

RESEARCH

Effect of ultrasound on dyeing of wool fabric with acid dye

G. M. Nazmul Islam¹ · Guizhen Ke¹ · Abu Naser Md. Ahsanul Haque² · Md. Azharul Islam³

Received: 9 March 2017 / Accepted: 26 October 2017 / Published online: 13 November 2017
© The Author(s) 2017. This article is an open access publication

Abstract Wool fiber strength and handle is damaged by holding for prolonged periods at normal dyeing temperatures (98 °C). Lower dyeing temperatures can be employed to color wool whilst reducing damage caused to the fiber. However, these lower temperature dyeing processes often have a long dyeing time and/or require the addition of chemicals to achieve adequate dye exhaustion and migration. The use of ultrasonic irradiation was used to reduce dyeing times and temperatures whilst increasing dye migration and fastness. It has used 30 kHz frequency level, effective power of 120 and 350 W heating power in ultrasonic machine. In this work, wool dyeing was carried out on single jersey knitted fabric using an acid dye with and without ultrasonic irradiation at 60, 70, and 80 °C. Dye exhaustion was measured using UV/visible absorbance of the dye bath before and during the dyeing cycle. For the measurement of nodal/anti-nodal point of energy, at 60, 70, and 80 °C dyeing was done in open bath of ultrasonic machine with and without sonication at high liquor ratio. To compare the dye uptake (%) at high/conventional process, sample was dyed at 95 °C. Optical and scanning electron microscopy were used to measure the diameter and surface changes of the fiber, respectively. Wash and rub fastness was measured on the dyed fabrics after rinsing and drying. Ultrasonic irradiation during the dyeing of wool caused an increase in the dye exhaustion rate for acid

dye. This change in rate is believed to have been caused by a reduction in the viscous boundary layer of liquor surrounding the fiber present in an ultrasonic irradiated environment. An increased dye migration due to cuticle cracking and fiber swelling was not deemed to have occurred as wet fiber diameter was not changed by submersion in the dye liquor in the presence of ultrasound and no surface cracking was evident in scanning electron microscopy images. Some cuticle structure changes occurred with turning up or ripping off of the cuticle tips evident. Both wash and rub fastness were improved for ultrasonically dyed fiber with dyeing temperatures of 70 and 80 °C being suitable for the low-temperature dyeing of wool.

Keywords Acid dye · Migration · Ultrasound · Wool · Dye exhaustion

Introduction

The morphology of wool fibers is very complex. There are essentially two main categories of cell: one is cortical cells which make up, approximately 90% of the fiber and the other is cuticle cells which are present at the fiber surface. The cuticle is separated from the underlying cortex by a cell membrane complex which also holds adjacent cortical cells together. The cell membrane complex is, therefore, the only continuous phase in a wool fiber. The cuticle structure is responsible for the surface properties of wool. Cuticle cells are nearly rectangular sheets with average dimensions of 30 µm length, 20 µm width and 0.5 µm thickness, however, these dimensions change relative to the fiber diameter and animal breed. The cuticle is considered to be made up of three distinct layers starting from the

✉ Guizhen Ke
guizhen.ke@wtu.edu.cn

¹ School of Textile Science and Engineering, Wuhan Textile University, Wuhan 430073, People's Republic of China

² Daffodil International University, Dhaka, Bangladesh

³ Mawlana Bhashani Science and Technology University, Tangail, Bangladesh



outside with the epicuticle, exocuticle and endocuticle. The epicuticle has an outer surface that is coated with a layer of highly acylated fatty acids of 18-methyleicosanoic acid which makes the cuticle surface highly hydrophobic and provides the fiber with its resistance to quick wetting, and attack from alkalis, oxidizing agents and proteolytic enzymes. The fatty acid structure is about 2.5 nm thick and amounts to approximately 0.1% of fiber weight [1, 2]. The intricacy of the cuticle structure and its hydrophobic surface is the limiting factor to penetration of dye molecules into the fiber as they must pass between the scale structure in the space between the cuticle cell overlap [3].

