SIMULATIONS AND EXPERIMENTS ON INTELLIGENT CONTROL OF A WOOD-DRYING KILN

Givon C. K. Yan*, Clarence W. de Silva* and George X. Wang**

*Department of Mechanical Engineering
University of British Columbia
Vancouver, B.C., Canada V6T 1Z4

**National Research Council Canada, IMTI
3250 East Mall
Vancouver, B.C., Canada V6T 1W5

Abstract: The paper first outlines the experimental kiln. Next, the control system that has been developed, which contains a fuzzy control module, is presented. Simulation results as obtained from an experimental model are given. Results from on-line experimentation of the physical kiln are given as well. The paper ends with a discussion of the results and conclusions. *Copyright © 2000 IFAC*

Keywords: intelligent adaptive control; wood drying; moisture control of wood; kiln control; fuzzy logic

1. INTRODUCTION

The province of British Columbia (BC), Canada, is a leading region in the world for wood production, where billion tons of wood are produced annually. Drying is the final process before the wood is available for general use. The specific application of wood is mainly determined by its final moisture content (m.c.) after drying. For example, an application like furniture making requires a final m.c. of 12%. Quality of the dried lumber product is unpredictable, unreliable and non-repeatable. Kiln operators should frequently monitor the kiln operation and should make parameter adjustments as appropriate. Many years of experience would be required before an operator is given charge of carrying out these tasks. Problems can arise due to unattended operation. Furthermore, in view of the complexity, nonlinearity, and time-variant and distributed nature of the drying process, the quality of the dried wood may not be uniformly satisfactory in general. The fact that the drying results are unpredictable and that the entire process requires humans to close the control loop, have motivated the development of a closed-loop automatic control system for the industrial lumber drying process, which aims at reducing energy consumption and improving quality of dried wood. This is the focus of the present paper.

2. EXPERIMENTAL SETUP

An experimental kiln dryer is available at the National Research Council (NRC), Vancouver, Canada. The research carried out using this facility mainly focuses on automating the wood drying process through developing and implementing a closed-loop adaptive controller based on the moisture content of the wood pieces (Yan, et al., 1999). The present paper outlines the outcomes of a related activity.

The test kiln is an insulated structure with dimension of 107"x38"x44". This setup has two actuators and four output variables. Sensors for the output variables include 12 thermocouples, 2 relative humidity sensors, 1 air velocity transmitter, and 8 pairs of wood moisture content sensors. The heater consists of a heater filament and it is an electrical on/off type. The variable speed fan draws air through the heater filament and then blows it out of the plenum, located on one side of the kiln, through the slots that are equally spaced within the plenum. These two actuators are located in a small chamber situated at the back of the kiln. The system outputs are all connected to a data acquisition and analogue output board (DAQ) and then to a personal computer (PC). The PC, on monitoring system variables, provides control signals to both actuators. All interactions are supported by the software programming and interface developed in Delphi. An overview of the experimental system is shown in figure (1).

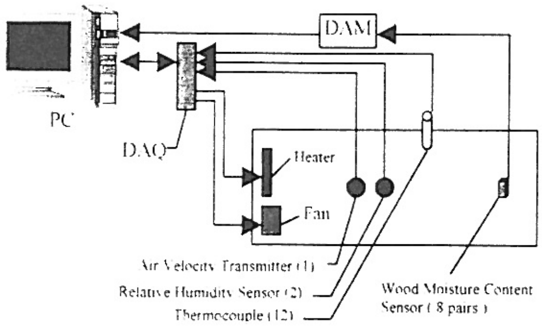


Fig. 1. An overview of the experimental system.

3. FUZZY LOGIC CONTROL SYSTEM

Lumber drying is a complex process, particularly due to nonlinearities and the coupling effect of temperature, relative humidity, and moisture content. It is also a time-variant process with delay. Conventional model-based control technique may not be able to provide good drying result since the controller performance is mainly determined by the accuracy of the system model. Intelligent control using fuzzy logic, on the other hand, is capable of handling complex nonlinear processes, and it can provide the flexibility that conventional crisp control does not provide. In the present work, a fuzzy logic controller is constructed and implemented for in-wood moisture content control, and its performance is investigated.

