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Ultrasound energy to accelerate dye uptake and dye–fiber interaction of reactive dye on knitted cotton fabric at low temperatures

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ABSTRACT

Acoustic cavitation formed due to propagation of ultrasound wave inside a dye bath was successfully used to dye cotton fabric with a reactive dye at lower temperatures. The energy input to the system during sonication was 0.7 W/cm^2. This was within the energy range that contributes towards forming cavitation during ultra-sonication. The influence of ultrasound treatment on dye particle size and fiber morphology is discussed. Particle size analysis of the dye bath revealed ultra-sonication energy was capable of de-agglomeration of hydrolyzed dye molecules during dyeing. SEM micrograph and AFM topographical image of the fiber surface revealed fiber morphology remains unchanged after the sonication. The study was extended in understanding the contribution of ultrasound method of dyeing towards achieving good color strength on the fabric, compared to the normal heating method of dyeing. Study showed color strength obtained using ultra sound method of dyeing is higher compared to normal heating dyeing. Ultrasound energy was able to achieve the good color strength on cotton fabric at very low temperature such as 30 °C, which was approximately 230% more than the color strength achieved in normal heating method of dyeing. This indicates that energy input to the system using ultrasound was capable of acting as an effective alternative method of dyeing knitted cotton fabrics with reactive dye.

1. Introduction

As far as the textile industry is concerned, textile dyeing is an essential process step which imparts esthetic properties to the fabric. The dyeing of textile fibers is carried out in an aqueous solution at elevated temperatures and therefore common textile dyeing processes demand high consumption of water and energy. This causes relatively high degree of environmental pollution. It is well known that cotton fabrics are best dyed using reactive dyes as reactive dyes are capable of making covalent bonds with cellulose structures [1]. Over six decades, various investigations were carried out to ascertain the possibility of using alternative energy forming mechanisms and chemical pre-treatment methodologies in textile processes. This will help to reduce the processing time for dyeing, reduce the environmental pollution and most importantly to improve the quality of the product [2–10].

In the sound spectrum ultrasound frequency lies in the range of 20 kHz to 10 MHz which is further divided into power (20 kHz to 2 MHz) and diagnostic (5–10 MHz) ultrasound [11,12]. Power ultrasound is of much important for a variety of chemical and physical processes, such as accelerated chemical reaction, emulsification, degassing and extraction [13–16]. These enhanced effect of ultrasound in the field of power ultrasound is due to the cavitation phenomena [17]. Acoustic cavitation is defined as the formation of gas-filled micro-bubbles or cavities in liquid once the pressure of the spot decreases below the saturation vapor pressure of the dissolved gas in the liquid [18,19]. The growth and collapse of these cavities (micro bubbles) under proper conditions create drastic local conditions (high temperature and pressure). Explosion of these acoustic cavitation near solid surfaces can generate micro-jets which facilitate the liquid to move with a velocity of up to 110 m/s [20]. Ejected micro-jets are capable of degassing the textile surface and also de-agglomeration of the dye particles inside the dye bath [21–25]. In addition these micro jets are effectively involved in improving wet textile treatments, where mass transfer occurs in the inter- and intra-yarn pores of the textile [26].

Some researchers have reported the successful use of ultrasound for dyeing different types of fabrics (cotton, Nylon, Lycra, polyester, wool) leading to good color strength and fastness properties [27–30]. In addition to the improved properties for the textile, ultrasound assisted dyeing reported to have lowered the

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dyeing time and temperature. It has been reported that the dyeing of cationized cotton fabrics with natural dye using ultra-sonication managed to reduce the dyeing time by half [31]. The use of ultra sound resulted in good color strength and better wash fastness for dyeing of acrylic fibers using basic dyes and polyester/Lycra with three different types of reactive dyes [31,32]. The improvement in fastness property is attributed to the good covalent fixation of dye with the fabric, due to the better dye penetration into the fibers. Although the presence of ultrasound during dyeing has improved the properties of the dyeing process, it was identified that the ultrasound pre-treatment for the fabric or dyeing solution does not improve the fastness or color strength of the dyed samples [33]. An investigation of the pre-treated Nylon fabric using ultrasound revealed that the use of ultrasound increases the percentage of the fiber crystallinity which will retard the dye uptake. However enhanced effect of power ultrasound can overcome this phenomenon while dyeing the fabric using ultrasound. In one research study effect of ultra-sonication for the acceleration of reactive dye uptake in bamboo cellulose fabric was investigated. In the presence of ultra-sonication the color yield of the fabric was improved to 5–6% [34]. Ultra sonication was also able to reduce the dyeing time of cotton fabric using reactive dyes in cold pad batch dyeing process where the dyeing time was reduced to 8 h compared to the conventional dyeing time of 12 h [35]. The use of power ultrasound on cotton fabric and dye bath pre-treatment in continuous dyeing process, has led to improve the dye uptake while maintaining good exhaustion and fixation [36].

