Asian Journal of Information Technology 6 (3): 356-361, 2007

A Low-Cost Colorimetric Sensor Using Optical Transmission for Real-time Control of Textile Dye Bath Exhaustion

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Abstract: The temperature is often the principal variable taken into account to control the exhaustion of the dye bath. This exhaustion is influenced by various factors such as: the temperature of the bath, pH, the salinity of the bath, duration, concentration of the dyes. However, the goal is not to control temperature per se, but to control the final color and strike (rate of dye uptake). Therefore, if one could control or predict the exhaution profile during dyeing, one could control the amount and rate of dye uptake onto the fabric. The difficulty is in the measurment of the dye concentration deposited onto the fabric. For this reason, the design of a low cost colorimetric sensor, enabled us to approach the field of the textile dyebath control with minimum investment (i.e., without expensive spectrophotometer). This sensor is based on Beer's Law (with transmission by optical fibre). A luminous flow is introduced into a measuring chamber where circulates permanently the textile dye bath. At the exit, the light flow is analyzed by four filters so as to cover all the spectrum of the visible light. A system of real-time data acquisition is developed. Results and test on single dye and mixture of dyes are encouraging.

Key words: Real-time processing, colorometric sensors, dyeing textile processes, dye exhaustion control

INTRODUCTION

The operation of dyeing, often carried out at the end of the textile cycle production, consists in transferring a dye contained in a solvent (water) towards the textile matter, thus one expects an exhaustion of solvent in the bath for the benefit of the matter.

The automation of the process of dyeing presents a great number of characteristics:

The system is nonlinear. The methods of dyeing are dominated by a total empiricism: the laws which govern the concentration of the dyes and their speed of exhaustion are badly known. That is mainly with the multiplicity of the classes of dyes and their physicochemical interactions with fibres.

The dye penetrates in fibre according to a dynamic balance in its concentration in the bath of dyeing and that in the matter to be dyed.

The laws which govern these balances vary according to the dyes, fibres, the additives used with the dyes, the physical conditions of the dyeing. It is difficult to control all these factors well. In batch dyeing, current methods attempt to control process variables,such as temperature or pH, as opposed to performance specifications such as color or desired shade (Mc Donald, 1997; Johnson, 1989). Shade variation among dye lots may lead to rework or grading system. In either case, off-shade dyeing is an undesirablie effect which dye houses have been trying to minimize for many years. the main parameters affecting final shade are variations in fabric and fiber properties, the dye concentration in the dyebath, temperture, pH, salt concentration and machine parameters. Currently,the industry uses open-loop control with respect to desired color,where the above parameters are all set to predetermined values. This method does not always give a consistent and repeatable shade because of unmodelled disturbances or incorrect setting which can occur during dyeing.

To better control the batch dyeing process, a systematic study was undertaken to measure factors which affect dyeing (Carbonell, 1991; Jun *et al.*, 1992). A real-time data acquisition system was developed to monitor a laboratory dyeing machine.Only after the data acquisition systems had been calibrated and tested and the dynamic models validated could a closed-loop feedback systems be designed and implemented.

The design of a colorimetric sensor will allow control via colorimetric measurements taken directly on the bath

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during dyeing. To attain this goal, it is assumed that the sensor should be installed in industrial site. In order to avoid the effects of many factors (such as moisture, temperature, vibrations) which may greatly corrupt colorimetric measurments, optical fibers are used for the transmission of measured values and the use of a spectrophotometer is substituted by cheaper components, simple and available. This sensor is based on Beer's law (with transmission by optical fibre). A luminous flow is projected onto a measuring chamber where circulates permanently the textile dyebath. At the output of the measuring cell, the light flow is conveyed by optical fibre and then split into four bundles of light. Each bundle is used to illuminate a related optical filter associated with a photo detector so as to cover all the spectrum of the visible light. This sensor is inserted into the feedback loop of the control system of the dyebath acting on the temperature and indirectly on the concentration, resulting in better control of the dye exhaustion in the bath.

