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Experimental study of the cavitation impregnation process of textile materials

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Abstract: *The paper investigates the efficiency of the cavitation method for impregnating textile materials and compares it with the conventional immersion method. The relevance of the study is determined by the need to improve the efficiency of textile impregnation processes using special substances while preserving the structural and mechanical properties of the materials. Particular attention is paid to the influence of ultrasonic cavitation on the intensification of mass transfer processes within the porous-capillary structure of textile materials. The research employed an experimental comparative method involving the determination of the weight characteristics of samples before impregnation, after impregnation, and after excess liquid drainage. The process efficiency was evaluated using the impregnation coefficient, percentage weight gain, liquid retention index, and impregnation rate. Experimental studies were carried out using an ultrasonic cavitation unit operating at a frequency of 40 kHz. The results of the study showed that the cavitation method increases the impregnation coefficient by an average of 6.9% compared to the conventional immersion method. An increase in the penetration rate of impregnating substances into the material structure and an improvement in the material's ability to retain the working liquid were also observed. Experimental results confirmed that, under rationally selected ultrasonic treatment conditions, no significant damage to the fiber structure of the textile material occurs. The scientific novelty of the work lies in the development of a comprehensive approach to the quantitative evaluation of the efficiency of cavitation impregnation of textile materials using integral indicators of impregnation and liquid retention. In addition, the regularities of the influence of ultrasonic cavitation on the intensification of mass transfer processes in the structure of textile materials were established. The practical significance of the obtained results lies in the possibility of applying cavitation impregnation to hard-to-impregnate textile materials, particularly in the production of flame-resistant products, protective workwear, and technical textiles. The proposed approach makes it possible to reduce the duration of the technological process and improve impregnation efficiency without deteriorating the operational characteristics of the material.*

Keywords: *cavitation, impregnation, ultrasonic treatment, textile materials, mass transfer, impregnation efficiency, flame-retardant treatment.*

1. INTRODUCTION

Modern industries such as construction, aviation, the production of protective clothing, and interior products impose increased requirements on the performance properties of textile materials. The issue of operational characteristics is becoming particularly important due to the growing demands placed on materials used in critical structures, which must ensure a high level of compliance with established standards [1]. Special attention should be paid to thick and multilayer materials (for example, batting and technical nonwoven fabrics), since traditional impregnation methods often fail to provide deep and uniform penetration of impregnating substances into their inner layers [2]. Methods such as conventional immersion or spraying frequently result in uneven distribution of impregnating components, which significantly reduces their effectiveness [3]. In this regard, the search for innovative impregnation methods, particularly those involving ultrasonic cavitation, has become a priority area of research in the field of flame protection [2].

An example of the need for high-quality fabric treatment is the flame protection of materials. In this case, the main purpose of textile impregnation is to provide materials with properties that either prevent ignition or significantly slow down flame propagation. This is achieved through the use of flame-retardant substances that operate through various mechanisms, such as the formation of a protective char layer, the release of inert gases, or heat absorption. However, for dense and thick materials such as batting, the depth of penetration of the impregnating solution is no less important than its chemical composition. Existing methods often fail to ensure sufficient impregnation, especially for materials with low capillarity.

In addition, modern treatment technologies must meet three main criteria:

- efficiency – ensuring deep and uniform impregnation, especially for thick materials;
- environmental safety – the use of non-toxic substances (for example, organophosphorus or mineral additives) and methods that minimize chemical consumption;
- preservation of mechanical properties – the treatment should not damage the fiber structure or reduce the strength of the material.

In the aspect of deep treatment, the cavitation impregnation model demonstrates significant advantages, since ultrasound promotes the distribution of flame-retardant substances without damaging the integrity of the material and allows reducing the required concentration of impregnating solutions on the material surface due to increased diffusion efficiency. Unlike aggressive chemical methods [4], ultrasonic treatment affects the material gently, without causing its degradation during short-term exposure, while preserving its functional properties.

Therefore, the main objective of this study is the experimental investigation of the efficiency of material impregnation using the phenomenon of ultrasonic cavitation. The limitations of existing technologies emphasize the need for the development of advanced methods such as cavitation impregnation, which not only solves the problem of penetration depth but also meets modern requirements for efficiency and environmental safety in industrial applications.

