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Research of Foam Gypsum Drying Process and Heat Flow Transfer

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Nowadays the house building technical progress is aimed to use materials with preferable properties. Foam gypsum on gypsum basis is one of these materials, and drying of foam gypsum is an obligatory condition of technological process. This drying process and its energy consumption have been researched theoretically and experimentally in this paper. The characteristic parameters of foam gypsum drying process depending on volume density of material have been determined. Heat flow transfer in foam gypsum drying process has been researched experimentally. Mathematical model of heat flow transfer of drying process has been developed. The thickness of layer for effective drying has been determined.

1. Introduction

Energy saving for housing and building materials' production is an important issue in Latvia and other countries. Huge primary energy consumption and CO_2 emissions are characteristic for production of various modern insulation materials. Latvia is rich with gypsum deposit and it is possible to obtain wide range of volume density of gypsum. Foam gypsum volume density is in range 250÷900 kg/m³ and it can be used as heat and sound insulation material (Brencis, Skujans et al., 2011). Foam gypsum drying is an obligatory condition of technological process, and it influences both physical properties of material (density, heat transfer coefficient, etc.) and mechanical properties significantly (strength indicators of dried gypsum are many times higher than indicators of wet gypsum sample) (Iljins, Skujans et al., 2009; Defraeye, Blocken et al., 2012). Porous material drying is a process of energy and time consumption. Decrease of energy consumption during the drying process may give a significant input in reduction of financial expenses. Mass and heat transfer processes are simultaneously taking place during the drying, and it is necessary to develop a simple drying model based on experimental data. Foam gypsum as well as other materials' drying processes can be viewed in two phases. The first phase includes a constant drying speed (Mujamdar, 1987), which is determined by parameters of surrounding environment – air moisture, temperature and flow speed (Dincer, Dost et al., 1995; Musielak, Kieca et al., 2009; Defraeye, Blocken et al., 2012). The further drying speed is determined by diffusion processes in the research material (Iljins, Skujans et al., 2009). Moisture diffusion coefficient is one of the most important parameters of drying of capillary porous materials. Its experimental determination has been done for wood materials (Fotsing, 2004), food (Togrul and Pehlivan 2003), clay materials (Chemkhi, Zagruoba et al., 2005), but there is no data about moisture diffusion coefficient for foam gypsum and its dependence on porous material volume density.

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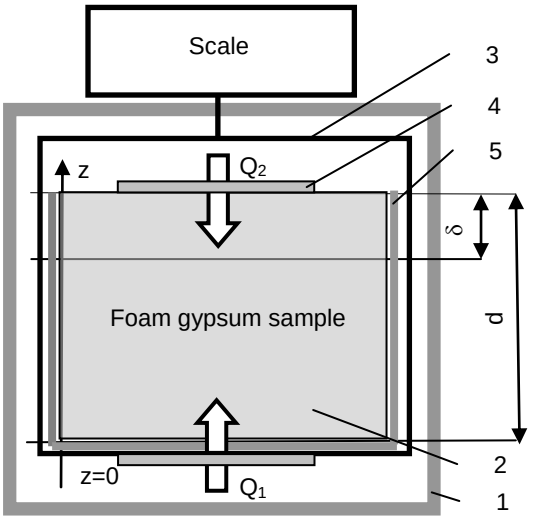

Figure 1: The scheme of experimental setup und theoretical calculations: 1- drying box, 2- sample, 3- scale hang 4- heat flow sensor, 5- steam barrier

2. Materials and methods

In order to check the obtained theoretical results, the foam gypsum samples were produced according to specific technology (Skujans et al., 2007) and the research was carried out on their drying using laboratory made experimental setup (Figure 1). The equipment consists of a drying box (ILV 115-T STD Pol Eko-Aparatura), which keeps the temperature stable. Immediately after making the foam gypsum sample, is placed in the scale cup (scale KERN FKB 16K 0,2 accuracy $\pm$ 0.2 g). The temperature of air and the sample, according to experiment tasks, are measured with K-type thermo-pairs. Heat flows are measured by accurate flow sensors. Measuring data are read and recorded in computer. Temperature during the drying experiment is stabilized close to room temperature, at relative air humidity of 30-40% and air velocity of 0.02 m/s near the location of the sample surface. The moisture content of foam gypsum is calculated according to the following formula:

$$W = \frac{m}{V}, \qquad (1)$$

where m – mass of water in the sample, kg
V – volume of foam gypsum sample, m^3.

Generally the initial moisture content of foam gypsum is high W = 200 – 350 kg/m^3 (or 35 – 50% in relation to the dry sample).

