AN EXPERIMENTAL SET-UP FOR EVALUATING MOISTURE BUFFERING EFFECTS OF POROUS MATERIAL

José Walter Meissner, jose.meissner@ pucpr.br
Nathan Mendes, nathan.mendes@pucpr.br
Kátia C. Mendonça, k.mendonca@pucpr.br
Luís Mauro Moura, luis.moura@pucpr.br
Mechanical Engineering Graduate Program (PPGEM)
Pontifical Catholic University of Paraná (PUCPR)
Rua Imaculada Conceição, 1155 Curitiba - PR, 80.215-901 - Brazil

Abstract. *Moisture in constructions may be responsible for material deterioration, increasing of conduction cooling loads and is also related to indoor air quality. In this way, the present paper presents the development of an experimental set-up to evaluate moisture buffer capacity of porous materials, which can be defined according to their capability of absorbing/releasing moisture from/to the surrounding room air, reducing the indoor air relative humidity daily amplitude. The experimental apparatus is composed of two environmental chambers that control temperature and relative humidity, a 2mx2mx2m wood test cell and a supply air tunnel. One of the chambers is used as the external environment for the built-in test cell and the other one is responsible for supplying conditioned air via the supply air tunnel that works as an air handling unit. In order to measure the moisture adsorption/desorption capacity, four cell loads are used and several relative humidity, temperature and air velocity sensors are placed within both the test cell and the supply air tunnel. An uncertainty analysis of measurements, including sensors and data acquisition system is carried out and the experimental set-up capabilities are discussed.*

Keywords*: Moisture buffer effect, indoor air relative humidity, porous material, experimental apparatus.*

1. INTRODUCTION

Due to the high energy consumption of HVAC (Heating, Ventilation and air conditioning) systems, many countries have been investigating the use of building materials to assist in the reduction of energy consumption. Another recent concern is the attenuation of indoor air relative humidity oscillation for thermal comfort and building occupants' health as moisture causes mold growth, pulmonary problems (Toftum *et al.* 1998a), mucosa drying (Toftum *et al.* 1998b) and respiratory discomfort (Toftum *et al.* 1998a). Additionally, moisture greatly impacts on material deterioration (Lucas *et al.* 2002), on energy efficiency of refrigeration systems in supermarket buildings (Arias and Lundqvist, 2006) and HVAC equipment (Osanyintola and Simonson, 2006).

An important factor that influences the relative humidity variation is the water mass exchanged between the indoor air and the porous building materials due to their water molecules adsorption/dessorption capacity, which dynamics is hardly known by Engineers and Architects. In this context, the MBV (Moisture Buffer Value) index was created (Rode, 2003) focused mainly to building practionners. However, the MBV determination is still difficult as depends on many parameters.

In general, MBV is related to several physical parameters such as moisture accumulation ability, moisture diffusivity, water vapor permeability, time of cycles, material density, material thickness, surface roughness, surface treatment (*e.g.*, paint), ventilation rate, air velocity and temperature.

Several ways of characterizing moisture buffer effect have been suggested such as available water (Padfield, 1999), moisture accumulation ability and the material surface density as a function of relative humidity (Mitamura *et al.* 2001). (Ramos and de Freitas, 2004) presented a numerical and experimental work of the effects of hygroscopic inertia of some covering materials and proposed to characterize materials by hygroscopic inertia classes.

A NORDTEST project (Rode *et al.* 2005) introduced the definition of a practical MBV, for which is assumed a surface resistance corresponding to air velocity between 0.05 and 0.15 m/s and an exposure with daily variations with 8 hours of high relative humidity (75 % RH) and 16 hours with low humidity (33 % RH). This definition can be applied also for multilayer building components. In 2002, a Japanese standard (JIS A 1470-1) for building materials was published on a *Test method of adsorption/desorption efficiency for building materials to regulate an indoor humidity – Part 1: Response method of humidity*.

The Danish Technological University, the Technical Research Centre of Finland, the Lund University and the Norwegian Building Research Institute have participated of a Round Robin test (Rode *et al*. 2005) to measure moisture buffer performance of eight materials and the results obtained by the Nordic institutions were considerably similar, even though the equipment was not the same, confirming the usefulness of the MBV concept for standardization purposes.