Recent studies in the textile industry have focused on the development of environmentally friendly and efficient methods for material impregnation. Methods involving the impregnation of materials with environmentally safe chemical compounds through the conventional immersion of textile fabrics in a solution are becoming increasingly popular. For example, the use of natural plant extracts has demonstrated a significant improvement in the flame resistance of cotton fabrics. This method involves soaking the fabric in a solution followed by heat treatment, which promotes dehydration and the formation of a protective layer [5]. Similar results are achieved using phosphorus-nitrogen compounds, which create a synergistic effect and reduce peak heat release by 85.4% [6]. Both flame-retardant treatment methods employ the conventional impregnation technique by immersing the fabric in a solution, which may be ineffective for thick, multilayered, porous materials and materials with a capillary structure that is difficult for impregnating solutions to penetrate.

Paper [7] presents the theoretical foundations of vibration-assisted fabric impregnation, which increases the efficiency of impregnant penetration into the depth of the material, particularly through the influence of various factors on the depth of liquid penetration into the porous-capillary structure of the material. The theoretical studies conducted by the authors demonstrate that the impregnation process depends on the pressure generated by hydrostatic, capillary, and vibration forces, as well as on the properties of the liquid itself and the structure of the fabrics.

The authors established that an increase in the amplitude and frequency of oscillations leads to a greater impregnation depth, which is confirmed by experimental data and mathematical models. The influence of shock waves in gas-liquid media on the impregnation process is also analyzed. It is shown that wave parameters (velocity and oscillation frequency) depend on the size of gas bubbles and external pressure. For example, an increase in external pressure results in a higher propagation velocity of compression waves and a higher oscillation frequency of the bubbles.

An important aspect of the study is the analysis of fabric structure, particularly the size of pores and capillaries, which determine impregnation efficiency. A geometric model considering the arrangement of threads in the fabric is used to calculate pore area.

In conclusion, it is noted that vibration-assisted impregnation is an effective method for improving the quality of fabric treatment, especially in cases where deep liquid penetration is required. However, the results may vary depending on the material properties, oscillation parameters, and the equipment used, which necessitates an individual approach for each specific application case [2].

The vibration-assisted method has significant potential for integration into modern textile processing technologies. Its application can improve impregnation efficiency, reduce time and energy consumption, and promote the use of environmentally friendly flame retardants. For further research, it is recommended to focus on the experimental verification of combining cavitation with existing methods (for example, sol-gel technology) and on evaluating their influence on the mechanical properties of fabrics [7].

These findings may be useful for further studies of the ultrasonic cavitation method for material impregnation in the field of material processing, particularly for the optimization of technological processes in the textile industry. It should also be noted that the above-mentioned studies make it possible to identify the general direction of development in treatment technologies toward increasing the environmental sustainability of processes and, accordingly, improving treatment quality through the use of innovative impregnation methods capable of overcoming technological limitations in the treatment of coarse textile fabrics.

2. PROBLEM STATEMENT

Despite the availability of theoretical and experimental developments in the field of intensifying the impregnation of textile materials, the issues of quantitative evaluation of the efficiency of ultrasonic cavitation and its influence on the material structure remain insufficiently studied. The absence of a systematic comparison with the conventional immersion method complicates the justification for implementing cavitation technology in industrial production. In this regard, the purpose of this article is to experimentally evaluate the efficiency of the cavitation method for impregnating textile materials, compare it with the conventional impregnation method using quantitative indicators, and determine the effect of ultrasonic treatment on the preservation of the material structure.

3. RESULTS

Fabric impregnation performed by saturating materials with chemical compounds can conventionally be divided into the impregnation of individual fibers (threads, carried out before the beginning of fabric weaving) [3] and fabric impregnation (performed after the material has already been woven into a continuous textile sheet) [8]. Thread impregnation is not a complex process, since in this case there is no issue related to the formation of pores and the retention of air bubbles during material saturation. Fabric impregnation differs from thread impregnation in that its primary objective is the displacement of air bubbles from the thickness of the material.