THE BATCH DYEING PROCESS

Important system parameters which affect the batch dyeing process are temperature, conductivity (salt concentrations), pH and the individual dye concentrations (Carbonell, 1991; Jun *et al.*, 1992). Measuring the first three parameters are relatively simple using commercially available analog sensors.However, the goal is not to control temperature *per* se, but to control the final color and strike (rate of dye uptake), which is a nonlinear function of the system parameters. Therefore, if one could control or predict the exhaustion profile during dyeing, one could control the amount and rate of dye uptake onto the fabric. This is the first step in reducing color variation between dyeings. The difficulty is in the measurement of the dye concentrations deposited onto the fabric. To be able to predict the concentration on the fabric, the system is assumed to be closed: the sum of the dye on the fabric and dye in the solution is constant. The change in the dye concentration in the solution over time will equal the amount of dye exhausted onto the fabric. The dye concentration in the solution is calculated using measured values as given by the colorimetric sensor. A small quantity of the dyebath is circulated through flow cell. Most pure dyes obey Beers Law, given as:

$$A = \text{Log}\ (S_m / S_r) = C.d.e$$

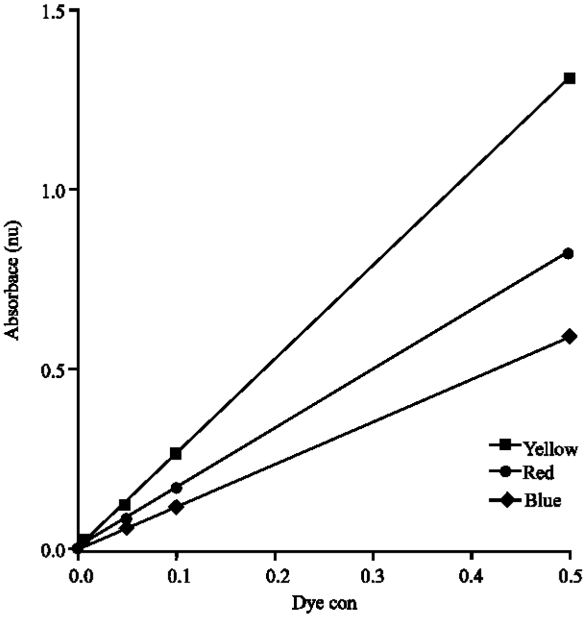

Fig. 1: Beer's Law analysis of individual dyes

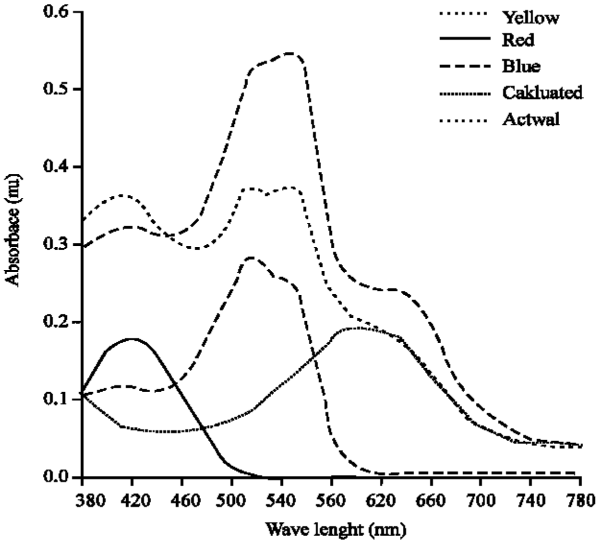

Fig. 2: Effects of mixing three dyes.The sum of three absorbance spectra does not equal the experimentally observed spectra of the three-dye mixture

