form of concentric cylindrical tubes or in the form parallel plane plates FLETCHER (1964). For a capacitor composed of two parallel plates the capacitance (in pico Farad) is given by:

$$c = 9.8 \frac{L \omega}{d} k_m \qquad (1)$$

where:

c	capacitance, pico Farad
ω	width of each plate, m
L	length of each plate, m
d	frontal distance between the plates, m
k_m	dielectric constant of the body contained between the plates.

For a capacitor composed of two infinite parallel cylinders the capacitance per unit length L is given by:

$$\frac{c}{L} = 12.1 \frac{k_m}{\log\left(\frac{2d}{\phi}\right)} \qquad (2)$$

where:

d	distance between the cylinders, m
ϕ	diameters of each Cylinder, m.

The dielectric constant of a porous capillary moist material can be given for:

$$k_m = k_s X_s + k_a X_a + k_w X_w \qquad (3)$$

where:

k_s	dielectric constant of the solid material contained in the porous material,
k_a	dielectric constant of air (= 1,0),
k_w	dielectric constant of water (= 78),
X_s	volumetric fraction of the solid material
X_a	volumetric fraction of the air in the porous material.
X_w	volumetric fraction of the water in the porous capillary .

The sum of the three volumetric fractions is unity and the sum of the volumetric fractions of air and water in a moist material corresponds to its porosity ε so:

$$1 = X_s + X_a + X_w = X_s + \varepsilon \tag{4}$$

Substituting the numeric values of the dielectric constants of the air and the water in equation (4) and introducing it in equation (3):

$$k_m = k_s \left(1 - \varepsilon\right) + \varepsilon + 77\, X_w \tag{5}$$

The volumetric fraction of the water is related to the dry basis moisture of the bed u for:

$$X_w = \frac{u}{u_{sat}}\ \varepsilon \tag{6}$$

where: u moisture content of the bed, kg water/kg dry material (% dry basis)

u_{sat} saturation moisture of the bed, %db.

Introducing equation (6) in equation (5):

$$k_m = \frac{77\varepsilon}{u_{sat}}\ u + k_s\left(1 - \varepsilon\right) - \varepsilon \tag{7}$$

The following properties were experimentally found for the fluorapatite bed studied in the present work:

porosity	$\varepsilon = 0.39$
dielectric constant of the solid material	$k_s \approx 5.0$
saturation moisture	$u_{sat} = 23.2$ %db.

Applying those values in equation (7) it is obtained a linear relationship among k_m and u:

$$k_m = 1.3\,u + 3.4 \tag{8}$$

Equation (8) indicates that a fluorapatite bed completely dry has a dielectric constant of 3.4 and a bed completely moist of 33.6. One is almost ten times the other. This strong dependence of the capacitance with moisture suggests that the method of moisture determination through measurements of electric capacitance can be quite sensible.

In the present work a fix bed dryer was constructed. It was designed in such a way that the moisture flow in the bed is always one-dimensional. Its bed has the form of a long and thick parallelepiped with surrounding walls hermetic and adiabatic except one extremity which is open to natural drying conditions.

The dryer has a long length in relation to its traverse section in order to allow the installation of a series of pairs of metallic plates along its length. Each pair of frontal plates acts as a local electrical capacitor in the near region of the bed where it is located. In order to be able to install a significant number of sensors the width of the metallic plates must be relatively thin in relation to its length and consequently to the distance to its frontal pair. In that way, equation (1) does not applies because the border effects could be very significant. In spite of the fact that equation (2) is valid only for infinite cylinders it may be qualitatively used for the proposed instrument. But to do so it is necessary to substitute the diameter of the cylinders by the width of the plates ω and also consider the length of each plate L:

$$c \cong 12.1 \frac{L}{\log\left(\frac{2d}{\omega}\right)} k_m \tag{9}$$

Equation (2) is valid only for a single pair of cylinders but in the proposed instrument each local capacitor has at least one neighbor relatively close, it can then occur an influence of the neighbors sensor in the measurement of the capacitance. To compensate this influence it is introduced in equation (9) a correction factor α. Even if the walls of the dryer have no metallic parts, they can also affect the measurement of the capacitance. An other correction factor β is added in the equation (9) to account that influence.

$$c = 12.1\,\alpha \frac{L}{\log\left(\frac{2d}{\omega}\right)} (1.3\ u + 3.4) + \beta \tag{10}$$

where: α correction due to the presence of nearby neighbors sensors
β correction due to the effects of the walls and borders of the equipment

Despite all capacitors are built with the same dimensions, the effects of the boundaries of the equipment on each capacitor implies in different values for the correction factors α and β. So in the present work they were experimentally determined for each sensor.

