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Experimental study of the efficiency of heat and mass transfer during ultrasonic drying of textile materials

Vladimir Khmelev, *Andrey* Shalunov, *Ivan* Manyakhin, *Sergey* Terentiev*, and
Viktor Nesterov

Department of Measuring and Automation Methods and Tools, Biysk Technological Institute
(Branch) Altai State Technical University, Biysk, Russia

Abstract. The article presents the results of experimental studies of the process of ultrasonic drying of textile wool. It was found that additional ultrasonic exposure makes it possible to accelerate convective drying up to 7.5 times under constant initial experimental conditions. When cotton wool is exposed to ultrasound, thermal diffusion occurs. Water molecules move from the more heated center of the drying object to the less heated surface.

1 Introduction

Reducing energy costs during dehydration of fibrous materials is a priority direction of modern science. The drying process requires energy, which is very wasteful and requires burning huge volumes of natural gas, oil, coal and other minerals that are harmful to the environment. Cotton wadding is a representative of the class of fibrous materials. The main areas of application include: medicine, cosmetics, thermal insulation building materials and the textile industry [1, 2].

The production of cotton wool is a multi-level process, during which drying occurs quite often. At the initial stage of production, the procurement of raw materials was recorded. Raw cotton collected from the field is cleaned mechanically, separating seeds and debris, it can be chemically cleaned, since the cotton plant can be infected by pathogenic methods, then the raw material is washed and dried to a certain moisture content.

There is a method for producing gyroscopic wool by chemically removing pectin. Gyroscopic wool has increased wettability, which is most in demand in the field of medicine [3-5]. Apart from this, gyroscopic wool is also very useful for the textile industry as it provides better coloring compared to low grade wadding. Chemical methods of processing cotton wool are also used when applying cotton wool. Depending on the production technology, the material can be immersed in an alkaline environment, and an acidification operation can also be performed [6, 7]. After such operations, the raw materials for the production of cotton wool must be thoroughly washed from chemical reagents and dried. The quality of the resulting cotton wool determines how many times the drying operation will be performed. The more often washing and drying are undertaken, the greater the volume of

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* Corresponding author: sergey@bti.secna.ru

operations aimed at acquiring new properties, which increases the time to obtain the finished product. Ultrasound makes it possible to reduce the drying time during the production of cotton wool and thus bring it to market as quickly as possible.

Exposure to high-frequency ultrasonic vibrations makes it possible to impart energy into materials that is proportional to the square of the vibrations. The maximum effect of ultrasonic drying, as a rule, is observed in other drying technologies, for example, convective, when the drying object is treated outside of ultrasound with a flow of heated air [8]. According to the method of influence, they come from two ultrasonic dryers: contact and non-contact. The contact method allows you to transfer ultrasonic energy directly to the drying object [9]. The arguments for this drying conclusion are that the drying area is limited by the radiation radius of the surface of the ultrasonic emitter. Cotton wadding has a small lamp, so the volume occupied by the wadding will have a small weight. The situation changes when using a non-contact drying outlet, where the drying agent is air. The drying object, cotton wool, is located in the space between the ultrasonic emitter and the reflector, between ensuring a constant sound pressure level [10].

2 Materials and methods

To study the processes and phenomena that occur during non-contact ultrasonic drying, an experimental stand was developed, the structural diagram of which is shown in Figure 1. The developed installation allows you to maintain the temperature and speed of air flow entering the drying object, as well as ensure a stable sound pressure level between the ultrasonic emitter and a reflector inside the drying chamber.

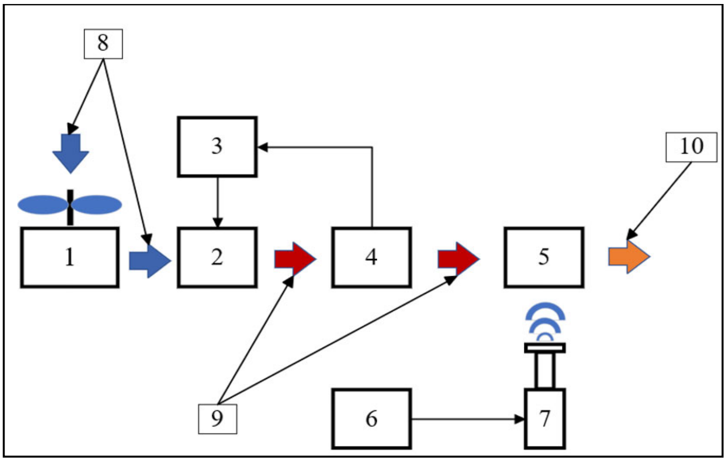

Fig. 1. Block diagram of an experimental setting for ultrasonic drying of textile wool. 1 – air intake, 2 – heater, 3 – air flow temperature control system, 4 – thermocouple, 5 – drying chamber, 6 – ultrasonic vibration generator, 7 – ultrasonic emitter, 8 – flow of cold air, 9 – flow of heated air, 10 – flow of heated air saturated with water vapor.

