Dynamics of drying of fibrous material by the acoustic-convective method

A A Zhilin\textsuperscript{1,2}

\textsuperscript{1}Khristianovich Institute of Theoretical and Applied Mechanics SB RAS, 4/1 Institutskaya st., Novosibirsk, 630090 Russia
\textsuperscript{2}Siberian State University of Water Transport, 33 Shetinkina st., Novosibirsk, 630099 Russia

lab20@itam.nsc.ru

Abstract. The drying of a cellulosic fibrous material by acoustic-convective and thermal-convective methods under different conditions has been studied. Using the thermal-vacuum drying method, the weight of an absolutely dry sample of the starting material was determined and used to calculate the initial absolute and relative moisture contents, which were 12.38\% and 10.96\%, respectively. The dynamics of capillary impregnation and sorption wetting of samples was determined. The limiting values of the absolute and relative moisture content of cellulose fibers were found to be 862.16\% and 89.47\%, respectively. The kinetic curves of moisture extraction obtained in acoustic-convective and thermal-convective drying under different conditions were constructed, analyzed, and compared. It is shown that the acoustic-convective extraction of moisture has an advantage over the thermal-convective method.

1. Introduction

In recent years, projects for the construction of environmentally responsible low-rise housing have been actively developed in many regions of Russia. As a rule, cellulosic fibrous materials are used as heat-insulating materials for this class of housing. Spring floods and heavy rains lead to significant wetting of some buildings, as result of which the heat-insulating material absorbs a large amount of moisture and ceases to perform its heat-insulating function. Therefore, in order for fibrous heat-insulating material to preserve useful properties, it should have minimum moisture content. In addition, the removal of excess moisture from heat-insulating materials significantly reduces the load on the load-bearing structures of buildings.

Traditionally, excess moisture is removed from heat-insulating materials using a thermal-convective approach based on the supply of heat to the material to be dried [1, 2]. Under prolonged heating, wet material begins to actively evaporate excess moisture. The spent warm moist air is exhausted into the environment, resulting in large heat losses and hence high costs per unit of dried material. In this paper, it is proposed to dry fibrous heat-insulating material using the novel approach developed at the ITAM SB RAS. The approach is based on the exposure of materials being dried to high-intensity acoustic-convective flow. The proposed technology provides a significant intensification of moisture extraction from a wide range of biological [3-7], inorganic [8-12], etc. materials. One of the main advantages of this technology is the absence of heating of the dried material [13], i.e. drying proceeds at room temperature.
2. Material
We studied cellulose wool, a heat-insulating fibrous material containing 80% cellulose and 20% additives that reduce flammability and protect against fungal microorganisms and bacteria. Before starting the study, it was required to determine the initial moisture content of the material selected for the study. For this, several control groups of three samples each were prepared from the studied material. The samples in each group were equivalent in weight, with the weight of the second sample being two times the weight of the first sample, and the weight of the third sample four times the weight of the first. The groups of samples were placed in a vacuum oven at a working temperature of 100 °C. The samples were removed from the oven at predetermined time intervals to perform measurements and determine the current moisture content. The experiment was continued until the current moisture content of samples with higher initial weight became comparable with the current moisture content of samples with lower initial weight. Moisture content deviations between three samples did not exceed one percent. As a result, the total drying time was about 40 h.

The results obtained in the experiment were processed and averaged within each group. Subsequently, the obtained data were analyzed and averaged between the groups. As a result, the studies of the drying of cellulosic fibrous samples showed that the absolute initial moisture content of the studied material was $W = 12.38\%$ and their relative initial moisture content $w = 10.96\%$.

Next, the limiting moisture content of the material studied was determined. This was done using two wetting methods: capillary impregnation and sorption wetting in two modes.

In the study of the dynamics of capillary impregnation, all samples were placed in a bath of water for predetermined time intervals and then removed and weighed. The dynamics of capillary impregnation of the samples is presented in Figure 1, which shows that all samples absorb moisture very rapidly and reach the final equilibrium value in just three to four seconds. This is due to the high porosity of the cellulosic fibrous material; i.e., its large surface area through which moisture is absorbed. At subsequent times, the moisture content of the test material remained almost unchanged. As a result, the limiting final moisture content averaged over all test samples was 862.16 (89.47)%.