There are many processes to dye wool fabric with acid dye. Many low-temperature wool dyeing processes have been proposed by the use of pretreatment and chemicals [4, 5] and enzyme or plasma pretreatments [6–8]. McNeil and McCall [9] introduced that ultrasound gave potential to reduce the chemical and extra energy requirements in wool dyeing with reactive and acid milling dye. Yukseloglu and Bolat [10] confirmed these improvements using ultrasound in dyeing of wool fabrics at 80–90 °C with a pre-metallized dye. Studies on wool dyeing explained that with the assistance of ultrasonic, a better fiber dye uptake% can be achieved with a variety of dyes in a shorter dyeing time period and at a lower temperature [11–13]. Such work was done by Shanker and Vanker on wool with natural dye and resulted good dry rub as well as wash fastness [14, 15]. Ultrasound significantly enhanced the application of dyes which have no optimum application procedures developed for wool or that have poor dye uptake% to wool [16], cotton [17–19] or other fibers [20]. Micro-cracking of the wool fiber cuticle was proposed as a method of increased dye uptake for samples that had undergone ultrasonic pretreatment in an alkaline scouring solution [21]. The collapse of bubble formed by ultrasonic irradiation within a liquid is dependent on its proximity to a surface. If collapse occurs in a bulk liquid away from a surface it results in an implosive collapse that can generate huge amounts of energy at the collapse location in the form of heat (5000 °C) and pressure (1000 atm), however, the ambient conditions of the liquid remain relatively unchanged. A collapse in close proximity to a solid surface is believed to be quite different in its morphology. It is widely held that the mechanism of bubble collapse close to a solid boundary layer involves an asymmetric collapse via a liquid jet (up to 400 km/h) through the bubble interior [22–24]. It is felt that the collapse of bubbles near to a surface reduces the thickness of the viscous boundary layer (normally 30 µm thick) as its thickness is inversely proportional to the square root of the frequency [25]. A surface subjected to ultrasonic irradiation at 30 kHz has a 4.4 µm viscous boundary layer whereas one subjected to 900 kHz has one of ≈ 0.8 µm. As diffusion rate of solution chemistry

through the boundary layer is rate controlled a reduction in the thickness of this layer will result in an increase in molecules reaching the surface over time.

Dyeing is the process of adsorption of dyes from a dye solution onto the surface of a fiber [26, 27] followed by migration of the dye molecule into the fiber. Normally, the dyeing of wool is undertaken at close to the boiling point of water as this enables swelling of the fiber diameter and an opening of the cuticle structure. This provides a pathway for the dye molecules into the fiber that is not present at lower temperatures [28]. To increase dyeing rate at a lower temperature, the method must increase the swelling of the fiber and or increase the rate of adsorption of the dye onto the fiber surface. The reduction of the thickness of the boundary layer around a fiber with the use of ultrasonic irradiation may be the reason for increased rates of dyeing seen by others. Alternatively, the high-speed implosion jets of water may be forcing their way into the cortex between the cuticle overlaps to provide accelerated swelling of the fiber and a pathway for dye entry.

Application of ultrasound can be incorporated with industrial dyeing machine as it reduce the need of electrolyte in dyeing [29] and it is reported that this method can be applied effectively in different textile wet processes including pretreatment and dyeing-finishing steps [30].

This work has been designed to determine if the increased rate of dye uptake at lower temperatures using ultrasonic irradiation is achieved by an increase in the adsorption of the dye onto the fiber surface and/or by changes in the swelling of the wool fiber and/or changes in the morphology of the cuticle structure. It used dyeing and microscopy to confirm which was the contributing mechanism to dye exhaustion improvement. Though many research were done to study the effect of ultrasound on the dyeing behavior of wool fabric, the specialty of this project is that it used low-frequency level (30 kHz), effective power of 120 W and heating power of 350 W of ultrasonic machine which was lower than any other previous projects. This research has reduced not only the temperature but also increased the dye uptake% more than other projects. By this way, it has proposed lower processing cost and reduced time as dyeing was done using lower frequency level, lower effective power and lower heating power.

Experimental

Materials and methods

Pure wool knitted single jersey fabric (GSM 218 g/m², Yarn count-57 Nm) was rinsed in running cold water to remove impurities. Rinsing was complete when there was no longer foam formation present in the rinse water.



The acid dye used was light yellow 17 (Red Sun Dye Chem, India) which presents a maximum absorbance peak at 620 nm. In this study, this acid dye was selected due to its simplicity and reliability in application and also for its economical efficiency. It also has the low cost production of a wide range of shades with good all round fastness.

