APPLICATION OF ULTRASOUND IN THE PRETREATMENT OF COTTON FABRIC

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In recent years, the researchers' focus has been on the use of cleaner technologies in textile wet processing, which generate less pollution and reduce the waste water load. This can be achieved by increasing the mass transfer from the application medium to the fiber. Ultrasonic application attracts interest in this pursuit. In the present investigation, ultrasonic waves of 53 KHz frequency were generated using 50 watt input power. Comparative or superior desizing efficiency was obtained at room temperature (25 °C) by using ultrasound with 70 to 75 percent reduction in enzyme concentration within 30 minutes, instead of 180 minutes in the conventional desizing process. Instantaneous water absorbency of the desized fabric indicates removal of natural impurities, which otherwise require long hours of alkaline scouring. Experimental evidences suggest that ultrasonic energy is efficient, it reduces the chemical dosage input, increases the mass transfer and reduces the process time and temperature for achieving comparable or even improved efficiency.
Ultrasound application to a single stage combined desizing-scouring and bleaching [D-S-B] process, using potassium persulfate as hydrogen peroxide booster, resulted in the removal of starch, wax and other natural impurities, while yielding a CIE whiteness value of 74 within 30 minutes at room temperature. The tensile strength and surface morphology of the sonicated fabrics were not affected.
These experimental results substantiate previously published research claiming that ultrasound holds promise in developing cleaner technologies.

Keywords: ultrasonic cavitation, desizing, combined D-S-B process, increased mass transfer, energy savings

INTRODUCTION

Textile chemical processes consume large quantities of water, electrical and thermal energy. These processes require chemicals to assist in either accelerating or retarding the reaction rates in order to accomplish the process in a reasonable time. Temperature is often applied to shorten the process duration and increase process efficiency. The use of thermal energy to reach a desirable temperature can be replaced either partially or fully by using ultrasonic energy. Huseyin *et al*. have used a combination of ozone and ultrasound in the pretreatment of cotton fabric prior to natural dyeing.[1] Coman *et al*. have used 38.5 KHz frequency ultrasonic waves in the application of anthocyanin dye extracted from red onion on flax fiber and claimed that ultrasonic waves facilitate dye fiber contact and chemical reaction between the dye and the fibre. This novel approach is both economical and ecological.[2] Thakore[3,4] has claimed that the rate of dyeing cotton fabric with direct dyes is higher due to ultrasonic cavitation in the experiments carried out in isothermal environment, *i.e.* the rate of dye diffusion within the fiber was accelerated, although the dye baths were heated at the same rate in the experiments with and without ultrasound. It has been also reported that ultrasonic cavitation shortens the time for reactive dye wash-off by more than 50 percent.[5] Thus, ultrasonic treatment is beneficial leading to accelerated penetration of chemicals into the complex structure of fibre. However, it would be interesting to find whether or not the effects of cavitation are also beneficial in the removal of natural and added impurities, such as starch, wax, pectins and natural colouring matter in the pretreatment of cotton fabric. The present investigation has been motivated by the desire to disclose the answers.

Enzymatic desizing of cotton fabric using ultrasound has been well studied.[6-14] Efforts have been also made to study enzymatic desizing assisted by ultrasound on a pilot scale unit, using a combination of low frequency high power and high frequency low power ultrasound.[15] The earlier presumption that ultrasound may deactivate enzymes, resulting in poor efficiency, has been ruled out by these studies.

Enzymatic processing of cotton textiles, like any wet processing system, involves transfer of mass (enzyme molecules) from the processing liquid medium (enzyme solution) across the surface of the textile substrate. The detailed mechanism of enzymatic reactions is very complicated and is still being investigated. In very general terms, the enzymatic reaction could be summarized according to the following stages: 1) transfer of enzyme molecules from the aqueous phase to fibre surface; 2) adsorption of enzyme molecules onto the substrate surface; 3) catalysis of surface hydrolytic reactions by a specific enzyme; and 4) transfer of the hydrolytic reaction product to the aqueous phase.