The kiln system is divided into or represented by two sub-systems; namely, the *heat-temperature* process and the *temperature-moisture content* process, as shown in figure (2). Both the heat-temperature process and the temperature-moisture content process are experimentally evaluated and taken to be second order SISO systems. A white noise input signal (in the form of a pulse-width-modulated or PWM signal) is applied to the kiln so that all the dynamic modes of the system are excited. By making use of the collected input/output (I/O) data, which contain the dynamic information for controlling the system, appropriate input/output models for various processes of the kiln system are established (Ljung, 1999). The associated model parameters are estimated so that they will represent the best fit to the data, in the sense of least squared error. For the computer simulation, the transfer function representing the second order ARMA models of the heat-temperature process and the temperature-moisture content process, respectively, are given by

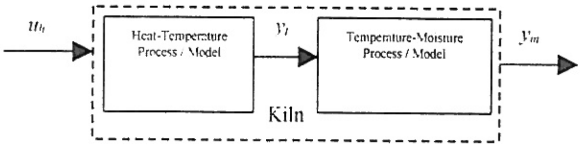


Fig. 2. Block diagram for model identification.

where

u_h = control signal to the heater (ON/OFF)
y_t = temperature response (output)
y_m = moisture response (output).

$$\frac{Y(z)}{U(z)} = \frac{1.0882\,z^{-1} + 0.2046\,z^{-2}}{1 - 1.6243\,z^{-1} + 0.6299\,z^{-2}} \qquad (1)$$

and

$$\frac{Y(z)}{U(z)} = \frac{-0.0967\,z^{-1} + 0.0915\,z^{-2}}{1 - 0.8201\,z^{-1} - 0.1309\,z^{-2}} \qquad (2)$$

3.1 *Membership Functions*

In the present study, triangular membership functions, with a peak grade of unity for the most representative value of the fuzzy quantity, are chosen for the input variables. Both triangular and trapezoidal functions are chosen as the membership functions of the output variables.

The fuzzy variable representing the moisture error is defined to have five fuzzy states with the corresponding membership functions denoting the input variables. The five states are: negative small (NS), zero (ZR), positive small (PS), positive medium (PM) and positive large (PL). The fuzzy variable of the control inference, which is the desired kiln temperature is also assigned a resolution of 5. These fuzzy states of the action variable are defined as very low (VL), low (L), medium (M), high (H) and very high (VH), with associated membership functions chosen as discussed before.

3.2 *Fuzzy Rulebase*

In general, a rule in a fuzzy knowledge base of direct fuzzy control, is a relation of the form:

$$\text{IF } A_i \text{ THEN } C_i \qquad (3)$$

where, A_i is a fuzzy quantity representing process measurement (in the present situation it represents wood moisture error) and C_i is a fuzzy quantity representing a control action; here it represents a change in reference temperature. The compositional rule of inference is given by

$$\mu_{C'}(c) = \sup_{a} \min[\mu_{A'}(a), \mu_R(a,c)] \qquad (4)$$

where $\mu_{C'}$ is the membership function of the control inference, and $\mu_{A'}$ and μ_R are the membership functions of the measurement fuzzy set A' and fuzzy relation R, respectively. Note that R represents the control rulebase. The final crisp control inference is obtained through defuzzification of the fuzzy inference C' using the centroid method (De Silva, 1995).

The support set S of a fuzzy set A is the crisp set formed by the collection of all elements $x_i \in X$ such that $\mu_A(x_i) > 0$. Let the membership function of a control inference be given by $\mu_{c'}(c)$, with a support set S. The crisp control action $\hat{c}$, using the centroid method, is determined by, in the discrete case,

$$\hat{c} = \frac{\sum_{c_i \in S} c_i \mu_{c'}(c_i)}{\sum_{c_i \in S} \mu_{c'}(c_i)} \qquad (5)$$

The moisture error (crisp) obtained from the moisture setpoint and the actual wood moisture sensor measurements is first fuzzified in order to apply the compositional rule of inference (equation (4)). The resulting control inference (C') is defuzzified to provide the crisp control action ($\hat{c}$), using equation (5).

The rule base of the fuzzy moisture controller consists of five rules that are of the form given by (3), and is summarized below:

IF moisture is NS THEN temperature is VL
or IF moisture is ZR THEN temperature is L
or IF moisture is PS THEN temperature is M
or IF moisture is PM THEN temperature is H
or IF moisture is PL THEN temperature is VH