The dyeing process was carried out under isothermal conditions with and without the use of ultrasound. The dyeing temperatures used were 60, 70, and 80 °C. Dyeing was conducted in a 30 kHz JP-100ST ultrasonic bath (Shenzhen Jiemeng Washing Machine Company, China). The bath had a volume of 2.0 L, a heating power of 350 W and an ultrasonic irradiation power of 120 W. At each temperature, two dyeing methods were applied. First one, named ‘with beaker’ involved 100 ml beaker which was placed in the water of ultrasonic bath and dyeing was performed inside the beaker with 50:1 liquor ratio. pH control (pH = 4) was achieved by the addition of laboratory grade acetic acid (Jinzhou King Changsheng Chemical Co. Ltd., China), a fabric sample weight of 2.0 g and a dye concentration of 2.0% owf (on the weight of fabric) was used. In the second method of dyeing named ‘open bath’ (without beaker), for the study of nodal/anti-nodal point of energy, 2 g of fabric was dyed with 2 g of dye at 60, 70, and 80 °C in 2 L of dyeing solution, pH of the bath was 4 and no beaker was used.

The ultrasonic bath was heated to the dyeing temperature. Dyeing then continued over 240 min for ‘with beaker’ process and 60 min for ‘open bath’ process with a 1.0 ml volume of dye solution removed every 10 min for spectrophotometric measurement to monitor dye exhaustion. The final sample was washed in cold water, squeezed by hand to remove excess water and air-dried at 100 °C. Both with and without ultrasound dyeing was conducted in the same apparatus with/without the ultrasonic irradiation turned on. Only one sample (2 g) was dyed at 95 °C with high-temperature laboratory dyeing machine for ensuring the ultrasonic sonication activity at low temperature for 4 h.

Dye solution absorbance was measured before and during dyeing using a 2550 UV–Vis Spectrophotometer (Shimadzu, Japan) and measurements were evaluated using ‘Vision 32’ software. Where required, samples were diluted so that maximum absorbance of the dye solution remained under 1.0 so that measurements would behave according to Lambert–Beer Law.

The percentage dye uptake was calculated using Eq. 1.

$$\text{Dye Uptake (\%)} = \frac{A_b - A_a}{A_b} \times 100 \quad (1)$$

where A_b is the absorbance of the dye bath before dyeing and A_a is the absorbance of dye bath after dyeing.

Rubbing Fastness Tests were carried out according to GB/T3920-1997 (ISO 105-X12:1993).

Washing Fastness tests were carried out according to ISO 105 C06.

Fiber surface morphology was examined using a JSM-6510 scanning electron microscope (JEOL Ltd. Japan). Measurements were conducted with an EHT of 5 kV, a working distance (WD) of 7.4 mm and an aperture size of 30 μm. For analyzing the fabric surface morphology or SEM analysis, samples were prepared by ‘Gold Powder’ (Anhui Shenjian New Materials Co. Ltd. China) as coating materials.

Optical microscopy was carried out on a number of single fibers to determine the presence of swelling. Single fibers were attached on one side of a glass slide at both ends using clear plastic tape so that 40 mm of fiber was exposed. The fibers were marked at approximately half way along their length with a black permanent marker to enable imaging in the same place after each treatment. Microscopy was done using an optical microscope (PUDA, China). Images were captured with an iPhone 6 camera (Apple, USA) before being cropped using Photoshop. An image of the fibers at 100 time magnification was captured in a dry state. The fibers were then oven dried at 105 °C for 20 min. The dried fibers were placed in pH 4 dyeing liquor, without dye, at 60 °C for 20 min without ultrasound. An image of each of the wet fibers was then captured at 100 times magnification in the same position as the dry measurement. The drying and wet treatment steps were then repeated with ultrasonic irradiation used in the wet step. An image of each of the ultrasound-treated wet fibers were then captured at 100 times magnification in the same position as the dry measurement.

Results and discussion

Dyeing uptake analysis

An accelerated dyeing rate was observed for ultrasonically irradiated dyeing baths for all three dyeing temperatures (60, 70 and 80 °C) studied in this work when compared to the dyeing without ultrasonic irradiation (Figs. 1, 2, 3). The most pronounced difference in exhaustion levels was noticed in the 60 °C dyeing. These dyeing did not proceed totally to exhaustion in the 240 min dyeing time, however, the ultrasound-assisted dyeing had a higher exhaustion than the dyeing without ultrasound (93.2 and 89.1%, respectively). Comparing the dyeing in open bath with the conical flask dyeing, dye uptake is little bit lower. In Fig. 1, it is seen that at 60 °C the exhaustion rate% with ultrasound is higher than without ultrasonic. The dye uptake% with ultrasonic and without ultrasonic were 63.2% (open bath)