Yoshino *et al.* (2006) presented an experimental apparatus developed in Japan, which is composed of a 4.6-m^3 gypsum test cell mounted within a climatic chamber. A scale is used to measure the evaporated water from a humidifier placed in the test cell and a wind tunnel is used to exhaust air from the cell, while a 100-mm diameter opening is used to supply air from the climatic chamber controlled at 20ºC e 50% RH. Velocity, temperature and RH sensors were strategically positioned and results were presented in terms of test-cell indoor air RH when the internal surfaces are covered or not by an impermeable coating material.

A continuous and progressive interest on this research topic has been observed and discussed by the participants of the International Energy Agency's project on *Whole Building Heat, Air and Moisture Response* – IEA ECBCS Annex 41, showing the need of continuity of research on this subject as the phenomenon is complex and it is still not very clear the relevance among the different parameters.

In this way, this document presents the development of a new full-scale experimental apparatus to evaluate the moisture buffer value, which is composed of two environmental chambers that control temperature and relative humidity, a 2mx2mx2m test cell and a supply air tunnel. One of the chambers is used as the external environment for the built-in test cell and the other one is responsible for supplying conditioned air via the supply air tunnel that works as an air handling unit.

The moisture adsorption/desorption is measured by using four cell loads and several relative humidity, temperature and air velocity sensors are placed within both the test cell and the supply air tunnel. This tunnel is composed of re-heater, fan and a humidifier so that the supply air thermodynamics state can finely tune by a PID control system.

The paper is presented as follows. In section 2, the theory about the moisture buffer value concept is provided, while in section 3 the development of the experimental set-up is shown. In section 4, an uncertainty analysis of measurements, including sensors and data acquisition system is carried out and the experimental set-up capabilities are discussed. Finally, in section 5, the conclusions are addressed.

2. MOISTURE BUFFER THEORY

As most building materials are porous media, they can absorb/release moisture from/to the surrounding room air and consequently reduce its relative humidity amplitudes. This capability of porous materials is known as Moisture Buffer Capacity (MBC) and may be defined by different ways.

One way is based on the heat-moisture transfer analogy. A similar parameter to the thermal effusivity, *b*, that indicates the ability of the material to absorb and release heat when it is subjected to a sudden variation on its surface temperature, is defined to describe the ability of the material to absorb and release moisture when it is subjected to a sudden variation on its surface humidity. This parameter is called moisture effusivity, b_m, and is based on standard material properties as shown in Eq. (1).

$$b_m = \sqrt{\frac{\delta_p \rho_0 \xi_u}{p_{sat}}} \tag{1}$$

Where, δ_p is the water vapour permeability (kgm^{-1}s^{-1}Pa^{-1}), ρ_0 is the dry density of the material (kgm^{-3}), ξ_u is the specific moisture capacity (kgkg^{-1}), which is defined as the slope of the sorption isotherm at a constant temperature, and p_{sat} the saturation vapour pressure (Pa).

The water vapour permeability indicates the facility of water vapour to be transported by diffusion into the material and can be expressed by the symbol δ_v when its units are (m^{2}s^{-1}).

$$\delta_p = \frac{\delta_v}{R_v T} \tag{2}$$

Where R_v is the gas constant for water vapour (= 461.5 Jkg^{-1}K^{-1}) and T is the absolute temperature (K).

Again, a similar parameter to the thermal penetration depth, which indicates the penetration depth of heat into the material when it is subjected to harmonic fluctuations on its surface temperature, is defined to indicate the penetration depth of moisture into the material when it is subjected to periodic variations on its surface relative humidity. Then, the moisture penetration depth, d_p, where the amplitude of moisture content is 37% of the amplitude at the surface, is given by

$$d_{p,37\%} = \sqrt{\frac{D_w t_p}{\pi}}\,, \tag{3}$$

where, D_w is the moisture diffusivity (m^{2}s^{-1}) and t_p is the time period (s).

