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Foam properties and application in dyeing cotton fabrics with reactive dyes

Coloration Technology

Society of Dyers and Colourists

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The foam dyeing of cotton fabric with CI Reactive Red 120 has been studied as a low-add-on technology. The foamability of different types of foaming agent and the stability of foam stabilisers were compared. Factors influencing foam dyeing, including wet pick-up, fixation agent, foam stabiliser, and blow ratio, were evaluated by colour strength and dye fixation rate. Wet pick-up, fixation agent, and foam stabiliser were found to be the main factors in the foam dyeing process. The comparative build-up properties, dyeing properties, and total consumption between foam dyeing and conventional dyeing were assessed. The results indicate that, in foam dyeing, the dyestuff has a better build-up property, the dyed fabric has excellent wash and rub fastness, and large amounts of water and energy are saved. Moreover, foam dyeing requires smaller dosages of chemical agents and reduces the difficulty of effluent treatment.

Introduction

Water is a valuable raw material and has limited availability. The dyeing of textiles has traditionally relied on water as the solvent for dyestuffs. In the case of cotton fabrics, for example, these are dyed under aqueous conditions using reactive dyes, with chemical auxiliaries such as alkali, salt, and levelling agents, in the dyebath. Unfortunately, residual auxiliaries and dyestuff may be present in the effluent and may cause pollution. The effluent can be decolorised by destroying the dyestuff. This, however, does not eliminate pollution and can also cause problems with sludge disposal. The wastewater problem has become one of the most pressing issues in the dyeing of textiles [1].

In order to avoid such environmental factors, alternative dyeing processes have been developed that restrict or avoid the use of water. Examples include dyeing with a low liquor ratio [2], shortened wet steam dyeing, pigment dyeing, and inkjet printing [3], all of which offer an innovative approach to the dyeing and printing of textiles. However, dyeing with a low liquor ratio requires dyestuff with excellent solubility and stability. The humidity ratio in the steamer has to be strictly controlled in shortened wet steam dyeing. Pigment dyeing or inkjet printing do not result in good hand feel or rub fastness of the fabric.

Foam technology in the processing of textiles, as a low-add-on technology, uses foam to apply chemicals and colorants to the textiles, resulting in large water and energy savings owing to the replacement of water with air. Foam technology is usually applied at a wet pick-up ranging from 20% to 40%; however, in conventional pad dyeing the wet pick-up is in the 60–100% operating range. Foam technology has attracted interest in the textiles field; this technology allows single-side treatment [4,5], accelerates production with a reduced drying time, lowers the demand for chemicals, and eliminates migration.

The initial application of 'foam' in the processing of textiles was by Peter Schmid in about 1906 [6] and 1907 [7]. Silk fibre was not submerged in the bath and suffered less damage when foam technology was used. In the 1970s and 1980s, because of energy shortages and rising energy costs, foam technology [8] received a great deal of attention and was applied in continuous production, including foam mercerisation [9], foam dyeing [10], foam printing [10,11], and foam finishing [12–17]. Foam dyeing, which required an excellent levelness of dyeing, made high demands on equipment, so at that time it was applied only in the dyeing of pile fabric, such as carpet.

With the development of equipment for foam technology and the serious shortage of natural resources in the twenty-first century, foam dyeing is attracting much attention once again. The foam dyeing of woven fabric with reactive dyes was successfully carried out by Farias [18] using a Gaston Systems (USA) foam applicator, and three different application sequences were evaluated. Li *et al.* [19] analysed influencing factors in the foam dyeing of cotton fabric and optimised the process.

The present investigation has led to a novel method for the foam dyeing of cotton fabric with reactive dyes using the Neovi-foam system (Neowin Chemicals Co., Ltd, China). In this study, foamability and stability were used to characterise the properties of the foam and its performance in the dyeing of cotton fabric, which was evaluated by colour strength and dye fixation rate. Foam dyeing and the conventional pad dyeing were compared.

Experimental

Materials

Scoured and bleached plain-weave cotton fabric of 117 g m^{-2} was obtained from Hua Fang Co. Ltd (China). Sodium dodecyl sulfate, sodium dodecylbenzene sulfonate, cetyl trimethyl ammonium bromide, Tween 80, glycine betaine, dodecanol, sodium alginate, sodium carboxymethylcellulose, polyvinyl alcohol, sodium carbonate, and sodium chloride were purchased from Shanghai Chemical Agent Company (China). Guar gum was purchased from Feng He Company (China).

