

# Secondary Effects on Water Vapor Transport Properties Measured by Cup Method

Z. Pavlík, J. Fořt, J. Žumár, M. Pavlíková, and R. Černý

**Abstract**—The cup method is applied for the measurement of water vapor transport properties of porous materials worldwide. However, in practical applications the experimental results are often used without taking into account some secondary effects which can play an important role under specific conditions. In this paper, the effect of temperature on water vapor transport properties of cellular concrete is studied, together with the influence of sample thickness. At first, the bulk density, matrix density, total open porosity and sorption and desorption isotherms are measured for material characterization purposes. Then, the steady state cup method is used for determination of water vapor transport properties, whereas the measurements are performed at several temperatures and for three different sample thicknesses.

**Keywords**—Water vapor transport, cellular concrete, cup method, temperature, sample thickness.

## I. INTRODUCTION

WATER vapor transport and storage in porous building materials significantly affect the buildings performance and durability. Condensed water vapor can cause for example serious damage to thermally insulated building envelopes, roof structures, etc. Highly humid interior environment of buildings is also accompanied by negative health effects, related especially do mould growth. On the other hand, dry environment is also not very convenient for building occupants because of respiratory problems. Therefore, building engineers and researchers must deal with the problem of water vapor transport within the porous structure of building materials, and investigate the material parameters characterizing water vapor transport.

Diffusion of water vapor in air is presently well understood phenomenon. On the other hand, in porous building materials diffusion is more complicated, and while it takes place in air

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(in the pore space), it is impeded by the reduction of the accessible cross-section, adsorption effects on the pore walls and the tortuosity of the pore paths [1]. In modeling the water vapor transmission in porous building materials the methods of linear irreversible thermodynamics and linear theory of mixtures are usually employed. The simplest models applied in the practice reduce the generally n-component system to only two components, water vapor and the porous skeleton of the solid phase, and account for only one generalized thermodynamic force which is the gradient of either partial pressure or concentration of water vapor in the porous space [2]. We then have two relations for the flux of water vapor  $j_v$  ( $\text{kg/m}^2\text{s}$ )

$$j_v = -D \cdot \text{grad} \rho_v, \quad (1)$$

$$j_v = -\delta \cdot \text{grad} p_v, \quad (2)$$

where  $\rho_v$  ( $\text{kg/m}^3$ ) is the partial density of water vapor,  $D$  ( $\text{m}^2/\text{s}$ ) the diffusion coefficient of water vapor in the porous material,  $p_v$  (Pa) the partial pressure of water vapor,  $\delta$  (s) the water vapor diffusion permeability.

Assuming water vapor to be an ideal gas, we can write the equation of state in the form

$$p_v = \frac{\rho_v RT}{M}, \quad (3)$$

where  $T$  (K) is the temperature,  $R$  the universal gas constant,  $M$  is the molar mass of water vapor. Under isothermal conditions we obtain from (1)-(3) the following relation between the water vapor diffusion coefficient and water vapor diffusion permeability

$$D = \delta \frac{RT}{Mn}. \quad (4)$$

Besides  $D$  and  $\delta$  several other coefficients are used, for the sake of better clarity for the building practice. Among them, the water vapor diffusion resistance factor  $\mu$  (-) defined as [3]

$$\mu = \frac{D_a}{D} \quad (5)$$

is the most often used material parameter for description of water vapor transport properties of building components as thermal insulation boards, vapor-tight layers etc. Here,  $D_a$  ( $\text{m}^2/\text{s}$ ) is water vapor diffusion coefficient in air.

The above given procedure for determination of water vapor transport properties was originally derived for isothermal conditions only. However, the building envelopes are worldwide exposed to severe weather fluctuation, whereas the variation of temperature between + 40°C and -30°C is a realistic possibility. Temperature is one of the main forces for moisture movement and influences sorption characteristics of the both organic and inorganic building materials [4, 5]. Quite naturally it is to be expected that temperature variations have distinct effects on the moisture management strategy of the building envelopes. Increase of temperature induces greater mobility in the water molecules in any form of moisture and it is widely accepted that water vapor transmission through any material is a function of temperature [6, 7]. Under non-isothermal conditions, such as those prevailing in real environment of buildings, diffusion of water vapor may be enhanced as compared to isothermal conditions [8, 9]. Two main phenomena are responsible for this enhancement as described by Philip and deVries [10].

