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Dyeing of cotton fabric with a reactive disperse dye in supercritical carbon dioxide

Jia-Jie Long[a,*], Guo-Dong Xiao[a], Hong-Mei Xu[a], Ling Wang[a], Chuang-Long Cui[a], Jing Liu[a], Mu-Ying Yang[a], Ke Wang[a], Chen Chen[a], Yi-Meng Ren[a], Tao Luan[a], Zhi-Fang Ding[b]

[a] *College of Textile and Clothing Engineering, Soochow University, Suzhou 215123, China*
[b] *Jiangsu Shazhou Printing and Dyeing Co. Ltd, Zhangjiagang, Suzhou 215626, China*

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ABSTRACT

A novel method was developed for the dyeing of cotton fabric with a vinylsulfone reactive disperse dye in supercritical carbon dioxide by carrying out dye adsorption (or uptake) and a catalytic fixation reaction with a phase transfer catalyst—Triethylene diamine (TEDA) in separated baths, respectively. The results show that the dye adsorption or uptake in supercritical carbon dioxide dyeing bath significantly depended on system temperature and pressure, as well as an appropriate experiment time; significant improvements of dye fixation efficiency and color strength on wet and dry cotton fabrics after a Soxhlet extraction were achieved by employing the catalyst of TEDA under various conditions. The fastness data indicate that acceptable rub and staining fastness rated at 4–5 was obtained for the dyed cotton samples involving a catalytic fixation step, except that a fading fastness should be further improved.

1. Introduction

Textile manufacture such as dyeing, printing and finishing, is an important traditionary industry not only providing basic clothing in our daily lives, but also acting as an important exchange link of friendship and civilization for people with different cultures, nationalities, arts and religions in the world. However, the textile production with conventional wet-chemical processes, especially for the dyeing, printing and finishing of textile, is also one of the main environmental pollution resources due to the discharge of large amounts of wastewater to environment. According to some literature reports [1,2], there were over 600 billion meters of fabrics which were dyed, printed and finished in China in 2010, and more than 24.0 billion tons of effluents were discharged to environment, which resulted in a serious environment burden and concern even after some pretreatments.

The dyeing of textile in supercritical carbon dioxide fluid, a water free and clean process with numerous essential advantages, has been extensively investigated in laboratory and even pilot scales as a promising alternative to the conventional water based processes in recent future [3–8]. To date, the coloration of synthetic fibers, such as polyethylene terephthalate (PET), polyamide 6 and 66 (PA6 and 66), with disperse dyes in supercritical carbon dioxide is able to achieve commercial requirements, and even some attempts for commercialization in practice are available [9]. However, the dyeing of natural fibers, especially for cotton fiber, is difficult and still under development due to the fact that conventional water-soluble polar dyes, which are suitable to cotton fiber in traditionary processes, such as reactive, direct, vat dyes, are hard to dissolve in hydrophobic supercritical carbon dioxide fluid. However, cotton fiber, as one of the most important natural fibers, is extensively favored by customer due to its naturally comfortable service properties, and enjoys a high global market share of about 37% in textile industry [10]. Therefore, a clean and water free dyeing process for cotton fiber with supercritical carbon dioxide is also desirable.

In the last decades, many methods have been developed to dye cotton fiber in supercritical carbon dioxide. One possibility is to modify the hydrophobic carbon dioxide fluid with polar co-solvents, such as ethanol, methanol, and even various contents of water to improve the solubility of conventional dyes for cotton fiber, and the research results show that some satisfactory dyeings were obtained with conventional reactive and direct dyes in a modified polar supercritical carbon dioxide [10–12]. Moreover, Sawada et al. [7,13–15] took the advantages of reverse micellar system by employing surfactants such as perfluoropolyether to solubilize water-soluble dyes in an aqueous microenvironment at the interior of water-pool micelles in supercritical carbon dioxide, and applied it to dye cotton fiber, as well as silk and wool fibers.