In the cavitation impregnation method, microjets generated during the collapse of cavitation air bubbles in the liquid penetrate into pores containing air bubbles that must be displaced from the material thickness. During cavitation impact, the air bubble trapped within the pore structure of the material is released and replaced by liquid. In addition, ultrasonic irradiation produces a vibrational impregnation effect, which also exerts a positive influence on the material impregnation process [7].

Despite the long-standing existence of innovative methods for the impregnation of materials and structures, the cavitation method remains relatively uncommon and insufficiently studied. In order to identify the effectiveness of this method, a series of comparative experiments was conducted, and the obtained results are presented in Table 1.

The research methodology involved the application of a comparative approach based on comparing the weight of impregnated material samples treated using the conventional immersion method and immersion assisted by an ultrasonic cavitation generator, the radiation of which was directed directly at the investigated sample.

Batting was selected as the experimental material due to its structural characteristics and the presence of air cavities, which enabled a clear demonstration of the effectiveness of the cavitation impregnation method. The investigated samples were characterized by the following parameters: overall dimensions – length 150 mm, width 150 mm, and thickness 2 mm; dry material weight (sample weight values are presented in Table 1); material density – 1000 g/m².

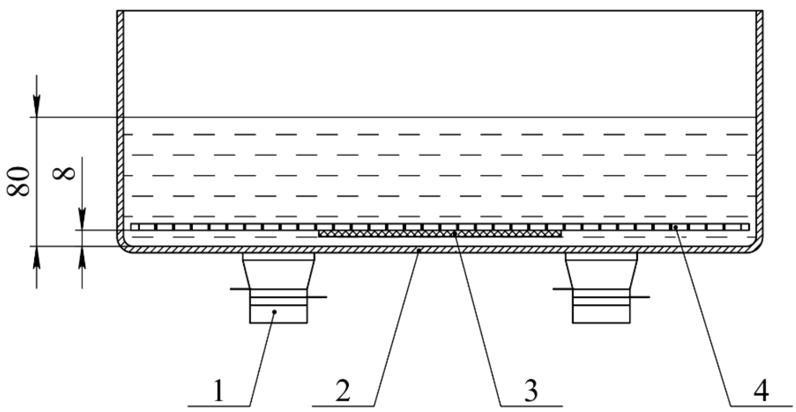
The laboratory experimental conditions were as follows: atmospheric pressure – 770 mmHg; ambient temperature – 20 °C; temperature of the liquid in which the investigated samples were immersed – 12 °C; immersion depth in the liquid – 72 mm.

The technical characteristics of the equipment used for measurements were as follows:

- cavitation bath: emitter operating frequency – 40 kHz; power of a single emitter – 60 W; total system power – 240 W (4 emitters);
- electronic balance: measurement accuracy – 0.01 g.

The experimental setup was based on an ultrasonic emitter (1) positioned beneath the bath (2) containing the solution. The experimental sample (3) was placed into the liquid and secured with a retaining grid (4) in order to keep the sample submerged within the liquid medium.

Figure 1 presents a model of the experimental setup.



Legend: 1 – ultrasonic emitter; 2 – liquid container;
3 – experimental sample; 4 – retaining grid.

Figure 1. Model of the experimental setup.

The investigation of the conventional impregnation method in the given setup was carried out without activating the ultrasonic emitter (1), whereas the cavitation method was studied with the emitter switched on. In both cases, the experiment duration was 1 minute.

Figure 2 illustrates the sequence of sample weight measurements.

(a) (b) (c)

Figure 2. Photographs of the material impregnation results for Experiment No. 3:
(a) – weight of the dry sample; (b) – weight of the impregnated sample;
(c) – weight of the sample after 1 minute of liquid drainage.