Since at least two stages of the enzymatic reaction, which involve transport of enzyme molecules and enzymatic reaction products to and from the fiber surface, are controlled by diffusion, the overall reaction rate of hydrolysis could also be determined by the diffusion rate of enzyme molecules. In general, large enzyme molecules have low diffusion rates and tend to react with external cellulose fibers in cotton yarn. This sometimes results in excessive damage to the fibers.

Mechanical agitation of an enzyme processing solution usually improves transport of bulky enzyme molecules toward the surface of the cellulose fabric and into the interior of the cotton yarn. However, it is well known that mechanical agitation is a not a very effective stirring mechanism for the immediate border layer of liquid at a solid/liquid interface, where the enzymatic reaction actually occurs.

In view of this fact, ultrasound appears to be a very promising alternative technique to provide a far more efficient stirring mechanism for the immediate, border layer of the liquid at the fiber's surface. Generally, sonication of liquid media causes two primary effects, namely cavitation and heating. Cavitation is the formation of very small bubbles in the liquid, which generate powerful shock waves as they collapse. The phenomenon of cavitation is generally considered responsible for most of the physical and chemical effects of ultrasound observed in solid/liquid and liquid/liquid systems. The effect of cavitation is several hundred times greater in heterogeneous systems (*e.g.*, all textile wet processes) than in homogeneous systems. In water, the maximum effects of cavitation occur at 49 °C, which also happens to be the optimum temperature for most enzymatic processing applications.

Several researchers have reported that ultrasonic energy has been used successfully for intensification of textile treatments, such as mercerization of cotton and cotton blends, desizing and scouring of fibers and yarns, peroxide bleaching, as well as dyeing and finishing processing. It was observed that the introduction of ultrasonic energy into the dyebath provided a significant increase in the rate of dye adsorption onto cotton fibers and resulted in faster and more uniform uptake of dye.[3,4,17] Another important observation was that ultrasonic energy breaks down aggregates of dye molecules in solution, thereby keeping them in a monomolecular state, which improves the overall diffusion rate.

The application of ultrasound in the pretreatment processes of cotton has been studied by several researchers.[6-14,18,19] These studies focused on a single process, such as desizing or scouring or bleaching. Research reports are not known to the authors on a combined desizing-scouring-bleaching (D-S-B) process as a single stage process assisted by ultrasound. This paper presents the results of using ultrasonic energy of 53 KHz frequency to assist desizing as a separate process and a single stage combined D-S-B process.

EXPERIMENTAL

Materials

Fabric. Grey cotton fabric of 145 g/m^2 weight, having 35 tex warp and 31 tex weft yarn count, and 19 reed and 26 pick/cm construction, was used. Fabric specimens of 12 grams weight were used for each experiment.

In all the tests, at least three samples of the same fabric were treated under identical conditions for each trial to ensure good reproducibility of test results.

Chemicals. All chemicals used were of laboratory analytical grade supplied by a reputed manufacturer.

Ultrasonic applicator. The ultrasonic applicator was a square stainless steel tank of 1.6 liter capacity fitted with piezo-electric crystals. Ultrasound waves of 53 KHz frequency were generated by a power input of 50 watts.

Methods

Determination of ultrasound induced heat energy

It was observed that when the ultrasonic device was switched on, the bath temperature rose from the ambient temperature of 20 °C. The rise of temperature was recorded as a function of time.

Desizing

The desizing baths were prepared containing the desired concentration of Biolase Enzyme. Desizing assistants, such as sodium chloride, and a non-ionic wetting agent were added as per the recipes shown in Table 2. Experiments were carried out at a fabric-to-liquor ratio of 1:30. Table 1 presents the experimental details for desizing.

Desized fabric was washed and soaped using a 2 g/l concentration of non-ionic soap at 90 °C temperature for 5 minutes, rinsed with cold water and dried. The dried fabric was accurately weighed to determine the weight loss. The desized fabric was tested for residual size.

Bleaching

Based upon the promising results obtained from the desizing experiments, a combined pretreatment process (D-S-B) on grey fabric was carried out. The experimental setup is shown in Table 2.