The moisture penetration depth, d_p, where the amplitude of moisture content is 1% of the amplitude at the surface, is given alternatively by

$$d_{p,1\%} = 4.61\sqrt{\frac{D_w t_p}{\pi}}\,. \tag{4}$$

Padfield (1999) proposed to use a parameter called available water, a_w, based on the moisture penetration depth on the specific moisture capacity to characterise the MBC (Moisture Buffer Capacity) of porous building material. According to Eq. (5), it gives the amount of water per square meter in a given cycle time,

$$a_w = d_{p,37\%}\xi_u\,. \tag{5}$$

All parameters already mentioned consider only the material properties. Alternatively, Mendes (2003) proposed a modified Biot number called Effective Moisture Buffer Capacity Number (*Me*) to characterise the MBC of porous building material. As a mass Biot number, it expresses the relation between the accumulated moisture that enters into the porous material and the moisture that diffuses into it, in that way, not only the material influence is considered but also the environment. In addition, it takes into account the coating resistance, the material density and the moisture capacity, as stated by

$$Me = h_M \rho_0 \xi_u\,, \tag{6}$$

where Me is given in ($kgm^{-2}s^{-1}$), and h_M is the convective moisture transfer coefficient calculated as

$$h_M = \left[\frac{\rho_{air} c_{air} Le^{2/3}}{h_T} + \frac{461.52(T_s + 273)}{coatingpermeance}\right]^{-1}, \tag{7}$$

where ρ_{air} is the dry air density (kgm^{-3}), c_{air} is the specific heat of the dry air ($Jkg^{-1}K^{-1}$), Le is the Lewis relation and for laminar and turbulent flow it can be respectively considered 0.9 and 1, h_T is the convection heat transfer coefficient ($Wm^{-2}K^{-1}$), T_s is the surface temperature (°C) and the coating permeance unit is ($kgm^{-2}s^{-1}Pa^{-1}$). Normally, the following values are considered: ρ_{air} = 1.166 kg/m³, c_{air} = 1.007 kJ/kgK and Le = 1. If there is no additional resistance such as paint, the h_m can be considered as Eq. (8).

$$h_M = \frac{h_T}{\rho_{air} c_{air} Le^{2/3}}\,, \tag{8}$$

Two other parameters for evaluating the Moisture Buffering Capacity of building materials were proposed by the NORDTEST project (Rode *et al.*, 2005). Those parameters also consider the environment influences. The first one is called Ideal Moisture Buffer Value (MBV_{ideal}) and is expressed by the following equation:

$$MBV_{ideal} \approx 0.00568 b_m p_{sat}\sqrt{t_p}\,, \tag{9}$$

with b_m being the moisture effusivity ($kgm^{-2}Pa^{-1}s^{-1/2}$), p_{sat} the saturated water vapour pressure at the material surface (Pa) and t_p the time period (s).

This parameter is based on a time variation of the surface humidity, where 1/3 of the time period the surface is subjected to a high humidity level and the remaining 2/3 subjected to a low level. The ratio between the amount of moisture accumulated in 1 m^2 of material in the time period and the difference between the low and the high levels of relative humidity gives the MBV_{ideal}.

The second parameter is called Practical Moisture Buffer Value ($MBV_{practical}$). Conversely to the parameters previously discussed, it is based on the fluctuations of the relative humidity of the surrounding air instead of those of the material surface. Also, it cannot be understood as a property material since the convective surface resistance cannot be neglected for many building materials.

The $MBV_{practical}$ is defined as the relation between the measured amount of moisture exchanged, per open surface area during a given period, in an experimental apparatus, where the material is exposed to high relative humidity during 8 hours and low relative humidity during 16 hours, and the percentage of relative humidity variation.

3. EXPERIMENTAL SET-UP

In order to evaluate moisture buffer capacity an experimental set-up based on dynamic climatic chamber tests has been developed. The principle of this apparatus is to subject a test cell made of the material to be investigated to a RH signal and measure its weight changes, while the supply air and the surrounding exterior conditions are both controlled in terms of temperature and relative humidity. To reach this aim the experimental apparatus consists of the test cell itself, a calorimeter and an air supply tunnel.

3.1. Calorimeter

The calorimeter was originally developed to test non-ducted air conditioners until 3 tons of refrigeration (10,550 W) according to ISO 5151:94. Basically, it is composed of two chambers with individual temperature and humidity controls connected to each other by a 1m^2 window, as shown in Fig. 1. Temperature and relativity humidity operation ranges are -10 to 60°C ±0.1°C and 30 to 70% ±5%RH for chamber 1, and -25 to 70°C ±0.1°C and 30 to 99%RH ±1%RH for chamber 2.