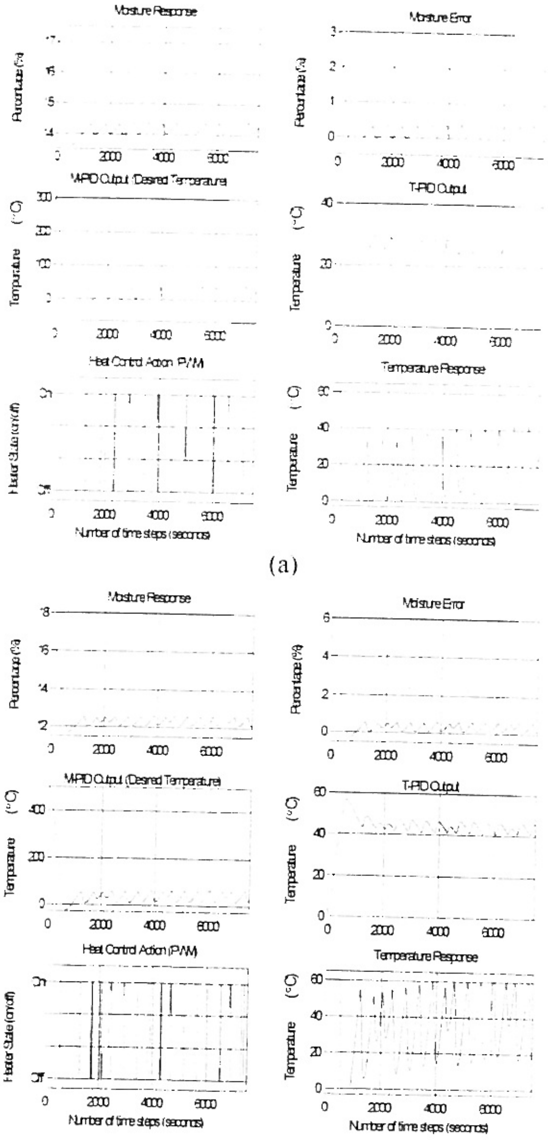
Through implementation of the linguistic rules and membership functions, a direct fuzzy logic controller for moisture control is developed. The simulation results of the fuzzy logic control system, implemented using MATLAB Simulink, is presented in the next section.

4. SIMULATION RESULTS

The fuzzy logic controller is developed by implementing the rule base with the corresponding membership functions of the fuzzy variables in MATLAB using the Fuzzy Toolbox. Simulations for the desired removal of 3% and 5% of moisture are performed.

The moisture error is computed and is corrected by the fuzzy logic controller to provide the desired output temperature. Similarly, the temperature error is corrected by the inner T-PID controller, which provides a heat control action as a pulse-width-modulated (PWM) signal. The proportional gain (K_p), integral gain (K_i), and derivative gain (K_d) for T-PID are selected using the Ziegler-Nichols technique (Ziegler and Nichols, 1942).

It was found that the fuzzy logic controller is able to dry the wood from a moisture content of 17% down to 14% with a maximum deviation of 0.3%, which is only half the error resulted from the PID controller. Simulations were run for two hours, and no saturation was found to occur during the entire simulation period. The average desired operating temperature is approximately 50 °C and the average value of the percentage duty cycle of the PWM heater controller is less than 15%, compared with a 50% duty cycle for the PID controller. This shows a distinct improvement due to the fuzzy logic control system, where a conventional PID controller is integrated with intelligent control. Figure (3) shows the simulation results for the conventional PID control system, and figure (4) shows the simulation results for the fuzzy logic control system in removing 3% and 5% of moisture.



(a)

(b)

Fig. 3. Simulation results from the PID control system for a desired reduction of moisture by (a) 3% and (b) 5%.

Again, the fuzzy control system was found to be capable of removing the moisture content from 17% to 12% with a maximum error of 0.3%, which as before is only half of the error resulted from the PID control system. Saturation did not occur throughout the simulation. The average value of the pulse-width-modulated heater control is less than 30% duty cycle. The average desired temperature is 70 °C for the entire simulated drying process. In this case, the required energy (PWM duty cycle) and the desired temperature are higher than those for the 3% moisture removal since a larger quantity of moisture was removed.

