Improving Computer Control Of Batch Dyeing Operations

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Abstract

Several approaches are possible fol upgrading textile wet processing control systems. To that end, some fundamentat constraints and limitations of present control systems must be alleviated. Considerations for novel control algorithm: are presented as well as specific simulation and experimental results for fuzzy logic and for adaptive control systems are presented.

Table I: Suppliers of wet processing control systems and supplies.*

- Arel
- ABB
- ACS
- Beacon
- BYK-Gardner,
- Datacolor
- Erhardt & Leimer
- Foxboro
- Gaston County
- International
- Keiltex
- Kurabo
- Latex
- Macbeth
- Mahlo
- Micro Services
- Milton Roy
- Select Controls
- SheLyn
- Strandberg
- Zimmer

*Not all suppliers in wet processing may be listed.

Introduction

Process control is one of the most critical aspects of quality assurance. In textile operations, such as batch dyeing, there are many variables which are under the dyer's control, but many more which are not.[9] Typically these controllable and uncontrollable factors interact in a very complex way. The dyehouse of the future must feature even better process controls.

Traditional manual control methods in textile processes have been automated using microprocessor systems, with corresponding improvement in process repeatability. However, this mode of control utilizes only a minuscule fraction of the total capabilities of modern microprocessor hardware.

In an attempt to improve microprocessor utilization, there are two avenues to pursue. The most celebrated of these is the macro scale global linking of information referred to as Computer Integrated Manufacturing (CIM), to which much attention has recently been devoted.[14,15] In typical CIM implementations, sophisticated user interfaces, attractive graphics and computer networking capabilities are employed to make information from machines and machine groups available to managers for real time and post process analysis. The focus is on the use of state of the computing hardware and sensors to acquire data from processes, set up common database formats, link islands of automation, and provide management information in a timely manner in a macro or global sense.

In CIM, individual workstations are connected through networking paths, and data are stored in a standardized central database, accessible to all workstations. The general structure of such a system is shown in Figure 1.

One of the most important features of CIM is that it provides data to managers for strategic decision making.[7] This implementation, although useful in certain ways, is incomplete because it fails to focus on optimized hardwareand sensor utilization at the micro level, and also because it does not address the under utilization of the microprocessor and other hardware capabilities per se.

An important, but far less travelled avenue for enhanced microprocessor utilization is the development of novel control strategies which fully utilize data processing capabilities at the micro level, which use improved control models and also employ improved theoretical and empirical process models, The key at this level is not only a better understanding of processes but a willingness to evaluate known control technologies from other disciplines (e.g.-aerospace) and to develop new textile Wet processing technology and science ity as well as interfacing to a multitude of peripheral devices, including networking, clustering, and supervisory computers. Microprocessor abilities to upload and download process information, perform real time or post process audits, and generate exception reports and other information is currently in place in many operations.

At recent equipment shows, dozens for feasibility testing.

At this time, the basic concept of using microprocessors for control in textile wet processing operations is to automate manual procedures and control methods of the past. This paper presents some current research results in the development of novel control and process models, based work of the Dye Applications Research Group of N.C. State University (DARG).

State of the art controllers

Control hardware has made great strides in recent years. The emergence of low cost, versatile, high speed digital microprocessors has facilitated all manner of textile wet processing applications. Microprocessor hardware has developed to a high state of reliability and performance, and typically includes multichannel input/output (l/O) capabilof displays were presented by companies which were manufacturers of stand alone controllers. At a recent ITMA, in fact, more companies were showing controllers than were showing dyeing machines. These controllers have reached a high level of performance. In recent review, over 20 major companies were listed as specializing in controllers specifically for textile wet processing use. Tables I, II and III summarize suppliers, processes and proppet-ties for which fof the shelf controllers are offered.[1] Typical control systems include microprocessors with

(a) control algorithms and interfaces
(b) multichannel I/O with two way digital/analog conversion
(c) synchronous and asynchronous communications abilities
(d) monitoring and sensors, with interfaces
(e) process devices (eg valves, pumps)
(f) networking, upload/download capabilities

The state of the art in microprocessor control of textile wet processes is quite advanced, as can be seen from the preceding, but there is still potential for a quantum leap in performance if one is willing to discard certain traditional constraints in textile control concepts. Many of these constraints have become embedded in controller design concepts over time during the evolution of modern textile wet processing control systems. In contrast, DARG has focused on discarding many of these preconceived notions about control in order to evaluate the feasibility of novel systems in terms of performance and overall cost. Methods under evaluation include adaptive, real time, multi channel control strategies which include sophisticated empirical and theoretical dye models, and which are based on innovative control algorithms.

Figure l-Structure of a future dyehouse.