For the experiments to study the wetting dynamics of the fibrous material by sorption, we prepared an experimental setup consisting of a bath with water, above which test samples were placed without touching water. The assembled setup was placed in a sealed polyethylene bag to maintain constant parameters. Due to the tightness, the moisture content was maintained at 100% and the temperature at 19 °C. During the sorption wetting experiment, the samples were sequentially, at a predetermined time interval, briefly removed from the setup and subjected to weighing.
The dynamics of sorption wetting of the samples is shown in Figure 2. After the first three days of wetting, the moisture content of the samples increased quite rapidly: by 9.14 (6.90)% for the samples of the first group, by 9.12 (6.88)% for the second group, and by 8.31 (6.31)% for the third group; i.e., on average, by 8.86 (6.69)% for the three groups. After the next four days of continuous sorption wetting, the moisture content of the test samples increased by 4.24 (2.85)%, 2.14 (1.47)%, and 1.19 (0.83)%, respectively, for each group of samples. The average value over four days was 2.53 (1.72)%. The general wetting dynamics over the next six days with periodic removal of samples from the setup and weighing is characterized by a significant slowdown and a gradual approach to asymptotic behavior. The increase in moisture content for the samples of each group was 3.07 (1.95)%, 2.71 (1.78)% and 2.84 (1.92)%. After averaging over the groups, we have 2.97 (1.88)%.

Thus, after 15 days, the average moisture content of the samples increased by 14.26 (10.29)% and amounted to 26.67 (21.25)% in absolute value.

3. Acoustic-convective drying
Experiments on acoustic-convective drying of the fibrous material were carried out on the acoustic-convective dryer (ACD) of the ITAM SB RAS. The dryer operates as a Hartmann gas-jet generator [14]. The flow pattern occurring in the dryer duct consisting of two perpendicular channels was obtained numerically in [15, 16]. The ACD was started without the material to be dried. After the startup period, the drying flow parameters were recorded. Next, containers with prepared samples were loaded. During the experiments, the static pressure in the ACD settling chamber was kept constant and equal to 6.5 atm. In the study, five ACD modes were used, by analogy with [12]. Switching between modes was performed by changing the cavity depth [17]. The modes had the following characteristics. In Mode 1, the frequency was \( f = 123 \text{ Hz} \) and the intensity \( I = 161 \text{ dB} \); in Mode 2, \( f = 285 \text{ Hz} \) and \( I = 178 \text{ dB} \); in Mode 3, \( f = 848 \text{ Hz} \) and \( I = 171 \text{ dB} \); in Mode 4, \( f = 1.7 \text{ kHz} \) and \( I = 168 \text{ dB} \); in Mode 5, a resonant frequency was absent, i.e., convective flow occurred.

Figure 3a shows the drying dynamics of cellulose fibrous samples in different acoustic-convective flow modes. After 30-min drying in ACD in Mode 1, the absolute moisture content of the samples decreased by 241.23%, and the relative moisture content by 20.10%. During the same time of drying in Mode 2 with a frequency of 285 Hz and an intensity of 178 dB, the absolute moisture content of the fibrous material samples decreased by 262.10% and the relative moisture content by 23.86%. In the next Mode 3 with drying flow at a frequency of 848 Hz and an intensity of 171 dB, there was a significant increase in rate of moisture extraction: after 30-min drying, the absolute moisture content...
decreased by a record-breaking value 346.52% and the relative moisture content by 50.45%. Mode 4 with a resonant flow frequency of 1.7 kHz and an intensity of 168 dB turned out to be slightly less efficient: the loss of the absolute moisture was 327.43% and that of the relative moisture was 41.99%. The results of ACD cellulose in background Mode 5 showed a decrease in absolute moisture content by 239.12% and in relative moisture content by 19.76%.

Thus, the moisture extraction by drying the material at a flow frequency of 848 Hz is twice as high as that at a frequency of 285 Hz and two and a half times higher than that in the case of no distinct resonant frequency in the drying flow. It is also seen that the drying dynamics of the test material in acoustic-convective flow with operating parameters corresponding to Mode 1 and background mode 5 is almost identical.

Figure 3. Dynamics of moisture extraction from the cellulosic fibrous material in different modes of acoustic-convective (a) and thermal-convective (b) drying.
4. Thermal-convective drying
To compare the proposed drying method with the traditional thermal-convective method, we designed a test bench which allowed us to perform experiments on drying the fibrous material in two thermal-convective flow modes: Mode 1 at a temperature of 77 ºС and Mode 2 at 136 ºС.

Pre-wetted cellulose samples were placed in the center of the thermal-convective flow. At intervals of five min, the samples were removed from the thermal flow and weighed. The duration of the experiment on thermal-convective drying (TCD) in the first and second mode was 30 min.

The processed weighing results for both thermal-convective drying modes are presented in Figure 3b. It can be seen that after 30-min drying of samples at a thermal flow temperature of 77 ºС, the absolute moisture content decreased by 221.94% and the relative moisture content by 17.15%. After the same time of TCD at a flow temperature of 136 ºС, the absolute moisture content decreased by 252.55% and the relative moisture content by 22.06%. Thus, a twofold increase in the temperature of the drying flow leads to a slight acceleration of drying by only one-quarter. It should be noted that a final moisture content of 165.49 (62.33)% of the material dried at a flow temperature of 77 ºС was reached in 30 min and at a temperature of 136 ºС in about 22 min. Practice shows that, to achieve even lower moisture content, the differences in drying times at different temperatures become more significant.