Commercial samples of CI Reactive Red 120 were kindly supplied by Zhenyang Dyes Ltd (China). The molecular structure of CI Reactive Red 120 is given in Figure 1. All chemicals were used as received without any

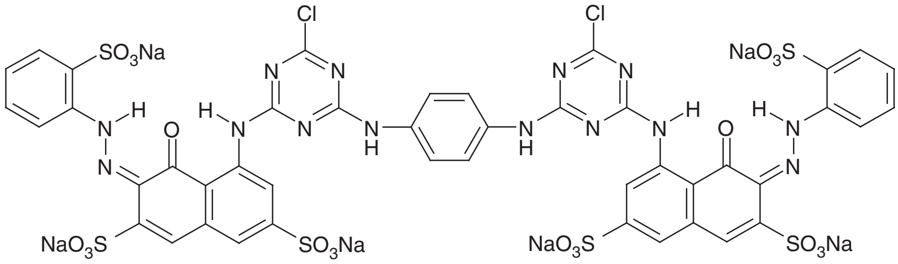

Figure 1 Molecular structure of CI Reactive Red 120

further purification. Deionised water was used in all experiments.

Foaming by mechanical agitation

Aqueous solutions (100 ml) containing different types of surfactant and stabiliser in a range of concentrations were stirred to foaming by mechanical agitation (1000 rpm, 3 min). Foamability and foam stability were judged by measuring the blow ratio and half-life ($t_{1/2}$) [10]. Each measurement was repeated strictly at least three times, and the average value was calculated.

The blow ratio is defined as the ratio of the weight of liquid feedstock used to make the foam to the weight of an equal volume of this foam. For instance, a blow ratio of 10:1 means that 10 ml of foam is created from 1 ml of liquid. A larger blow ratio represents good foamability.

The half-life ($t_{1/2}$) is defined as the time required for one-half of the liquid in the initial foam to separate from the foam by self-drainage. A longer $t_{1/2}$ represents good foam stability.

Foam dyeing of cotton fabric

Dyeing liquors contained 2 g l^{-1} of foaming agent, 0–2.1 g l^{-1} of stabiliser, 0.3%, 0.6%, 0.9%, 1.2%, 1.5%, and 1.8% owf of CI Reactive Red 120, and sodium carbonate (Na_2CO_3), the concentration of which was 15, 15, 20, 20, 40, and 40 g l^{-1}, depending on the CI Reactive Red 120 dosage. The Neovi-foam system generated tiny dyeing foam of various blow ratios by controlling air flow and chemical flow, and evenly applied a certain amount of dyeing foam onto the fabric according to the wet pick-up value input before. Steaming fixation was carried out at 148 °C and a relative humidity of 65% for 4 min, followed by soaping (soap flakes 2 g l^{-1}, Na_2CO_3 g l^{-1}, liquor ratio 1:30, 95 °C, 10 min) and washing (warm rinse and cold rinse). The foam dyeing process is shown in Figure 2.

Conventional pad dyeing of cotton fabric

Compared with foam dyeing (wet pick-up 30%), two-bath pad steam dyeing of cotton fabric with CI Reactive Red 120 (wet pick-up 80%) was carried out. Cotton fabric was padded with dyeing liquor containing 0.3%, 0.6%, 0.9%, 1.2%, 1.5%, and 1.8% owf of CI Reactive Red 120 and predried at 100 °C for 2 min, followed by fixation liquor containing 80 g l^{-1} of NaCl and 15, 15, 20, 20, 40, and 40 g l^{-1} of Na_2CO_3, depending on the CI Reactive Red 120 dosage. The next steps were exactly the same as those in foam dyeing. The conventional dyeing process is shown in Figure 3.