Another correction that should be taken into account is owed to the variation of the dielectric constant of the moist material with the temperature of the bed and in consequence of its capacitance. As every drying is always accompanied by the presence of thermal gradients this correction can be significant. In the present work a correction in the capacitance for temperature variations, determined experimentally by CUNHA(2000) for fluorapatite beds, based on a linear adjustment, was adopted:

$$c^* = c + 0.51\left(T - 20.4\,^{\circ}C\right) \tag{11}$$

where: c^* capacitance corrected by the influence of temperature variations, pF
T temperature, °C.

EXPERIMENTAL PROCEDURE

The equipment proposed in the present work it is composed by a camera for the contention of the bed, a system for temperature measurement and a system for electric capacitance measurement.

In Figure 1 it is presented the camera with a volume of internal dimensions: 0,002 x 0,145 x 0,25 m..

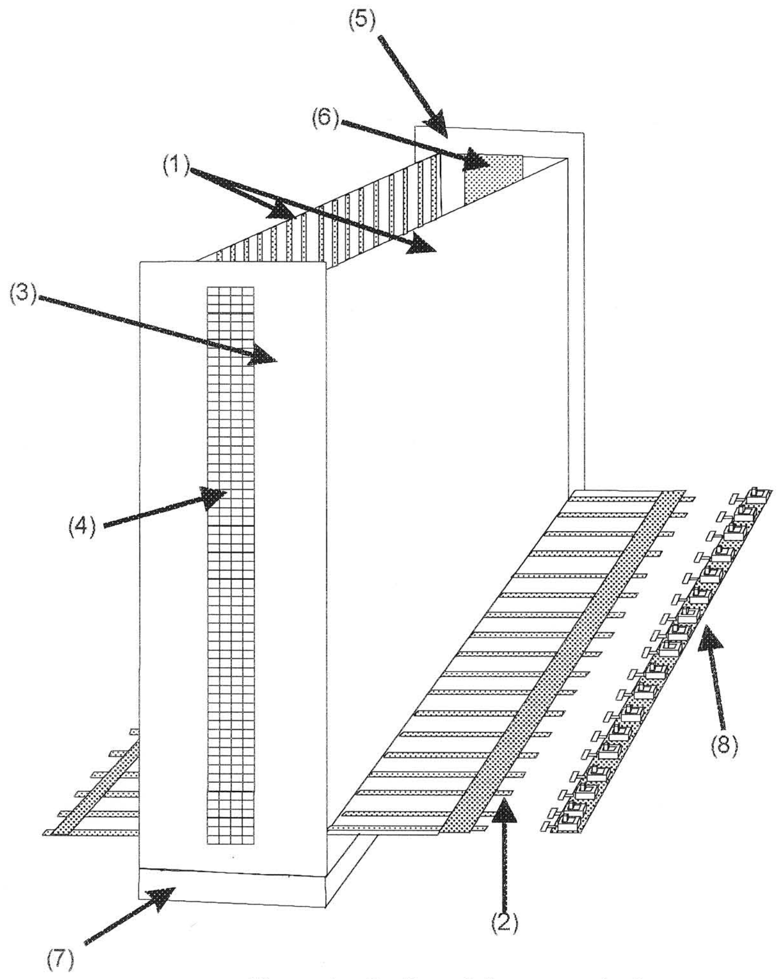

Figure 1 - Outline of the camera bed

The bed camera is surrounded by:

- two vertical walls (1) where 18 pairs of metallic capacitance sensor (2) were installed,
- a frontal vertical wall (3) where an inox screen (4) was installed,
- a rear vertical wall (5) where a copper bar (6) was adapted
- a base (7) that leans over a support where two switching boards (8) can be coupled.

The inox screen (4) sustains the bed and allows the passage of moisture during the drying of the material.