5. Discussions
Let us compare the experimental results on the dynamics of drying of the cellulosic fibrous material using the acoustic-convective and thermal-convective methods in different modes. Figure 4 shows the results on moisture extraction from fibrous samples in the first 30 min of drying.

Consider in detail the result of drying the test samples. It can be seen that the slowest process is TCD in the first mode at a temperature of 77 ºС, where the moisture content decreased by 221.94 (17.15)% in 30 min. The background and first modes of ACD at a flow temperature of 14.45 ºС showed almost the same results: the moisture content was reduced by 239.12 (19.76)% and 241.23 (20.10)%, respectively. A slightly better result was obtained in the second mode of TCD at a flow temperature of 136 ºС; here the moisture content decreased by 252.55 (22.06)%.

Thus, appropriately choosing the resonant frequency of the drying flow correctly provides a significant (almost twofold, as in this case) increase in the efficiency of acoustic-convective drying of the fibrous material at the same energy consumption.

6. Conclusions
Using thermal-vacuum drying, the absolute and relative initial moisture content of the fibrous material was determined to be 12.38% and 10.96%, respectively.

It was shown that during acoustic-convective drying of the fibrous material at room temperature of 14.45 ºС, an appropriate choice of a resonant frequency led to a significant increase in the rate of moisture extraction.

In the studies of the dynamics in different ACD modes, it was determined that the optimal drying mode was Mode 3 with a frequency of 848 Hz. It was found that a two-fold (from 77 ºС to 136 ºС) increase in the temperature of the thermal-convective flow drying the fibrous material led to a one-quarter decrease in the drying time.

Comparison of the acoustic convective and thermal-convective drying methods showed that after 30-min drying in the optimal ACD mode at room temperature, the moisture loss from samples is twice as much as that in thermal-convective drying at a flow temperature of 136 ºС.
Figure 4. Comparison of the changes in the absolute (a) and relative (b) moisture content in cellulose in different modes and methods of drying.

Acknowledgments
The research was carried out within the framework of the Program of Fundamental Scientific Research of the state academies of sciences in 2013-2020 (project No. AAAA-A17-117030610139-4).

References
[1] Lykov A V 1968 *The Theory of Drying* (Moscow: Energia Publ.) p 472
[2] Lykov A V 1956 *Heat and Mass Transfer in Drying Processes* (Moscow: State Power Engineering Publ.) p 464
[3] Zhilin A A and Fedorov A V 2016 *J. Eng. Phys. Thermophys.* 89 323–33
[4] Korobeinikov Yu G, Trubacheev G V, Fedorov A V, Chu K M, Zheong D M and Kim Yu I 2008 *J. Eng. Phys. Thermophys.* 81 676–9
[5] Fedorov A V and Zhilin A A 2014 *J. Appl. Mech. Tech. Phys.* 55 1016–9
[6] Zhilin A A and Fedorov A V 2014 J. Eng. Phys. Thermophys. 87 879–86
[7] Zhilin A A, Fedorov A V and Grebenschikov D M 2018 Dynamics of acousto-convective drying of sunflower cake compared with drying by a traditional thermo-convective method Foods and Raw Materials 6 370–8
[8] Korobeinikov Yu G, Fedorov A V, Buluchevskii E A and Lavrenov A V 2009 J. Eng. Phys. Thermophys. 82 246–50
[9] Zhilin A A and Fedorov A V 2011 J. Eng. Phys. Thermophys. 84 965–74
[10] Korobeinikov Yu G and Fedorov A V 2003 J. Eng. Phys. Thermophys. 76 6–9
[11] Zhilin A A and Fedorov A V 2017 J. Eng. Phys. Thermophys. 90 1412–26
[12] Zhilin A A 2019 AIP Conference Proceedings. 2125 030085
[13] Gosteev Yu A, Korobeinikov Yu G, Fedorov A V and Fomin V M 2005 J. Appl. Mech. Tech. Phys. 46 711–6
[14] Borisov Yu G 1967 Gas-jet sound emitters of Hartmann type Density matrix theory of coherent ultrafast dynamics Physics and Technology of Powerful Ultrasound ed L D Rozenberg (Moscow: Nauka Publ.) book 1: Sources of powerful ultrasound pp 7–110
[15] Kravchenko A S, Zhilin A A and Fedorova N N 2018 AIP Conference Proceedings. 1939 020018
[16] Kravchenko A S and Zhilin A A 2019 J. Phys.: Conf. Ser. 1268 012037
[17] Zhilin A A and Golubev E A 2018 AIP Conference Proceedings. 1939 020016