The study was conducted in two stages with repeated use of the same samples in order to avoid errors associated with variations in material density. In addition, the experiment accounted for the influence of liquid surface tension and its accumulation in the upper layers of the material; therefore, weight measurements of the samples were also performed after liquid drainage. In Table 1:

- column 1 presents the weight values of the material samples before the impregnation efficiency study. During the investigation of impregnation efficiency using both the conventional immersion method and the cavitation method, the same experimental samples were reused to eliminate errors caused by structural differences between samples. Initially, a dry sample was impregnated using the conventional method, after which it was dried until its original mass was restored and subsequently reused for cavitation impregnation. This experimental procedure minimizes errors associated with differences in density and structure among material samples, as well as possible structural changes caused by cavitation treatment;
- column 2 presents the impregnation results of samples treated using the conventional immersion method, g;
- column 3 presents the impregnation results of samples treated using ultrasonic cavitation, g;
- column 4 presents the material weight after liquid drainage from the sample surface following impregnation using the conventional immersion method;
- column 5 presents the material weight after liquid drainage from the sample surface following cavitation impregnation.

The number of experimental studies was determined using approaches of mathematical statistics to estimate the required sample size when comparing two dependent populations [9]. Since a paired experimental design was employed in this study (comparison of the conventional and cavitation methods using the same samples), the minimum required number of experiments can be estimated using the following formula:

$$n \geq \left(\frac{t_{\alpha,\nu} \cdot s_d}{\Delta}\right)^2, \quad (1)$$

where $t_{\alpha,\nu}$ is the critical value of Student's t-distribution at the significance level $\alpha$and the number of degrees of freedom ν;
s_d – standard deviation of the differences between paired measurements;
Δ – minimum significant difference between the methods.

Table 1. Results of cavitation impregnation of materials

Experiment No.	Weight of investigated material samples, g				
	Samples before impregnation	Impregnation without cavitation	Impregnation with cavitation	Weight after 1 min drainage, g	
				Without cavitation	With cavitation
	1	2	3	4	5
1	4.66	44.86	45.80	40.15	43.60
2	5.06	44.82	50.41	37.2	38.94
3	5.06	45.18	50.58	40.11	39.33
4	5.06	41.75	49.1	37.31	39.15
5	5.43	49.76	49.42	39.5	44.11
6	5.71	51.03	54.43	39.83	45.79
7	5.06	49.69	48.18	39.11	44
8	4.6	43.6	44.46	35.81	39.68

For engineering experiments conducted at a confidence level of 0.95 and a coefficient of variation within the range of 10–20%, the minimum sufficient sample size generally consists of 6–10 paired observations. In the present study, 8 experiments were performed, which corresponds to the lower limit of the statistically acceptable range and provides an opportunity to identify the general trend in process efficiency variation.

It should be noted that the limited number of experiments is обусловлено technological characteristics of the process, in particular the considerable drying time of treated textile samples after impregnation, which significantly increases the duration of a single experimental cycle. Therefore, the obtained results should be regarded as preliminary, while further studies should focus on expanding the sample size in order to improve the statistical reliability of the results.

Based on a series of experiments, it can be stated that cavitation impregnation demonstrates higher efficiency compared to the conventional immersion method. This is clearly evident from the experimental results (Table 1), where ultrasound-treated samples exhibited more intensive liquid saturation. For example, in Experiment No. 2, the difference between the methods amounted to 5.59 g (50.41 g versus 44.82 g), indicating improved liquid penetration into the material when cavitation was applied. Furthermore, after the liquid drainage phase, cavitation-treated samples demonstrated a higher residual weight, confirming the method's enhanced ability to retain liquid within the material structure.

Several key indicators may be used for the quantitative assessment of impregnation efficiency. The impregnation coefficient $\left(K_p\right)$ is calculated as the ratio of the weight of the impregnated sample to its initial weight. The percentage weight increase $(\Delta W\%)$ indicates the extent to which the material mass increased after treatment. The liquid retention efficiency (E_r) determines the fraction of liquid remaining in the material after drainage. To compare the methods, the relative efficiency indicator (E_c) is used, demonstrating by what percentage one method outperforms the other.

The assessment of material impregnation efficiency is performed using the impregnation coefficient and is determined by the following formula:

$$K_p = \frac{m_p}{m_s}, \qquad (2)$$

where m_p is the weight of the sample after impregnation, g;
m_s – weight of the dry sample before impregnation, g.