Evaluation of treated fabric

Residual size

Residual size on desized fabric was determined by the Iodine drop test. This test is used as a qualitative assessment to determine the removal of starch. The following procedure was carried out: a drop of 0.1 N iodine solution was placed on a test specimen, the specimen was rubbed gently and the colour changes were observed. Thus, if no colour change is observed, it indicates the absence of starch, a blue-black colour indicates the presence of starch, and brown indicates its partial removal.

Weight loss calculation

The loss in weight caused by the chemical processes was determined by weighing the treated and the untreated fabrics. This was expressed as percentage weight loss (wt%), using the following formula:

$$Wt\% = \frac{W_1 - W_2}{W_1} \times 100 \quad (1)$$

where W_1 and W_2 are the fabric weight before and after treatment, respectively. In enzymatic desizing, higher weight loss means higher efficiency of desizing.

Table 1
Experimental setup for desizing

Variables	Conventional desizing	Ul-1*	Ul-2	Ul-3	Ul-4	Ul-5	Ul-6	Ul-7	Ul-8	Ul-9
Biolase (% owf)	2	1	0.75	2	0.5	2	2	1	1	0.5
NaCL (% owf)	5	5	5	5	5	5	5	5	5	5
Wetting agent (% owf)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Temperature (°C)	60	60	60	RT	RT	RT	30	30	RT	30
Time (h)	3	3	3	3	1.5	1.5	0.5	3	1	1.5

*Ul – with ultrasound; RT = room temperature; % owf = percent on the weight of the fabric, pH = 6.5

Table 2
Experimental setup for combined D-S-B* of grey cotton fabric

Chemical recipe and conditions	Conventional	Ul-1	Ul-2	Ul-3	Ul-4	Ul-5	Ul-6
H_2O_2 (% owf)	4	4	4	4	4	4	2
Caustic soda (% owf)	2	2	2	2	2	2	2
Na_2SiO_3 (% owf)	2	2	2	2	2	2	2
Wetting agent (% owf)	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Potassium persulfate (% owf)	1.5	1.5	1.5	0	0.5	0.5	1.5
Temperature (°C)	95	RT	RT	RT	RT	90	RT
Time (h)	2	1	0.5	0.5	0.5	0.5	1

*combined D-S-B = combined desizing, scouring, bleaching; M:L = 1:30, pH 10.5 to 10.8;
The experiment labeled Ul-3 represents the recipe used for conventional peroxide bleaching process in the absence of potassium persulfate

Water absorbency (scouring efficiency)

The scouring efficiency was determined using the drop test method. AATCC Test Method No. 79 was used to measure fabric wetting. A fabric specimen was held below a burette filled with water at a distance of about 1 cm and a drop of water was allowed to fall. The time for complete absorption of the water was measured using a stop watch. Less than 5 seconds time for water absorption indicates the removal of wax, and hence an efficient scouring.

Bleaching efficiency

Bleaching efficiency was determined by measuring the percent reflectance (%R) against a white standard on a visible spectrophotometer. %R values were converted into CIE Whiteness Index (WI), using the formula available in the software. The measurement was done for day light (D65) under a 10 degree observer [D65/10°].

Fluidity

The viscosity (fluidity) of bleached cotton fabric was determined according to the method described in Indian standard specification IS: 244-1984. The specimens were dissolved in a cupraammoniun hydroxide solution and their viscosity was measured at 25 °C.

Physical properties

Physical properties, such as tensile and tear strength, were determined according to the AATCC/ASTM procedures. For tensile strength and elongation (%), a strength tester connected to a computer was used, and the results were computed using Tenso Lab software. The procedure was performed according to ASTM D5034 for fabric traction (Grab) test.

The improvements due to ultrasonic energy were determined by comparison with the results obtained without ultrasound (conventional process).

Scanning Electron Microscopic studies (SEM)

Morphological studies were carried out on a Cambridge Stereoscan Model S4-10 SEM, with a vacuum coating unit.