The chambers were conceived used to quantify the total capacity, sensible capacity and energy efficiency ratio of direct-expansion air conditioning equipment, at given indoor and outdoor environment conditions for both temperature and relative humidity. The indoor chamber is connected to an equipment that reads the chamber heating power and the air conditioning system consumption. The indoor environment is represented by the 40.66-m³ chamber two, which has the following dimensions: 3.66 x 3.22 x 3.45m (length, width, height). On the other hand, the outdoor environment is represented by the 25.11-m³ chamber one, which dimensions are 3.00 x 3.22 x 2.60m (length, width, height).

For experiments carried out according to ISO 5151, chamber 1 represents the outdoor environment for the air conditioning system to be tested, which is placed at the "window" between the two chambers, while chamber 2 provides the psychrometric conditions to represent the indoor environment with the heating and humidifying loads.

To the moisture buffer evaluation experiment, the test cell (described in Section 3.2) is placed within the chamber 2 of the calorimeter. In this case, chamber 2 simulates the outdoor environment for the moisture buffer evaluation test. The role of the other chamber is to provide supply air at pre-defined conditions to the air tunnel (described in Section 3.3), so that the conditioned air is supplied into the test cell. The whole experimental set-up scheme is described in Fig. 1.

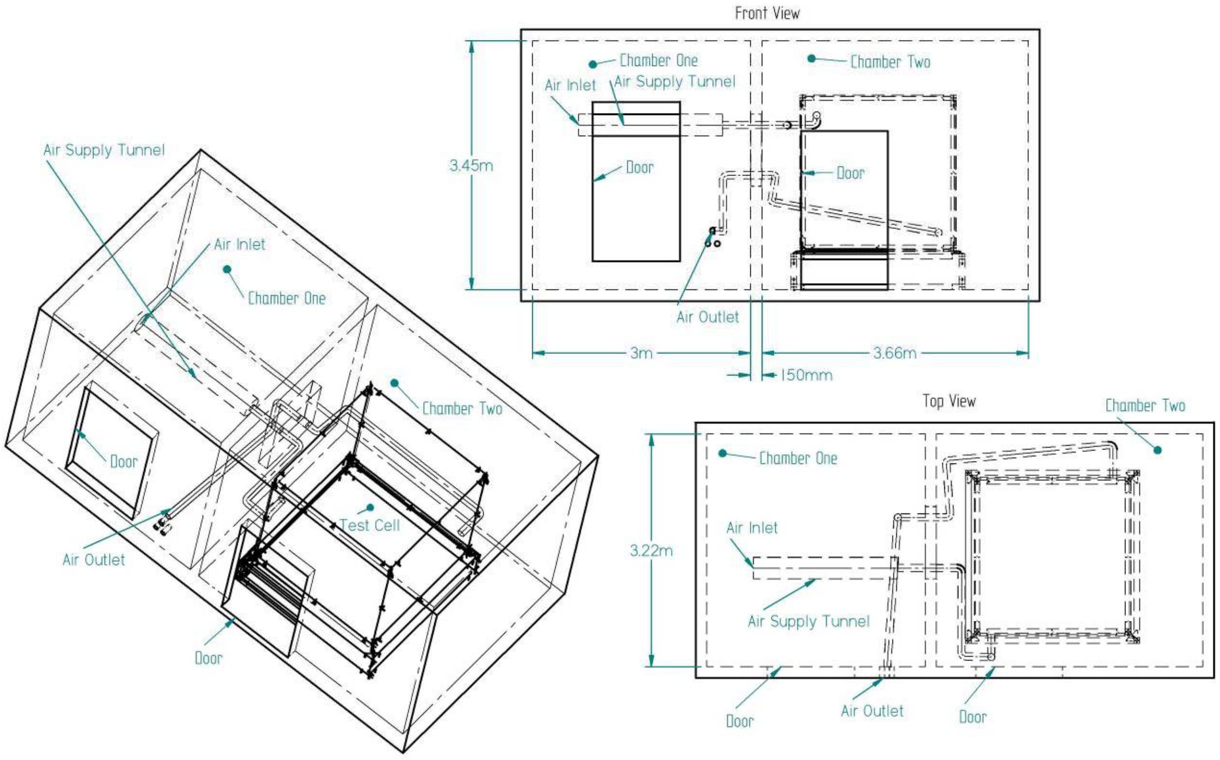

Figure 1. Experimental set-up scheme.

