Experimental investigation of the influence of the relative humidity of air on the drying process of porous building materials

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Abstract. The paper presents the experimental analysis of influence of the relative humidity of drying air on the drying process of porous building materials. Investigations were conducted by applying the stand which worked in a closed-loop flow and equipped with the following elements: the cooler (condenser), fan with variable rotation speed, throttle, humidifier, heater and control and acquisition systems. During experiments the temperature and velocity of air were equal to 40 ℃ and 3 m/s, respectively, while its relative humidity was varied in the range from 16 to 40%. Two different materials were investigated, i.e., the red brick and mortar. Specimens were placed in the duct and had the top surface exposed to flowing air. Variations of the moisture content and temperature in considered building materials were measured by system of two force meters and thermocouples, respectively. The relative humidity of drying air significantly influenced on the drying process of building materials. The increase of the relative humidity of drying air resulted in the rise of the drying duration, the decrease of the drying rate and the increase of the level of temperature plateau (i.e., equilibrium temperature) which resulted from evaporation in the medium. Moreover, for the mortar drying rates were found much slower than for the red brick.

1. Introduction

Many experimental investigations related to moisture transport in porous materials or drying of these materials were reported in literature [1-8]. These studies were concerned on either the analysis of influence of different factors on the moisture transfer/drying process, generation of data required for the validation of mathematical and numerical models or indirect measurements of hygro-thermal properties of porous materials. Different materials were investigated, different drying techniques were studied, and different measurements techniques and concepts of the experimental stand were applied. This brief review is concentrated only on measurements related to moisture transport in porous building materials and its applications.

Many studies of the influence of different factors on hygro-thermal transport phenomena in building materials were carried out to find out hygro-thermal behavior of these materials. They are especially important in the case of new building materials, e.g., hemp concrete, because allow for finding of their potential application fields and benefits of their usage. For example, Colinart et al. [1] performed numerical and experimental analysis of the hygrothermal behavior of a coated hemp concrete wall. A special facility was designed to measure mass variations as well as the temperature and relative humidity.
fields within coated or multilayered samples on the material and wall scale. In the next paper Chikhi et al. [2] studied the behavior of a block of the cement mortar, subjected to variable external temperature and humidity conditions. The aim of the study was to understand the hygro-thermal behavior of construction walls, to make an adequate design according to the climatic parameters and thus to improve the control of the energy used for heating. In turn, Karagiannis et al. [3] performed experimental and numerical investigations drying kinetics of building materials (e.g., stones, bricks and mortars) saturated with capillary absorbed water. The performed investigation might be very useful in the understanding the causes of decay of building materials and in saving cost and improving the energy efficiency of constructions.

When new heat and moisture transfer models are proposed their credibility analyses should be carried out. The aim of these analyses is to validate proposed models, i.e., to proof their accuracy. Such investigations were performed in many papers. For example, Colinart et al. [1] developed the coupled 1D heat and moisture transfer model. Results of simulations were compared to experimental ones obtained on a specially designed experimental stand. Karagiannis et al. [3] validated a first order drying kinetics mathematical model applied for the simulation of the drying process of capillary absorbed water of building materials. They generated data for validation using the semi-industrial air dryer which consisted of an air tunnel with square cross-section. Van Belleghem et al. [4] proposed the new 3D heat and mass transfer model in porous building materials which was implemented in the commercial software. The model was validated using convective drying experiment, in which the saturated with water ceramic brick sample was dried by flowing dry air over one side of the sample surface. The temperature and relative humidity measurements at different depths in the sample, moisture distribution profiles and mass loss measurements were compared with simulation results. Recently, Busser et al. [5] carried out the review of studies in which the results obtained with numerical models and experimental data were compared. In their paper influence of the experimental parameters and boundary and initial conditions as well as modeling of physical phenomena on the agreement between the experimental measurement and the numerical results was discussed.