Measurements

A micrograph of the foam was obtained on a Nikon YS100 instrument (Optical Industry Co, Japan). The colour strength (*K*/*S*) of each dyed fabric was calculated using the Kubelka–Munk equation as follows:

$$K/S = \frac{(1-R)^2}{2R} \quad (1)$$

where *K* is the absorption coefficient of the substrate, *S* is the scattering coefficient of the substrate, and *R* is the reflectance of the fabric at maximum absorption, measured using a Datacolor SP600$^+$ spectrophotometer (Datacolor Co., USA). The wavelengths measured ranged from 400 to 700 nm; the dye fixation percentage of each dyed sample was determined by means of the equation

$$\%F = \frac{M_2}{M} \times 100 = \frac{M - M_1}{M} \times 100 \quad (2)$$

where *F* is the dye fixation percentage, M_2 is the dye quantity on the cotton fabric after washing, *M* is the dye quantity on the cotton fabric before washing, and M_1 is the dye quantity in the total liquor of soap bath and wash bath, which can be calculated by measuring the absorbance on a UV-vis 3310 instrument (Hitachi Co., Japan). The wash fastness of the dyed cotton was tested according to ISO 105-C10:2006 [20]. Rub fastness was tested according to ISO 105-X12:2001 [21].

Results and Discussion

Foam properties

Foamability

Foam is formed by dispersing gas into the liquid to form bubbles. It is a two-phase system in which gas bubbles are enclosed by liquid boundaries. It is known that pure liquids do not foam, but the presence of surface-active molecules that preferentially absorb at a liquid/gas interface change this situation radically [22] .

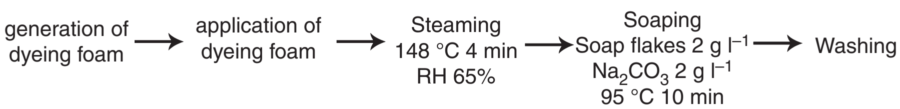

Figure 2 Foam dyeing process

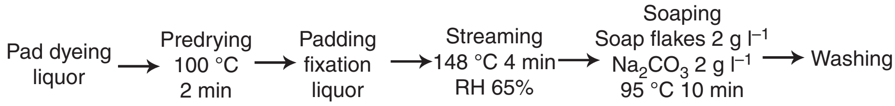

Figure 3 Conventional pad dyeing process

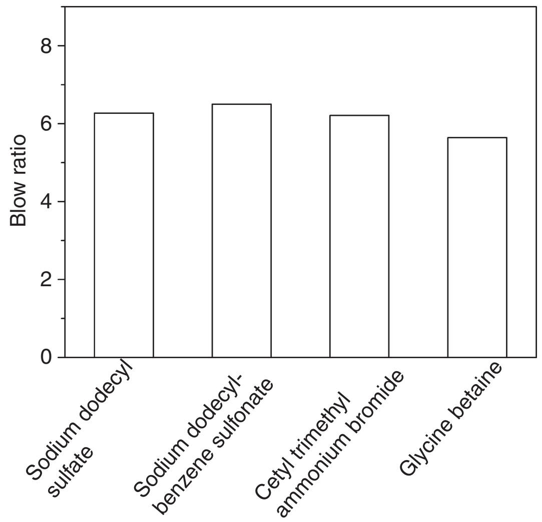

Figure 4 Foamability of surfactants

The foamability of different types of surfactant at 25 °C is shown in Figure 4. The concentration of each surfactant was 5 g l^{-1}, and each solution was agitated at the same speed for the same amount of time. Among the surfactants, sodium dodecyl sulfate (SDS), sodium dodecylbenzene sulfonate, and cetyl trimethyl ammonium bromide are ionic surfactants, and they all have good foamability. The foamability of ampholytic surfactant glycine betaine is slightly lower than that of ionic surfactants. The foamability of nonionic surfactant Tween 80 is too poor to measure. Hence, SDS was chosen as the foaming agent to be used in this research, given its good foamability, ecofriendly properties, and low cost. Figure 5 presents the effect of SDS concentration on foamability and clearly shows that 2 g l^{-1} of SDS is sufficient to obtain foam with good foamability. The blow ratio of the foam did not seem to change much beyond 2 g l^{-1} of SDS.

Foam stability

Figure 6 shows the effect of SDS concentration on foam stability, in good agreement with the effect on foamability, which indicates that a minimum concentration of surfactant is necessary, but beyond this value the foamability and stability of the foam do not appear to change to such a marked extent.

If SDS alone is used in the foam dyeing liquor, the foam produced is not stable enough, lasting little more than a few minutes. Foam used in the foam dyeing process must be stable enough to be delivered through the applicator head without collapsing. However, foam should not be so stable that is does not break quickly upon contact with the fabric. Hence, proper foam stability is achieved by adding proper foam stabilisers.

Foam stability of foams generated from dyeing liquor including 2 g l^{-1} of SDS and 2.5 g l^{-1} of various foam stabilisers is shown in Figure 7.