According to our theoretical calculations the drying time of the sample is inversely proportional to the square of its thickness (2). Therefore the thickness of the sample was chosen d = 2 cm, so that the length of the sample drying period would not exceed one week. All the surfaces of the sample, except the top surface through which the moisture evaporates are covered with a steam barrier (Figure1 -5). During the process of drying the average moisture content of the sample was determined by weighing it with scales. The amount of heat consumed during the process of drying was measured with heat flow sensors which were glued to the top and bottom surfaces of the sample. During the process of drying the surface temperatures and the temperatures inside the sample at the depth of 1 and 2 mm from the top surface were measured by K type thermo-pairs.

3. Theoretical research

In many cases in scientific literature drying theoretical models, even irrespective of the sphere of application, are based on a simple solution of Fick's diffusion equation (Togrul and Pehlivan, 2003). However, they are not able to describe the changes of the material moisture in time accurately enough (El-Beltagy et al. 2007), if the initial moisture content of the material is high – approximately 200 - 400 kg/m^3 free unbound water. Therefore we offer to describe the process of drying on the basis of solution of diffusion equation in two interrelated stages with different boundary conditions at each stage (Iljins, Skujans et al., 2009).

Under such conditions it is expected that initially (while there is water in the pores of the material) evaporation will take place at a constant speed, which is determined not by the sample material properties, but by the temperature and relative humidity of the surrounding air.
In course of time the sample dries and after a certain period we called it t_{cr} (Iljins, Skujans et al., 2009). When the first stage of sample drying is completed, moisture has reached the equilibrium moisture level W_0 on the sample surface z=d. Starting from this time t_{cr}, the sample has entered the second stage of drying in which the drying speed $\varphi(t)$ is determined by diffusion speed (depending on physical parameters of the sample material), and it reduces exponentially depending on time. Thus the average moisture content in the sample can be calculated by these expressions:

$$< W(t) >= \begin{cases} \frac{1}{d}\int_0^d W_I(t;z)dz = W_S - \frac{\varphi \cdot t}{d}, & if \quad t < t_{cr}; \\ \frac{1}{d}\int_0^d W_{II}(t;z)dz = W_0 + \frac{2}{\pi}\sum_{n=0}^{\infty}\frac{(-1)^n A_n}{2n+1}\cdot exp\left(-\frac{\pi^2(2n+1)^2}{4d^2}D(t-t_{cr})\right), & if \quad t > t_{cr}. \end{cases} \quad (2)$$

where

$$A_n = \frac{(-1)^n}{\pi}\left(\left(W_S - W_0 - \frac{\varphi}{d}t_{cr} + \frac{W^*}{6}\right)\cdot\frac{4}{2n+1} - \frac{2W^*}{2n+1}\cdot\left(1 - \frac{8}{\pi^2}\cdot\frac{1}{(2n+1)^2}\right) - \right.$$

$$\left. - \frac{8W^*}{\pi^2}\sum_{k=1}^{\infty}\frac{2n+1}{k^2}\cdot\frac{1}{(2k)^2-(2n+1)^2}\cdot exp\left(-\frac{\pi^2 k^2}{d^2}Dt_{cr}\right)\right)$$

$W_I(t, z)$, $W_{II}(t, z)$ – sample moisture content depending on time t and coordinate z in the first and second stages of drying, kg/m^3;
d – thickness of the sample, m;
φ - drying speed kg/(m^2 s) ;
D – diffusion coefficient, m^2/s;

W_s, W_0, W* - respectively initial, equilibrium moisture (content), $W^* = \frac{\varphi \cdot d}{D}$, kg/m^3;

Using the comparison of theoretical expressions (2) and experimental data, it is possible to calculate the unknown values t_{cr}, φ, D of the models with the least square method. The equilibrium moisture W_0 cannot be determined by this method, therefore it is assumed to be equal to zero.
In the presented model it is assumed that drying takes place from the surface of the sample, which thickness is infinitely small.
However, taking into account the high level porosity of foam gypsum samples, it is expected that drying will partly take place also from the pores which are located close to the surface of the sample. In the first approximation it can be assumed that this intensity of drying will decrease exponentially in the direction towards interior of the sample. The power density used for drying depending on the coordinate z will be calculated according to the formula:

$$q(z) = q \cdot exp(-\frac{d-z}{\delta}), \quad (3)$$

where q – power density used in the drying process on the sample surface z=d (Figure 1), W/m^3;
δ – effective drying depth, m.

Then according to the first stage of drying, where the drying speed is assumed to be constant, it is possible to develop a one dimensional stationary model for the temperature calculation inside the sample (Figure1-2). The model contains Laplace's equation, boundary condition on the bottom surface of the sample z=0 and boundary condition on the top surface of the sample z=d.

$$\frac{\partial^2 T}{\partial z^2}+\frac{q(z)}{\lambda}=0\,; \qquad \lambda\frac{\partial T}{\partial z}\Big|_{z=0}=\alpha_1(T|_{z=0}-T_0)\,; \qquad -\lambda\frac{\partial T}{\partial z}\Big|_{z=d}=\alpha_2(T|_{z=d}-T_0)\,, \quad (4)$$

where λ – sample thermal conductivity W/(m K);

α_1 – heat transfer coefficient from the bottom surface of the sample, W/(m^2 K);

α_2 – heat transfer coefficient from the top surface of the sample, W/(m^2 K).