In the case of estimating hygro-thermal material proprieties of building materials many indirect methods were proposed. Among them were methods which based on observed (experimental) data and identification techniques (hygro-thermal inverse problems). In these methods parameters (e.g., the relative humidity, moisture content, temperature, etc.) registered during specially designed experiments were applied in inverse algorithms to find hygro-thermal properties, e.g., sorption curve or vapour permeability. The experiment design in these methods, e.g., applied boundary and initial conditions during experiments, the type of sensors as well as their quantity and location, is of importance and influence on the accuracy of estimated parameters. The problem of optimal configuration of the experimental method was studied by Berger et al [6]. They discussed the concept of Optimal Experiment Design for the estimation of material properties of porous walls which was based on in-situ measurements and identification method. The proposed optimal conditions ensure to provide the maximum accuracy of the identification method and thus the estimated parameters. Busser et al. [7] proposed a dynamic measurements and identification method for the determination of the vapour permeability and moisture sorption curve. They developed the experimental facility which enabled measurements of the relative humidity within the material and the total moisture content at the same time. A novel indirect method for the determination of the water retention curve from drying tests performed on capillary active materials was proposed by Bianchi et al. [8]. The method was based on the lumped parameter analysis, assuming approximately uniform temperature and water content inside the specimen and at the specimen surface. Moreover, they applied non-destructive techniques (i.e., the gravimetric analysis, infrared thermography) for measuring water content, drying rate and surface temperature during time for a set of material samples.

In this paper the previously developed experimental stand [9] with the closed-loop flow is applied for investigation of drying process of two building materials available on the Polish market. The paper is organized in the following way. At first the stand, samples and measurement protocol are briefly
described. Then results of measurements, i.e., relative moisture contents and variations of temperature in two locations inside samples are shown. At the end studies are summarized.

2. Experimental investigation

Experimental investigations of influence of the relative humidity of drying air on the drying process of porous building materials were carried out with fixed temperature and velocity of air equal to 40°C and 3 m/s, respectively. The relative humidity of air used for drying was varied in the range from 16 to 40%. Two different porous building materials were investigated, i.e., the red ceramic brick and mortar sample. The specially developed stand [9] was used to experimentally investigate the drying process of these materials.

![Diagram of experimental stand](image-url)

Figure 1. Schematic of the closed-loop flow experimental stand: a) side and b) top view as well as cross-section of the specimen pocket with main dimensions: c) side and d) perpendicular to the flow direction view (where: 1 – cooler/condenser; 2 – fan; 3 – heater; 4 – humidifier; 5 – flow stabilizer; 6 – integrated velocity, temperature and humidity transmitter; 7 – force meter; 8 – sample; 9 – integrated temperature and humidity transmitter; 10 – throttle) [9].

2.1. Experimental stand

The development of the experimental stand used for investigation of influence of the relative humidity of drying air on the drying process of porous building materials was described in detail in [9]. The schematic of the stand is presented on figure 1. Its main features were following:

- Closed-loop air flow,
- Ability to control of the velocity, temperature and relative humidity of drying air in the wide range,
• Ability to measure temporal variations of the mass of the sample and the temperature in several points of the sample,
• Two parallel measurements channels which allow for two measurements at the same time.

The sample was located in the specially designed holder with force meter (see figure 1c) and was thermally insulated and made waterproofed at side and bottom walls. Its top wall was in the same plane as the bottom boundary of the channel. This wall was the only surface in contact with drying air. Therefore, heat and moisture were transported between the sample and drying medium only through the top wall. Temporal variations of temperature in several points of the sample were measured applying 2×0.2 mm T-type wire thermocouples with PFA insulation and external dimensions of 1.3×2.0 mm, located in drillings in the sample. The IR camera might be also applied to measure temperature distribution at the top wall of the sample.

The stand was equipped with the data acquisition and control systems developed based on the measurement and automation devices which provide analog and digital inputs and outputs as well as on the in-house software developed in the LabView environment. The control time step in the control system was 100 ms, while the acquisition time step in the data acquisition system was 6 s. The measurement of drying air parameters took place 1.5 cm above the duct bottom surface and 800 mm before the specimen.

2.2. Specimens
Specimens for investigation of influence of the relative humidity of drying air on the drying process were prepared as cuboids of dimensions 250×120×65 mm made of the red ceramic brick and mortar. Ceramic bricks were easily available building materials which came from the Polish market. Mortar specimens were made of market available masonry mortar dry mix and water. They were formed in wooden forms. Next mortar specimens were conditioned in the surroundings for more than one month to obtain the proper mortar binding. In each specimen 5 thermocouples were placed 60 mm from the leading surface, 32.5 mm from the side surface and every 10 mm from the top (drying) surface. Before each measurement specimens were fully submerged in the water bath for 24 h to saturate it with liquid moisture.