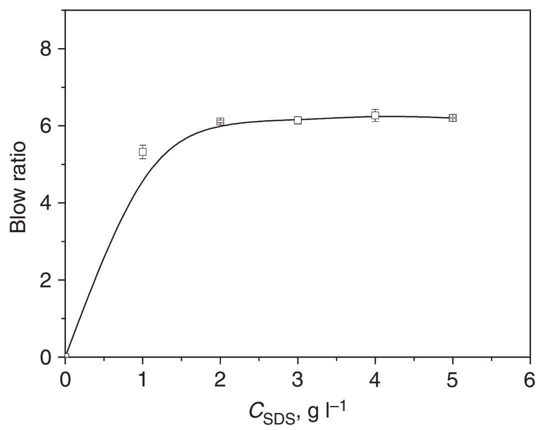

Figure 5 Effect of SDS concentration on foamability

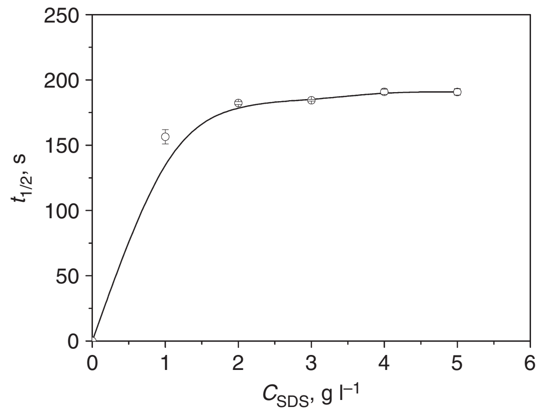

Figure 6 Effect of SDS concentration on foam stability

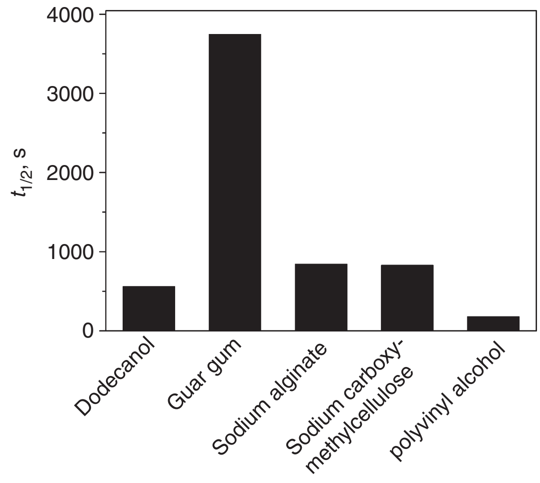

Figure 7 Foam stability of stabilisers

Enhanced stabiliser dodecanol added to foam liquor can reduce the repulsive force between SDS molecules on the air–water interface via the formation of a hydrogen bond between –OH of dodecanol and $-OSO_3^-$ of SDS. Hence, dodecanol increases the density of SDS at the air–water interface, simultaneously enhancing the strength of bubble films and foam properties. A greater degree of stability, accompanied with a marked increase in foam viscosity, is achieved by including a thickened stabiliser. Among the thickened stabilisers (guar gum, sodium alginate, sodium carboxymethylcellulose, and polyvinyl alcohol), guar gum is most effective in increasing foam stability. Therefore, dodecanol and guar gum were selected as the foam stabilisers in the foam system. The mixed systems of dodecanol and guar gum (3:4) can provide superior foam stability (shown in Figure 8).

Bubble size and distribution

Figure 9 presents a micrograph of foam produced from dyeing solution and used for foam dyeing. The foam has travelled the distance from the foam generator to the foam applicator head. When the foam comes into contact with the cotton fabric, the diameter of the bubbles is 0.1–0.2 mm and the bubble distribution is uniform.

The dyeing solution containing reactive dyestuff, surfactant, and stabilisers is foamed by the foam generator, and the uniform and small bubbles with a certain foam stability are conveyed to the foam applicator from many pipes of equal length. The Neovi-foam system can continuously and uniformly distribute foam across the width of an open fabric, because the foam travels the same distance from the entry point of the foam applicator to the fabric.