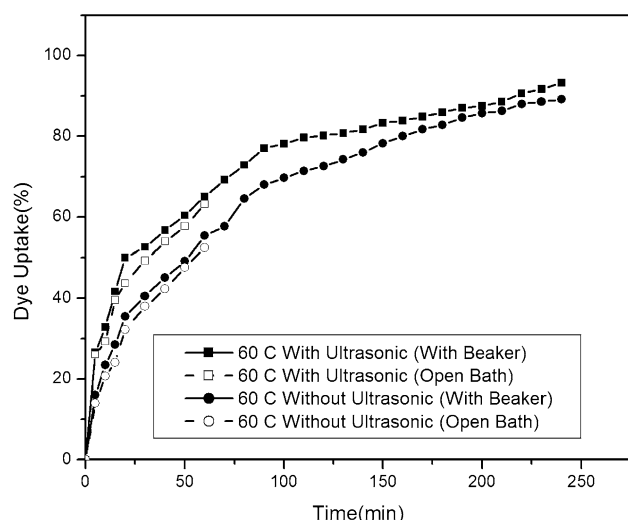


Fig. 1 Comparison between the exhaustion levels of wool fabric dyeing at 60 °C (Beaker and Open bath)

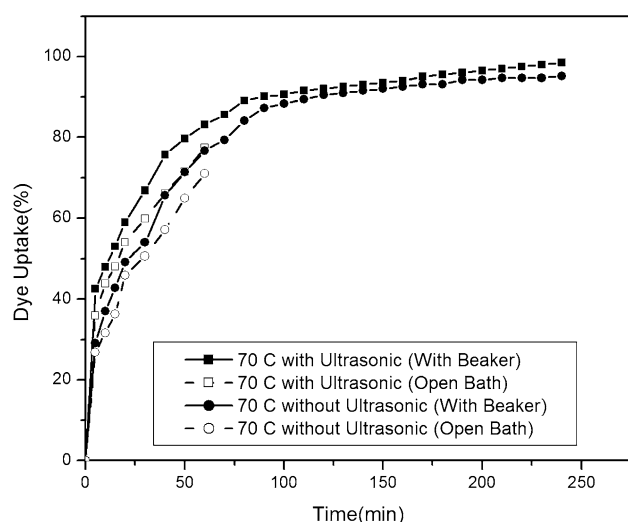


Fig. 2 Comparison between the exhaustion levels of wool fabric dyeing at 70 °C (Beaker and Open bath)

and 65.1% (with beaker) and 52.4% (open bath) and 55.4% (with beaker), respectively, even after 60 min dyeing run time. Both the dyeing at 70 and 80 °C were close to full exhaustion at the end of the 240 min dyeing time. Again the dye exhaustion level was larger for the ultrasonic irradiated dyeing to those without ultrasonic irradiation (70 °C were 98.5 and 95.2%, respectively and 80 °C were 99.7 and 95.9%, respectively). In Fig. 2, at 70 °C the dye uptake% of with ultrasonic and without ultrasonic were 77.4% (open bath) and 83.2% (with beaker) and 70.9% (open bath) and 76.7% (with beaker), respectively. In Fig. 3, at 80 °C the dye uptake% of with ultrasonic and without ultrasonic were 80.6% (open bath) & 85.3% (with beaker) and 74.2% (open bath) and 79.6% (with beaker), respectively, after 60 min dyeing run time. These types of

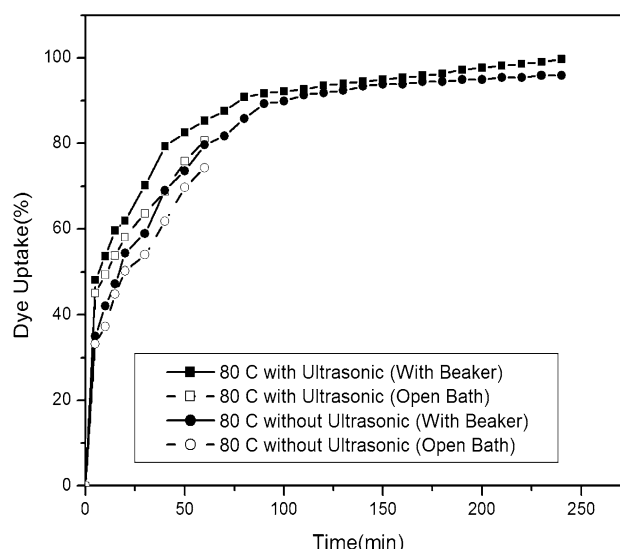


Fig. 3 Comparison between the exhaustion levels of wool fabric dyeing at 80 °C (Beaker and Open bath)

results were lower because of high volume of liquor (2 L solution) in bath. But the trend is similar to the dyeing results of conical flask dyeing. The high dye exhaustion rates observed at both 70 and 80 °C show that coloration in the presence of ultrasonic irradiation could be used to undertake effective low-temperature dyeing of wool without the need for additional chemicals or pretreatments.