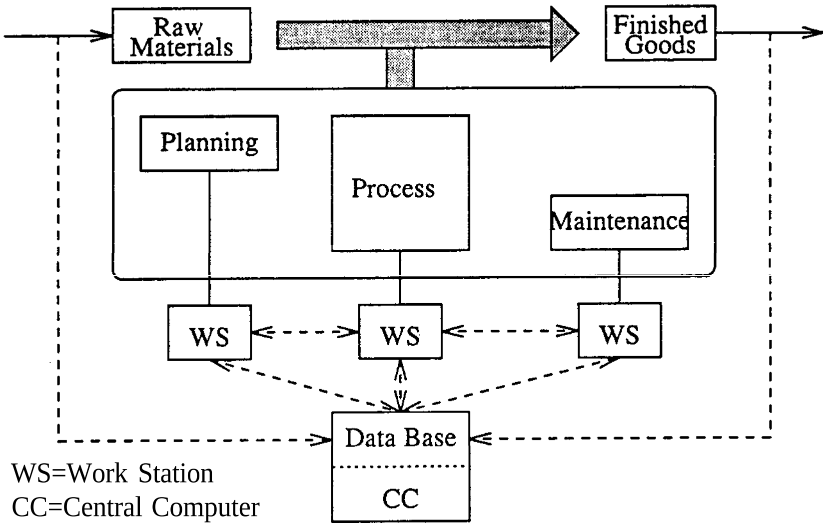
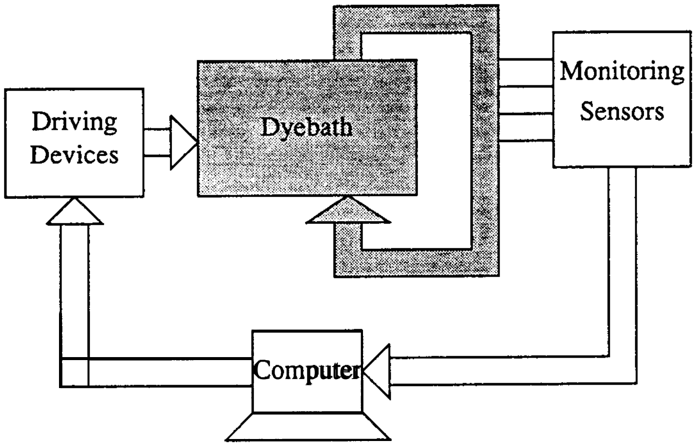


Figure P-Structure of a dyeing process control system.



Novel control concepts

Traditional dye process control methods attempt to conform as closely as possible to a specific predetermined process profile (eg time, temperature) to achieve correct results. Discipline is emphasized. Uncontrollable variances are accepted and, in some cases, remedied after the fact, for example by shade sorting or dye adds.

Several innovative concepts are embodied in this feasibility study. Our approach attempts to control the ultimate product property of interest (in this case, dye shade) by adjusting controllable process parameters in such a way as to arrive at the desired end result. In this approach, the process may or may not be the same each time it is run, but the goal is only to arrive at the correct result. The process may be varied each time it is run to compensate for non controllable factors, such as variances in water quality, substrate preparation, and raw materials.

The first and most fundamental departure from traditional control concept is the use of predictive result-oriented strategies, as opposed to process conformance strategies. Sophisticated and theoretically sound dyeing models are combined with extensive real time data acquisition to assess the state of the system and predict process outcome (i.e.-final dye shade) about every two minutes during the dyeing. These predictions are the basis for real time process modifications and departures from nominal process specification. Controllable process parameters are used to offset uncontrollable variances.

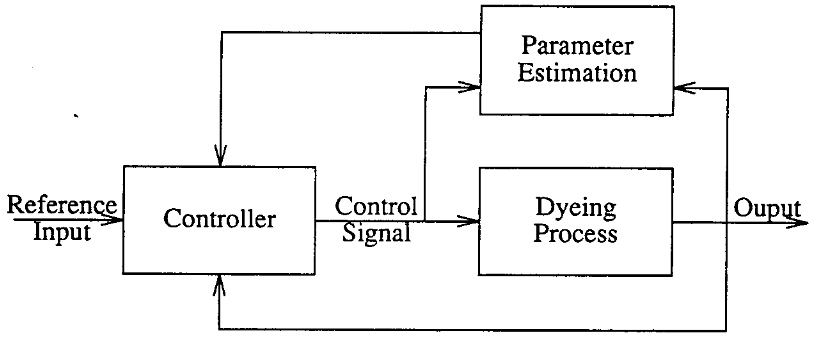
Another departure from traditional methods is the use of multi/multi control strategies as opposed to the traditional one-to-one approach. For example, in a traditional control algorithm, a standard temperature of 200 “F may be the process specification. If temperature deviates from the process specification, the controller will open steam valves to correct. This one to one control strategy senses temperature and controls steam. The novel approach does not control temperature for its own sake, but rather predicts the effect of a temperature variation.

If no undesirable effect arises from that situation, the controller does nothing. However, if a problem such as an unacceptable dye shade is predicted then the controller takes action, but no necessarily by opening a steam valve to correct temperature to a nominal value Rather, action is taken by whatever means will correct the predicted outcome to the desired result (shade) a minimum cost and production time. The best action may be, for example, to add salt or change the pH. Of course, there are constraints built in to prevent the controller from taking absurd actions For example, rate of temperature change or permissible pH or temperature values may be limited. Central to this concept is the ability to accurately predict a result from the present state of the system. Several prediction methods are used for this. Their presentation is far beyond the scope of this article, but they will be described in other publications.[16]

Accurate real time data acquisition is another prerequisite for this approach. The present work was done with a system capable of monitoring real time values of temperature, rate of rise and cooling. conductivity, pH, time and up to 3 dye concentrations in exhaust dye oaths. This system, comprising control logic units, dyeing machine, sensors and interfaces has been described in detail in other publications.[3,4,11]

Another feature of the novel control strategies is their adaptive nature. Most colorists are aware of the necessity of making numerous standard dyeings as data input for laboratory color matching systems. Of course, this would not be feasible in a commercial production setting, therefore the controller must have some adaptive method of altering its database and control algorithm--i.e.--to "learn" from actual production dyeings. Traditional control strategies do not do this and, in fact, dyers are constantly altering dye recipe percentages to adjust to standard. The set point temperature, for example, would rarely if aver be changed for an individual shade. In this novel approach, nominal starting set points for various controllable process parameters (temperature, etc.) are adjusted, according to results of previous dyeings, to optimum values which would produce desired shade at the lowest cost and minimum production time.