T_0 – surrounding temperature, °C;

Solving the system (4) following solution is obtained:

$$T(z)=T_0+Az+B+\frac{q}{\lambda}\delta^2\,exp(-\frac{d-z}{\delta})\,, \quad (5)$$

where

$$A=-\frac{q\delta}{R_T}\left(\frac{\delta}{\lambda}\left(1-exp(-\frac{d}{\delta})\right)\right)+\frac{1}{\alpha_2}+\frac{1}{\alpha_1}exp(-\frac{d}{\delta})\,;\; B=-\left(\frac{q\delta+\lambda A}{\alpha_2}+\frac{q\delta^2}{\lambda}+Ad\right);\; R_T=\frac{1}{\alpha_1}+\frac{1}{\alpha_2}+\frac{d}{\lambda}\,.$$

The amount of supplied heat flow (Figure 1) Q (W/m^2) can be calculated by using the boundary conditions (4)

$$Q_1=\lambda\frac{\partial T}{\partial z}\Big|_{z=0}=q\delta\,exp(-\frac{d}{\delta})+\lambda A\;; \qquad Q_2=-\lambda\frac{\partial T}{\partial z}\Big|_{z=d}=-q\delta-\lambda A\,. \quad (6)$$

Total amount of supplied heat

$$Q=Q_1+Q_2=-q\delta\left(1-exp(-\frac{d}{\delta})\right)=-\varphi L\,, \quad (7)$$

where L – latent heat of moisture drying from foam gypsum surface, J/kg.

Comparing the theoretical model with experimental data unknown values δ and L of the model can be calculated with the least square method.

4. Experimental part

To test theoretical models, foam gypsum drying experiments were carried out according to the experiment scheme shown in Figure1. Detailed results of the experiments are shown for one foam gypsum sample with a thickness of 2 cm and volume density of 345 kg/m^3 in dry state. The volume density mentioned above is within the optimal range (250 – 450 kg/m^3) in terms of the use of foam gypsum as heat insulation and sound absorption material.

Comparing the expression (2) with the experimental data of sample weighing during the drying process (Figure 2a) the average moisture drying curve is obtained, which has two explicit drying stages. The following drying parameters are determined for the given sample: diffusion coefficient D=4.79·10^{-9} m^2/s; drying speed φ=3.91·10^{-5} kg/(m^2/s); length of first stage t_{cr}=1.13 d.

Using measurements of the sample temperature and obtained heat (Figure 2b and 2c), as well as the calculated drying speed φ, it is possible to determine δ with the least square method, which represents the thickness of the layer (Figure 1) from which an effective drying takes place. Whereas from the expression (7) it is possible to calculate the latent heat L of foam gypsum drying.

The obtained results are as follows:

δ=3.2 mm, L=1.77·10^6 J/kg. The obtained latent heat is lower than water evaporation heat at a temperature of 20 °C (2.45·10^6 J/kg), since drying here takes place in the foam gypsum surface, which