| Mean value of temperature (°C) | Standard deviation of temperature | Mean value of relative humidity (%) | Standard deviation of relative humidity | Mean value of velocity (m/s) | Standard deviation of velocity |
|-------------------------------|----------------------------------|------------------------------------|---------------------------------------|----------------------------|-------------------------------|
| 40.01                         | 0.21                             | 16.16                              | 2.61                                  | 3.08                       | 0.07                          |
| 39.99                         | 0.18                             | 20.34                              | 1.01                                  | 3.07                       | 0.07                          |
| 40.00                         | 0.17                             | 30.66                              | 0.79                                  | 3.15                       | 0.07                          |
| 40.00                         | 0.29                             | 40.27                              | 0.59                                  | 3.09                       | 0.08                          |

2.3. Drying measurement of the ceramic brick
In the first experimental series the red ceramic brick was considered. Measurements were carried out with four relative humidity of drying air, i.e.,
• 16% – the lowest operational value of the relative humidity for the stand for drying air at 40°C (for these drying air parameters the dew point temperature was equal to 9.4°C, control of the relative humidity at the stand below 16% was observed difficult due to very low working parameters of the cooler/condenser),
• 20%,
• 30%,
• 40% – the highest practically reasonable relative humidity of drying air at 40°C for the real drying processes in the field condition (for these drying air parameters the dew point temperature was equal to 23.8°C, in hot climates the walls have maximal temperatures up to 20-
25°C, higher values of the relative humidity of drying air might lead to moisture condensation on walls which are drying).

Table 1 presents stability indicators of drying air state, i.e., the mean value and standard deviation of controlled parameters of drying air. The standard deviation for the temperature was approx. 0.2°C which is similar value to standard deviations presented in literature [4]. The standard deviation of the relative humidity was decreasing with the rise in the mean value of the relative humidity which resulted from the increase of the hygric inertia of air with the rise in its moisture content. The standard deviation of the velocity was stable and on the low level, i.e., under 0.1 m/s.

Table 2. Relative moisture content after 24 h and the drying time required to achieve the relative moisture content of 0.3 for the ceramic brick.

| Relative humidity of drying air (%) | Relative moisture content after 24 h | Drying time to relative moisture content of 0.3 (h) |
|------------------------------------|------------------------------------|-----------------------------------------------|
| 16                                 | 0.32                               | 25.20                                         |
| 20                                 | 0.43                               | 34.37                                         |
| 30                                 | 0.44                               | 45.37                                         |
| 40                                 | 0.56                               | 62.83                                         |

Figure 2 presents temporal variations of the relative moisture content for drying of the ceramic brick for different relative humidity of drying air.

Figure 2 presents temporal variations of the relative moisture content for drying of the ceramic brick for different relative humidity of drying air, where the relative moisture content was defined as the ratio of the current to the initial moisture content. Table 2 shows relative moisture contents after 24 h of drying process as well as drying times required to achieve the relative moisture content equal to 0.3 for different relative humidity of drying air. In first stage of the drying process drying rates were similar for all values of the relative humidity of air. This was related to the rapid evaporation from the top surface of the sample. Differences between drying rates for relative humidity of 16, 20 and 30% were on the level of measurement uncertainty but for 40% the drying rate was the smallest which probably was due to water condensation on the surface of the sample. Moreover, for 40% the sample first increase its temperature to the equilibrium temperature in the porous structure (see Fig. 3), which additionally hindered the drying. In the second drying stage it was found that the increase of the relative humidity of air led to the increase of the drying time by 35% between two consecutive measurement points as well as the decrease in the drying rate.

Figure 3 presents temporal variations of temperature of the sample measured in two different points, i.e., 10 and 30 mm from the top surface of the sample. In the first stage of the drying when evaporation from the top surface of the sample was dominant, the level of temperature plateau (i.e., equilibrium temperature in the porous medium) which resulted from evaporation in the porous building material was found to increase with the rise in the relative humidity of drying air. This effect was related to the change of the wet bulb temperature of drying air with the variation of its relative humidity. For the relative
humidity lower than 20% the sample temperature in the first drying stage decreased from the initial one to the equilibrium temperature in the porous medium. Then in the second drying stage when the diffusive transport of moisture from the inside of the sample was dominant the temperature was slowly approaching to the asymptotic steady state temperature. For the relative humidity of 30% the initial temperature was close to the equilibrium temperature in the porous medium and then started to increase to the asymptotic steady state temperature. For the relative humidity of 40% the temperature rose to the equilibrium temperature in the porous medium and then again was approaching to the asymptotic steady state temperature.