Figure 3—Structure of an adaptive controller for dyeing processes.



By combining the above concepts of real time, adaptive, multi channel, predictive process control with state of the art computing devices and sensors, outstanding results have been achieved and in fact, as will be shown in the owing examples, dye bath exhaustion can be brought consistently to a desired get value, thus producing excellent shade repeats in batch dyeing. The same novel control principles could apply to any process. We have selected batch dyeing as our example for feasibility evaluations.

Novel control schemes

Due to the complexity and uncertainty of dyeing processes, they are very difficult to contrrol.[9] Possible control schemes can be divided into two categories: parametric methods and nonparametric methods.

The parametric methods require prior

Figure 4--Dyeing Process Control Simulation with One Regulation Level Which I the Desired Final Exhaustion of the Process and Represented by the Circle.

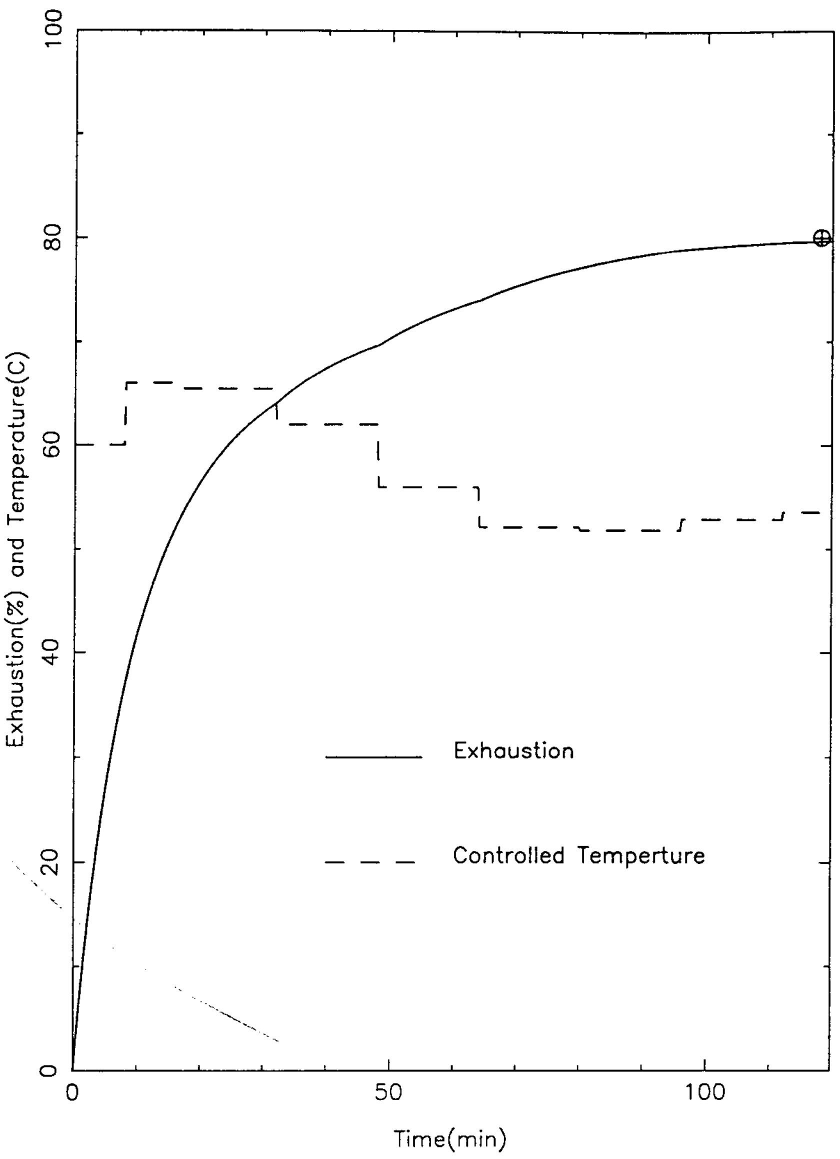


Table II: Wet processes offering off the shelf controllers.

Atmospheric dyeing
Bar code tracking
Batch dyeing
Batching
Beam dyeing
Beck dyeing
Bleaching
Calendaring
Carpet dyeing
Chemical weighing, mixing, dosing
Coating
Color measurement
Color matching
Communications
Conditioning
Continuous dyeing
Curing
cutting
Deizing
Drying
Dye weighing, dissolution, mixing
Fabric handling
Fastness testing
Fiber blending
Finishing
Fluorochemical application
Foam finishing
Garment dyeing
Gravimetric dispensing
Guiding, spreading
Heat recovery
Heat setting
Inspection
Inventory, storage
Jet dyeing
Jig dyeing
Laboratory dyeing
Management
Package winding
Package dyeing
Padding
Paddle dyeing
Pressure dyeing
Printing
Recipe control (dye/finish)
Resin application
Rotary dyeing
Scouring
Screen printing
Skein dyeing
Shade sorting
Shearing
Slashing
Slitting
steaming
Tentering
Trimming (edge)
Vulcanizing
Wsshing
Weft straightening

knowledge of process model structure and the range of process model parameters. Nonlinear robust control and adaptive control belong to this Category.