The sensors (2) were made of foils of nickel/cadmium of dimensions 0.145 x 0.003 m. The capacitance sensor plates were frontally spaced by the bed width (0.02 m). On each board (8) were installed 18 manual on/off switches to allow the selection of each individual capacitance sensor.

In Figure 2 the components used in the operation of the tests are presented.

The capacitance circuit of the commercial equipment for measurement of water content of cereals Geole 400 was used as the capacitance measurement system (11). It is quite compact so it was coupled to the support of the bed camera (9). Each one of its poles was connected to one of the switch boards (3). Values of the capacitance for each sensor obtained by the Geole circuit were checked with the measurements of an apparel LCR-815B of Minipa Corp. with test frequencies of 1 kHz..

On the base of the camera (7) 19 thermocouples (13) were installed. They were manually selected in the switch key (14) and the temperatures were read in the indicator (15) and registered.

The heating system (16) it is composed of an electrical resistance of 42.5 Ohms. An expert controller system (18) could be used to keep a constant temperature in the rear of the bed. The copper bar (6) with dimensions 0.145 x 0.02 x 0.005 m promotes an uniform heating of the bed.

During each calibration or drying test the camera, coupled to its support (9), was placed over a scale (10). For the determination of the capacitance in each sensor (2), each one was manually selected by the switches on/off of the board (8) and its capacitance were read in the indicator (11) and registered.

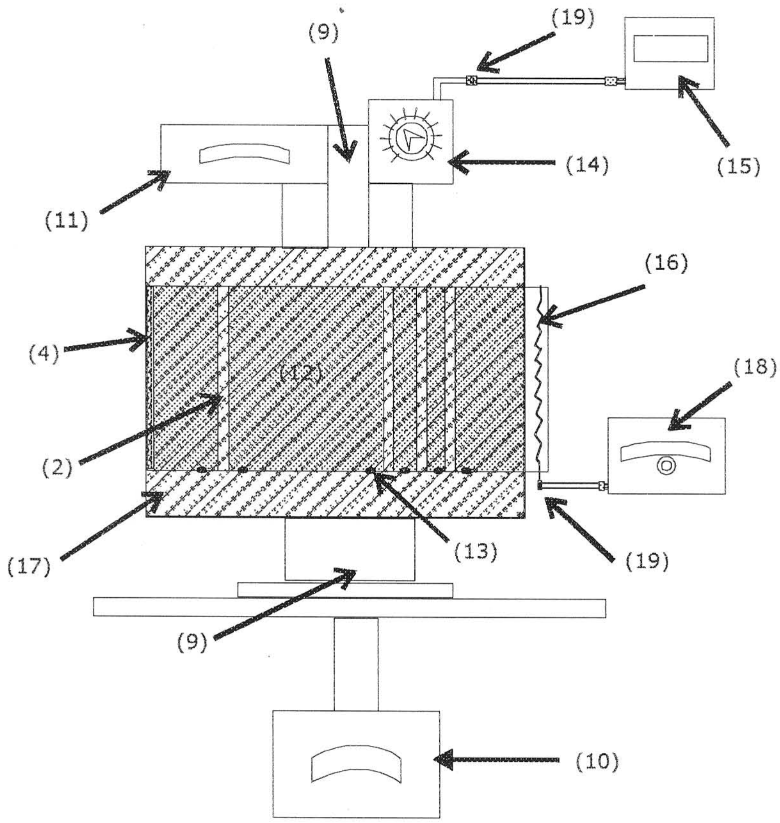

Figure 2 - Outline of the equipment

In the accomplished experiments the test porous material was fluorapatite ore with apparent density of 1640 kg of dry material/m^3. For the preparation of the bed (12) in a standardized way, the bed recipient was completely submerged into water and then the fluorapatite ore was decanted inside the recipient. During the decantation of the fluorapatite the recipient was systematically ''knocked'' and agitated in order to obtain an uniform and compact sedimentation and to assure that there will be no formation of air bubbles nor that the bed could be submitted to subsequent shrinkage, GOMBERT (1991).

After the completion of the recipient with the saturated fluorapatite, it was dried externally, thermally isolated with a layer of isopor 0.028 m thick (17). The equipment was weighed and left open to loose moisture. Every 24 h the recipient was disconnected from the heating and temperature measurement systems through the clamps (19) and was again weighed in the scale (10) and its mass was registered.