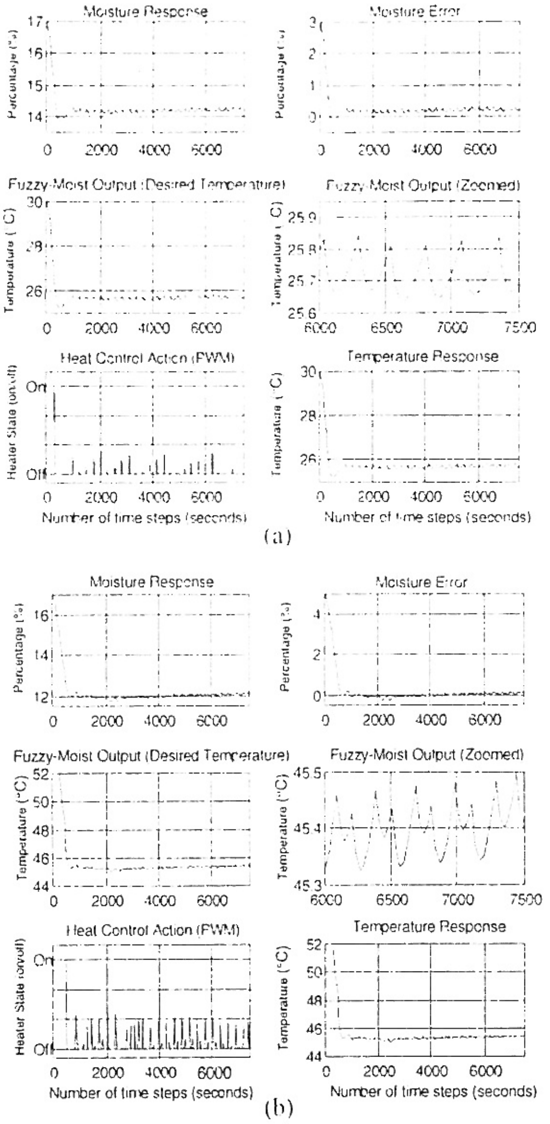


Fig. 4. Simulation results from the Fuzzy + PID control system for a desired reduction of moisture by (a) 3% and (b) 5%.

5. ON-LINE EXPERIMENTATION

The Fuzzy-plus-PID control system developed in the present work and studied using computer simulations, is implemented in the prototype kiln system for the on-line investigation of controller performance. Also, the fuzzy logic controller for moisture control is tuned on-line in order to achieve improved performance. On-line performance of the conventional PID control system is presented in figure (5). The best experimental result of the fuzzy control system is presented in figures (6), and the gains for the PID temperature controller are kept the same as those that give the best performance results in the conventional PID control system.

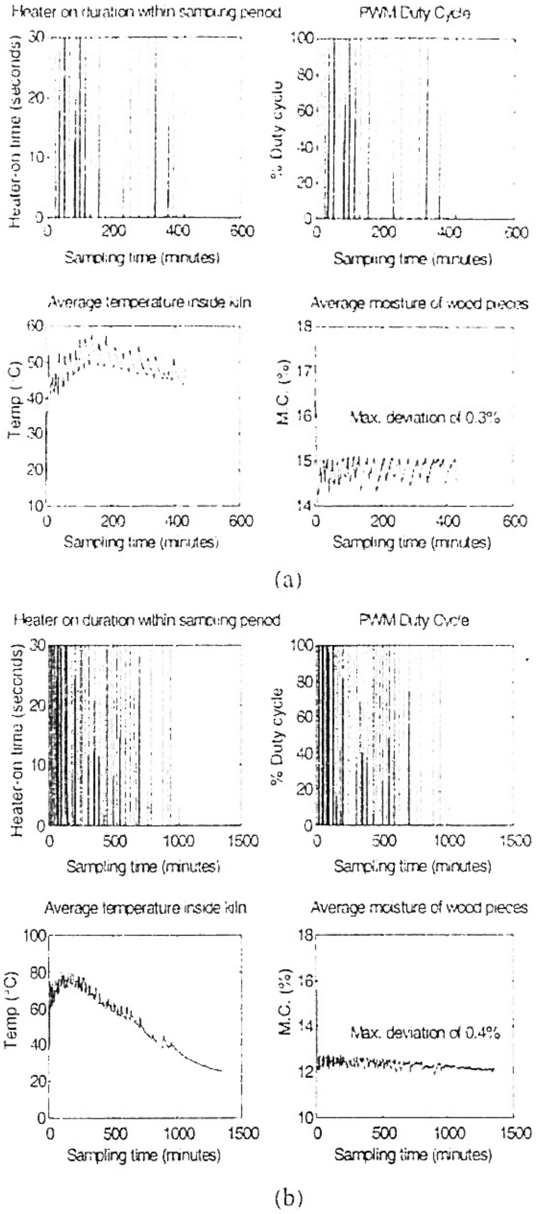
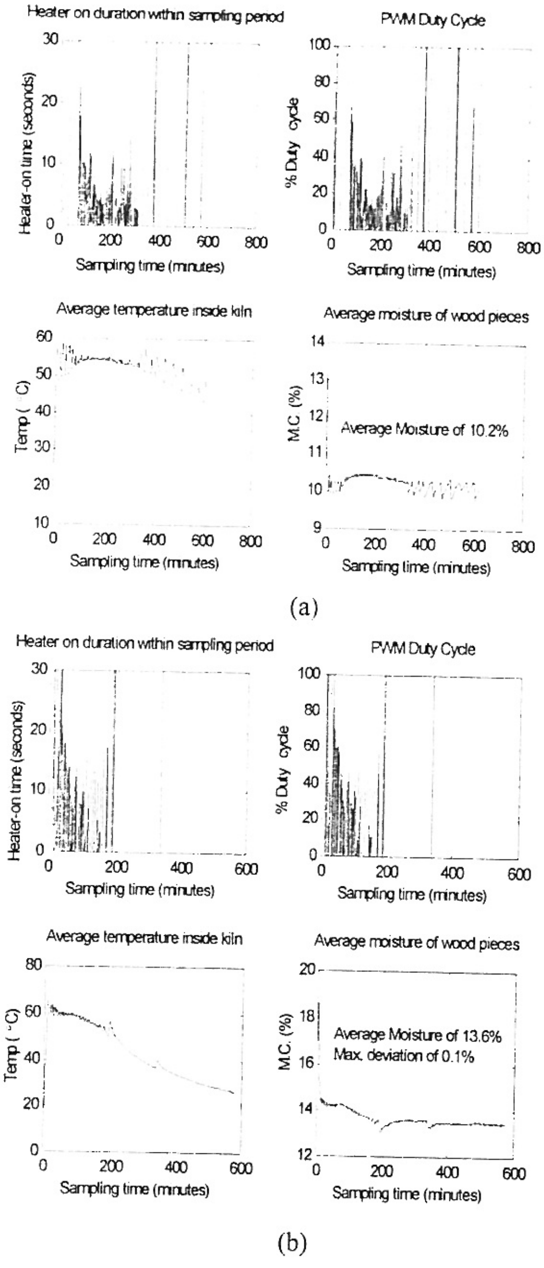