Adaptive control is a technique to handle uncertainties by designing the control algorithm to be self-adapting. There are two basic approaches to adaptive control. The first approach, which is called model-reference adaptive systems *(MRAS),* attempts to make the I/O behavior of the controlled process identical to that of pre-selected models. The adjustment of parameters can be determined based on gradient methods or stability theory. The other approach is called self-tuning regulator (STR) because it has facilities for tuning its own parameters.

Sliding mode control is a very important scheme of nonlinear robust control. By utilizing specific information about the dyeing system which is being controlled, a sliding surface $s = 0$ is define, where s is a function of state variables and time which defines desirable process dynamics. The control law is defined so that the sliding surface $s = 0$ becomes “attractive” in the state space, i.e. a desirable state to which the system will converge.

The nonparametric methods include artificial neural network (ANN) control, fuzzy logic (FL) control and expert system (ES) control which are also called knowledge based control or intelligent control.

ANN is a massively parallel architecture for information processing, which has results in a new paradigm for learning, similar to that in the nervous system. There are several ways to design an ANN controller. Supervised control is a common one, which is an ANN “learns” desired control actions **from sensor output. Training sets can be** supplied by system models, other well designed control systems, or human experts. Neural adaptive control, direct inverse control and other methods are also used. The primary advantage of an ANN controller is its learning ability, which can continuously improve its control performance.

The FL and ES control are both used to simulate the decision-making activties of an experienced expert. The difference between them is the logic. Classical expert system control uses crisp logic. Currently, the two approaches are often used together in many cases. Usually, the control decisions of an expert can be expressed linguistically as a set of heuristic decision rules. These rules are used to build rulebases for FL and ES controllers. Also certain algorithms are used to convert the rules to quantitative control outputs. The disadvantage of all the nonparametric methods is that

Table III: Typical properties monitored/controlled by currently available control systems.

Add on
Blending
Chemicals
Color (product)
Concentrations
Curl (fabric)
Cycle time
Density (cloth/package)
Differential pressure
Distortion (fabric)
Dosing rate (dye/chem)
Flow direction
Flow rate
Humidity
Inventory
Level (water)
Liquor ratio
Machine alignment
Mass (package)
Metal presence
Moisture content
Motor speed
Nip pressure
Number of actions
Over/under feed rate
pH
Position
Preshrinkage
Pressure
Print registration
Pump speed
Hate of rise/cool
Selection (ingredient)
Speed (fabric)
Static charge
status (machine)
Temperature
Tension
Time
Twist (fabric)
valve status
Volume of bath
Weight
Width

the control parameters do not correlate with physically meaningful parameters.

Any of the aforementioned schemes can be used for dyeing process control. Two designs of dyeing process control, i.e. adaptive control for parametric methods and fuzzy logic control for non-parametric methods, have been evaluated for feasibility and performance in batch dyeing, as explained below.

Case studies

Adaptive control:

The general structure of an adaptive control system is shown in Figure 3. The dyeing model used here is Langmuir type kinetic model. Work by Burley [5] and McGregor [8] gives a number of interesting applications of this type model. According to the model, the dynamical behavior in a dyebath can be described by equation.[1]

$$\frac{dC^f}{dt} = k_A C^s(S - C^f) - k_D C^f \qquad (1)$$

$C^f(g/kg)$ is the dye concentration of the fabric.
$C^s(g/l)$ is the dye concentration of the solution.
$S(g/kg)$ is the saturation value.
$k_A(l/gs)$ is the dyeing adsorption coefficient.
$k_D(1/s)$ is the dyeing desorption coefficient.

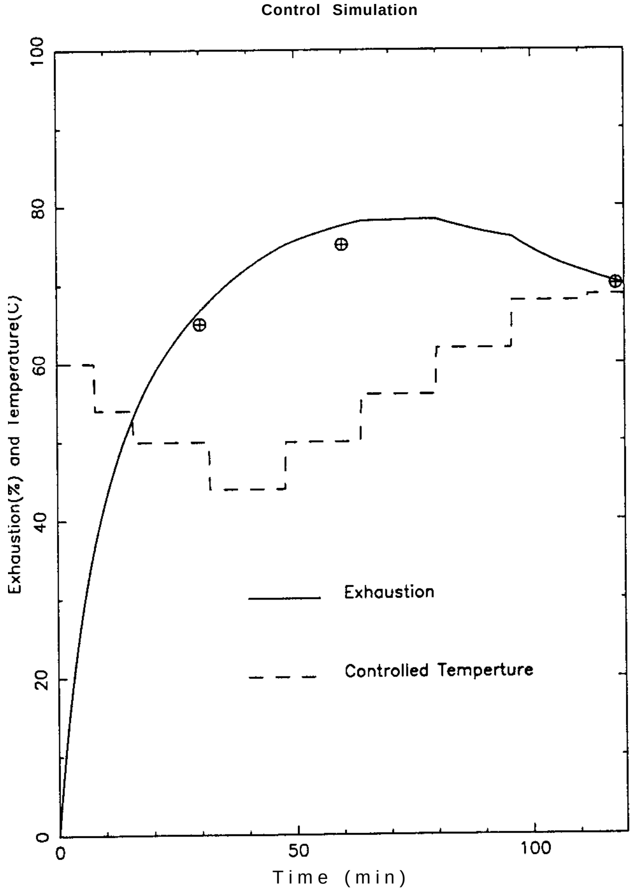
The equilibrium behavior is governed by equation (2).

$$\frac{C^f_\infty}{C^s_\infty} = K_L(S - C^f_\infty) \qquad (2)$$

$K_L l/g)$ is the ration of the adsorption coefficient to the desorption coefficient.
C^f_∞ is the equilibrium dye concentration of the fabric.
C^s_∞ is the equilibrium dye concentration of the solution.