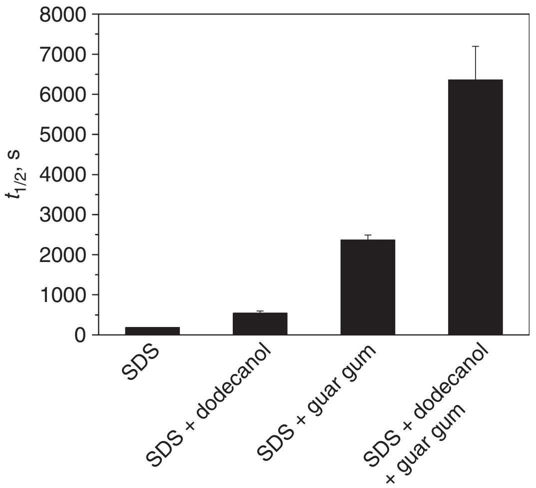

Figure 8 Effect of the mixed system of dodecanol and guar gum on foam stability

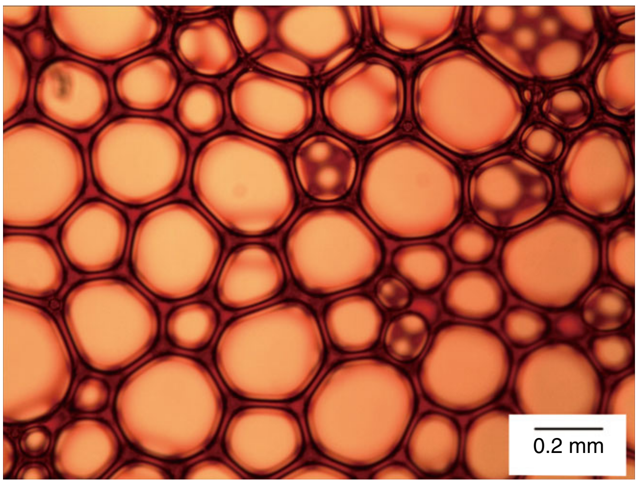

Figure 9 Micrograph of foam made from dyeing solution [Colour figure can be viewed in the online issue which is available at wileyonlinelibrary.com.]

Foam dyeing behaviour

The Neovi-foam system applies dyeing foam evenly to the cotton fabric across both the width and length. Once foam from the applicator head has come into contact with the fabric, the bubble breaks quickly and the dyeing liquor evenly diffuses into the fabric. During the foam dyeing process, there are many factors that affect the dyeing properties, including wet pick-up, blow ratio, and concentration of additives. The effects of these factors on the *K*/*S* value and dye fixation were investigated in this research.

Wet pick-up

Figure 10 shows the effect of wet pick-up on the *K*/*S* value and dye fixation rate. As foam dyeing uses air as the dispersant instead of water, it is a low-add-on technology. Wet pick-up is the most important factor affecting the foam dyeing properties. To investigate the effect of wet pick-up on dyeing properties, the dye concentration has to be varied with wet pick-up to maintain the same quantity of dye conveyed onto the cotton fabric. The quantity of reactive dye conveyed onto 1 g of cotton fabric is 0.003 g. From this, it is evident that the *K*/*S* value and dye fixation rate reach maximum values at a wet pick-up of 40%. A 40% wet pick-up is sufficient for CI Reactive Red 120 to penetrate into the cotton fabric. Below a 40% wet pick-up, the *K*/*S* value and dye fixation rate are improved with increasing wet pick-up. However, when the wet pick-up is increased to 50%, the *K*/*S* value becomes lower and the dye fixation rate stays the same. The *K*/*S* value represents the apparent depth of the cotton fabric, while the dye fixation rate represents the quantity of dyestuff combined on the cotton fabric, including that absorbed on the surface and that absorbed inside the cotton. When the wet pick-up is increased from 40% to 50%, the quantity of dyestuff fixed on the fabric is the same, causing no change in the dye fixation rate. However, the presence of abundant water promotes diffusion of the dye molecules into the fabric, so the corresponding *K*/*S* value is reduced. Compared with a wet pick-up of 40%, a wet pick-up of 30% also gives good dyeing properties.