3.2. Test Cell

The test cell is divided into two main parts: the frame and the porous sheets to be tested. The structure supports all the sensors and provides mechanical support to the specimen sheets, which are placed on the frame to form a 8m^3 cube with 24m² of surface area. A second frame was designed to lift the cube structure 0.5m up from the chamber floor intended to provide air circulation around all specimen sheets, and also to support the four load cells that are positioned on the corners below the cube, as illustrated in Fig. 2.
Since the specimen sheets are wood made, the frame structure is also wood made and varnished to reduce the frame material interference.

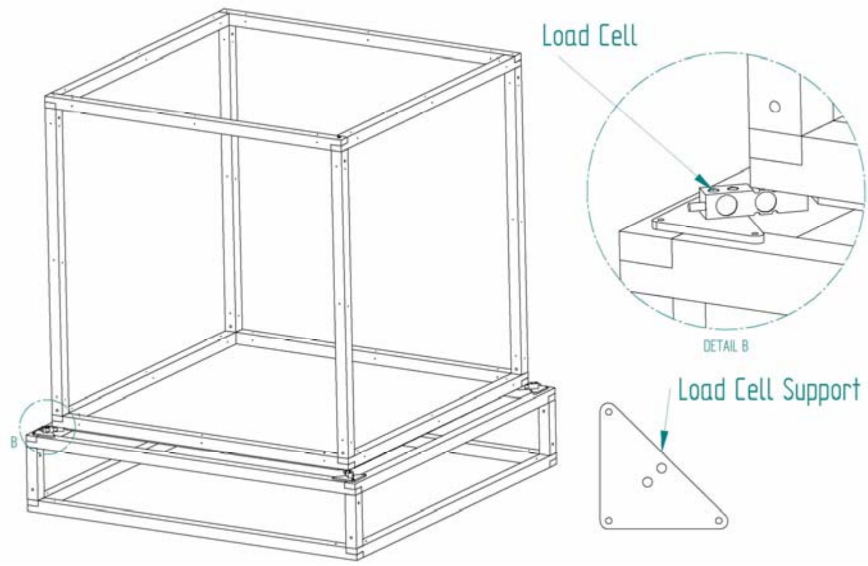

Figure 2. Frame Structure.

Temperature, relative humidity and air velocity are measured within the test cell according to the zones in which the indoor air volume was divided (Fig. 3). Every sensor zone is equipped with three thermocouples and an air humidity sensor, while one absolute pressure sensor is placed in zone 9 and five air velocity sensors are positioned within zones spaces 1, 2, 7, 8 and 9 to assure the air circulation inside the test-cell cube. In each sensor zone the humidity, velocity and temperature probes are fixed next to each other in the middle of the sensor zone to minimize the distance influence. The probes are fixed using nylon wires assuring minimum fixing interference possible. Two other absolute pressure sensors measure the pressure inside chamber 2 and the pressure of the supply air.

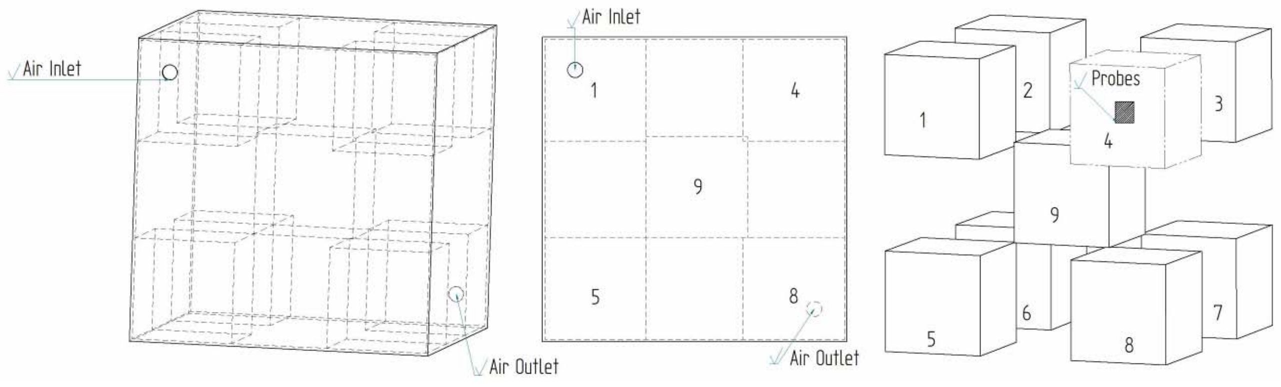

Figure 3. Sensor Zones.