The controller works as follows. During the process, C^s is measured and C^f is

Figure 5--Dyeing Process Control Simulation with Multiple regulation Levels Which are the Desired Exhaustion at Diferent Time During the Process, Represented by Circle.



computed through mass conservation. k_A, k_D, and K_L are estimated On-line with a recursive least-squares algorithm.

For dyeing processes, the control objective is to bring the dye concentration in the fabric to a prescribed level$_{f\ final}$ at the end of the process, despite different initial conditions, raw material, or other uncontrolled variances. This is done by acting on controllable dyeing process parameters, such as temperature, pH, and salt concentration. In these experiments, many variables are sensed, but for simplicity of demonstration, only temperature has been adjusted to meet the control objective. Current and future work of DARG is focused on controlling other parameters, especially chemical and dye dosing.

The dyeing process is a low order and well damped system. Knowing these characteristics and the control objective, the novel adaptive control algorithm can be designed. The above control objective can be achieved if the closed-loop system behavior is given by equation (3).

Figure 6-Controlled Experimental Dyeing Process Starting at a High Temperature and the Temperature was Adjusted During the Process to Meet the Desired Final Exhaustion.

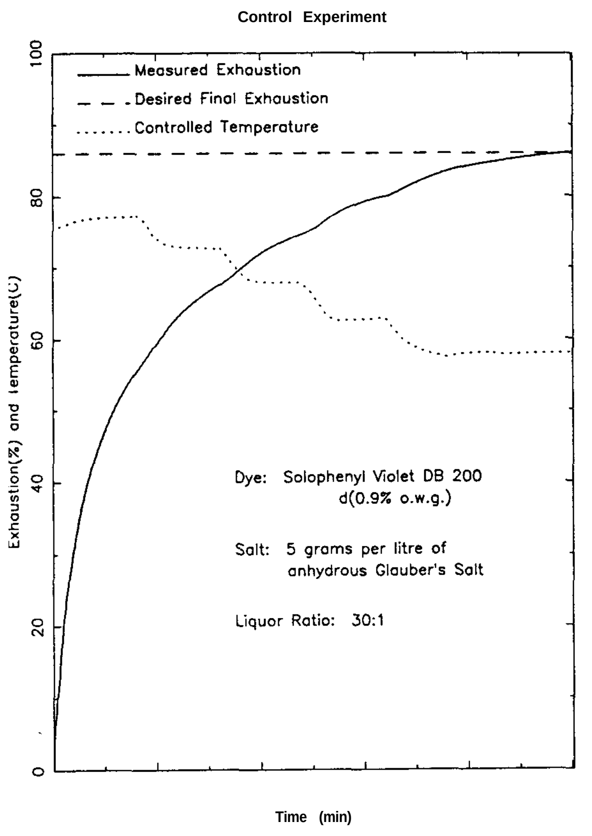


Figure 7-Controlled Experimental Dyeing Process Starting at a Low Temperature and the Temperature Was Adjusted During the Process to Meet the Desired Final Exhaustion.

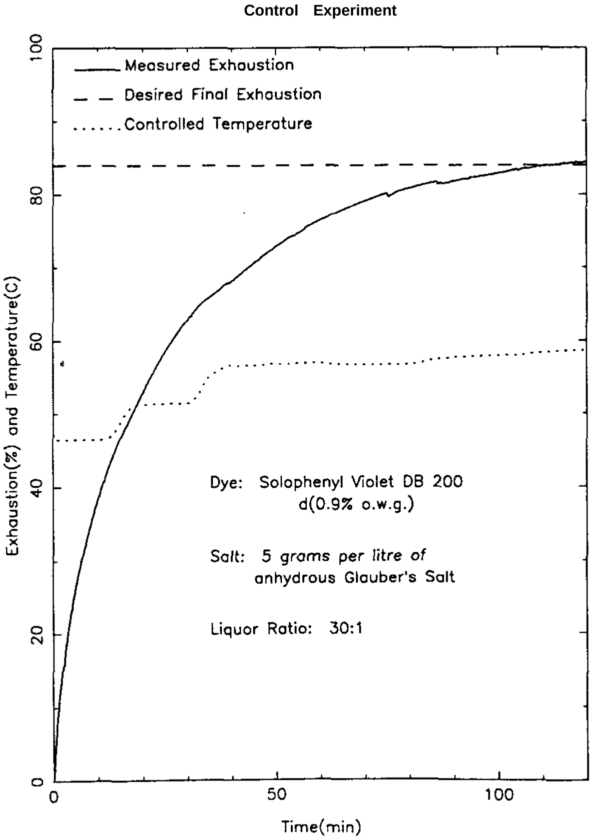
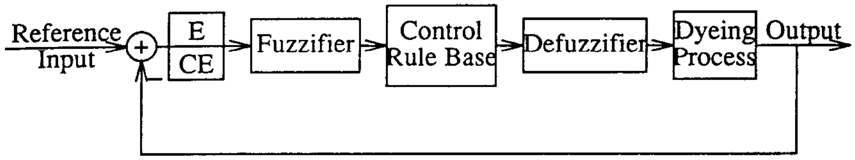