The air intake (1) sets the air flow rate. The heater (2) maintains the temperature of the air flow with a given accuracy using the flow temperature control system (3), which reads the temperature values from the thermocouple (4). The air flow passes through the drying chamber (5), where the cotton wool samples are located. The stand circuit contains an ultrasonic vibration generator (6) connected to an ultrasonic emitter (7) located in the lower part of the drying chamber. The implemented laboratory stand is shown in Fig. 2.

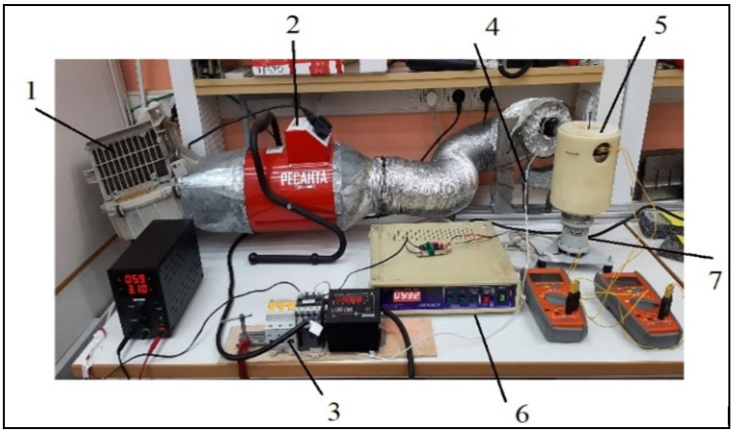

Fig. 2. Experimental setting for ultrasonic drying.

The drying chamber of the laboratory bench consists of a caprolon cylindrical body (1), a cover (2), an ultrasonic emitter (4) and a mesh tray (5), on which samples of the material to be dried (3) are placed (Figure 3).

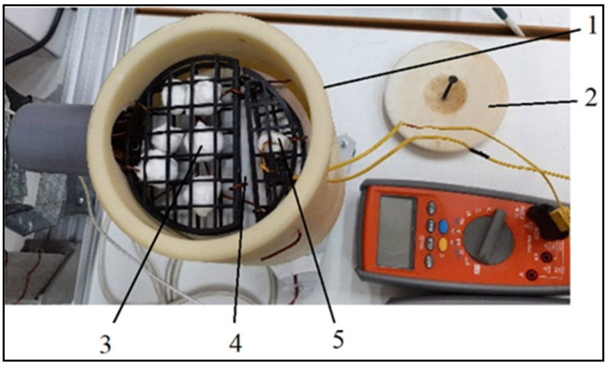

Fig. 3. Drying chamber. 1 – caprolon body of the drying chamber, 2 – drying chamber cover, 3 – samples of the material to be dried, 4 – piston emitter, 5 – mesh tray.

To conduct the research, we used an ultrasonic apparatus of the “NIGHTINGALE” family, model UZAGS-0.1/22-O, with a piston emitter (Figure 4).

Fig. 4. Appearance of an ultrasonic apparatus for studying gaseous media. 1 – electronic generator, 2 – ultrasonic oscillating system with a piston emitter.

The main technical characteristics of the ultrasound device are presented in Table 1.

Table 1. Technical characteristics of the ultrasound device.

Device parameter	Value
Power, VA, no more	100
Ultrasonic vibration frequency, kHz	22±1.65
Power supply from AC mains voltage, V	220±22
Maximum sound pressure level (within 1 m), dB, not less	120
Continuous operation time, hr	8
Overall dimensions: electronic generator, mm	330x290x115
Emitter diameter, mm	100
Emitter height, mm	102

Wool mass measurements were carried out on a Pocket Scale MH-200 scale (measurement accuracy ±0.01 g). A UT363S digital anemometer was used to monitor the air flow speed.