3.3. Supply Air Tunnel Description

The supply air tunnel assures the air mass flow rate to the test cell and the inlet air conditions control. It takes the pre-conditioned air from chamber 1 and regulates the temperature and the humidity of the air to a desired condition using an electrical resistance and an ambient ultrasonic humidifier, respectively. The mass air flow rate is also computer controlled by a *Coriolis* effect MicroMotion® probe and a variable speed radial fan. The three variables are controlled using PID control running a software designed in LabView®, which offers a flexible range of the supplied air condition. Since the data acquisition system is integrated to LabView®, the controlled parameter can be applied to any probe measurement. A sketch of the supply air unit is presented in Fig. 4.

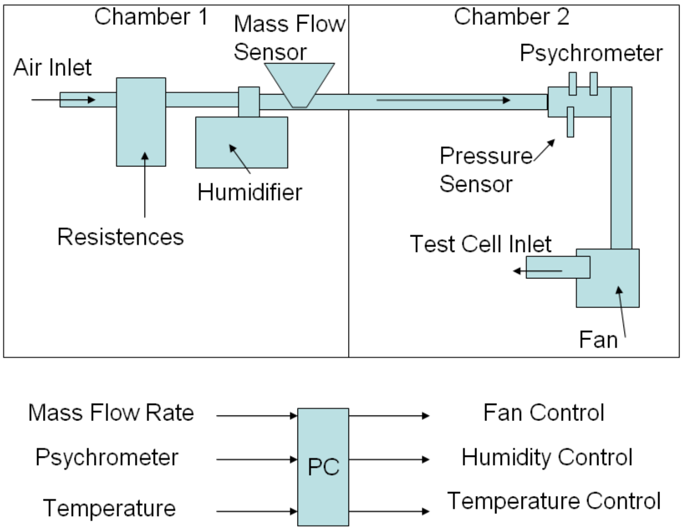

Figure 4. Supply Air Tunnel Diagram.

3.4. Measurement System

The physical quantities (pressure, temperature, velocity, humidity) of the air and the test cell weight have been acquired by a 6½ digits resolution data acquisition system (Agilent 34980A model that handles 8 slots for module connections) connected to a LabView® platform in a PC, via USB or Ethernet interfaces. Four Agilent® 34921A modules have been used to measure 160 channels up to 100 channels/second scan rate. A summary of the measurement system characteristics is presented on Tab. 1 and Tab. 2.

Table 1. Probes Accuracy.

Measurement / Probe		Working Range	Accuracy ± (%of reading + %of range)	Output
Air Temperature	PT-100	0 to 50 °C	± (0 + 0.184)	ITS-90 Resistance
	Novus Transducer	-40 to 80 °C	Show in Figure 5	Linear 0 to 10V
Air Humidity		0 to 100 %RH	±(0 + 1.5)	
Air Velocity	Hot Wire Anemometry	0 to 2 m/s	±(2 + 3)	
Air Pressure	Novus Transducer	0 to500 kPa	±(0 + 0.3)	
Weight	Load Cell	0 to 100 kg	± (0 + 0.05116)	2 mV/V

Table 2. Data Acquisition Accuracy.