RESULTS AND DISCUSSION

Ultrasound induced heat

The rise in temperature of the liquid due to ultrasonic cavitation was recorded as a function of time and shown in Figure 1.

Figure 1 shows that the initial rise in temperature was rapid – of about 0.3 °C/min for up to 90 minutes and then reached a plato. After this period, the further increase in temperature was only marginal. This may be due to dissipation of the heat energy, as the vessel was kept open for carrying out the experiments. The induced heat may be considered an additional advantage, since most textile chemical processes are carried out at temperatures above 50 °C, and several others at even higher temperature.

In many textile chemical processes that require temperatures of about 60 °C, external heating may be dispensed with, either partially or fully, by using ultrasound, depending upon the process requirements. Condering the costs involved, the cost of electrical energy used to generate ultrasonic energy may be compensated by savings in consumption of external energy, either electrical or thermal.

The mechanism of heating may be explained by the propagation of high frequency sound waves in water. Gas or air dissolved in water forms bubbles, which expand and contract due to the propagation of waves. These bubbles expand to a stage where further expansion is no longer possible and they collapse, releasing large amounts of energy, which is responsible for the rise in the temperature. As has been demonstrated below, an ultrasound assisted process yields better results, even when it is carried out at room temperature, compared to the same process but performed without ultrasound at nearly boiling temperature.

Effect of ultrasound on desizing

The data in Table 3 indicate one or more of the following possibilities for a good desizing efficiency using ultrasound: 1) reduction in enzyme concentration by 75 percent; 2) reduction in time by 75 percent; 3) elimination of heating in desizing.

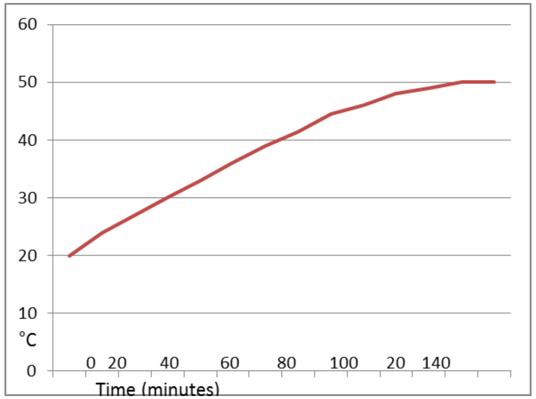


Figure 1: Increment in the temperature of the liquid due to ultrasonic heating

Table 3
Effect of ultrasound on desizing of cotton fabric

Sr. No	Fabric	Treatment conditions			Tests and results			
		Enzyme (%)	Temperature (°C)	Time (h)	Iodine for starch	Weight loss (%)	Water absorbency (seconds)	Wax content (%)
	Grey	--	--	--	Present	--	Many hours	
1	Conventional desizing	2	60	3	Absent	6.4	> 60	1.1
2	Ul-1	1	60	3	Absent	9.2	1	0.15
3	Ul-2	0.75	60	3	Absent	8.3	2.5	0.25
4	Ul-3	2	RT	3	Absent	8.5	1	0.11
5	Ul-4	0.5	RT	1.5	Absent	6.8	2	0.21
6	Ul-5	2	RT	1.5	Absent	9.2	<1	0.12
7	Ul-6	2	30	0.5	Absent	7.2	1	0.09
8	UL-7	1	30	3	Absent	9.4	1	0.13
9	UL-8	1	RT	1	Absent	8.6	1.8	0.23
10	Ul-9	0.5	30	1.5	Absent	7.1	3	0.27

Wang *et al*., in their studies on enzymatic desizing of cotton using ultrasonic energy, suggest that the ultrasonic power value and the cavitation effect were the two most important factors for improving the enzymatic desizing efficiency. The obviously saved treatment time indicates that the overall reaction rate between the enzyme and starch could be accelerated by ultrasonic energy. Comparing with the conventional enzymatic desizing process, the ultrasound assisted system can save half of the processing time and improve the desizing efficiency.[20]

Water absorbency is not generally considered as a test for the desized fabric. However, it was determined in the present investigation as the preliminary experiments indicated good water absorbency. A desized fabric exhibits weight loss because of the removal of sizing and this depends upon the amount of sizing applied. This is generally in the range of 4 to 6 percent, since excessive sizing is avoided. The results tabulated in Table 3 show weight loss ranging from 6.4 to 9.4 percent, depending upon the conditions of enzyme concentration, desizing time and temperature.