To study the process of ultrasonic drying of textile wool, it was decided to conduct two series of experiments:

- convective drying (control experiment),
- ultrasonic drying with the same parameters of the drying agent. In each series of experiments, experiments were carried out at the following values of process parameters: at flow temperatures of 30°C, 40°C, 50°C; for each temperature, the flow speed was set to 1 and 3.5 m/s.

In the process of experimental studies, initial (37%) and final (8%) humidity levels were provided, corresponding to the industrial technology of drying textile wool at the last stage of its production.

The mass of cotton wool samples (m_{dw}) corresponding to a given humidity (ω) was determined by formula (1):

$$m_w = \frac{100*m_{dw}}{100-\omega} \tag{1}$$

m_w is the mass of absolutely dry cotton wool (50.7 g.).

To form a high-intensity ultrasonic field, a standing wave mode was provided in the drying chamber. To do this, the resonant distance between the surface of the emitter and the lid of the drying chamber was selected experimentally. A water aerosol generated by a household humidifier was used as a visual indicator of a standing wave (Figure 5).

Fig. 5. Standing wave.

For ultrasonic systems, a standing wave is characterized by a spatially stable arrangement of alternating maxima (antinodes) and minima (nodes) of the oscillation amplitude, while aerosol particles accumulate at the nodes of the standing wave. In Figure 5, the distance between the emitter and the cover is two wavelengths of ultrasonic vibrations in air.

3 Temperature for convective and combined drying

To understand the mechanisms of heat and mass transfer in textile wool, which allow accelerating the drying process of textile wool, 24 experiments were carried out. Each experiment was carried out in several stages. At the first stage, textile wool with an initial moisture content of 37% was loaded. The wool was then placed on a mesh tray in the drying chamber. The measurement tray has a block structure. The small unit is designed to measure the temperature on the surface and inside the wool using two APPA 99ll multimeters. The multimeter thermocouples are not removed from the drying chamber during the drying process. The large block is designed to measure the mass of cotton wool on a scale. The initial temperature for all experiments was 22°C.

After the preparatory operations before the experiment, the timer was started and the drying process began. The drying process was completed when the moisture content of the wool became 8% or less.

Figure 6 shows the dependences of temperature and flow velocity on the surface and inside a sample of textile wool with and without ultrasound, at air flow temperatures of 30°C, 40°C, 50°C and a speed of 1 m/s.

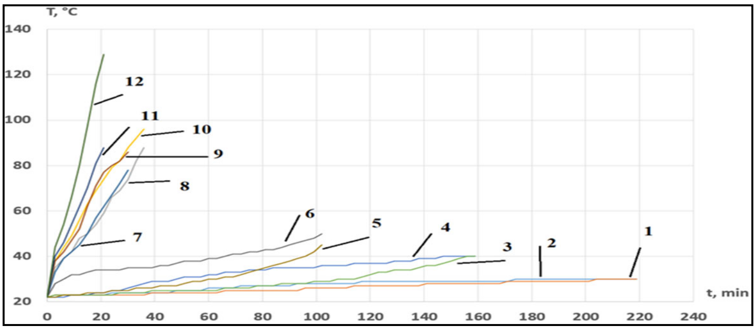

Fig. 6. Temperature curves of textile wool during drying, at a flow speed of 1 m/s. Inside the wool: 1 – 30 °C without ultrasound; 3 – 40 °C without ultrasound; 5 – 50 °C without ultrasound; 10 – 30 °C with ultrasound; 9 – 40 °C with ultrasound; 12 – 50 °C with ultrasound. On the surface of cotton wool: 2 – 30 °C without ultrasound; 4 – 40 °C without ultrasound; 6 – 50 °C without ultrasound; 8 – 30 °C with ultrasound; 7 – 40 °C with ultrasound; 11 – 50 °C with ultrasound.

At a heated air flow rate of 1 m/s and a temperature of 50 °C in the drying chamber, the maximum temperature inside the wool during drying in combined drying was 129 °C.

Based on the dependencies presented in the graph (Figure 6), we can conclude that during convective drying the temperature behaves in a classical way. Heating of the wool begins from the surface; over time, the sample warms up to the maximum temperature - the temperature of the air flow in the drying chamber. In this case, neither on the surface nor inside the wool can the temperature be higher than the temperature of the drying agent. Warming up inside is slower than on the surface.