It was very interesting that at 95 °C (Fig. 4), the dye uptake% was greater than 80 °C till 230 min dyeing time (95 °C were 99.2% and 80 °C were 99%). But at the final stage 240 min, the dye uptake% of 80 °C was greater (99.74%) than 95 °C (99.59%). Thus in this stage, the temperature can be reduced. This was the significant effect of ultrasound sonication.

Three variables could have an effect on dye uptake rate of the ultrasonically irradiated dyeings. These are a change in boundary layer thickness (liquid movement dead zone) around the fiber, changes in swelling of the fiber caused by high-speed jets of liquor from ultrasonic implosions near to the surface penetrating between the cuticle overlap and micro-cracking of the cuticle surface. It is not easy to measure the changes in boundary layer in the dyeing system used here, however, the changes in fiber swelling and cuticle micro-cracking can be easily evaluated with microscopy. Optical microscope images captured of a number of single fibers in a dry state before treatment, in a wet state after immersion in pH 4 dyeing liquor, without dye, at 60 °C with and without ultrasound show that there is no changes in swelling (Fig. 5). As the immersion time, temperature and liquor conditions were the same for both the ultrasonically treated and untreated fibers, it can be assumed that ultrasonic-induced swelling does not play a part in the increased rate of dye uptake.



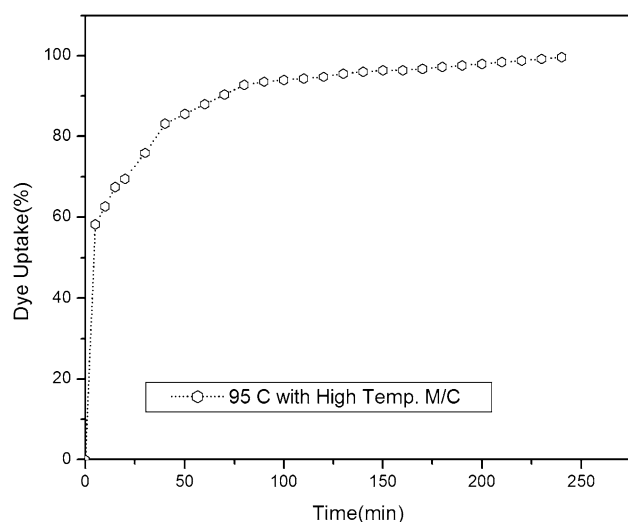


Fig. 4 The exhaustion levels of wool fabric dyeing at 95 °C (with beaker)

To understand if the presence of cracking of the cuticle had contributed to the increase in dye exhaustion levels during the dyeing process with ultrasonic irradiation, surface morphology was investigated using scanning electron microscopy (Fig. 6). No cracking of the cuticle was evident as that observed in previous work [19], however, this may have been eliminated due to the acidic nature of the dye-bath and the difference in ultrasound frequency and lower power employed in this work. There were noticeable changes to the cuticle structure with turning up of the tip and cuticle fragments present on the fibers. These changes in cuticle could be expected to have some effect, however, it is believed that the level of these changes would be low at the initial stages of the dyeing process where the highest changes in dyeing rate were observed. At the treatment time extends the influence of cuticle changes could contribute to the changes observed in total dye uptake and may explain the difference in final exhaustion levels observed. Both the optical and scanning electron microscopy images strengthen the hypothesis that the rate of dye uptake change is caused by a reduction of the boundary layer around the fiber allowing faster movement of the dye molecules to the fiber surface.

Dyeing fastness

The benefits of an increased rate of dyeing and exhaustion level at a lower temperature cannot be achieved at the reduction of wash and rub fastness levels. The wash fastness results for the 60 °C dyeing were not as good as those for the 70 and 80 °C, however, in all cases, the wash fastness of the dyeing with ultrasound were better than those without (Table 1). The lower wash fastness is possibly related to poor migration of the dye within the fiber.