In addition, the percentage weight increase is determined, which demonstrates the percentage increase in material weight after impregnation:

$$\Delta W\% = \left(\frac{m_p}{m_s} - 1\right) \cdot 100\%, \tag{3}$$

where m_p is the weight of the sample after impregnation, g;
m_s – weight of the dry sample before impregnation, g.

The liquid retention efficiency after drainage is determined using the following formula:

$$\mathrm{E}_r = \left(\frac{m_{pd} - m_s}{m_p - m_s}\right) \cdot 100\%, \tag{4}$$

where m_{pd} – is the weight of the sample after liquid drainage, g.

To compare the effectiveness of the cavitation impregnation method and the conventional impregnation method, the following relationship is used:

$$\mathrm{E}_c = \left(\frac{\Delta W_{cav} - \Delta W_{canv}}{\Delta W_{canv}}\right) \cdot 100\%, \tag{5}$$

where ΔW_{cav} refers to the cavitation method;
ΔW_{canv} refers to the conventional method.

A significant advantage of the cavitation impregnation method is the increased impregnation rate. The impregnation rate of the material is determined as follows:

$$v_{imp} = \frac{m_p - m_s}{t}\ g/s, \tag{6}$$

where t is the impregnation time, s.

The calculation results are presented in Table 2.

The cavitation method demonstrates higher efficiency compared to the conventional method, with an average impregnation coefficient K_p of 9.964 versus 9.133. The best result (10.00) was recorded in Experiment No. 3, confirming the method's ability to achieve better material saturation with liquid.

The application of cavitation resulted in a weight increase (percentage weight increase, $\Delta W\%$) ranging from 810.129–899.605% (average – 866.388%), whereas the conventional method demonstrated results within the range of 725.099–882.016% (average – 813.293%). The most significant difference (16.689%) was observed in Experiment No. 4, indicating the particular effectiveness of this method for the given sample of material with a complex structure.

In addition, higher liquid retention efficiency (E_r) was observed for the cavitation treatment method, with a higher average value of 0.833 (range: 0.747–0.947) compared to the conventional method, which demonstrated an average value of 0.816 (range: 0.753–0.883). This indicates improved liquid diffusion into the fibers and better liquid retention after completion of the process.

In the comparative efficiency assessment (E_c), the cavitation method outperformed the conventional method with an average efficiency improvement of 6.931%. Exceptions were observed in Experiments No. 5 and 7, where the conventional method proved to be more effective, which may be attributed to the structural characteristics of the specific material samples or deviations in experimental conditions.

A higher impregnation rate, (v_{imp}), was observed for the cavitation method, amounting to 0.733 g/s compared to 0.688 g/s for the conventional method. This, in turn, indicates the possibility of reducing the duration of technological processes while maintaining the required weight-related performance indicators, as well as the overall higher efficiency of the method.

Table 2. Results of efficiency calculations for material impregnation methods

Experiment No.	**Conventional impregnation method**				**Cavitation impregnation method**				**Comparative method efficiency, E_c, %**
	K_p	$\Delta W\%$	E_r, %	v_{imp}, g/s	K_p	$\Delta W\%$	E_r,%	v_{imp}, g/s	
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
1	9.63	862.661	0.883	0.670	9.83	882.833	0.947	0.686	2.338
2	8.86	785.771	0.808	0.663	9.96	896.245	0.747	0.760	14.059
3	8.93	792.885	0.874	0669	10.00	899.605	0.753	0.760	13.460
4	8.25	725.099	0.879	0.612	9.70	870.356	0.774	0.740	20.033
5	9.16	816.390	0.769	0.739	9.10	810.129	0.879	0.737	-0.767
6	8.94	793.695	0.753	0.755	9.53	853.240	0.823	0.816	7.502
7	9.82	882.016	0.763	0.744	9.52	852.174	0.903	0.718	-3.383
8	9.48	847.826	0.800	0.650	9.67	866.522	0.880	0.664	2.205
Average values	9.133	813.293	0.816	0.688	9.664	866.388	0.838	0.733	6.931

The application of the above-described approach for evaluating impregnation efficiency enables a qualitative assessment of the advantages of the cavitation method. The calculations demonstrate that cavitation impregnation provides, on average, 6.931% better performance according to the main indicators. This makes the method promising for applications requiring deep and uniform material saturation, such as the textile industry, the production of flame-retardant coatings, and the manufacturing of protective clothing. The method is particularly effective for materials with a complex porous structure, where conventional methods may prove insufficiently effective.