Moreover, instantaneous water absorbency allows the presumption of removal of other impurities, such as pectin, wax, *etc*. The question arises as to how these impurities are removed without the use of enzymes like pectinase used in bio-scouring or alkaline high temperature treatment, as used in the conventional high temperature scouring process. Waxes do not respond to amylase-type enzymes alone.

To ascertain the wax content in fabric after desizing, the extraction of fats and waxes was carried out in a Soxhlet apparatus, using carbon tetrachloride solvent. The extract was weighed after recovery of the solvent. Natural cotton has varied wax content, but it is generally of about 1.1 to 1.3 percent. The fabric desized by the conventional process had 1.1% wax, as shown in Table 4, and presents water absorbency of over 60 seconds, while after the ultrasound assisted process, the wax content decreased to about 0.3 percent or less. Thus, ultrasound-assisted desizing removed more than 80 percent of wax, which may be the reason for excellent water absorbency. The mechanism of action of ultrasound as regards the efficient wax removal under neutral pH conditions still needs to be understood and calls for further research.

The general trend that was observed in all the tests indicated that the introduction of ultrasound energy during enzymatic processing of cotton textiles resulted in a substantial improvement in the enzyme's performance. The enhancement induced by sonication may be caused by various physical and chemical effects, resulting from the interplay between ultrasound waves, enzyme molecules and liquid media.[14] The action of ultrasound on the enzymatic desizing of cotton fabric is presumed to cause the following effects:

- An increased number of free sites for enzyme reaction by reducing the adsorption of enzyme molecules onto the surface of cellulosic fibres;
- Increased activity of the enzyme by prevention of possible agglomeration of enzyme molecules;
- Acceleration of the diffusion rate of enzyme molecules toward the fibre surface through the border layer of the liquid at the liquid/solid interface. The concentration of enzyme molecules in this layer is a controlling factor, which defines the overall rate of reaction;
- Improved removal of enzymatic hydrolysis products from the reaction zone, which accelerates the overall rate of enzymatic reaction;
- Improved transport of enzyme molecules through the cotton yarns, which results in more even enzymatic treatment of cellulose fibres and, accordingly, minimizes the loss of tensile strength of the fabric;
- Degassing by expulsion of dissolved or entrapped gas molecules from fibre capillaries and interstices at the crossover points of the fabric into liquid and their removal by cavitation;
- The effects of ultrasonic cavitation in water cause a large increase in pressure and temperature at the microscopic level, which could significantly increase the specific activity of the enzymatic reactions.

While these postulates seem reasonable, much more detailed studies should be carried out to insure better understanding of the mechanism of ultrasound influence on the enzymatic treatment of cotton fabric.

Effect of ultrasound on bleaching (combined D-S-B pretreatment)

Alkaline scouring boil is generally performed after desizing, with the principle objective of increasing the water absorbency of fabric by removing saponifiable and emulsifiable impurities. In the present investigation, the objective was achieved through desizing. Instead of conventional bleaching of desized and scoured fabic using the peroxide boiling process, a combined oxidative pretreatment process for grey fabric was selected with a view to evaluating the effects of ultrasound on the later processes, which pose more challenges in terms process efficacy and the quality of the bleached fabric. The results are presented in Table 4.

