A fuzzy controller for infrared roasting of cereal grain

R.B. Brown[1], T.M. Rothwell[2] and V.J. Davidson[1]

[1]*School of Engineering, University of Guelph, Guelph, Ontario, Canada N1G 2W1; and* [2]*Agricultural and Energy Engineering, RR#1 Moorefield, Ontario, Canada N0G 2K0*

Brown, R.B., Rothwell, T.M. and Davidson, V.J. 2001. **A fuzzy controller for infrared roasting of cereal grain**. Canadian Biosystems Engineering/Le génie des biosystèmes au Canada. **43**:3.9-3.15. A computer control system was developed to regulate a continuous infrared roaster used to process cracked cereal grain. The rule-based controller used fuzzy set representation for process variables such as grain temperature and production rate, and simple control rules extracted from the operator's practical experience in regulating the process. Bulk average temperature of the grain exiting the roaster was used to adjust the infrared panel temperature and ensure an adequate degree of roast. The system was tested at a processing plant with cracked wheat and a commercial electric infrared roaster. Under both setpoint and load disturbances (i.e., changes in required final grain temperature and grain flow rate) the controller maintained satisfactory control of the process with no intervention by the operator.

Un système de contrôle informatisé fut développé pour permettre le réglage d'un four de grillage à infrarouge en continu utilisé dans le traitement des grains concassés. Le régulateur utilisait des ensembles flous pour représenter les paramètres du procédé de traitement comme la température des grains et le taux de production, et des règles de contrôle simples qui découlent de l'expérience pratique d'un opérateur dans le réglage du procédé. On a utilisé la température moyenne de la masse de grains sortant du four pour ajuster la température des infrarouges sur le tableau de contrôle, et s'assurer que les grains sont bien grillés. Les tests furent faits dans une usine de transformation avec du blé concassé et un four à infrarouge électrique commercial. Le régulateur a permis de contrôler le procédé de manière satisfaisante sans l'intervention de l'opérateur, et ce dans des conditions où le point de réglage et les charges étaient modifiés (i.e. changements de la température finale des grains désirée, et du débit des grains).

INTRODUCTION

Many thermal processing operations for food products (e.g., roasting, drying, or cooking) still rely largely on human supervisory control. Automatic model-based control is not normally used in such operations because the processes involved in colour and flavour development are either too complex or incompletely understood to be described adequately in a mathematical form. In addition, some of the sensory variables necessary to control the processes are vague and subjective in nature, and can not be expressed strictly as numerical data. However, human perceptions can be captured by fuzzy techniques of data representation, and then used to make control actions.

This research was conducted at a production plant that processes a number of cereal grain and oilseed products which are heat-treated using an infrared (IR) roasting process. One product is a 3-grain breakfast cereal product which is a mixture of cracked hard wheat, cracked rye, and whole flaxseed. The cereal product has to be cooked in boiling water by the consumer. Production of the 3-grain cereal is a continuous process which involves coarse grinding of the wheat and rye components, blending the three feedstock materials in correct proportion, and roasting the blended grain in a continuous electrical infrared roaster (Model 6BEV, Flakee Mills, Lincoln, NE).

Control of the entire grinding, blending, and roasting process has historically been the responsibility of one person. This imposed considerable demands on the operator since several tasks had to be executed synchronously, and frequently off-spec product resulted from disturbances cascading through the process. The temperature controllers for the IR heating panels (3 separate stages), the grain feed rate, and the depth of the grain in the roaster were all manually set. Occasionally grain in the roaster would catch fire, so the operator had to constantly check the machine.

The objective of this work was to develop a roaster control system to:

1. produce a consistent roasted product, and,
2. relieve the operator of having to pay constant attention to the machine.

BACKGROUND and REVIEW OF LITERATURE

Control technologies for drying and roasting

The equipment and processes for grain drying and roasting are similar. Typically a number of low-level control functions, such as thermostatic control of a gas burner, are tied together into a complete automatic control system. Roasters and grain dryers are usually equipped with three separate low-level control systems:

1. Heater (or burner) temperature regulation control, usually through a simple on-off duty-cycle controller, or less frequently using modulated control [i.e., proportional (P), proportional-integral (PI), or proportional-integral-derivative (PID) feedback control],
2. Product discharge or loading rate flow controls, and
3. Safety controls (e.g., temperature high-limit, airflow failure, product flow, and low-level sensors) - often coupled with alarms.