An important criterion limiting the applicability of a particular material impregnation method is the preservation of the mechanical properties and structural integrity of fabrics. During the investigation of the cavitation impregnation method, its suitability for preserving the above-mentioned fabric characteristics was experimentally evaluated. A material with a clearly defined yarn and fiber structure was selected for the study, which enabled an effective comparison of the impact of ultrasonic cavitation on the fabric. In addition, an important criterion for selecting the investigated sample was its relatively low mechanical strength, which made it possible to demonstrate the safety of the method's effect on the fabric.

The material selected for the study was cotton, with the following weave characteristics:

– plain weave repeat with parameters $R_o = R_{oy} = 2$ (threads), where R is the weave repeat (the number of interlacings in the warp and weft directions after which the interlacing sequence repeats); R_o is the weave repeat in the warp direction (the number of warp threads after which the interlacing sequence in the weft direction repeats); R_{oy} is the weave repeat in the weft direction (the number of weft threads after which the interlacing sequence in the warp direction repeats);

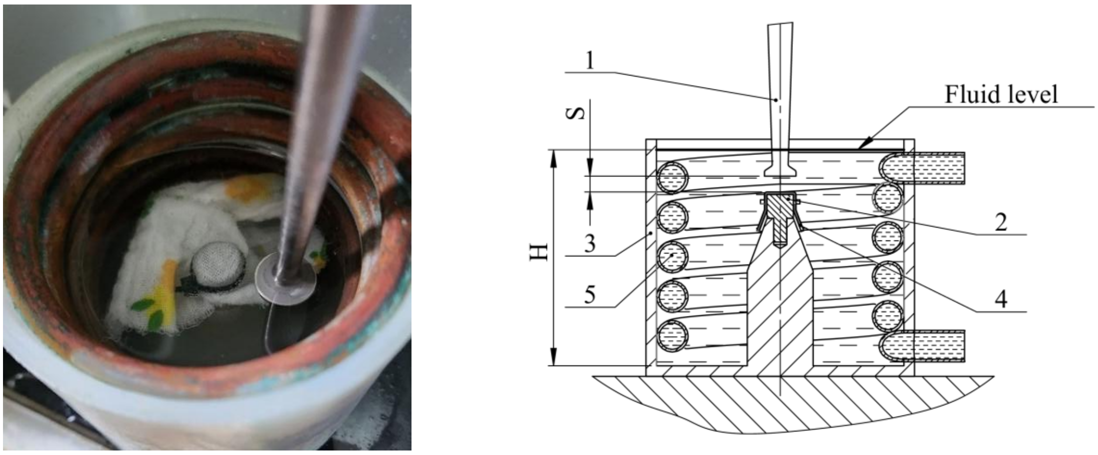
– interlacing parameters: $\eta_{F\text{o}} = \eta_{F\text{y}} = 1$, where η_F denotes the interlacing point (the location where warp and weft threads intersect); $\eta_{F\text{o}}$ is the warp interlacing (the point on the front side of the fabric where the warp thread passes over the weft thread); $\eta_{F\text{y}}$ is the weft interlacing (the point on the front side of the fabric where the weft thread passes over the warp thread);

– shift parameters: $S_\text{o} = S_\text{y} = 1$, where S is the number indicating the displacement of a single interlacing point relative to the corresponding previous interlacing; S_o is the vertical shift (the number of weft threads between two successive warp interlacings); S_y is the horizontal shift (the number of warp threads between two successive weft interlacings).

The investigation of the cavitation wear resistance of the material was carried out using a UZDN A machine. Distilled water was used as the liquid medium in which the experimental sample was immersed, with a water temperature of 12°C.