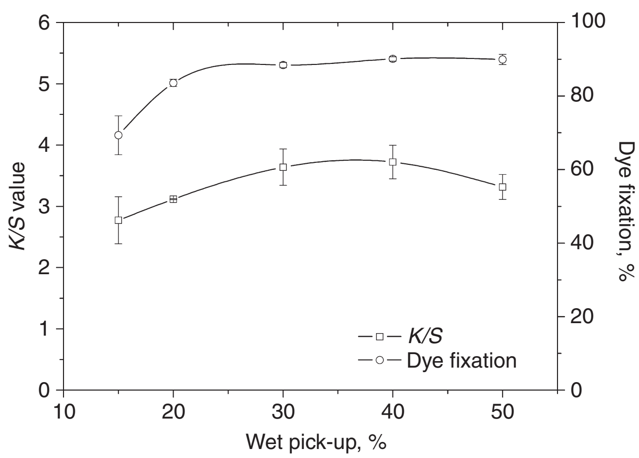

Figure 10 Effect of wet pick-up on the *K*/*S* value and dye fixation

Therefore, foam dyeing with a wet pick-up of 30% was adopted in the later research in order to save more water.

Fixation agent

Figure 11 shows the effect of Na_2CO_3 concentration on dyeing properties. Dye fixation to cellulosic fibres occurs under alkaline conditions. Na_2CO_3 was used as the fixation agent during the foam dyeing of cotton fabric with CI Reactive Red 120. The presence of a fixation agent makes the cotton fabric present O^-, and a covalent bond is formed quickly between the monochlorotriazine reactive group of the dyestuff and the cotton fabric in the superheated steam. The *K*/*S* value and dye fixation rate reach their maximum values at an Na_2CO_3 concentration of 15 g l^{-1} when the quantity of CI Reactive Red 120 is 10 g l^{-1}. The *K*/*S* value declines when the Na_2CO_3 concentration is higher than 15 g l^{-1}, but the dye fixation rate remains almost the same. This is in good agreement with the effects of wet pick-up on *K*/*S* value and dye fixation rate when the wet pick-up reaches 50%, which indicates that more dyestuff is fixed inside the cotton fabric rather than on its surface when the concentration of Na_2CO_3 is higher than 15 g l^{-1}.

Foam stabiliser

Figure 12 shows the effect of the concentration of the foam stabilisers on the dyeing properties. Dodecanol and guar gum were used as foam stabilisers in foam dyeing, and their mixture proportion was 3:4. The *K*/*S* value increases and the dye fixation rate decreases with increasing concentration of the foam stabilisers. This is because the presence of foam stabilisers increases the viscosity of the dyeing solution, resulting in a decline in dye molecule diffusivity. When the concentration of the stabilisers is higher, it is harder for dye molecules to penetrate freely into the fabric and achieve even dyeing. A larger proportion of dye accumulates on the surface of the cotton fabric, accompanied with the white core phenomenon.

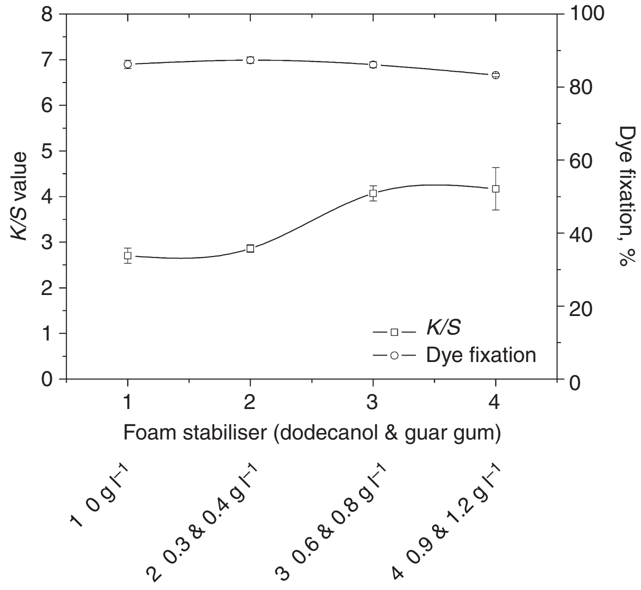

Figure 12 Effect of foam stabiliser concentration on the *K*/*S* value and dye fixation

Blow ratio

Figure 13 shows the effect of blow ratio on dyeing properties. For foam dyeing, foams with blow ratios ranging from 6:1 to 14:1 are generally required. One volume of dyeing solution can produce 6–14 volumes of foam via control of the gas and liquid flow. Change in the blow ratio of the dyeing foam does not have any great impact on the *K*/*S* value of the dyed cotton fabric and dye fixation rate. The reason for this is that the blow ratio is one parameter of the foam, and, once the foam from the applicator head has come into contact with the fabric, the bubble breaks quickly. The foam properties will not affect the dyeing performance. Foam is just one form of the dyeing solution before reaching the fabric. A blow ratio ranging from 8:1 to 10:1 is much more suitable for foam dyeing.