The first two systems allow the operator to adjust the setpoint values. The least automated of these systems involves strictly manual adjustment. In the infrared roasting situation, the human operator periodically checks product discharge characteristics (product moisture, colour) and adjusts the appropriate low-level controller setpoints (grain flow rate, heater temperature) in accordance with intuition and heuristic rules of the process operation. The operator occasionally exercises anticipatory control by observing grain properties ahead of the roaster if process upsets are suspected.

In grain drying, automatic control systems have become commonplace. Moreira and Bakker-Arkema (1992) have provided an overview of modern dryer control systems. The best systems use conventional adaptive control, with feedforward and feedback. These systems require a mathematical description of the process and the ability to sense the process variable (i.e., grain moisture) on-line. However, unlike grain drying where product moisture is the process variable, the success of roasting is not defined by a single variable.

Another prerequisite for effective conventional control over the roasting of cereal grains is accurate characterization of the process. Physical parameters must be known in order to quantify gain values for PID controllers and coefficients for model-type controllers. This is difficult for the IR cereal-roasting process. Brown and Davidson (1996) found that the cracked cereal grain actually becomes lighter in colour as it is roasted, with a corresponding drop in its IR absorption as it passes through the roaster. Also, since IR radiation does not penetrate more than a few millimetres into the grain, the bed depth affects the final bulk grain temperature. The final temperature of the cereal is also affected by its initial moisture level. On-line measurements of at least one, and possibly all, of these parameters would be needed for model-based control.

Fuzzy process control

Fuzzy control systems have been developed for processes that are difficult to model mathematically and may have multiple control objectives which cannot be observed directly on line. Zhang and Litchfield (1991) created a fuzzy logic control system for a corn dryer that maintains physical quality and at the same time regulates final moisture. A fuzzy control system for drying soybeans, where seed coat cracking, seed viability, and moisture content were all considered, was developed by Davidson et al. (1996). A fuzzy logic controller using sensor inputs and linguistic observations from the operator was used by Davidson et al. (1999) to control a hot-air peanut roasting process. The colour and flavour of dry-roasted peanuts was controlled by adjusting the product flow rate in a continuous roaster according to heuristic rules that also simultaneously considered the roasting temperature, peanut kernel size, initial moisture content, and the final colour characteristics.

The examples listed above either used rule-based fuzzy logic control or a combination of fuzzy rules with fuzzy arithmetic models. A different approach using a fuzzy model of the process itself has been developed by Postlethwaite (1994). A fuzzy relational model used to control a distillery grain dryer outperformed human operators, achieving half the standard deviation in final moisture relative to manually controlled runs (Bremner and Postlethwaite 1997).

In the infrared roasting process there are multiple control objectives, including final grain moisture, grain temperature, and degree of roast (colour and flavour) which are difficult to measure on-line. Also, the dynamics of heating and roasting are challenging, if not impossible, to describe accurately with mathematical models. Some process parameters, such as colour and IR absorption, are known to vary in a nonlinear fashion. Consequently, the IR roasting process appeared to be an ideal candidate for a fuzzy control system.

INFRARED ROASTER and CONTROL SYSTEM

Infrared roaster

The Flakee Mills Model 6BEV infrared roaster has a 3-stage vibrating conveyor table that is 0.56 m wide and 3.78 m long. Six electric infrared heater panels (18 kW each) are mounted in pairs directly above the table. Each pair of heater panels is controlled by a dedicated PID controller that maintains panel temperature with feedback from a K-type thermocouple inside the panel housing. The plant operator adjusts both the grain flow rate and the heater panel temperature to regulate the degree of roast. The thickness of the grain layer in the roaster varies with loading rate and the frequency of table vibration (i.e. conveyor speed). In this study, grain flow rate was about 1000 kg/h, grain depth was 10 mm, and average residence time was 90 s.

T-type thermocouples were installed to measure bulk grain temperature at the discharge end of the roaster table. The thermocouples were mounted in shallow dwell hoppers which intercepted the grain as it dropped from the end of the roaster table, ensuring that the thermocouple junctions were always in direct contact with the roasted grain.