Normally, diffusive transport of water vapor is obstructed by the presence of liquid islands in the pore throats and diffusion is reduced at higher saturations. However, under a temperature gradient, a vapor pressure gradient develops in the gas phase and causes water to evaporate from one side of the liquid island, and diffuse in the gas phase to a liquid island of lower temperature where it condenses. Water flows through the liquid island as a result of differences in meniscus curvature between the two sides. The evaporation-condensation process repeats itself on the other side of the liquid island and the result is an enhanced diffusive flux through the medium. See [10] for the schematic description of the process.

The second enhancement mechanism proposed by Philip and deVries relates to the use of an average temperature gradient in Fick's law. The thermal conductivity of the solid phase is greater than that of the liquid phase, which in turn is greater than the thermal conductivity of the air phase. Therefore, the mean temperature gradient averaged over all three phases is smaller than the temperature gradient across the vapor-filled pores. Water vapor moves primarily through the air spaces where the higher local temperature gradient provides a driving force for the diffusion of water vapor.

Although the cup method was originally proposed for isothermal conditions only, it can be adapted for temperature dependent water vapor transport properties measurement easily. In [4] authors reported about application of "modified cup method" for measurement of temperature dependency of water vapor transmission properties of gypsum fireboard. They introduced simple and versatile technique that allows the user to vary the temperature condition of the cup test without altering the relative humidity. The five temperature levels under consideration were between 7°C and 43°C. The obtained results demonstrate that there is a steady exponential increase of water vapor transmission rate through both the materials tested with temperature. Since the applicability of the "modified cup method" was proved, we followed the similar procedure in our experiment.

## II. EXPERIMENTAL

### A. Studied Material

The measurements were performed on cellular concrete samples coming from company H+H Ltd., Czech Republic; its official product label is P2- 350.

### B. Determination of Basic Material Properties

The experimental assessment of matrix density  $\rho_{mat}$  (kg/m<sup>3</sup>), bulk density  $\rho_b$  (kg/m<sup>3</sup>) and total open porosity  $\psi$  (-) was done at first, in order to characterize the studied material. The experiments were done on cubic samples of side dimension 50 mm. The particular samples were firstly dried, and their dimensions and mass were precisely measured. In this way, the bulk density of the brick body was accessed. The matrix density was measured by helium pycnometry using the apparatus Pycnomatic ATC [11]. On the basis of the knowledge of the matrix density and bulk density, the total open porosity of the brick body was calculated [12].

### C. Measurement of Sorption and Desorption Isotherms

The dynamic device DVS-Advantage (Surface Measurement Systems Ltd.) was used for the measurement of adsorption isotherms of several types of building materials in this paper. The instrument measures the uptake and loss of vapor gravimetrically, using highly precise balances having resolution of 0.1  $\mu$ g. The partial vapor pressure around the sample is generated by mixing the saturated and dry carrier gas streams using electronic mass flow controllers [13]. The humidity range of the instrument is 0 – 98% with accuracy  $\pm$  0.5% at temperatures 5 – 60°C.

Before the measurements, the sample of studied material was dried at first, and maintained in desiccator during cooling. Then, the sample was put into the climatic chamber of the DVS-Advantage instrument and hung on the automatic balances in the special steel tube. The experiment was performed at 25°C. The sample was exposed to the following partial water vapor pressure profile: 0; 10; 20; 30; 40; 50; 60; 70; 80; 90 and 98% relative humidity. During the experiment, the DVS-Advantage instrument was running in dm/dt mode (mass variation over time variation) to decide when equilibrium was reached. A fixed dm/dt value of 0.0000% per min was selected for all relative humidity segments. This criterion permits the DVS software to automatically determine when equilibrium has been reached and complete a relative humidity step. When the rate of change of mass fell below the threshold over a determined period of time, the relative humidity set point proceeded to the next programmed level [14].

