Ultrasound Dyeing Experiment

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Abstract

The effect of ultrasound on dyeing of wool fabric at room temperature and normal atmospheric pressure is investigated in this research. The ultrasonic method is compared with traditional soak-and-stir method in the experiment in which wool fabric is dyed with natural gardenia yellow pigment. It is observed that the ultrasonic method leads to better dyeing result over its traditional counterpart - the process is faster, with the resulting color more evenly-distributed and staying longer.

1. Introduction

Traditional soak-and-stir method of dyeing wool fabric, which uses acid-dye or acid-medium dye, is a very time-consuming and energy-wasting process. A typical procedure often involves multiple temperature raising and lowering steps, for example, the temperature of the solution has to be raised before dyeing and maintained during dyeing; it has to be lowered when additional acid or salt is needed; then raised again in order to continue. Finally follows the water-washing and drying process [1]. In this study, a new dyeing process with natural gardenia yellow pigment, which uses ultrasound at room temperature under normal atmospheric pressure, is proposed and compared with the traditional method.

2. Fundamental principle

When the study of ultrasonic cavitation and sonochemistry, parameters, such as maximum temperature and maximum pressure reached in an imploding cavitation bubble, are usually adopted to characterize the level of ultrasound energy concentrated in any active micro-bubble. The conservative values estimated are given by the following equations,

\[ T_{\text{max}} = T_{\text{min}} P_m (\gamma - 1) / P_v \]  \hspace{1cm} (1)

\[ P_{\text{max}} = P_v [P_m (\gamma - 1) / P_v]^{\gamma/(\gamma - 1)} \]  \hspace{1cm} (2)

Where, \( T_{\text{min}} \) is the surrounding temperature of the solution, \( P_m \), the external pressure when the bubble closes, \( P_v \), the vapor pressure in bubble and \( \gamma \), the heat rate of the vapor. Assuming room temperature and normal atmospheric pressure, i.e., \( T_{\text{min}} = 25^\circ \text{C}, P_m = 1.013 \times 10^5 \text{ Pa}, P_v = 2.33 \times 10^3 \text{ Pa} \) and \( \gamma = 1.33 \), then the maximum temperature, \( T_{\text{max}} \), and maximum pressure, \( P_{\text{max}} \), will be 4290K and 9.80 \times 10^7 \text{ Pa}, respectively. From these values, it is obvious that the energy released from the micro-bubble is significantly large. In some studies [2-4], it is found that the temperature rising rate in the imploding bubble can reach \( 10^9 \text{ K/s} \), and the velocity of the jet and shock wave induced approaches 400km/h. This creates a unique and extreme physical and chemical environment that is impossible to build under ordinary condition. The idea of using ultrasound for dyeing is to take advantage of this unique feature - if an ultrasonic cavitation field can be created in the container with the dyeing solution, the cooperative effects of high temperature and high pressure released by a large number of micro-bubbles and the accompanying jet and shock wave will promote the action and binding between the dye particles and wool fiber, thus making the dyeing process faster and the quality better.
3. Experimental set-up, material and method

Experimental set-up consists a multipoint-selective wideband generator and a set of piezoelectric transducers with individual exponential amplitude-varying rods. The working frequency of this device ranges from 20 KHz to 1.7MHz and the maximum output electric power is 600W. The ultrasound emitting head is made of titanium alloy. The colorless wool fabric and the natural, non-toxic gardenia yellow pigment used in this study are supplied by Hailan Group and Biotalen Corporation respectively, both from Jiangsu, China. Before dyeing the fabric is cut into square or quadrilateral pieces with size of around 3~5cm on each side and the aqueous dyeing solution used in the experiment has a concentricity of 2 ‰ and pH of 5. A 500ml beaker is used as the container. Before experiment the wool fabric samples and the titanium ultrasound-emitting head are immersed in the solution. During dyeing, the ultrasound is guided directly into the solution, inducing an ultrasonic cavitation field in the container. To protect the solution and the ultrasound-emitting head from overheating, the container is placed in cooling water. In addition, the ultrasonic signal output at an on-off ratio of 50:1 is adopted, and the total accumulated period of applying ultrasound is locked in 30 minutes, thus the temperature of the cavitating solution is maintained at less than 60℃ during the entire experiment. One of the experimental set-ups is shown in Fig.1. The ultrasonic result is compared with the soak-and-stir result under same conditions (piece sample, container, dyeing solution and period, temperature and pressure).

4. Results

Fig.2 Soak-and-stir dyeing sample (left); ultrasound dyeing sample (right)

Fig.2 shows the samples dyed with ultrasound (right) and traditional soak-and-stir process (left) before being washed. The yellow color resulted from ultrasonic dyeing is deeper and more evenly distributed (notes: it is one of the characteristics of the wool fabric that it curls up when immersing in aqueous solution, as seen in the picture. This has nothing to do with the ultrasound effect). Fig.3 shows the original colorless wool fabric sample (left) and the samples dyed with soak-and-stirring method(middle) and ultrasound (right). The yellow color is formed after dyeing, air-drying and washing with Diao Pai soap (Zhejiang Nice Chemical Co., Ltd.) for three times and washing with Liby cleaner (Guangzhou Liby Enterprise Group Co., Ltd.) for three times. The lower-middle and lower-right samples in Fig.3 show the experimental results after using the dyeing solution the second time. The ultrasonic dyeing result still has a deeper yellow. Fig.4 shows another set of samples after dyeing, washing and air-drying, but with additional smoothing. The ones at upper-left are the original colorless samples, upper-right and lower-left are the samples dyed by soak-and-stirring, lower-right are the samples dyed with ultrasound.
5. Conclusions and discussions

It can be concluded from this experiment that at room temperature and under normal atmospheric pressure, the ultrasound dyeing method leads to better dying result on wool fabric over the traditional soak-and-stir method - the process is faster, with the resulting color more evenly-distributed and staying longer. Power ultrasound can easily make dyeing solution to form a cavitation field where the large number of cavitation bubbles generated from the ultrasound going through series of cycles from oscillating, expanding, shrinking, imploding to regenerating and the dynamic behaviors spreading to the almost entire field in the container. The large amount of the mechanic and heat energy released continuously from the imploding micro-bubbles greatly intensifies the contact, affinity and chemical action between gardenia yellow pigment molecules and wool fibers. Because the hair marrow structure of the central tissue in wool fiber is porous and possesses capillary effect, it provides an ideal cavitation environment for the absorption and permeation of dye molecule into the fibers. This in turn translates to an easier dyeing process, more evenly distributed and long-lasting color [1~5]. Another benefit of using ultrasound is that new interfaces of solid (wool fabric piece)-liquid (dyeing solution) are formed when the samples are immersed into the solution. This creates additional cavitation nuclei, hence makes cavitation events happen more frequent and the cavitation action or dyeing effect more efficient. It is worth pointing out that although the number of the micro-bubbles is large, the space occupied by them in the solution is relatively very small when compared to the space occupied by the hosting solution. Because of this, the solution temperature and pressure in the container as a whole do...
not rise significantly and the dyeing process can still be
categorized as a process at room temperature and under
normal atmospheric pressure [5-9]. Future studies,
that’s worth pursuing is to focus on the influences of
such parameters as acoustic intensity and pigment
concentration, and wool fabric types and container size
etc.

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