where A is the absorbance or log of the ratio of input to output intensity for a specified wavelength (normally λ_{max}), d is the specific absorbance or extinction coefficient, *e* is the path length and C the concentration of the dye. This linear behavior is shown graphically in Fig. 1 for the three reactive dyes. It is important to remember that the absorbance value A assigned to each dye from this plot is given at one wavelength for each dye, namely 425 nm for yellow, 520 nm for red and 595 nm for blue dye, the λ_{max} values for these three dyes. The calculation of the concentrations of multiple dye mixtures from the absorbtivities is complicated by the fact that although individual dyes obey Beer's Law, mixtures of dyes may not, due to dye-dye and dye-salt interactions. One cannot simply add the absorbance spectra of each of the dyes in a mixture to predict the spectra of the mixture itself, as illustrated in Fig. 2. Comparisons of different techniques for predicting dye concentrations from absorbance spectra are given in (Burkinshaw, 1995). Using several different methods, the dye concentration and exhaustion can be calculated from the absorbtivity measurements and displayed in real-time as shown in Fig. 3.a and 3.b. The information is fed to the model (e.g., Langmuir) (Westland *et al.*, 2002; Koncar and Casetta, 2001) to control the rate of exhaustion in the dyebath. The rate of exhaustion can be controlled by changing the temperature, salt concentration, or dye concentration (dosing). Controlling the process using suitable actuators can achieve the desired process conditions. The process control and the parameter control can follow very different strategies. The temperature is controlled with relays connected to the heating and cooling elements. A temperature controller, running as a background process, regulates the dyebath temperature using a modified pulse-width-modulation technique.

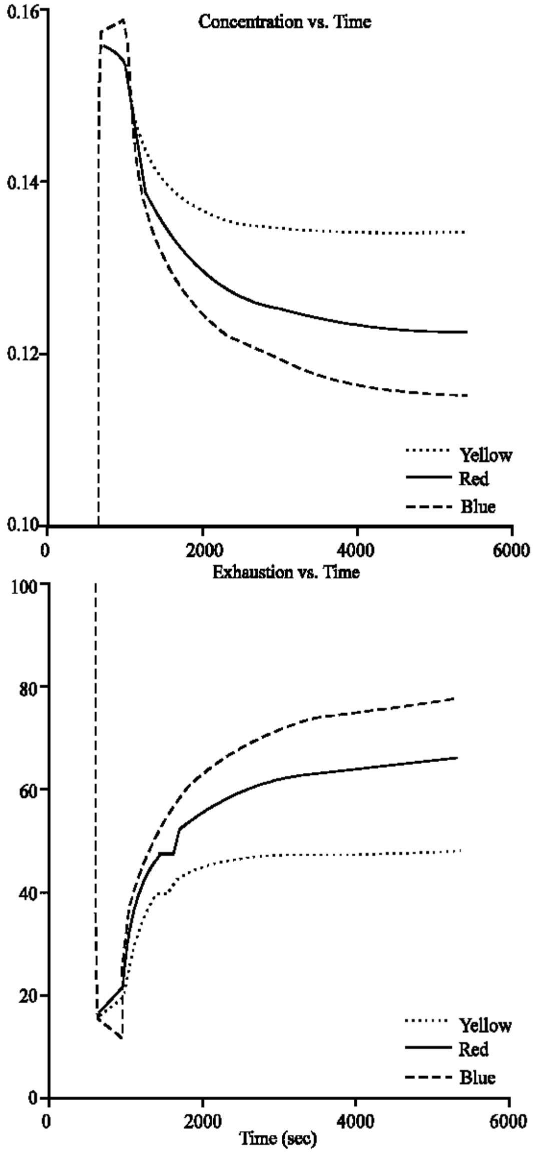

Fig. 3: Typical plots of concentration and absorption

SENSOR DESCRIPTION

The proposed sensor is composed of three parts: a lamp, a cell and a photosensitive system transforming the light into electric signal. The whole is followed by related electronic circuits.

The measuring process is based on the more or less large absorption undergone by the monochromatic light (known as the measurement wavelength, λ_M) when crossing the liquid circulating in the cell. Absorption is the relationship between the light intensities at the entry and the output of the cell. This absorption varies considerably with the wavelength used for measurement. The curve representing this absorption wavelength is called the absorbance spectrum (Fig. 4).

In a colorimetric sensor, one chooses the measurement wavelength λ_M which corresponds to maximum absorption in order to make measurement very sensitive and precise.