Another strategy is to pretreat or modify cotton fiber with specific auxiliaries in a pretreatment process in order to increase

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[*] Corresponding author. Tel.: +86 0512 67164993; fax: +86 0512 67246786.
E-mail address: longjiajie@suda.edu.cn (J.-J. Long).

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the hydrophobicity and/or dyeability of cotton fiber with disperse dyes. Selli et al. [16] used polyethylene glycol (PEG), such as PEG200–PEG5000, as plasticizing agent for cotton fiber in supercritical carbon dioxide fluid; their results show that the disperse dye uptake on cotton fiber was enhanced significantly, and the adsorbed dye could be entrapped in the pores of cotton fiber. Knittel et al. [17] employed cyclohexyl carbodimide to modify cotton fiber via substitution reaction with hydroxyl groups; their results indicate that the hydrophobicity of the modified cotton fiber was improved and the uptake of disperse dyes, as well as the interactions between the dye molecules and the fibers were increased. Ozcan et al. [18] utilized benzoyl chloride for cotton fiber modification to improve the fiber dyeability with disperse dyes due to a hydrophobic aromatic residuum covalently attached to the fiber macromolecule. N.N. (Hoechst) et al. [19] reported an application of alkyl amino-group reagents in cotton fiber modification and dyed the modified cotton fibers with reactive disperse dyes; their results show that both the hydrophobicity and the nucleophilicity of the modified fiber were significantly improved due to the attached alkyl chain and amino group on the cotton macromolecules, resulting in an enhanced dyeability of the substrate with disperse dyes.

However, all of the above methods or strategies suffer some disadvantages in the industrial applications of cotton fabric dyeing. First of all, it costs highly for an industrial high pressure system with an addition of organic co-solvents in dyeing processes due to an excess explosion-proof handling and high demands on the separation and reuse of carbon dioxide and co-solvents. As respect to the reverse micellar system, not all kinds of water-soluble dyes, especially for bulky structures, are able to solubilize in the interior of reverse micelles due to the insufficient size of the micellar aggregates [15]. Moreover, removal of the specific surfactants on fiber or fabric is still difficult, and the fastness properties of dyeings are not satisfactory comparable to those dyed in conventional processes [13]. The same problems would also be encountered in the strategy of complexation of ionic dyes with special surfactants.

Although a satisfactory dyeability of cotton was enhanced by a prior impregnation with various PEG, only a minor improvement of dye fixation was obtained. Furthermore, the chemically prior modifications of cotton fiber led to a poor handle, a longer process time and excess energy consumption, making the industrial application of the supercritical dyeing process unsuitable.

In order to overcome the above disadvantages, up to date, different kinds of reactive disperse dyes have been employed to dye cotton fiber in supercritical carbon dioxide fluid due to their significant advantages. First of all, the hydrophobic parent molecular structure of a reactive disperse dye provides sufficient dye solubility in supercritical carbon dioxide fluid without any help or modifications of co-solvents or other specific surfactants. Moreover, the reactive group(s) in dye molecule can react with the functional groups of cotton fiber to form a covalent bond, providing a possibility of permanent dye fixation on fiber and improved color fastness properties. Schmidt et al. [10] described the dyeing of cotton fiber by employing modified C.I. Disperse Yellow 23 with 2-bromoacrylic and 1, 3, 5-trichloro-2, 4, 6-triazine as reactive groups. It was found that cotton fiber was able to be dyed with the modified dyes without any pretreatment of the fiber, although the color yields were lower than those on silk and wool fibers. Furthermore, a polyester/cotton fiber blend was dyed in a one step process, and the fastness properties of dyeings such as wash, rub and light fastness, were rated at 4–5. N.N. (Hoechst) et al. [19] investigated the dyeing of modified cotton fiber with monochloro-2, 4, 6-triazine reactive disperse dyes via a substitution reaction, they declared that the combination of the reactive disperse dyes and fiber modification improved the dye uptake and the reactivity between those dyes and cotton fibers. Fernandez Cid et al. [8] synthesized a series of fluorotriazine reactive dyes and applied to dye cotton fiber in supercritical carbon dioxide, and claimed that good dyeing results were obtained by presoaking cotton fiber in a protic solvent and employing a co-solvent in dyeing process with time over 4.0 h, and no damage of cotton fiber was observed with the fluorotriazine dyes even at a concentration of 10% (o.m.f).