Figure 8—Structure of a fuzzy logic controller for dyeing processes.



$$\frac{dC^f}{dt} = G_8 (C^f_{final} - C^f) \qquad (3)$$

Here, G_p, is a design parameter which is greater than zero. If G_p is treated as a constant, this means the closed loop dynamics are linear. It can also be treated as a function of time and other variables of state, as is appropriate based on dye models, but it: value must be positive. Closed-loop dynamics can be obtained by external linearization of the nonlinear dyeing system. Combining equation (3) with the Langmuir model in equation (1), the non linear control law can be implemented as equation (4).

$$G_P\ (C^f_{final} - C^f) = k_A C^s (S - C^f) - k_D C^f \qquad (4)$$

The control law in equation (4) car then be restated in equation (5).

$$K_L = \frac{G_P(C^f_{final} - C^f)}{k_D C^s (S - C^f)} + \frac{C^f}{C^s (S - C^f)} \qquad (5)$$

k_L and k_D are functions of temperature which can be obtained either through on-line adaptive parameter estimation or from theoretical models. By a series of model based calculations, the controller computes proper temperature, T_d, which is required to bring the entire system to its desired final exhaustion state.

After computation of T_d, because of he limitations of a real dyeing system, some additional constraints on temerature may be needed. The restrictions of maximum and minimum temperture are:

$$\begin{aligned} T_d &= T_{min} && \text{if } T_d < T_{min} \\ T_d &= T_{max} && \text{if } T_d > T_{max} \qquad (6) \\ T_d &= T_d && \text{otherwise} \end{aligned}$$

The restrictions of temperature change are:

$$\begin{aligned} T_d &= T_{new} - \Delta T && \text{if } (T_{new} - T_d) < \Delta T \\ T_d &= T_{new} + \Delta T && \text{if } (T_d - T_{new}) > \Delta T \\ T_d &= T_d && \text{otherwise} \end{aligned} \qquad (7)$$

Where ΔT is the maximum allowable ate of rising or cooling. Based on equation (5), if *C^f is smaller than C^f_{final}* the first part of equation (5) will be positive. 'his can increase K_L(increasing C^r). If C^f is larger than C^f_{final}, the first part of equation (5) will be negative. This can decrease K_L(decreasing C^f). When final, equation (5) is the same as aquation (2), the equilibrium equation.

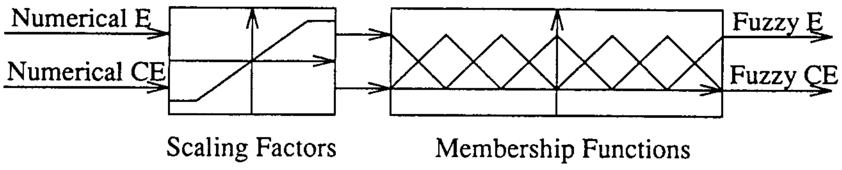
With this kind of control scheme, the closed-loop system is exponentially stable and the regulation error e,. = $(C^f - C^f_{final})$ converges to zero:

$$\lim_{t\to\infty} C^f = C^f_{final}, \qquad (8)$$

Figure 4 shows the simulation control results with one target point at the end of the process. The point is the desired final exhaustion corresponding to C^f_{final}. Figure 5 is the simulation control results with multiple target points at different times during the process. The solid line is the simulated dye process exhaustion and the dash line is the controlled temperature. The model coefficients were adaptively estimated during the process. The temperature was calculated by the above procedure. As can be seen in each case, the desired target exhaustion was reached.

Application of this control technology to real dyeings provides fascinating results. Two dyeings of 0.9% owg Solophengl Violet DB200 on 100% cotton with 30:1 Liquor ratio and 5 g/L of Glauber's salt were done to test the control scheme. Figure 6 shows the actual experimental dyeing with erroneous high starting temperature and Figure 7 shows the actual experimental dyeing with erroneous low starting temperature. Note that in each case, the controller changed the dyeing temperature during the process to achieve the desired final exhaustion. Thus the dyeing was, in each case, run according to nonstandard profile, but achieved the correct final dye shade. these are actual dyeing done on an Ahiba Texomat dyeing machine in the DARG lab at N.C.S.U.

Figure 9-Structure of the fuzzifier.



Fuzzy logic control

The structure of a fuzzy logic controller is shown in Figure 8. It comprises three parts: fuzzifier, rule base, and defuzzifier. A computation of the control action consists: of the following stages:

1) Compute current error (E) which the difference between the ideal output and the measured output, as well as its rate of change (CE).

2) Convert numerical E and CE into fuzzy E and CE.

3) Evaluate the control rules using the fuzzy logic operations.

4) Compute the deterministic input required to control the process.