After having passing through an optical filter, the light beam emitted by a lamp is divided into two rays of equal intensity (Fig. 5) one of them is directed onto

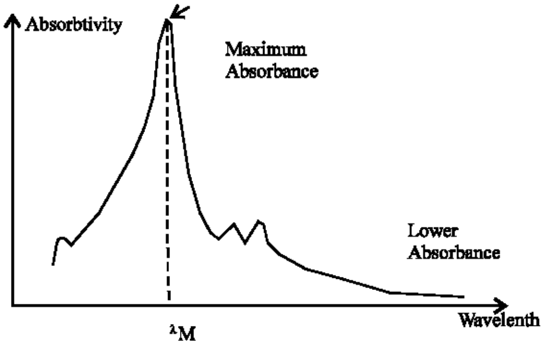

Fig. 4: Absorbance spectrum

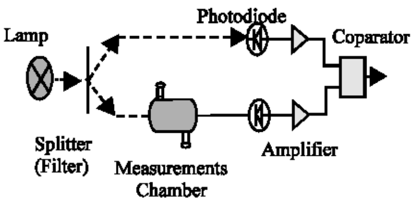

Fig. 5: Layout of the colorimeter

a photodiode which makes it possible to collect an electric signal S_R as a reference signal. The other light beam is conducted across the measuring chamber before being applied to a photodiode which then emits an electric signal S_m. By using Beer's Law, a comparison of the two signals S_R and S_m makes it possible to determine the concentration of the dye which circulates inside the measuring chamber, according to the following formula:

$$\text{Log}\ (S_m / S_r) = A$$

where A is referred to as the index of attenuation.

This index, for a given wavelength, is proportional to the concentration C of the substance, i.e., to the number of molecules of this substance per volume unit. The proportionality factor is given by e.d because the exact relation between A and C is A=C.d.e, from which follows the relation Log (S_m/S_r) = A = C.d.e, (C is the dye concentration in the bath, d a constant related to the wavelength of the filter and e the width of the chamber of measurement).

The measurement chamber is installed in derivation of the dyeing machine so that the dyebath circulates permanently inside the chamber. The transmitter circuit consists of a source of white light, an halogen lamp whose power is between 25W to 40W with a small parabolic concentrator followed by a convex lens for focusing light on a receiving probe of the optical fibre cable (Fig. 6).

To improve the coupling between source and fibre the distance l can be adjusted, moreover the light beam is directed towards the receiving probe after having crossed an infrared filter of the KG5 type (a glass filter absorbing infrared rays) which also makes it possible to reduce the heat effects emitted by the source of light without decreasing its intensity in the visible spectrum, Fig. 7. Heat absorbing glass filters are used to reduce the amount of heat transmitted through illumination optical systems. KG glass filters absorbs the infrared radiation and then dissipates the heat into the air around the glass. The flow of white light emitted by the transmitting circuit is conducted by optical fibres to the measurement chamber and crosses then the dye bath. Two optical cables of a few meters have been used. The advantage of using two optical cables is especially a great safety between the receiving circuit and the chamber. In addition, this allows a transport of light without any heat contribution, i.e. in cold light. As it is known, the response of the photodetectors is influenced by heat. The receiving probe consists of a metal shield the section of which is covered with a thin plastic plate to eliminate reflected light.

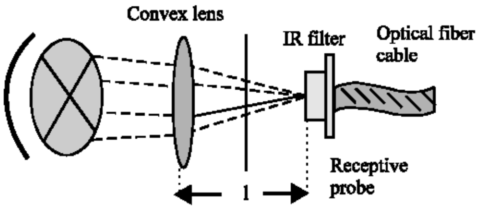

Fig. 6: Optical source focus system

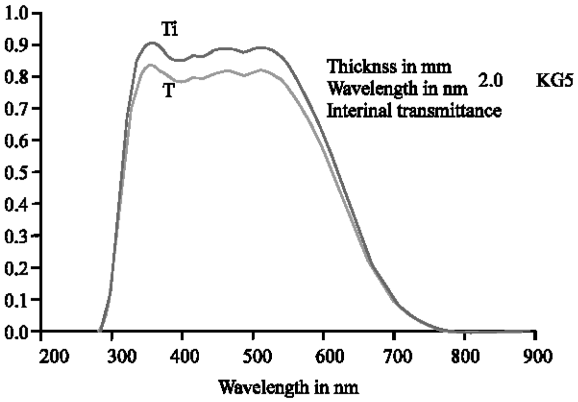

Fig. 7: Filter absorbing infrared rays (Balzers)