At the end of the drying experiment the bed was dismounted and the moisture content of nine samples, collected along the bed length, were measured by dry mass.

Two types of experiments were accomplished: calibration and drying.

During a calibration test the inox screen on the front of the camera must be kept closed and its top be left open. The moisture can only leave the bed by its top. This process must be slow to assure that the temperature will be constant and uniform. Even though the moisture varies vertically in the bed it will not vary horizontally, so on every position along the length of the apparel the moisture will be the same.

Several calibration tests, on different temperatures, are necessary to establish the parameters for the temperature correction equation (11).

During the drying tests the recipient must be closed on its top and be opened at its front so that the moisture could come out through the metallic screen. Now the moisture and temperature vary horizontally along the length but remain uniform along its height.

RESULTS AND DATA TREATMENT

In Table 1 some characteristic values of capacitance, obtained by a calibration test, are presented. They have already being corrected for temperature variation in accordance with equation (11). Only the odd numbered sensors are presented in Table 1 but in Figure 3 all 18 correspondent moisture values are shown:

Table 1 - Typical calibration Test: capacitance (pF) experimental corrected for temperature variation

Moisture	Sensor								
(%db)	1	3	5	7	9	11	13	15	17
6.55			100.1	98.2	96.8	95.6	95.6	96.0	97.8
5.11		98.2	93.0	91.0	89.4	88.5	88.9	89.0	90.8
3.78	98.9	91.9	88.2	86.1	84.5	84.0	84.1	84.2	85.5
3.61	92.1	86.2	82.6	80.7	79.0	78.7	78.8	78.8	79.8
2.61	87.9	82.0	78.6	76.6	75.0	74.8	75.1	74.8	76.3

Although the moisture in every position along the bed length were maintained approximately the same, during the calibration test, the capacitances in the sensors are different as shown in Figure 3.

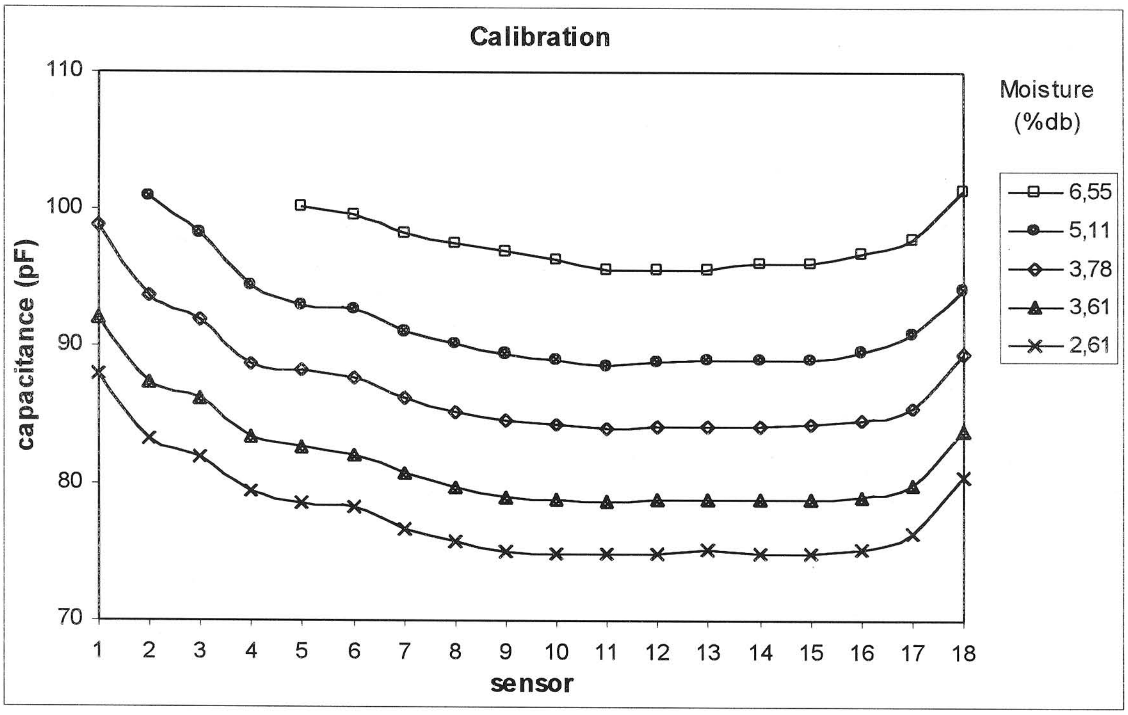

Figure 3 - Calibration Test: capacitance profiles along a uniform moisture bed.