The fuzzifier is used to quantize the available measurements E and CE which may be of limited accuracy, into certain coarse levels. The fuzzifier in cludes a scaling part and a membership function part as shown in Figure 9. The scaling factors can be linear or nonlinear, also the membership functions can have different shapes, eg triangle, bell, trapezoidal, sinusoidal. Here, a linear scaling factor and triangle membership function are used. The fuzzifier converts numerical E and CE, such as 2.01, - 0.93, into fuzzy E and CE, such as LN (large negative), MN (medium negative), SN (small negative), ZE (zero), SP (small positive), MP (medium positive) and LP (large positive), with grades of membership $\mu(E)$ and $\mu(XE)$ from 0 to 1. The grade of membership values are assigned subjectively to define the meaning of the fuzzy values, such as large negative.

The rule base contains the control rules which are developed heuristically for the particular control task and implemented as a set of fuzzy conditional statements of the form: If E is LN and *CE is ZE, then CTRL is MP.* This expression defines a fuzzy relationship between error (E) and error rate (CE) and change of process control input (Ctrl) for the particular system state. Figure 10 gives the structure of the control rule base. Also the rules used are evaluated by using the fuzzy logic operations, such as union, intersection, complement of fuzzy sets. The control rules can also be represented graphically as a surface in the three dimensional space (Fig. 11).

The defuzzifier is the inverse of the fuzzifier. It converts fuzzy process control input obtained through rule evaluation into numerical deterministic process control input. Many algorithms can be used here, the center of gravity method being the most popular one.

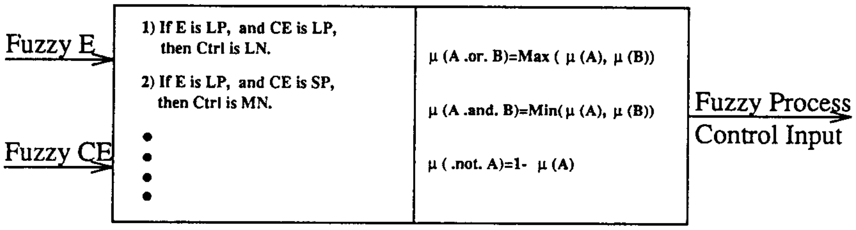
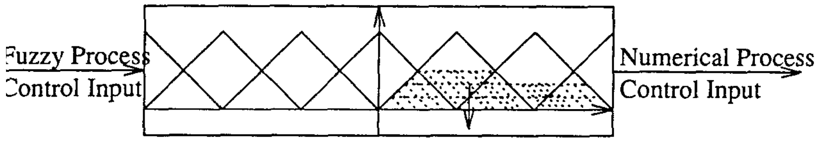


Figure 12-Structure of the defuzzifier.



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References

(1) American Dyestuff Reporter Process Controls Buyer's Guide, ADR, November, 1991

(2) Astrom, K.J., Wittenmark, B., *Adaptive Control,* Addison-Wesley Publishing Company, 1989

(3) Beck, R.B.. Lefeber, M.R., Smith, C.B., McGregor, R., Hunter, W.D., "Flow Injection Analysis of Dyebath", AATCC International Conference and Exhibition, Atlanta, GA., October, 1992

(4) Berkstresser (IV), G.A., Beck, K.R. Smith, C.B., McGregor, Ft., Jasper, W. "Novel Approaches for the Real-Time Prediction of Dye Concentration in Three Dye Mixtures", AATCC International Conference and Exhibition, in

(5) Burley, R., Wai, P-C., McGuire, G. "Process Engineering Approach to Dyeing Machinery-A Study of Package Dyeing Machine Dynamics", Chemical Eng. Res. Des., Vol. 65, pp 505-513 1967

(6) Dochain, D., Bastin, G., "Adaptive Identification and Control Algorithm for Non linear Bacterial Growth Systems", Automatica, Vol 20, No. 5, pp 621-634, 1984

(7) Ingle, Tony, private communication

(8) Kim, J., McGregor, R., "Theoretical Modeling of Batch Dyeing Process", Report of CRAFTM Sponsor Meeting, NCSU, 1991

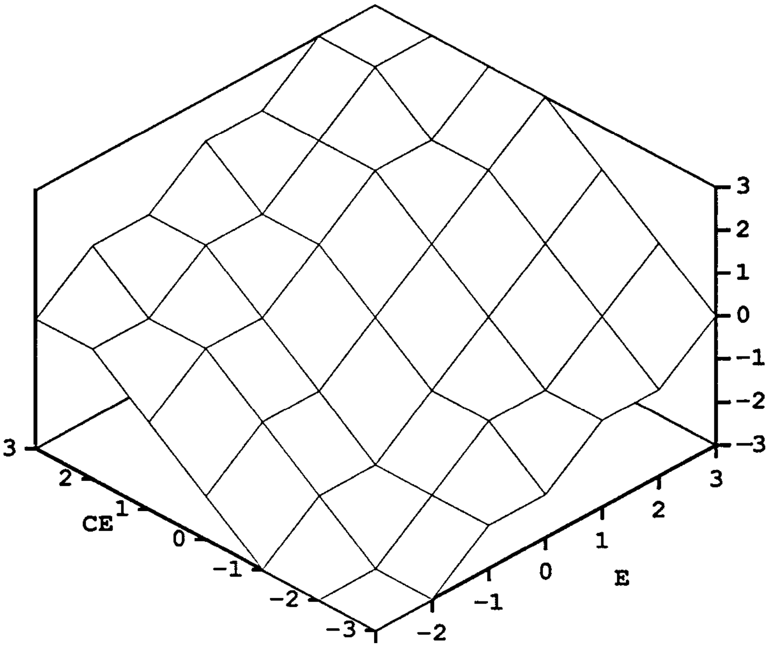
(9) Koksal, Guiser, et al. "A System Analysis of Textile Operations", TC &C, Vol 24, No 10, pp 30-45. 1992

(10) Lu, J., *Modeling and Control of Dyeing* Processes, Master's Thesis, NCSU, 1992

(11) Madderra, T., *Development of a Data Acquisition System for Real-Time Textile Batch Dyebath Analysis,* Master's Thesis, NCSU, 1990

(12) McGregor, R., Harris, P.W., "A Chemical

Figure 11 -Control rule surface with (- 3:LN) (- 2:MN) (- 1:SN) (0:ZE) (1:SP) (2:MP) 3: LP).