The combined D-S-B pretreatment of cotton fabric using ultrasonic energy offers promising results. In other words, ultrasound offers one or more of the following possibilities with comparable efficiency:

- CIE whiteness of fabric bleached with ultrasound is comparable with that obtained by the conventional peroxide boiling process, even when bleached for a short period and at room temperature;
- Reduction in temperature from 95 °C to room temperature during bleaching offers the possibility of substantial savings in thermal energy;
- Reduction in bleaching time from 2 hours to 0.5 hours offers savings in time by about 75%;
- Reduction in consumption of chemicals suggests savings in process costs;
- Elimination of a peroxide booster – potassium persulfate, which is considered essential for an efficient combined pretreatment process at room temperature, is possible.
- The cupra-ammonium fluidity values show that the fluidity of the fabric bleached with ultrasound is lower than that of the fabric subjected to conventional hot peroxide bleaching. As fluidity is a measure of damage to the polymer chains in cellulose in a bleached fabric, it can be concluded that there is no damage due to the use of ultrasound during the bleaching process.

These results call for further detailed research and efforts to scale up the application of ultrasound.

Effect of ultrasound on physical properties

Tensile strength and elongation at break were determined both for warp and weft on desized and bleached fabric samples. The results are presented in Table 5 and a graphical representation of the data is offered in Figure 2. These data suggest that, under desizing and combined single stage bleaching conditions used in the present study, ultrasonic irradiation did not cause any tensile strength loss to the fabric, even for a prolonged treatment time – of 3 hours.

In the experiment on bleaching at high temperature without using ultrasound, the warp tensile loss is of about 17 percent, as compared to the fabric treated with ultrasound (Ul-1), and it is of about 4 to 5 percent and less if the persulfate concentration is lower or the temperature is ambient. In all experiments involving ultrasound, the tensile strength achieved is at the level of desized and scoured fabric. Bleaching by an ultrasound assisted process offers the following advantages: reduction or complete elimination of external heating – thermal energy; reduction in process time by 50 to 75 percent for achieving comparable whiteness; tensile strength retention and reduced damage to the cellulose structure.

The results of the present investigation demonstrate that ultrasound application in a cotton fabric pretreatment process is very promising, on the one hand, and on the other, calls for further in-depth studies to find answers to some unanswered questions, such as the removal of impurities, *e.g.* pectins, wax and fats, seed coat materials, which under conventional process conditions require highly alkaline conditions at nearly boiling temperature.

Other researchers reported using a tube resonator for dyeing cotton fabric by the exhaust and pad batch process, which is more suitable in terms of process efficiency and energy consumption than the cleaning tank used in the present investigation.[15]

Table 4
Single stage combined desizing-scouring and bleaching (D-S-B) assisted by ultrasound

Sr. No	Fabric	Conditions			Tests and results				
		Temperature (°C)	Time (min)	PPS conc. (%)	Iodine for starch	Weight loss (%)	Water absorbency (seconds)	CIE whiteness	Fluidity (rhes)
1	Grey				present	--	hours	--	
2	Conventional	95	120	1.5	absent	12.65	1	75	7.9
3	Ul-1	95	60	1.5	absent	11.54	< 1	76.5	6.8
4	Ul-2	RT	60	1.5	absent	11.00	< 1	75	6.1
5	Ul-3	RT	30	1.5	absent	10.9	< 1	74	6.0
6	Ul-4	RT	30	only peroxide	absent	10.0	< 1	73,4	5.8
7	Ul-5	RT	30	0.5	absent	10.0	< 1	73.2	6.0
8	Ul-6	RT	60	1.5	absent	11.71	<1	73.7	6.3

RT – room temperature (25 °C), Ul – with ultrasound, PPS – potassium persulfate;
Acceptable standard fluidity is 8.0 rhes for a bleached fabric, higher than this indicates damage to cellulose chains

Table 5
Tensile strength and elongation of untreated, conventional and ultrasound desized and bleached fabrics