The variation of the capacitance with the position in the bed happens mainly because of the presence of the inox screen in the frontal part of the camera and of the copper plate in the other extremity. The obtained profiles are approximately parallel and, in accordance with what equation (10) would foresee, the separation among each profile is linearly proportional to their moisture difference. Introducing in equation (10) the dimensions of the apparel: $d = 0.02$ m, $L = 0.145$ m and $\omega = 0.003$ m and the adjusted values $\alpha \approx 2.5$ and $\beta \cong 35$ pF, the later one corresponds to the reading of capacitance of a single sensor with the empty apparel. Then it results:

$$c \;=\; 12.1 \; \frac{0.145}{\log\left(\dfrac{2 \text{ x } 0.02}{0.003}\right)} \; 2.5 \; \left(1.3\,u + 3.4\right) \; + \; 35 \;\cong\; 5\,u \,+\, 48 \qquad (12)$$

The influences of the equipment walls may be different for each sensor, so it is convenient to develop an individual calibration adjustment for each one:

$$c_i \;\cong\; a_i \; u + b_i \qquad (13)$$

where: c_i capacitance of the sensor i, $i = 1, \ldots, 18$

a_i, b_i linear adjustment coefficients for each sensor i

It is also convenient to determinate the values of the coefficients for a_i and b_i experimentally. An individual linear adjustment for each sensor one was then obtained. Those coefficients were obtained and are presented in the Table 2

Table 2 - Coefficients of the linear adjustment of calibration for each sensor one

Sensor i	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
a_i	7.1	6.7	6.2	5.4	4.9	4.9	4.9	5.1	5.1	5.0	4.9	4.9	4.8	5.0	5.0	5.1	5.2	5.2
b_i	67.4	63.9	64.2	64.2	65.2	64.7	63.2	61.8	61.2	61.2	61.4	61.6	61.7	61.1	61.2	61.1	61.8	65.6

In Table 3 some typical values of capacitance measurements during a drying test are presented. They have being already corrected for temperature variation. Only the odd numbered sensors are presented in Table 3 but in Figure 4 all the sensor are considered:

Table 3 - Drying Test: capacitance (pF) experimental corrected for temperature variation

Time	Moisture	sensor								
(h)	%db	1	3	5	7	9	11	13	15	17
0	10.4			97.2	96.6	95.9	95.0	97.0		
95	9.1			94.2	93.4	92.9	91.9	93.8	95.6	97.0
192	7.6		92.1	88.6	88.0	87.8	86.8	86.2	89.9	90.6
310	5.7	88.9	82.4	80.6	80.8	81.0	80.2	81.4	82.4	83.1
407	4.4	75.3	73.4	72.8	73.1	73.3	73.1	74.6	75.4	76.5
623	3.3	60.9	64.4	66.1	66.9	67.0	67.0	68.3	68.9	70.1

The capacitance values were introduced in equation (12) and the resulting moisture profiles are presented in Figure 5. The dry mass final moisture profile is also presented in the Figure 5 and it may be compared with the profile measured by capacitance for the final instant of the drying experiment because both refer to the same time (623 h).