Unfortunately, there are still some essential difficulties in the commercial applications of the supercritical dyeing process for cotton fiber. One basic difficulty is that the dye uptake, penetration and color yields are not met commercial requirements, especially for dark shades and/or in a dry supercritical carbon dioxide fluid. As known to all, native cotton fiber is a highly crystalline fiber, in which linear macromolecules tightly keep together via intra and intermolecular hydrogen bonds, and form an organized chain structure. Even its amorphous regions also consist of ordered stiff chains. As described in traditional pore model theory [16], dye molecules can only adsorb and diffuse or penetrate in the network of interconnecting channels or pores in amorphous regions of cotton fiber after being swelled by a plasticizing agent such as water in conventional dyeing processes. However, in the hydrophobic medium of supercritical carbon dioxide fluid, especially in a dry supercritical fluid, solid cotton fiber is in a glassy state even up to a high temperature [16]; moreover, the cotton fiber is readily to be dehydrated in the supercritical fluid. Consequently, it is very difficult for dye molecules to sufficiently diffuse or penetrate into the amorphous regions of cotton, resulting in a poor dye uptake behavior during dyeing process. To overcome this disadvantage, an economical and more environmental friendly method, in which a moist supercritical carbon dioxide fluid was used by addition of various amounts of water in dyeing system, was examined by Kraan et al. [6], and a thermodynamic equilibrium distribution model of water over textile phase and the fluid phase as a function of pressure and temperature was also proposed [20].

Another difficulty for the dyeing of cotton fiber with reactive disperse dye in supercritical carbon dioxide is that dye fixation or fixation efficiency is low, and cannot be commercially satisfactory due to an insufficient reactivity between the dye molecules and the fiber functional groups. Generally, at fixation reaction step in traditionary water-bath processes for the dyeing of cotton with reactive dyes, the reactive sites (such as primary hydroxyl groups) in cotton fiber are activated by the addition of alkali, and a powerful nucleophilicity (nucleophilic cellulose anion) is formed, which improve and accelerate the fixation reaction between the adsorbed dyes and the substrate. However, alkali shows a very poor solubility in supercritical carbon dioxide, especially in a dry one [10]. Moreover, the pH value of cotton fiber is usually lower than 4.0 due to the formation of carbon acid in moisture fibers [10]. Therefore, the fixation reaction between reactive disperse dyes and cotton fibers is hardly to achieve, otherwise, a fixation temperature higher than 160 °C and/or a fixation time longer than 4.0 h should be necessary according to the pH-temperature relationship [10]. Recently, Fernandez Cid et al. [21] described an acid-catalysed methanolysis reaction for the purpose of efficiently dyeing of cotton fiber with triazine reactive disperse dyes in supercritical carbon dioxide, in which an acid was used as catalyst by the uptake of protons into the triazine ring to improve the electrophilicity of reactive group(s) in the triazine dyes.

Furthermore, the reactive disperse dyes involving reactive groups such as epichlorohydrinde, 1, 3, 5-trichloro-2, 4, 6-triazine, fluorinated triazine and α-bromocrylic acid have been reported for the dyeing of cotton fiber in supercritical carbon dioxide [8,10,18,19]. However, the reactive disperse dyes with vinylsulfone as reactive groups for cotton fiber, particularly their dyeability, fixation efficiency and any improvement methodology for fixation reaction, are not available in the literature [10].