Measurement / System		Working Range	Accuracy ± (%of reading + %of range)	Output
DC Voltage	Agilent®	0 to 100 mV	±0.004 + 0.004	USB or Ethernet
		0 to 10 V	±0.002 + 0.0005	
DC Current		0 to 100 mA	±0.03 + 0.005	
RTD		-200 to 600 °C	±0.06	
Resistance		0 to 1 kΩ	±0.008 + 0.001	
Thermocouple T Type		-100 to 400 °C	±1.0	

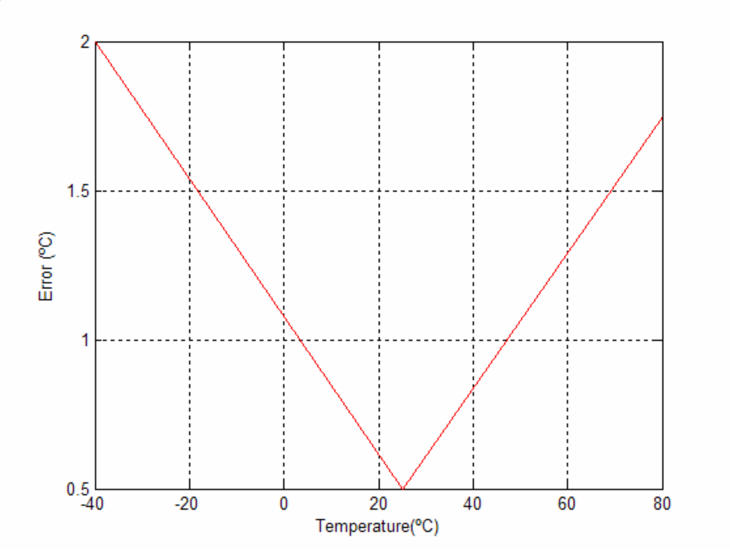

Figure 5. Novus Temperature Probe Error.

All probes are read by the Agilent® data acquisition system connected by a computer running LabView®. All the values read by the data acquisition system are logged in a text file for further analysis. In the total, 7 temperature PT-100 sensors, 10 temperature and humidity transmitters, 3 pressure transmittesr, 5 air velocity transmitters, a *Coriolis* effect transmitter, 30 T-type thermocouples and 4 load cells are used.

4. UNCERTAINTY ANALYSIS

The uncertainty analysis considers both the probe and the data acquisition system errors on all data measurements. All data is read and logged by a personal computer and for that, all signs are read by the acquisition system and are stored in the computer.

To consider the error propagation on a measured value, all errors from all instruments used on the measurement must be calculated by Eq. (10).

$$Error = \pm\sqrt{(Error1)^2 + (Error2)^2 + \ldots + (ErrorN)^2} \tag{10}$$

Tab. 3 shows the calculated errors. First the probe uncertainty is converted into the unit read by the acquisition system (voltage, resistance), then the total uncertainty is calculated using Eq. (10) and converted back to the measuring unit. As a high-quality data acquisition system is used, in most cases, the probe uncertainty is the dominant on the final measurement uncertainty.

Table 3. Uncertainties in physical measurements.

Measurement / Probe		Worst case	Probe Uncertainty	Total Uncertainty
Air Temperature	PT-100	50 °C	± (0.092) °C	± (0.1) °C
	Electronic	60 °C	± (1.30) °C	± (1.30) °C
Air Humidity		50 %RH	±(1.5) %RH	±(1.5) %RH
Air Velocity	Hot Wire Anemometry	2 m/s	±(0.08) m/s	±(0.08) m/s
Air Pressure	Electronic	500 kPa	±(1.5 k) Pa	±(1.5 k) Pa
Weight	Load Cell	93 kg	± (0.2) kg	± (0.21) kg

The load cell uncertainty has a great absolute value. However, most part of this uncertainty is due to the systematic error of reference masses. Because the used values will be the differences between the test cell mass, this uncertainty will be nullify and the final uncertainty of the test cell mass variation will be close to random uncertainties. The load cell random uncertainty is around +/- 20g. The thermocouple measurements have the same characteristic so that the temperature difference uncertainty is around 0.1 °C.

5. FINAL REMARKS

In this work a full-scale experimental apparatus has been proposed to evaluate the moisture buffer value (MBV) of porous materials, which has been shown good performance as a transient adsorption/desorption coefficient (Delgado *et al.*, 2006). This new concept is based on three temperatures and relative humidity controlled different environments and, besides, function of the proximity of real boundary conditions, it is expected a better results than the others related works. This configuration allows measuring the MBV parameter and it is also expected to propose a new moisture buffer parameter intend to be more realistic to physical effects. At the moment, the apparatus was completely designed and has been assembled. All physical transducers that will be employed have been calibrated and the data acquisition software has been developed. In addition, an uncertainty analysis has been performed to assure the results.

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