This research study has focused on analyzing the effects of ultrasound in dyeing of cotton fabric using a reactive dye. Reactive dyes can form covalent bonds between the fibers and the dye as shown in Fig. 1(b) [37]. The reactive dye used in this study is classified as a hot dye where dye fiber reaction is commonly taking place at temperatures above 60 °C [38]. However reactive dyes are prone to undergo undesirable hydrolysis in aqueous solution, resulting in decreasing the dye fixation which leads to the formation of dye agglomeration in the dye bath [39]. We hypothesize that the ultrasound can effectively breakdown the dye particles in the dye solution and provide a solution to the dye particle agglomeration which is prominent in the conventional dyeing process. Although the use of ultrasound in dyeing of cotton fabric using reactive dyes was investigated, to the best of our knowledge a little or no documentation on dye fiber interaction at relatively low temperature of dyeing was published. This study has specifically paid an attention to observe the dye fiber interaction at relatively low temperature utilizing the ultra sound energy. The dyeing was carried out at different controlled temperatures. Mass transfer (exhaustion) and fixation of dye under two dyeing conditions as normal heating and ultra-sonication were compared. This allowed us to evaluate the efficiency of the energy produced by ultra-sonication to normal heating for the dyeing process.

2. Materials and methods

2.1. Materials and reagents

Scoured and bleached 100% knitted cotton fabrics (203 g/m^2) and Remazol yellow 3RS (YD) dye powder was received from Textured Jersey Pvt. Ltd. Sodium sulfate and sodium carbonate were purchased from Sigma Aldrich. All chemicals were used without further purification. De-ionized water was used for dyeing experiments.

2.2. Preparation of the dye bath

Reactive yellow dye 1% on weight of fabric (owf) was dissolved in distilled water (1:20 material to liquor ratio). The dye mixture was stirred for 1 h until the dye particles are fully dissolved in the distilled water.

2.3. Dyeing procedure

Dye solution was transferred to the stainless steel vessel and bath temperature was maintained at the required running temperature using an external cooling unit. When ultra sound was used for dyeing, an ice bath was used to maintain the temperature. For normal heating dyeing procedure, the dye bath temperature was regulated using direct heating. Once the initial dye bath temperature reaches the required value, the fabric was added and the dyeing was continued for 30 min. After 30 min of dyeing a sample of dyed fabric and dye solution was taken from the dye bath to measure the exhaustion and fixation of the dye. At this stage sodium carbonate (10 g/L) was added to the dye bath and continued dyeing for another 30 min. After 1 h of dyeing, a sample of dyed fabric and dye solution was taken from the dye bath to measure the exhaustion and fixation of the dye.

For ultra sound dyeing method an ultrasound generating probe was used, UP400S (Hielscher™) with the probe tip diameter of

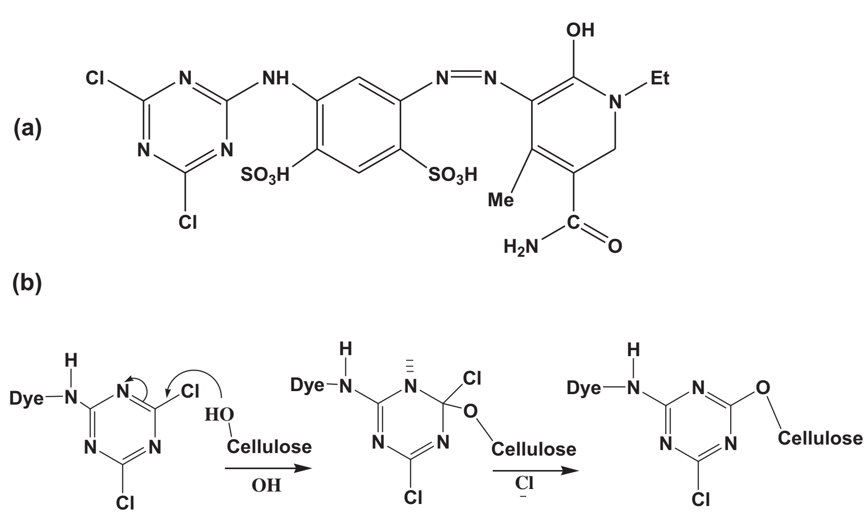

Fig. 1. (a) Chemical structure of the Reactive yellow dye. (b) Mechanism of dye attachment to the cellulose fiber.