### D. Cup Method

The sample size for the cup experiments was 100 x 100 mm, whereas the samples thicknesses were 20, 30, and 50 mm. The measurement was carried under isothermal conditions at temperature levels 10, 20, 30, 40, 50°C. It was based on one-dimensional water vapor diffusion and measuring the diffusion water vapor flux through the specimen and measuring partial water vapor pressure in the air

under and above specific specimen surface. Water vapor transmission properties of a studied material were found by placing a specimen of the material on the top of a stainless steel cup, whereas the specimen was on the contact with the cup sealed by technical plasticine. The cup contained sorption material, in our case silica gel. The sealed cup was placed in a controlled climatic chamber and weighed periodically. The steady state values of mass gain or mass loss were utilized for the determination of the water vapor transfer properties. As one measurement for one temperature level was finished, the samples were removed from the cups, dried and the measurement was repeated for another chosen temperature.

Within the measurement, the partial water vapor pressures above silica gel in particular cups and partial water vapor pressure in the climatic chamber were continuously monitored by combined temperature/relative humidity mini-sensors (see Fig. 1 for the experimental arrangement). In the climatic chamber, constant values of chosen temperatures and 50% of relative humidity were maintained.



Fig. 1 Experimental arrangement

In Fig. 2, there are presented temperature values measured within the particular experiments.

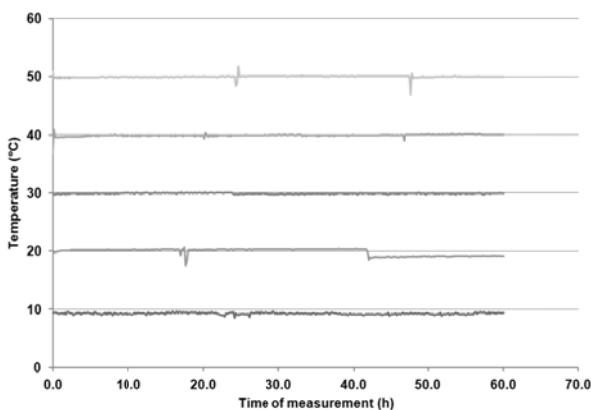


Fig. 2 Temperature variations within the performed experiments

Relative humidity in the climatic chamber varied mostly for temperature of 10°C (see Fig. 3). In this case, the partial water vapor pressure value corresponding to the steady state mass gain was used in the water vapor transmission properties

calculations.

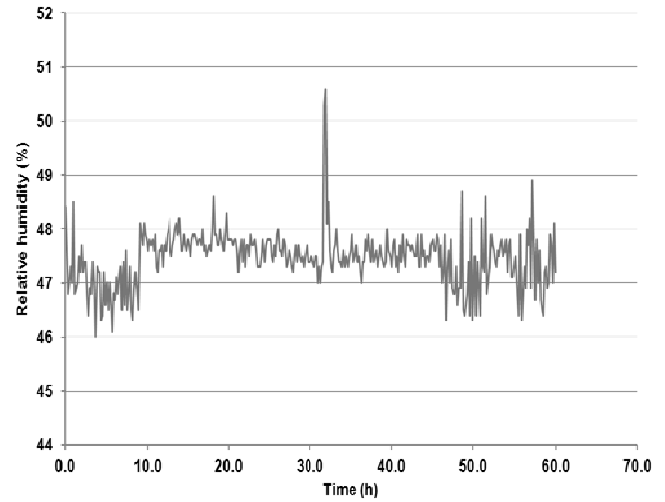


Fig. 3 Relative humidity measured within the experiment at 10°C

The water vapor diffusion permeability was calculated from the measured mass gain data according to the equation.

$$\delta = \frac{\Delta m \cdot d}{S \cdot \tau \cdot \Delta p_p} \quad (6)$$

where  $\Delta m$  is amount of water vapor diffused through the sample,  $d$  (m) is the sample thickness,  $S$  (m<sup>2</sup>) is the specimen surface,  $\tau$  (s) is the period of time corresponding to the transport of mass of water vapor  $\Delta m$ , and  $\Delta p_p$  (Pa) is the difference between partial water vapor pressure in the air under and above specific specimen surface.