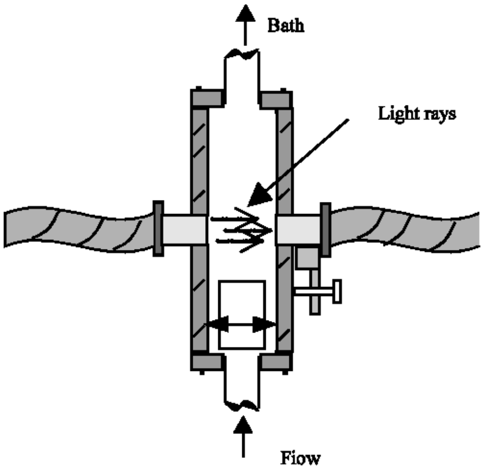

Fig. 8: Cell for colorimetric measurement

In order to improve the sensitivity, the thickness `e' of the measuring chamber can also be modified.

Transmitted luminous flow is then reconducted to the light receiver by means of another optical fibre which is splitted into four parts. Each part illuminates a related filter associated with a photodetector. A suitable electronics converts the four light intensities into four equivalent electric currents (Fig. 8).

To improve the sensitivity of the colorimetric sensor, the thickness ` e' of the measuring chamber can be

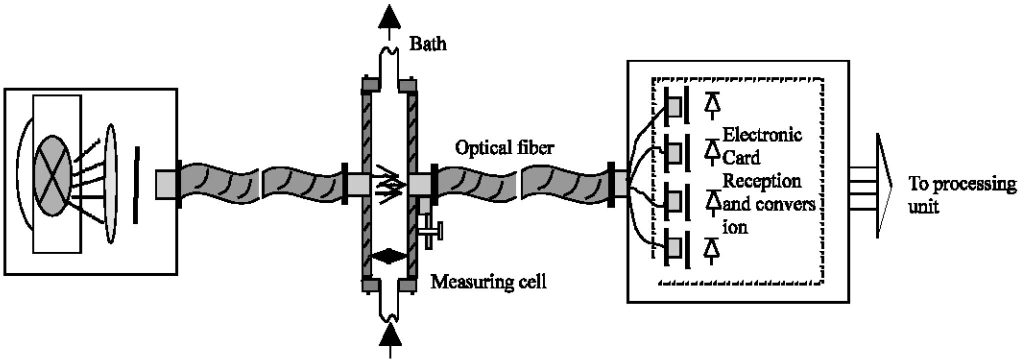

Fig. 9: Full sensor with the transmission and reception boxes

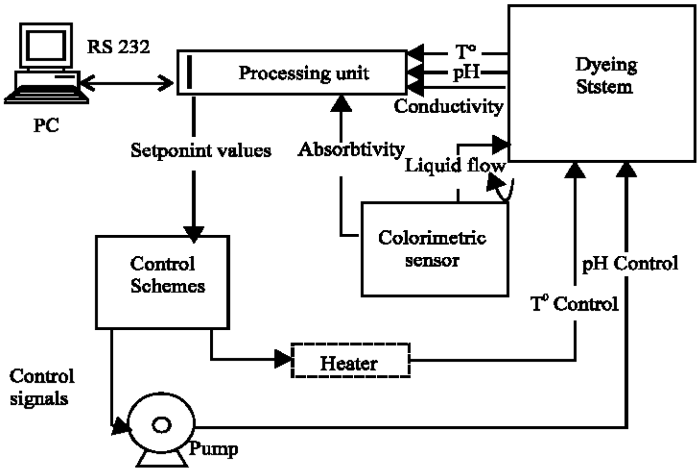

Fig. 10: Full system description and data flow diagram

modified according to the dyeing machine (i.e., for long duration bath or short duration bath).