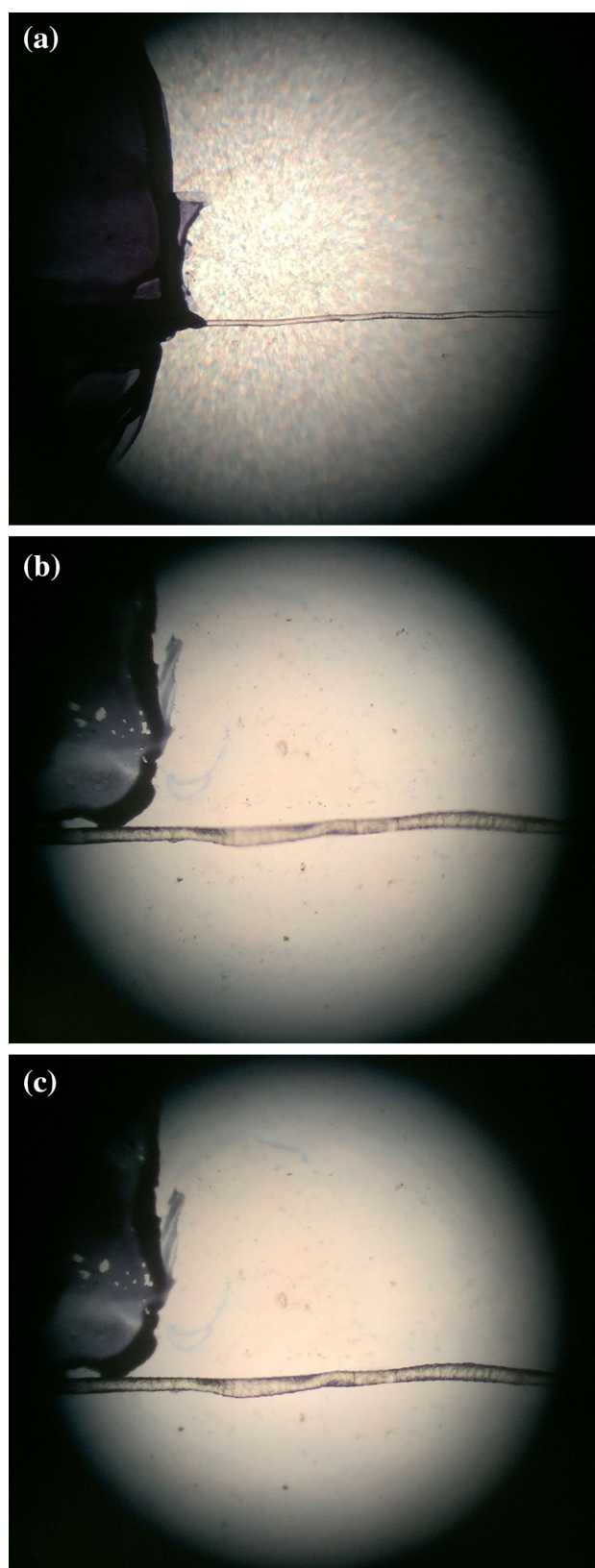


Fig. 5 Optical microscopy images of a single **a** dry fiber, **b** without ultrasonic, and **c** with ultrasonic