Diffusion coefficient of water vapor  $D$  and water vapor resistance factor  $\mu$  were calculated according to the equations (4) and (5). In these calculations, the temperature dependence of water vapor diffusion coefficient in air  $D_a$  was accounted for according to the equation (7) formulated originally by Schirmer [15]

$$D_a = 2.306 \cdot 10^{-5} \frac{p_0}{p} \cdot \left( \frac{T}{273.15} \right)^{1.81} \quad (7)$$

where  $p_0$  (Pa) is ambient pressure of the measured sample place into the climatic chamber,  $p$  standard atmospheric pressure (101 325 Pa = 760 mm of Hg),  $T$  (K) absolute temperature. The ambient pressure in climatic chamber was within the performed experiments continuously monitored.

### III. RESULTS AND DISCUSSION

Basic material properties of researched cellular concrete are summarized in Table I. We can see that the measured value of bulk density corresponds with the producer indication of the studied product. The material exhibited high total open porosity as well as relatively high matrix density.

TABLE I  
 BASIC PROPERTIES OF STUDIED MATERIAL

Bulk density (kg/m <sup>3</sup> )	Matrix density (kg/m <sup>3</sup> )	Total open porosity (%)
348	2 400	85

The sorption and desorption isotherms measured by DVS-Advantage device are graphed in Fig. 4. The obtained data exhibited high storage capacity of cellular concrete for water vapor molecules as well as high hysteresis of sorption/desorption process.

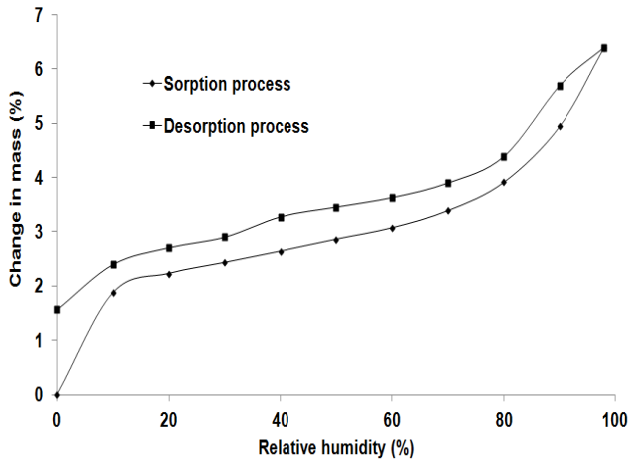


Fig. 4 Sorption and desorption isotherms of cellular concrete

Conditions of the sorption/desorption experiment describes Fig. 5. From this figure, time of sample exposure to particular relative humidity can be observed, as well as the achievement of steady state values of sample mass.

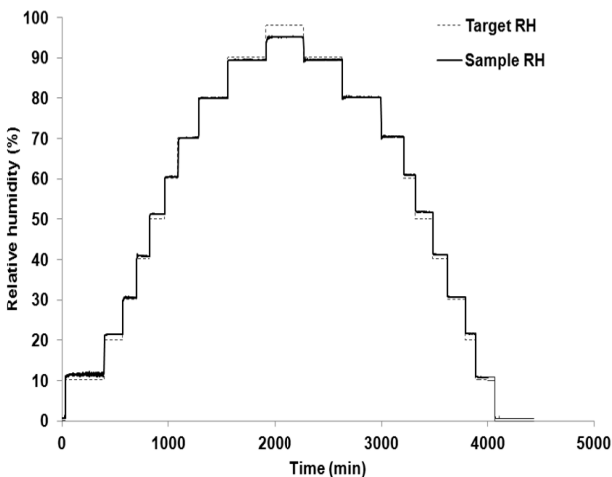


Fig. 5 Conditions of sorption/desorption experiment

In Fig. 6, there are presented typical mass gains of the sample for specific temperature levels. We can observe high influence of temperature on water vapor transport that was systematically enhanced with temperature increase.