Sr. No	Fabric	Max. force (N)/5 cm width		Elongation (%)	
		Warp	Weft	Warp	Weft
1	Grey	336	319	16.80	14.30
2	Desized-conventional	260	251	27.80	25.50
3	Scoured-conventional	248	242	25.80	23.10
4	Desized Ul-1	258	252	27.30	25.00
5	Bleached-conventional (D-S-B)	210	206	23.00	20.18
6	Ul-1 D-S-B	239	237	24.30	21.90
7	Ul-2 D-S-B	246	243	21.60	20.70
8	Ul-3 D-S-B	251	245	22.90	21.80
9	Ul-4 D-S-B	248	246	21.63	20.57
10	Ul-5 D-S-B	250	247	22.14	21.52
11	Ul-6 D-S-B	249	249	23.05	21.67

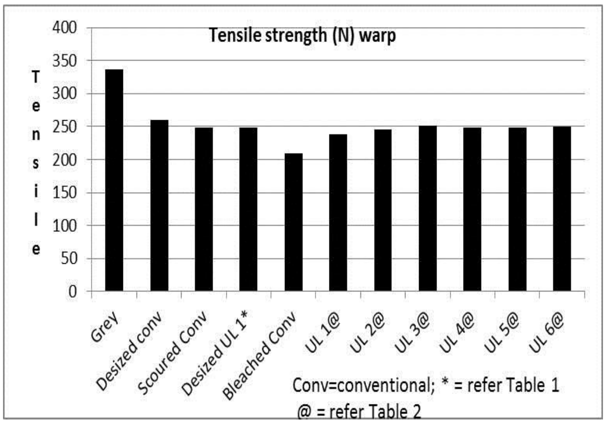
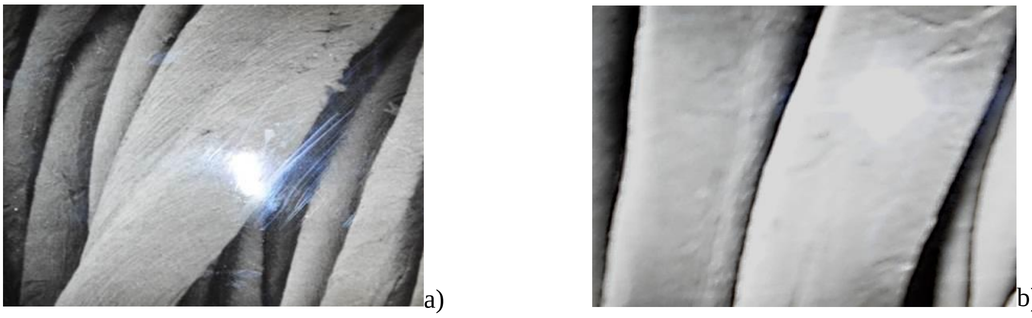


Figure 2: Tensile strength of fabric after desizing and bleaching with and without ultrasound



a) b)

Figure 3: Micrographs of a) control fabric bleached at 95 °C without ultrasound; b) fabric subjected to ultrasound assisted bleaching at room temperature for 90 min (x1540)

Scanning Electron Microscopy

Figure 3 (a) and (b) presents SEM micrographs of the fabric bleached by the conventional and ultrasound assisted D-S-B process, respectively.

The morphology of the sonicated fabric does not show any surface damage, such as fibrillation of fibers. Ultrasonic energy acts at the solid-liquid interface in heterogeneous systems, which may influence the cuticle as well as the primary wall of cellulose. While the removal of added and natural impurities is efficient, the primary wall is not damaged, as appears from the data on weight loss and wax removal after desizing or combined oxidative bleaching. The SEM observations are in line with the lower fluidity values and higher tensile strength retention of the fabric subjected to the ultrasound assisted treatment, compared to the corresponding values of the fabric treated by the conventional processes.

CONCLUSION

Ultrasonic waves of 53 KHz frequency were used to assist desizing and single stage desizing-scouring-bleaching processes for cotton fabric, and exhibited promising results of both desizing and the combined process. The temperature of the liquid rose by 30 °C within 90 minutes due to intense effects of cavitation. Due to this heat energy, the external heating required in most textile chemical processes can be dispensed with.