Simulation results obtained in Figure 13 and Figure 14 show that dyeing processes can be controlled effectively using heuristic rules based on fuzzy statements. The controller designer needs detailed knowledge of the dyeing processes in formulating the rules. To get better control performance, other process information like time delay and response speed is also needed.

In our most recent work, we have developed some enhanced FL schemes which can develop control rules automatically with very limited process knowledge, i.e. the controller has total learning ability. These schemes are now under further evaluation.

Summary

Fundamental considerations for novel control algorithms, as well as applications to batch dyeing process have been presented. Several sets of experimental results for adaptive control and fuzzy logic controllers have been evaluated with very promising results. □ □ □

Acknowledgements

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Figure 13 -Simulation one of fuzzy logic control for dyeing **processes** (solid line: desired exhaustion) dashed line: actual exhaustion) (dashed point line: controlled temperature).

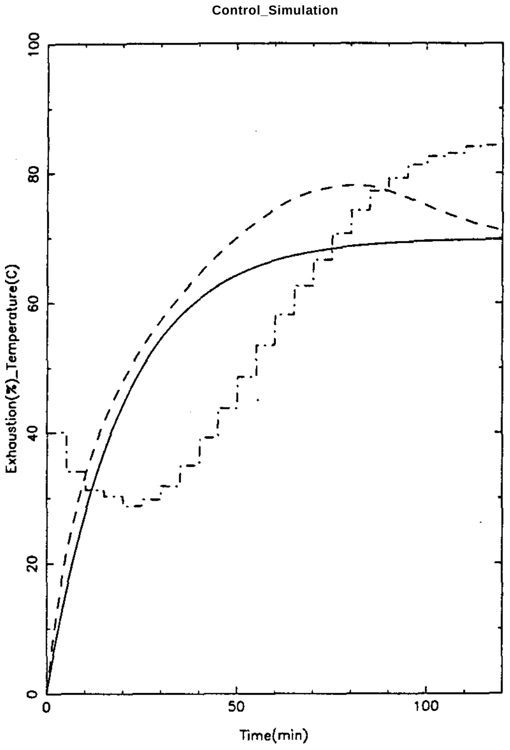
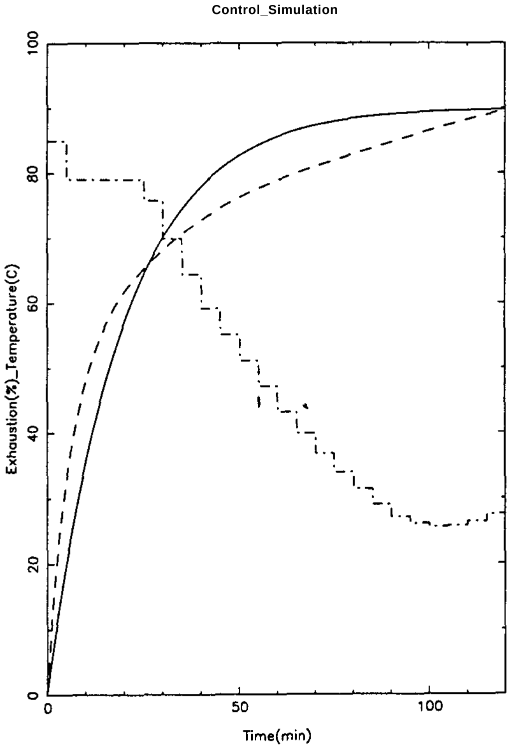


Figure 14 - Simulation two of fuzzy control for dyeing processes (solid line: desired exhaustion) dashed line: actual exhaustion) (dashed-point line: controlled temperature).



Engineering Approach to Dyeing Probtams: The Sorption of Acid Dyes by Polyamides" M-20 A Research Monograph From Allied Chemical, 1969

73) Preston, C., *The Dyeing of* Cellulosic Fibers Dyer's Company Publication Trust, 1986

(14) Banky, Paul *G., Flexible Manufacturing Cells and Systems,* ClMware Limited, Guilford, England

(15) Scheer, August-Wilhelm, C/M - *Towards* the *Factory of the Future,* 2nd ed., Springer-Verlag, New York, 1991

(16) Spiekermann, C., Lu, J., Smith, C.B., McGregor, R., "A Novel Approach for Modeling and Controlling Dyeing Processes", AATCC International Dyeing Symposium. Charlotte, NC, June, 1991

(17) Vickerstaff, T. The Physical *Chemistry of Dyeing,* London: Oliver & Boyd, 1954

(18) Warren J., *Batch Dyeing Optimization for Fiber Reactive Violet 5 Using* Real. *Time Data Acquisition,* Master's Thesis, NCSU, 1991