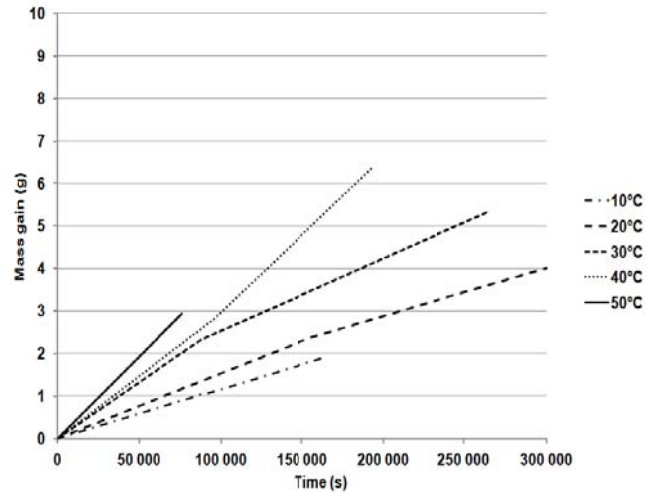


Fig. 6 Mass gains of the sample in dependence on temperature

Water vapor diffusion permeability plotted as function of temperature is given for three studied thicknesses of the samples in Fig. 7. The obtained data represent average value from the measurement of five samples. Also in this case one can observe high effect of temperature on the water vapor flux and consequently on water vapor diffusion permeability.

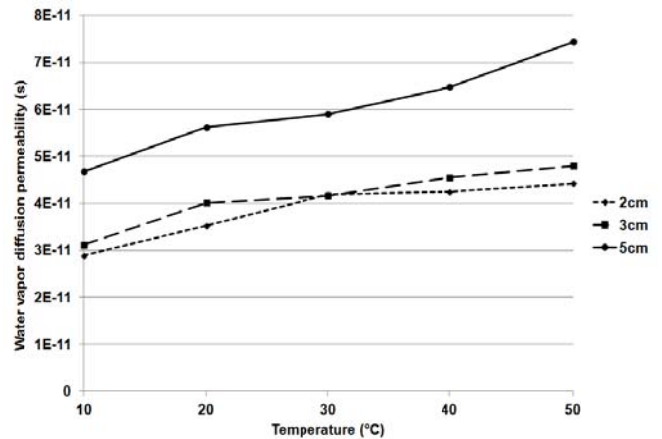


Fig. 7 Water vapor diffusion permeability of cellular concrete

Diffusion coefficient of water vapor for studied material is presented in Fig. 8. One can see similar course of this material function as in Fig. 7.

Water vapor diffusion resistance factor determined in dependence on temperature taking into account equation (7) describes Fig. 9. In this case, the highest resistivity to water vapor transmission was observed for lower temperatures what is again in agreement with previous results.

Concerning the sample thickness within the measurement, the highest values of water vapor transport properties were calculated for samples having thickness of 5 cm. On the other hand, the lowest values were obtained for sample thickness of 2 cm. In case of water vapor diffusion resistance factor, the results were - in accordance with its definition - opposite.