Comparison of foam dyeing and conventional pad dyeing

In the conventional continuous dyeing process, the fabric is immersed in a bath containing a dilute dispersion of the dyes. The saturated fabric is then passed through squeeze rolls to extract excess liquor and finally travels into an oven where it is dried. The wet pick-up varies with the type of fibres used and the fabric construction, but it is usually in the range 60–100%. Two-bath pad steam dyeing of cotton fabric with CI Reactive Red 120 (wet pick-up 80%) was carried out in this study.

Figure 14 shows the build-up properties of dyestuff in foam dyeing and conventional dyeing. The build-up prop-

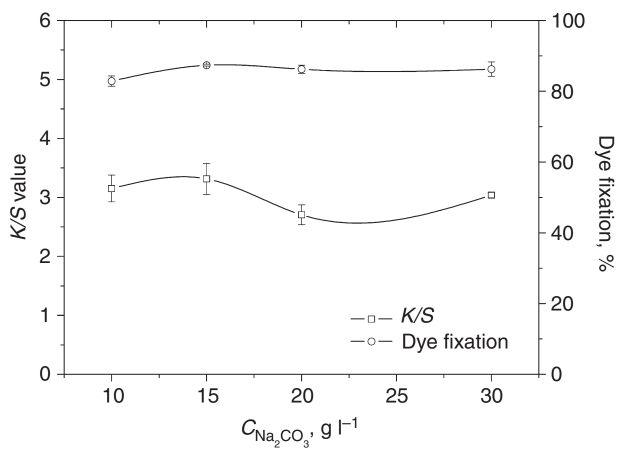

Figure 11 Effect of Na_2CO_3 concentration on the *K*/*S* value and dye fixation

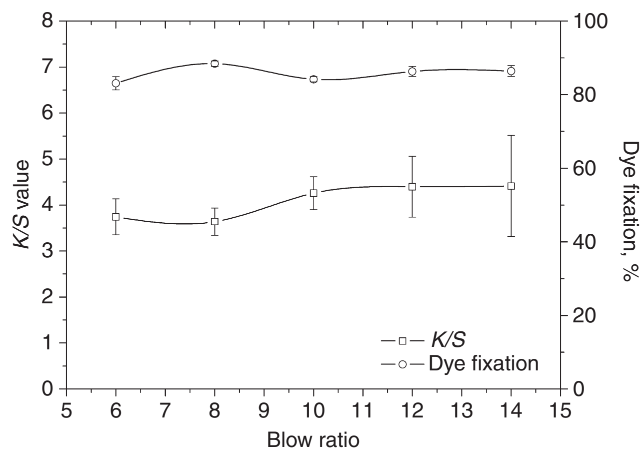

Figure 13 Effect of blow ratio on the *K*/*S* value and dye fixation

erty of dyestuff is the increasing degree of colour strength of the dyed fabric with increasing amount of dyestuff. Dyestuff with a better build-up property is the favourable choice in the dyeing of dark fabric. It is evident that a better build-up property of dyestuff can be achieved using the foam dyeing process. At each dye concentration, the *K/S* value of the fabric in conventional dyeing was lower than that in foam dyeing. On the one hand, in the conventional dyeing process, the presence of more water can promote the diffusion of dyes into the fabric. This conclusion is consistent with the results shown in Figure 10, in that excess wet pick-up not only wastes lots of water but also reduces the *K/S* value of the dyed cotton fabric. On the other hand, the hydrolysis of the dyestuff occurs much more readily in the fixation process owing to the high fixation temperature and the higher wet pick-up of fabric in the conventional dyeing process, which leads simultaneously to a decline in fixation efficiency. The hydrolysis of reactive dyes is an unfavourable reaction leading to a lower quantity of covalently bonded dyes on cellulosic fibres [23], and hydrolysis becomes more frequent with an increasing concentration of reactive dyes.

Compared with the conventional pad dyeing process, foam dyeing can achieve the same level (4–5) of wash fastness. Table 1 shows a comparison of rub fastness. The same level (5) of dry rub fastness and a half-level higher wet rub fastness can be obtained by foam dyeing.