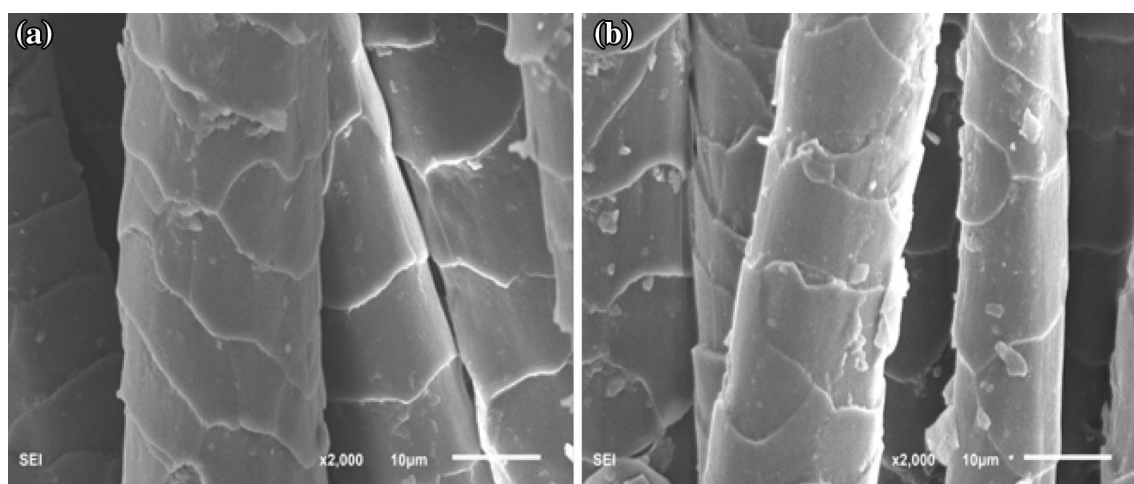


Fig. 6 SEM images of wool fibers after dyeing at 80 °C **a** without ultrasonic irradiation and **b** with ultrasonic irradiation

Table 1 Dyeing fastness to washing

Type of fastness test	Dyeing system	Dyeing temperature		
		60 °C	70 °C	80 °C
Staining on acetate	Without ultrasound	3	4	5
	With ultrasound	4	5	5
Staining on cotton	Without ultrasound	4	5	5
	With ultrasound	5	5	5
Staining on wool	Without ultrasound	3	5	5
	With ultrasound	4	5	5

Table 2 Dyeing fastness to rubbing

Type of fastness test	Dyeing system	Dyeing temperature		
		60 °C	70 °C	80 °C
Wet rubbing	Without ultrasound	3	4	4/5
	With ultrasound	5	5	5
Dry rubbing	Without ultrasound	4	5	5
	With ultrasound	5	5	5

Migration within a fiber is both time and pathway dependent. As the pathways are restricted due to low levels of swelling of the fiber, it is possible that dye is closer to the surface in the lower temperature-dyed samples. The ultrasound provides a higher rate of dye adsorption onto the fiber at lower temperatures and this possibly provides more time for dye migration and hence the better dye wash fastness results for the ultrasonically dyed fiber.

As the method of dyeing rate improvement is suspected to be caused by a reduced boundary layer thickness of liquor around the fiber then the increased surface adsorption at 60 °C would cause lower rub fastness if the dye is surface bound. The rub fastness of the ultrasonically dyed wool was better for all dyeing temperatures

and this may have been due to the increased times for dye migration due to the more rapid adsorption of dye (Table 2). The higher levels of wash and rub fastness seen for the 70 °C and 80 °C dyeing using ultrasound make it a suitable method for the low-temperature dyeing of wool fiber.

Conclusion

Ultrasound has a positive effect on the dyeing behavior of wool fiber. Ultrasonic irradiation during the dyeing of wool caused an increase in the dye exhaustion rate for acid dye. This change in rate is believed to have been caused by a reduction in the viscous boundary layer of liquor surrounding the fiber present in an ultrasonic irradiated environment. An increased dye migration due to cuticle cracking and fiber swelling was not deemed to have occurred as wet fiber diameter was not changed from submersion in the dye liquor in the presence of ultrasound and no surface cracking was evident in scanning electron microscopy images. Some cuticle structure changes occurred with turning up or ripping off of the cuticle tips evident. Both wash and rub fastness were improved for ultrasonically dyed fiber with dyeing temperatures of 70 and 80 °C being suitable for the low-temperature dyeing of wool.

Acknowledgements The authors greatly appreciate for the financial support by Hubei Modern Textile Engineering and Technology Research Center, Wuhan Textile University (153102), China.

Authors' contributions GMNI carried out the experimental work and the data collection and drafted the manuscript. ANMAH and MAI participated in the analysis of data and edition of the manuscript. GK carried out the study design, the analysis and interpretation of data. All authors read and approved the final manuscript.



Open Access This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made.