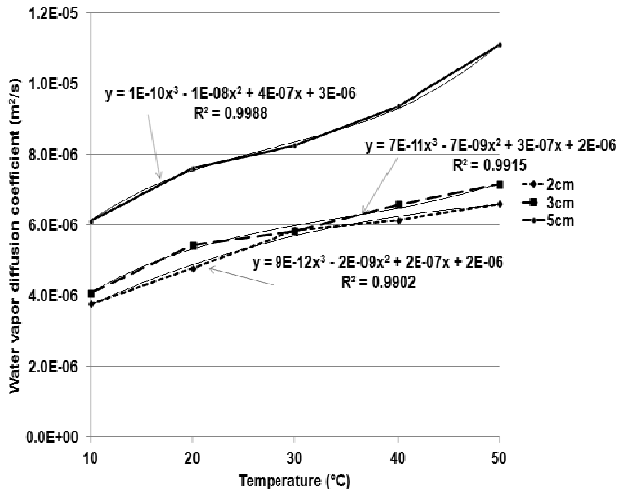


Fig. 8 Diffusion coefficient of water vapor for cellular concrete

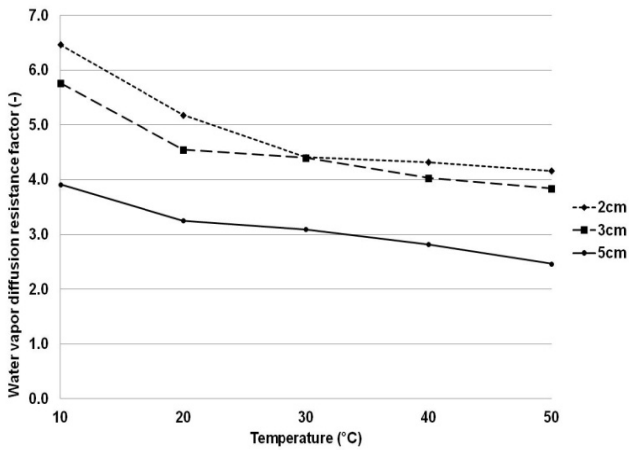


Fig. 9 Water vapor diffusion resistance factor of cellular concrete

For further illustration of the sample thickness effect on evaluation of the performed experiment, typical mass gains of the samples having different thickness are for two chosen temperatures presented in Figs. 10, 11.

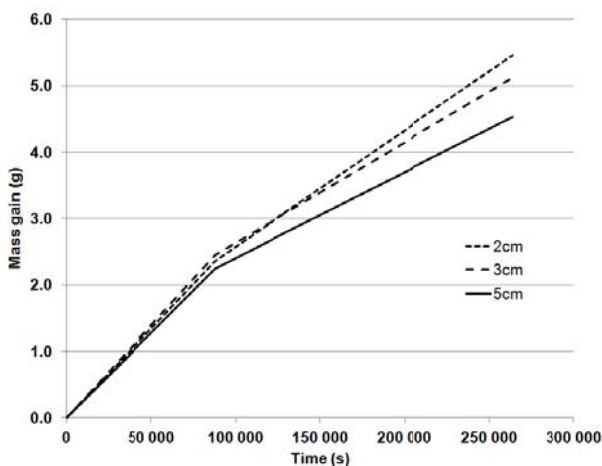


Fig. 10 Mass gains of the samples of specific thicknesses for 30°C

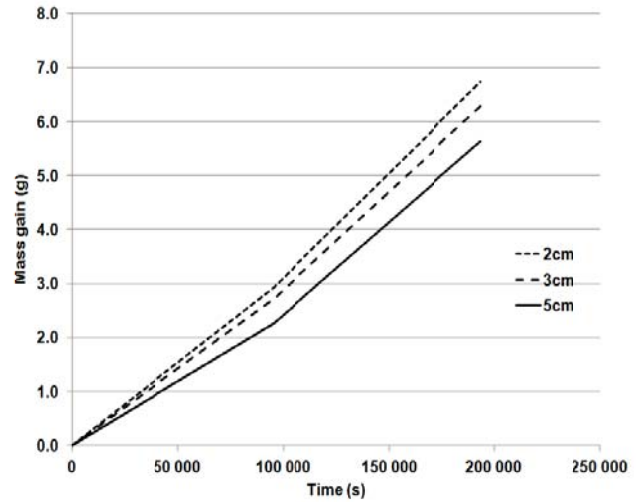


Fig. 11 Mass gains of the samples of specific thicknesses for 40°C

The data presented in Figs. 10, 11 show that the total water vapor flux decreases with the sample thickness but more slowly than it would correspond to the decreasing gradient of partial water vapor pressure in Eq. (6). Therefore, one can conclude that some additional effects on water vapor transport could appear in this case, possibly the water vapor diffusion resistance on the humid air/porous material surface or the diffusion resistance of the stagnant air layer in the cup.

#### IV. CONCLUSION

In this paper, determination of water vapor transmission properties of cellular concrete in dependence on temperature was done. The proposed measuring procedure based on slight modification of cup method proved its applicability for such type of analysis. The obtained data revealed an important effect of temperature on water vapor transport in studied material. A similar performance can be expected also for other porous building materials. With the increasing temperature, the water vapor diffusion coefficient and water vapor diffusion permeability increased (contrary to the decreasing water vapor diffusion resistance factor but this was in accordance with its definition). This finding and measured parameters represent a valuable information for practical application of researched material in the conditions of unfavorable climatic loading. The presented results also pointed out the substantial influence of sample thickness on the calculated water vapor transmission properties. This feature should always be considered within the evaluation of cup experiments.

#### ACKNOWLEDGMENT

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