Ultrasound energy has been found beneficial to enzymatic desizing and combined bleaching. This study has revealed that, by using ultrasound, one or more of the following benefits can be obtained:

- Reduction in temperature from 95 °C to room temperature during bleaching offers substantial savings in thermal energy;
- Reduction in process time from 2 hours or more to 0.5 hour offers savings in time by about 75% (this means an increase in productivity, if the process is successfully scaled up);
- Reduction in consumption of chemicals (implying lower process costs);
- Retention of tensile properties of cotton fabric and less damage to the cellulose structure;
- Processing with minimum or no damage to the fibre surface.

Prolonged irradiation for 3 hours did not cause any damage to the surface or construction of the cotton fabric.

A technique that holds so many promises must be explored through detailed investigations. Moreover, scale-up efforts to evaluate the techno-economic feasibility of the process on an industrial scale would certainly help determine its efficacy and provide guidance as to whether further study should be continued or not.

The results of the present work also present interest regarding the removal of natural impurities, such as pectin, wax, seed coats *etc*., by ultrasound under neutral pH conditions, a procedure that would otherwise require alkaline conditions and boiling temperature or pectinase enzymes. Future work may be focused on this area.

REFERENCES

[1] H. Benli and M. I. Bahtiyari, *J. Clean. Prod*., **89**, 116 (2015).
[2] D. Coman, S. Oancea, N. Vrinceanu and M. Stoia, *Cellulose Chem. Technol*., **48**, 145 (2014).
[3] K. A. Thakore, *Indian J. Textile Res*., **13**, 133 (1988).
[4] K. A. Thakore, *Indian J. Textile Res*., **13**, 208 (1988).
[5] K. A. Thakore, C. B. Smith and T. G. Clapp, *Am. Dyestuff Rep*., **79**, 30 (1990).
[6] P. B. Agrawal, V. A. Nierstrasz, M. M. C. G. Warmoeskerken and M. van der Veer, Patent GB 2432585, 2007.
[7] P. B. Agrawal, V. A. Nierstrasz and M. M. C. G. Warmoeskerken, *Enzyme Microb. Technol*., **42**, 473 (2008).
[8] G. H. Bouwhuis, A. A. Dorgelo and M. M. C. G. Warmoeskerken, *Melliand International*, **15**, 150 (2009).
[9] V. S. Moholkar, P. R. Gogate and A. B. Pandit, *American Institute of Chemical Engineers Journal*, **50**, 58 (2004).
[10] V. A. Nierstrasz and M. M. C. G. Warmoeskerken, in “Textile Processing with Enzymes”, edited by A. Cavaco-Paulo and G. M. Guebitz, Woodhead Publishing, Abington, England, 2003, pp. 120-154.
[11] M. M. C. G. Warmoeskerken, P. van der Vlist, V. S. Moholkar and V. A. Nierstras, *Colloid. Surfaces, A*, **210**, 277 (2002).
[12] P. Radhakrishnaiah, M. Xiaomin and H. Gan, *Textile Res. J*., **69**, 708 (1999).
[13] M. K. Traore and G. Buschle-Diller, *Text. Chem. Color. Am. Dyestuff Rep*., **1**, 51 (1999).
[14] K. S. Suslick, “Ultrasound: Its Chemical, Physical and Biological Effects”, VCH Publishers, New York, 1988.
[15] I. Gonçalves, V. Herrero-Yniesta, I. Perales Arce, M. Escrigas Castañeda, A. Cavaco-Paulo *et al*., *Ultrason. Sonochem*., **21**, 1535 (2014).
[16] G. Yachmenev, N. R. Bertoniere and E. J. Blanchard, *J. Chem. Technol. Biotechnol*., **77**, 559 (2002).
[17] K. A. Thakore, *Am. Assoc. Textile Chem. Colorist*., **11**, 66 (2011).
[18] A Madhu and J. N. Chakraborty, *J. Clean. Prod*., **145**, 114 (2017).
[19] L. Hao, R. Wang, K. Fang and J. Liu, *Carbohyd. Polym*., **96**, 474 (2013).
[20] W.-M. Wang, B. Yu and C.-J. Zhong, *J. Clean. Prod*., **33**, 179 (2012).