With the combined drying method, the sample is heated much faster than with convective drying. During ultrasonic exposure, the mechanical energy of ultrasonic vibrations is converted into the internal energy of cotton wool, which is accompanied by a sharp increase in the temperature of the sample.

Heating of the sample occurs more intensely inside than outside, as a result of which the process of thermal diffusion in the sample can be observed. Moisture mass transfer occurs along a temperature gradient from the center to the surface of the sample.

During each experiment, the time for drying a sample of textile wool was measured. To assess how quickly the object is dehydrated, an additional parameter “drying acceleration” was introduced, which is the ratio of the time spent on convective drying to the time of drying textile wool using a combined drying method. Table 2 presents the values of the “drying acceleration” parameter for experiments conducted at a heated air flow of 1 m/s.

Table 2. Acceleration of drying of textile wool with a heated air flow of 1 m/s.

Air flow temperature, °C	Acceleration of drying
30	7.5
40	5.3
50	5.1

At an air flow speed of 1 m/s, a reduction in the duration of ultrasonic drying by 5.1...7.5 times is observed.

Figure 7 shows the dependences of temperature and flow velocity on the surface and inside a sample of textile wool with and without ultrasound, at air flow temperatures of 30°C, 40°C, 50°C and a speed of 3.5 m/s.

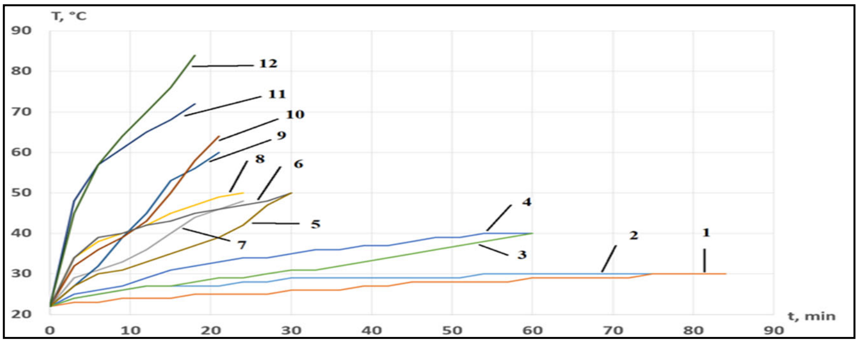

Fig. 7. Temperature curves of textile wool during drying, at a flow speed of 3.5 m/s. Inside the wool: 1 – 30 °C without ultrasound; 3 – 40 °C without ultrasound; 5 – 50 °C without ultrasound; 8 – 30 °C with ultrasound; 10 – 40 °C with ultrasound; 12 – 50 °C with ultrasound. On the surface of wool: 2 – 30 °C without ultrasound; 4 – 40 °C without ultrasound; 6 – 50 °C without ultrasound; 7 – 30 °C with ultrasound; 9 – 40 °C with ultrasound; 11 – 50 °C with ultrasound.

Based on the dependencies presented on the graph (Figure 7), we can judge that with an increase in the flow rate of heated air to 3.5 m/s, all the same phenomena and processes as described above can be observed for a flow rate of 1 m/s With. However, it is worth noting that the time spent on combined drying at a flow of 1 m/s and 3.5 m/s differs insignificantly. The convective drying time at a flow of 3.5 m/s was reduced by approximately 3 times compared to the time spent on experiments that were carried out at a flow of 1 m/s.

Table 3 presents the values of the “drying acceleration” parameter for experiments conducted at a heated air flow of 3.5 m/s.

Table 3. Acceleration of drying of textile wool with a heated air flow of 3.5 m/s.

Air flow temperature, °C	Acceleration of drying
30	3.5
40	2.9
50	2.4

At an air flow speed of up to 3.5 m/s, the acceleration of ultrasonic drying ranges from 2.4 to 3.5 times, depending on the temperature.

4 Conclusion

During the experimental study, it was found that at a lower temperature of the air flow, the contribution of ultrasound to the drying intensification process is greatest. Non-contact ultrasonic exposure can reduce the drying time of textile wool by 7.5 times. The effectiveness of having a combined thermal diffusion processor drying process in a textile bath. During the ultrasonic drying process, heating occurs more strongly in the center than on the surface. In this case, the temperature inside the wool can reach 129 °C. During convective operation with the maximum possible temperature on the surface and inside the textile wool sample, the air flow temperature is limited.

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