Table 2 shows the energy consumption and the dosage of chemical agents during foam dyeing (wet pick-up 30%) and conventional pad dyeing (wet pick-up 80%) with the same quantity of reactive dyestuff. The data were calculated during the dyeing of 1 t of cotton fabric. Water consumption was calculated only from the wet pick-up of fabric, evaporated in the drying process, and did not include the water for the washing process. The water consumptions for washing in foam dyeing and conventional pad dyeing were considered to be the same. At various wet pick-ups of the dyeing process, foam dyeing can save 81.25% of water and 80.75% of electricity consumption, and simultaneously double production. In spite of the foaming agent and foam stabilisers added in the foam dyeing process, the total chemical agent consumption and energy consumption are much lower than in the conventional dyeing process. In addition, NaCl has to be added in the conventional dyeing process, as the electrolyte to reduce the repulsive force between the dyestuff and the cotton fabric, which results in more difficult effluent treatment. NaCl promotes the absorption of reactive dyestuff on cotton fabric. However, in the foam dyeing process, NaCl is not added to the dyeing solution, because the dyeing solution is foamed by the foam generator and all the foam is conveyed onto the fabric by the foam applicator.

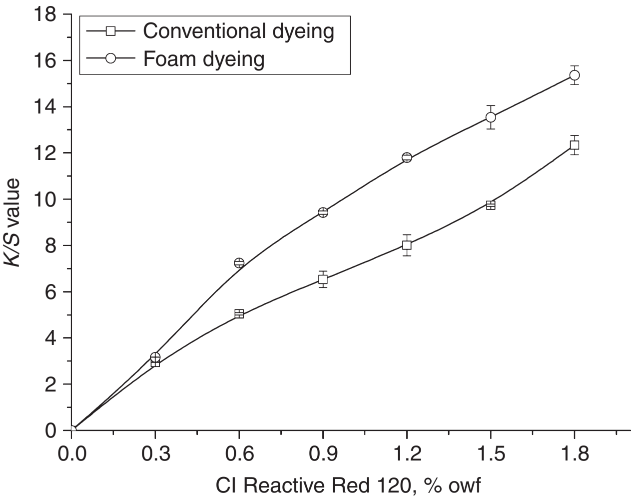

Figure 14 Build-up properties of dyestuff in foam dyeing and conventional dyeing

Table 1 Comparison of rub fastness between foam dyeing and conventional pad dyeing

CI Reactive Red 120, % owf	Rub fastness			
	Dry		Wet	
	Foam dyeing	Conventional dyeing	Foam dyeing	Conventional dyeing
0.3	5	5	4	3–4
0.6	5	5	3–4	3
0.9	5	5	3–4	3
1.2	5	5	3	3
1.5	5	5	3	2–3
1.8	5	5	2–3	2

Table 2 Comparison between foam dyeing and conventional pad dyeing[a]

	Foam dyeing	Conventional dyeing
Wet pick-up, %	30	80
Speed, m min^{-1}	80	40
Water consumption, kg	300	1600
Electricity, kWh	23.54	122.29
Dosage of NaCl, kg	0	64
Dosage of Na_2CO_3, kg	4.50	12
Dosage of SDS, kg	0.60	0
Dosage of stabilisers, kg	0.21	0

a Data from the foam dyeing and conventional dyeing of 1 t of cotton fabric.

Conclusions

The foam dyeing of cotton fabric has been examined. Sodium dodecyl sulfate was selected as the foaming agent because of its good foamability, and dodecanol and guar gum (3:4 in weight) were used as the foam stabilisers. The diameter of bubbles used for dyeing was 0.1–0.2 mm. Cotton fabric was dyed evenly with CI Reactive Red 120 by the foam dyeing process. A wet pick-up of 30–40%, a blow ratio of 8:1–10:1, and 15 g l^{-1} of Na_2CO_3 were suitable conditions for foam dyeing with 10 g l^{-1} of CI Reactive Red 120. The foam stabilisers increased the *K/S* value of the dyed cotton fabric, but reduced the dye fixation rate. Compared with conventional dyeing, the dyestuff had a better build-up property, the dyed fabric had excellent wash and rub fastness, and large amounts of water and energy were saved in foam dyeing. Furthermore, the dosage of chemical agents was lower and the difficulty of effluent treatment was reduced.

At a time of energy shortages, the use of foam dyeing in industrial production has great significance. Hence, foam dyeing using different types of reactive dye on cotton fabric with different weave structures and the compatibility of the bath components will be studied in future work.

Acknowledgements

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