References

- Negri AP, Cornell HJ, Rivett DE (1993) A model for the surface of Keratin Fibres. *Text Res J* 63:109–115
- Hocker H (2002) Fibre morphology. In: Simpson WS, Crawshaw GH (eds) *Wool: science and technology*. Woodhead Publishing Limited, Cambridge, pp 60–79
- Lewis DM (1992) *Wool dyeing*. Society of Dyers and Colourists, Bradford, England, p 372
- Rippon JA, Harrigan FJ (1994) New method of dyeing wool at temperature below the boil. *Wool Rec* 153:53–55
- Marif M, De la Maza A, Parra JL, Coderech L, Serra S (2001) Dyeing wool at low temperatures: new method using liposomes. *Text Res J* 71:678–682
- Riva A, Algaba L, Prieto R (2002) Dyeing kinetics of wool fabrics pretreated with a protease. *Color Technol* 118:59–63
- Perolatto M, Ferrero F, Giasetti M, Mossotti R, Innocent R (2010) Enzyme-aided wool dyeing with a neutral protease at reduced temperatures. *Eng Life Sci* 10:474–479
- Kan CW, Chan K, Yuen CWM (2004) The possibility of low-temperature plasma treated wool fabric for industrial use. *AUTEX Res J* 4:37–44
- McNeil SJ, McCall RA (2011) Ultrasound for wool dyeing and finishing. *Ultrason Sonochem* 18:401–406
- Yükselgözü SM, Bolat N (2010) The use of conventional and ultrasonic energy in dyeing of 100% wool woven fabrics. *Tekstil Vekonfeksiyon* 2:162–167
- Kamel MM, El-Shishtawny RM, Yussef BM, Mashaly H (2005) Ultrasonically assisted dyeing III. Dyeing of wool with lac as a natural dye. *Dyes Pigm* 65:103–110
- Dong CH, Zhu P, Sui SY, Zhan YZ, Wang XF (2008) Dyeing wool by ultrasonic wave. *Wool Text J* 10:10–13
- Zhan YZ, Wang XF, Zhao X, Wang W (2008) Effect of ultrasonic on dyeing behaviors of reactive dyes on Wool. *Dyeing (China)* 34:8–10
- Shanker R, Vankar PS (2004) Ultrasound energised dyeing of wool with portulaca flower extracts using metal mordants. *Colourage* 51(10):41
- Shanker R, Vankar PS (2005) Ultrasonic energised dyeing of wool with *Mirabilis jalpa* flowers. *Colourage*. 52(2):57–61
- Vankar PS, Shanker R, Dixit S, Mahanta D, Tiwari SC (2008) Sonicator dyeing of modified cotton, wool and silk with Mahonia napaulensis DC and identification of the colorant in Mahonia. *Ind Crops Prod* 27:371–379
- Kamel MM, El Zawahry MM, Ahmed NSE, Abdelghaffar F (2009) Ultrasonic dyeing of cationized cotton fabric with natural dye. Part 1: cationization of cotton using Solfix E. *Ultrason Sonochem* 16:243–249
- Kamel MM, El-Shishtawny RM, Youssef BM, Mashaly H (2007) Ultrasonic assisted dyeing. IV. Dyeing of cationised cotton with lac natural dye. *Dyes Pigments* 73:279–284
- Vankar PS, Shanker R, Srivastava J (2007) Ultrasonic dyeing of cotton fabric with aqueous extract of *Eclipta alba*. *Dyes Pigm* 72:33–37
- El-Shishtawny RM, Kamel MM, Hanna HL, Ahmed NSE (2003) Ultrasonic-assisted dyeing: II. Nylon fibre structure and comparative dyeing rate with reactive dyes. *Polym Int* 52:381–388
- Hurren CJ, Cookson P, Wang X (2008) The effects of ultrasonic agitation in laundering on the properties of wool fabrics. *Ultrason Sonochem* 15:1069–1074
- Crum LA (1979) Surface oscillations and jet development in pulsating bubbles. *J Phys Colloques* 40:C8-285–C8-288
- Lauterborn W, Bolle H (1975) Experimental investigations of cavitation bubble collapse in the neighbourhood of a solid boundary. *J Fluid Mech* 72:391–399
- Lauterborn W, Vogel A (1984) Modern optical techniques in fluid mechanics. *Annu Rev Fluid Mech* 16:223–244
- Morse PM, Ingard KU (1960) *Theoretical acoustics*. McGraw Hill, New York
- Haque ANMA, Hannan MA, Rana MM (2015) Compatibility analysis of reactive dyes by exhaustion-fixation and adsorption isotherm on knitted cotton fabric. *Fash Text* 2(1):1–12
- Haque ANMA, Islam MA (2015) The contribution of different vinyl sulphone-reactive dyes to an effluent. *J Taibah Univ Sci* 9(4):594–600
- Zhang L, Wang JH, Zhao YR (2015) Optimization of low temperature dyeing process for wool fiber. *Text Dyeing Finish J* 37:17–19 (in Chinese)
- Thakore KA (1988) Applications of ultrasonics in dyeing of cotton fabrics with direct dyes: Part I-Kinetics of dyeing. *Indian J Text Res* 13:133–139
- Ferrero F, Periolatto M (2012) Ultrasound for low temperature dyeing of wool with acid dye. *Ultrason Sonochem* 19:601–606

Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