In addition, optical filters associated with the photodetectors have been selected so as to cover all the spectrum of the visible light.This will allow the colorimetric sensor to generally take into account all possible measurements of the dyebaths (Fig. 9).

FULL SYSTEM DESCRIPTION

The system layout is represented in Fig. 10. The treatment unit is composed of electronic cards containing microcontrollers, memory boards, input/output interface circuits (i.e., A/D, D/A, DIO, RS232, GPIB…).

The treatment unit performs online analysis of various signals provided by the sensors and acts directly on the dyeing process. This unit is connected to a PC via an RS232 line. The PC isused to select between various programs of dyeing recipes saved in memory, for example: speed of exhaustion, duration, temperature profile of the bath, setpoint choices. The exhaustion and concentration curves can be calculated by colorimetric measurement and visualized on screen. The rate of exhaution can be controlled by changing the temperature, or salt concentration.

The system has the capability to change salt concentration or dye bath pH: A high precision pump is connected. The pump can be used for pumping precise quantity of salt solution. The temperature is controlled with relays controller running as a background process and regulating the dyebath temperature using modified PWM techniques. Other forms of regulation systems can be easily implemented such as rule-based fuzzy control techniques or iterative learning control.

MONITORING AND CONTROL

The collected colorimetric data, taken from measurement on dyebath, reveal certain difficulties that must be addressed: A relatively fast rise of the dye at the beginning is observed, then the attraction of the dye by fibres decreases, i.e., the dyes are not absorbed any more at the same speed, the ideal being to obtain a regular rise of the dye and a complete exhaustion of the bath. Many studies, based on simplifying assumptions, have been attempted to apprehend the kinetic behavior of dyeing relating to the absorption of the dye and consequently, many mathematical models have been built on, such as Langmuir's models (Koncar and Casetta, 2001ab; Westland *et al*., 2002). In the proposed approach which is the goal of our study, controlling dyeing process is based on direct measurements of dye concentration in the dyebath.The system must allow the automatic switch between colorimetric regulation and temperature regulation for the completion of dyeing.

One can act directly on the heating system of the bath and, if required,on the cooling system as well, in order to control the speed of the exhaustion of the dyebath, according to prescribed setpoints.

At the beginning of the dyeing cycle, the system takes some measures of the bath without the dyes and then with the dyes, this enables to automatically select the appropriate optical filters which transmit a significant variation of the starting nuance of the dyebath. The regulation of the bath exhaustion, using colorimetric data, is based on the light transmission evolution of these filters. Every 15 seconds and for each optical filter, the system computes the average after 8 measured values, this makes it possible to minimize the importance of the dispersions caused by possible bubbles of air or suspended matter. The sampling rate of 15 secondes was determined by tests carried out on industrial autoclaves. A shorter rate is not necessary to detect a noticeable evolution of the exhaustion of the dyeing bath. During dyeing, after each measurement the system selects the filter which reflects the fastest exhaustion and bases its regulation on it (heating, cooling). Thus, at any given moment, a dye which can become exhausted more quickly than the others is detected by thesystem which will immediately react on the bath temperature and will issue command signals accordingly.

The system stops the regulation when each of the selected filters transmit an equivalent exhaustion, equal to or higher than 90% or when the temperature for the final stage is reached.

CONCLUSION

The design of a low cost colorimetric sensor, using transmission by optical fibres, enabled us to approach the field of the control of the textile batch dyeing process with a minimum investment: there is no need for an expensive spectrophotometer, we only use simple and available components. After having calibrated and tested the colorimetric sensor, a system of real-time data acquisition is developed. Using real-time measurement of dye concentration, by means of four optical filters, we are currently determining the rate of dye uptake during dyeings with individual dyes and mixture of dyes. The obtained results are encouraging.

In our future research, we propose to implement systems that combines real-time multitasking operating systems with object-oriented programming and to apply more sophisticated control techniques. It is envisaged to adress the problem of controlling the batch dyeing process as a multivariable control issue by taking into account, in addition to the principal parameters (temperature and concentration), the salinity of the bath and the pH as well.

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