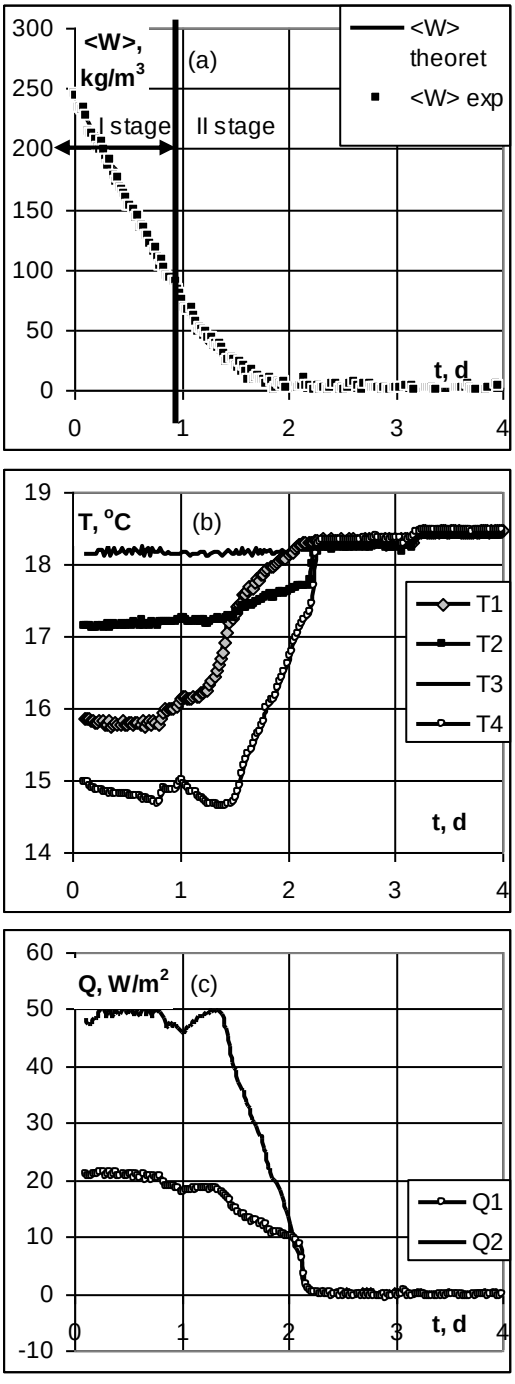

Figure 2: (a) average theoretical and experimental moisture amount of the sample, (b) the sample surfaces' (T2 and T3) 1 mm (T1) and 2 mm (T4) depth temperatures, (c) heat flow through sample surfaces (Q1 at z=0, Q2 at z=d) depending on drying time.

differs from regular evaporation. In a denser sample of foam gypsum (ρ=1055 kg/m^3 in dry state) the results are: δ=0.69 mm; L=2.02·10^6 J/kg respectively. It shows that the calculated parameters depend on the volume density of the foam gypsum sample. The latent heat of foam gypsum drying is a significant parameter to determine the amount of heat required for drying the material and the costs associated with the drying process.

In the proposed theoretical model the expression (5) represents the distribution of temperature inside the sample along the coordinate z. Experimental temperature measurements T1 and T4 inside the sample at the depth of 1 and 2 mm (Figure 3b) show that the temperature in the depth of the sample decreases when measuring from the top surface of the sample. Theoretically, the temperature dependence on the depth (coordinate z) calculated with the formula (5) gives temperature minimum to the sample, which is shown in Figure 3.

The figure shows that the temperature minimum is measured near the locality of top surface of the sample, and the calculated temperatures on the sample surfaces (bottom z=0 T=17.3 ^{o}C; top z=d T=16 ^{o}C) are close to the experimentally measured ones T3=18.2 ^{o}C and T2=17.2 ^{o}C in the first stage of drying (Figure 3b). It testifies that the presented mathematical model is adequate and shows a coincidence of quantitative theoretical research and experimental data.

The research on foam gypsum sample drying parameters D, φ, t_{cr} depending on the sample volume density is shown in Figure 4. The decrease of diffusion coefficient with the increase in the foam gypsum volume density is logical, since it is related to the porosity of foam gypsum.

At high sample volume density, the number of pores decreases considerably, which makes the drying process more difficult and lowers the thickness of the layer δ (Figure 1), from which an effective drying process can take place.

The drying speed φ of the samples in our drying model is considered to be constant. The experimental research (Figure 4) shows that in general this assumption is approved and there are relatively small changes in the drying speed within the limits of (3-4)·10^5 kg/(m^2 s).

In our opinion, the prolongation of the first stage of drying with the increase of sample volume density can be explained by the fact that decreasing the number of pores the total surface of pores, to

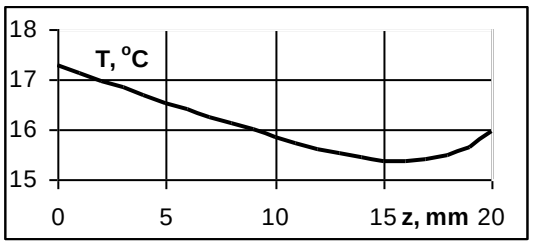

Figure 3: Theoretically calculated distribution of temperature in the sample of foam gypsum depending on the depth.

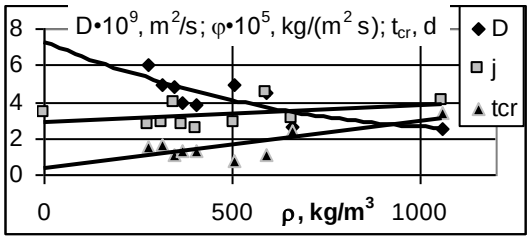

Figure 4: The dependence of foam gypsum sample parameters: diffusion coefficient D, drying speed φ, and the first drying stage time t_{cr} from the sample volume density.

which the moisture is bound inside the sample. Thus with the increase of the sample volume density, its free moisture amount, which does not directly come into contact with the foam gypsum, also increases, and it can freely reach the surface of the sample and dry out. At a constant drying speed it means the prolongation of the first drying stage time.

5. Conclusions

1. Mathematical foam gypsum drying models have been developed, that adequately describe the foam gypsum drying processes.
2. The main drying parameters of foam gypsum and their dependence on volume density of the material have been determined.

Acknowledgements

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