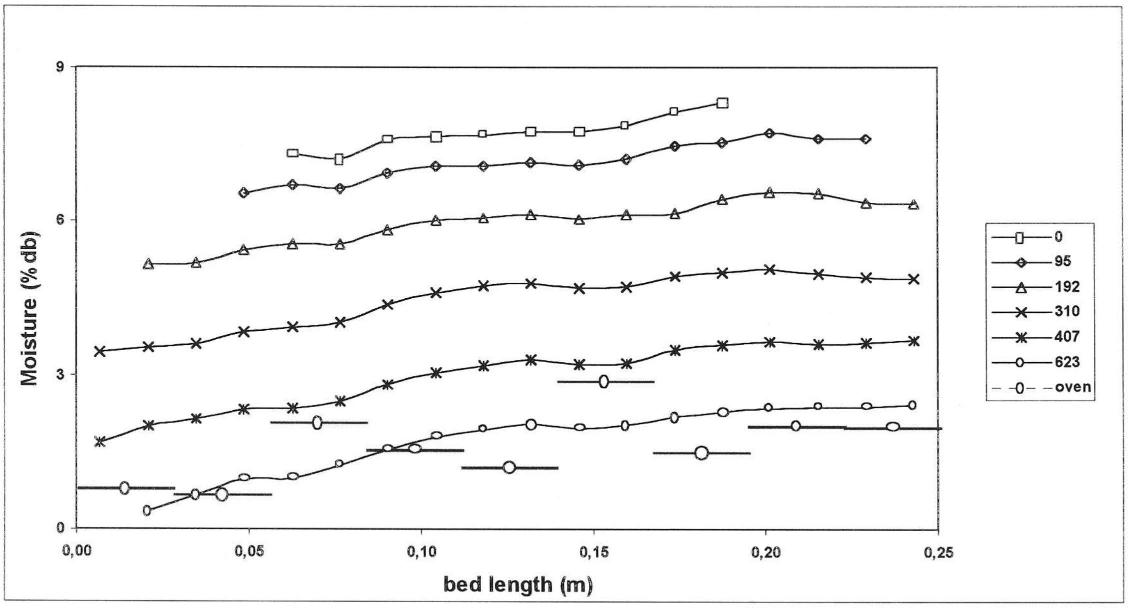

Figure 4 - Moisture profiles by capacitance (and by dry mass in the end of the test)

CONCLUSIONS

The proposed instrument was capable to determine moisture profiles for beds of fluorapatite ore with moisture contents between 2 and 8 % db approximately. This range can probably be extended with the use of a measurement circuit of capacitance of larger spectrum.

The calibration procedure for linear fittings has good theoretical justification and good experimental correlation.

A check factor F for calibration consistency may be stated. It compares each one of the measured values of the capacitance, corrected for temperature variations, with the values of the capacitance calculated by the equation (13):

$$F = \frac{0.255\ c_i + (T - 20.4)}{a_i\ u + b_i} \tag{14}$$

The factor F was calculated for all the values obtained during the calibration test and is presented in the Figure 5. All values of F are near unity.

Few tests for the verification of the measurements accuracy have been done, nevertheless it seems that, if a good calibration is accomplished, better (more precise) results can be obtained by the capacitance method than by the dry mass method.

Figure 4 presents two moisture profiles for the same instant: the profile (623 h) that was obtained by capacitance measures and the profile (stove) that was obtained by collecting samples of the bed and subsequent determination by dry mass. Both profiles presented the same general behavior but the moisture profile by capacitance shows a dispersion in the results much smaller than the for dry mass.

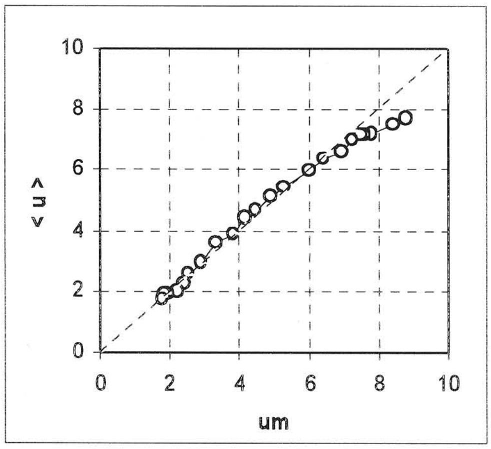

Figure 6 - Average moisture calculated by capacitance versus dry mass

The proposed equipment also allows to obtain the average moisture of the bed during drying by two processes: directly from the measurement of the total mass of the bed in the scale, which will be represented by u_m , and indirectly by calculating average of the local moistures obtained by capacitance. The later will be represented by $< u >$. In Figure 6 the values of $< u >$ were plotted versus u_m . Quite a good correlation is verified. However it presents a tendency to deviate for values above 7.5% db. This might be because for higher water contents the values of electrical resistance of the capillary porous material may affect the determination of capacitance values.

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