Fig. 5. Experimental results with the tuned conventional PID control system for a desired reduction of the moisture level by (a) 3% and (b) 5%.

As seen in figure (6a), the fuzzy controller is capable of performing the desired removal of 3% of moisture, by bringing the moisture level down from an initial value of 13.3% to 10.2%, with a maximum error of ±0.3% in a long run test of approximately 13 hours. The average desired operating temperature is maintained at 51.5 °C, with a maximum operating temperature of 60 °C, in the beginning of the drying process. The PWM duty cycle is recorded as well.

Similarly, another test is carried out to investigate the controller performance in a desired removal of 5% of moisture. This experiment is run for approximately 10 hours. It is observed in figure (6b) that the controller system again gives satisfactory results. An initial moisture content of 18.7% is brought down to an average value of 13.6%, which is very close to the ideal result, with a maximum error of just ±0.1%. The desired operating temperature is maintained at approximately 42 °C for the entire drying process, and the heater is found to be off after 200 minutes, except for a very short on period. The corresponding PWM duty cycle is recorded.



(a)

(b)

Fig. 6. Experimental results for the modified fuzzy PID control system for a desired reduction of the moisture level by (a) 3% and (b) 5%.

6. CONCLUSION

This paper presented a closed-loop control system with feedback from wood moisture sensors using fuzzy logic control. On-line experimental results were carried out and compared with computer simulations for both conventional and fuzzy PID control schemes.

Both control schemes showed promising results, and sometimes the PID control system showed drying result as good as those from the fuzzy logic control system. By examining the test runs as a whole, in general, it can be concluded that the fuzzy logic controller performed better than the PID controller with regard to the final moisture error and energy consumption. The fuzzy logic controller generally could produce better drying results, with a smaller final moisture deviation error. In some tests with the fuzzy controller, wood pieces could be dried to exactly the same condition as specified by the moisture setpoint, with an error of less than ±0.1%, which the PID controller was unable to achieve. Besides, the fuzzy logic controller only required an average temperature of 46 °C compared to 52 °C for the PID controller. Accordingly, the PWM duty cycle for operation was lower for the fuzzy control system than that for the PID control system. Also, the range of operation of the PWM duty cycle was found to be wider for the fuzzy control system. All these improvements in performance that result from the fuzzy logic control system may be credited to the fact that human experience and control episodic knowledge can be integrated into the control system through the use of a fuzzy-logic knowledge base (De Silva, 2000). A significant potential was established for improved performance when the developed technology is applied to industrial kilns.

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