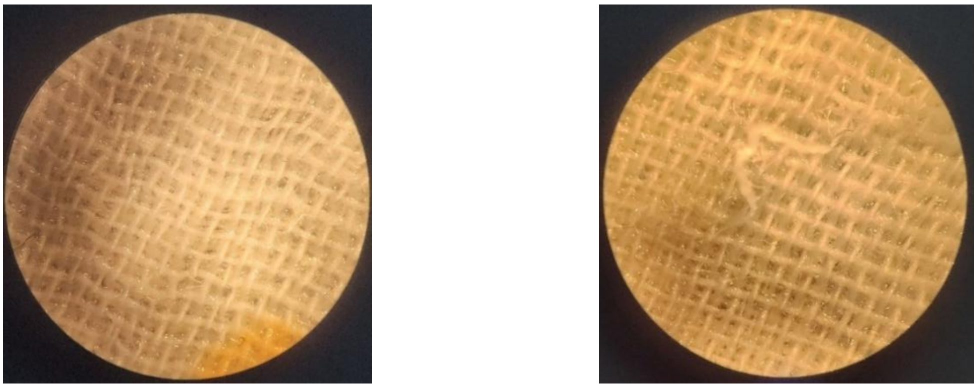
The general view of the sample fixed on the matrix of the experimental setup is shown in Figure 3.

The study established that the effect of cavitation on the experimental sample is not significant and does not alter the fabric properties during short impregnation periods. The material structure and fiber integrity are preserved at a treatment duration of 30 min (Fig. 4 a). A destructive effect on the fabric was observed at a treatment duration of 45 min; however, such a prolonged impregnation process is impractical, since material saturation occurs significantly faster than the onset of material degradation (Fig. 4 b).



(a) **(b)**

Figure 3. General view of the sample fixed on the matrix of the experimental setup:
(a) – general view of the setup; (b) – cross-sectional view of the setup: 1 – ultrasonic radiation source; 2 – replaceable matrix; 3 – reservoir; 4 – experimental sample; 5 – radiator with coolant.



(a) **(b)**

Figure 4. Results of the study on the effect of the cavitation method on fabric structure:
(a) – material sample after a treatment duration of 30 min;
(b) – material sample after a treatment duration of 45 min.

By analyzing the structure of the interwoven fibers of the experimental sample for the presence of damaged fibers and comparing it with an identical material that had not been subjected to ultrasonic cavitation, it can be concluded that mechanical changes occur during prolonged irradiation, although they have only a minor effect on the material strength.

Therefore, it is advisable to conduct further studies on the mechanical strength of treated samples.

The number of conducted experimental studies ($n = 8$) is sufficient to identify the general trend of increased efficiency of the cavitation impregnation method; however, it is insufficient to obtain statistically reliable results at a specified confidence level. Therefore, further investigation of the effectiveness of the cavitation impregnation method is required in order to establish a mathematically reliable understanding of the treatment process.

4. CONCLUSIONS

The effectiveness of the cavitation method for textile material impregnation was investigated experimentally. The cavitation impregnation method proved to be more effective compared to conventional immersion, demonstrating an improvement in performance of 6.9% in terms of the average weight of impregnated samples and their ability to retain liquid after drainage, respectively. This method is particularly beneficial for materials with complex structures, such as batting, and may find application in fields where deep and uniform impregnation is essential.

Cavitation impregnation is more effective for difficult-to-impregnate materials, such as batting. It ensures deeper and more uniform liquid penetration, while also increasing the amount of retained liquid, which is critically important for flame resistance. This technology has considerable potential for industrial applications, particularly in the production of protective clothing and construction materials.

For further improvement of the method, the following measures should be considered: optimization of ultrasonic treatment parameters (frequency, power, and treatment time); investigation of the combination of cavitation with innovative impregnating substances; and testing of the mechanical strength of materials after treatment to evaluate long-term effectiveness.

Cavitation impregnation may become a standard method in industries requiring deep and uniform impregnation, such as aviation, construction, and the manufacturing of protective clothing.

The obtained results are preliminary in nature and require further verification using an expanded sample of experimental data. Future studies should focus on the experimental evaluation of combining cavitation with existing methods (e.g., sol-gel) and assessing their impact on the mechanical properties of fabrics.

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