Figure 3. Temporal variations of temperature measured by thermocouple located: a) 10 and b) 30 mm from the drying surface for drying of the ceramic brick for different relative humidity of drying air.

2.4. Drying measurement of the mortar

The second series of measurements was carried out for the mortar sample. Due to low drying rates for this material and long measurement times only two relative humidity of drying air were examined, i.e., 20% and 40%. Table 3 presents stability indicators of drying air state, i.e., the mean value and standard deviation of controlled parameters of drying air. The standard deviation of the temperature was under 0.2°C which was similar as in the previous measurements for the red brick. Again, the standard deviation of the relative humidity was decreasing with the increase of the mean value of the relative humidity and it was lower than 0.8% which was better than for similar measurements presented in literature [4]. The standard deviation of the velocity again was stable and on the low level, i.e., under 0.1 m/s.

| Mean value of temperature (°C) | Standard deviation of temperature | Mean value of relative humidity (%) | Standard deviation of relative humidity | Mean value of velocity (m/s) | Standard deviation of velocity |
|--------------------------------|----------------------------------|-----------------------------------|----------------------------------------|-----------------------------|-------------------------------|
| 39.97                          | 0.13                             | 20.47                             | 0.75                                   | 3.22                        | 0.10                          |
| 40.01                          | 0.18                             | 40.17                             | 0.28                                   | 3.17                        | 0.07                          |

Table 4. Relative moisture content after 24 and 192 h of the drying of the mortar sample for different relative humidity of drying air.

| Relative humidity of drying air (%) | Relative moisture content after 24 h | Relative moisture content after 192 h |
|-----------------------------------|-------------------------------------|-------------------------------------|
| 20                                | 0.71                                | 0.54                                |
| 40                                | 0.73                                | 0.63                                |

Figure 4 presents temporal variations of the relative moisture content of the mortar sample, while table 4 shows the relative moisture content after 24 and 192 h of the drying of the mortar sample with different relative humidity of drying air. During drying process rapid removal of moisture in the first few hours was observed. Liquid moisture at the top surface and close to it was quickly evaporated during
this period. Unfortunately, after this stage the drying process rapidly slowed down and after 8 days of drying even the relative moisture content of 0.5 was not obtained. Very low drying rates in the mortar sample as compare to the red brick may be related to different mechanisms of moisture absorption and accumulation in the mortar than in the brick. In ceramic bricks most of moisture is absorbed by action of capillary forces and occupies pores. In the mortar most of moisture is probably chemically absorbed and bound in its structure. This explanation is confirmed by temperature temporal variations presented on figure 5. After rapid evaporation of moisture in the first very short stage of drying, the sample temperature was increasing to the steady state temperature much faster than for the red brick. Moreover, the mortar has a lower vapor permeability than the red brick which additionally hinder moisture transfer from the inside of the sample to the drying medium.

**Figure 4.** Temporal variations of the relative moisture content for the drying of the mortar sample for different relative humidity of drying air.

**Figure 5.** Temporal variations of temperature measured by thermocouple located: a) 10 and b) 30 mm from the drying surface for drying of the mortar sample for different relative humidity of drying air.

### 3. Conclusion

In this paper experimental investigations of influence of the relative humidity of drying air on the drying process of porous building materials was presented. Two different materials were examined, i.e., the ceramic red brick and mortar. Measurements were carried out for four and two different relative humidity of drying air, respectively. Results of experimental measurements show that the relative humidity of drying air has significant impact on the drying process. For the red brick the increase of the relative humidity of drying air by 10% resulted in the rise of the duration of the drying process by approx. 35%. The relative humidity of drying air affected also the level of temperature plateau in porous building materials. This level increased with increasing of the relative humidity of drying air. For mortar sample the drying rates were found to be much slower than for the red brick due to different mechanism of moisture absorption and accumulation in mortar as well as different hygric parameters than for the ceramic brick.

In the future more materials will be examined, e.g., silicate bricks. Additionally, influence of other parameters of drying air, e.g., the temperature and velocity, will be investigated separately and in
superposition. Obtained data of future works will be applied for the validation of mathematical and numerical models of heat and moisture transfer in porous building materials which are currently under development [10, 11] and for optimization of the drying process of masonry walls.

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