Control hardware and software

A personal computer was used for process data acquisition and system control. Thermocouple measurements of grain temperatures and heater panel temperatures, and the shaft encoder output from the grain feeder drive were read in through an A/D board. The individual PID controllers for the IR heater panels were replaced by remotely addressable units (Model CN76020-485, Omega Engineering Ltd., Stamford, CT) which accepted setpoint values from the control computer through an RS-485 serial interface. This approach allowed the operator to disengage the computer control system at any time and run the roaster in a stand-alone mode.

A data-logging function was developed to maintain a log of process information. The process log was required for quality assurance in the production of the roasted cereal product, and was also used to evaluate the controller performance. A graphical interface was created to present the current process information to the operator. The sampling interval for temperature measurements was 20 s, or about 1/4 of the grain residence time in the roaster. Automatic or manual modes of control were available to the operator, but in either case the computer continued to log and display data. In automatic mode, the grain flow rate was set by the operator; heater panel temperature was adjusted by the high-level controller. In manual mode, the operator adjusted the infrared panel temperatures as well as the grain flow rate.

The fuzzy controller

A fuzzy preprocessor for the C programming language (Fuzz-C, Byte Craft Ltd., Waterloo, ON) was used for programming the control system. A feature of Fuzz-C is that most standard C

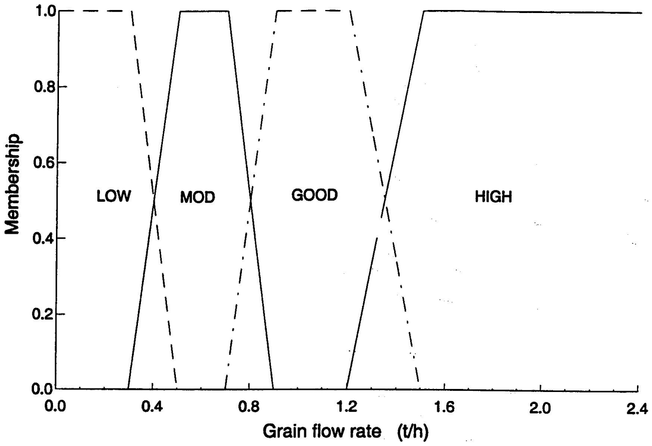

Fig. 1. Fuzzy set memberships for production grain flow rate (PROD).

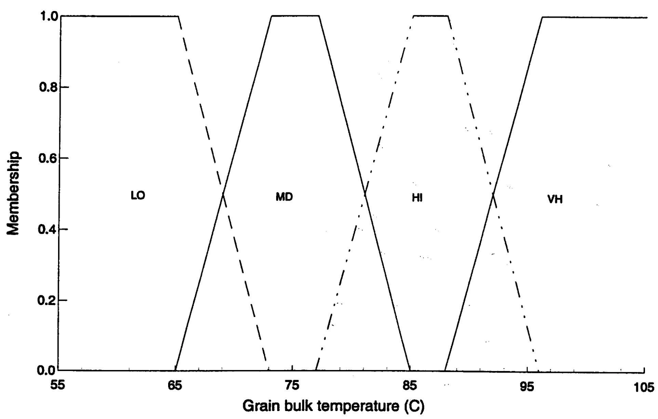

Fig. 2. Fuzzy set memberships for grain bulk temperature (TB).

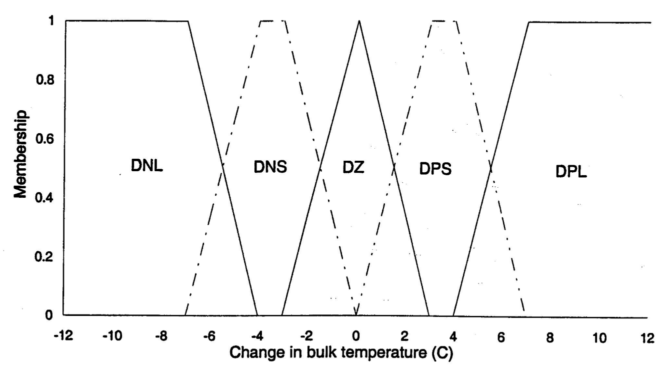

Fig. 3. Fuzzy set memberships for the change in bulk grain temperature (DTB).

operations or commands can be written into the fuzzy code. The source code generated was incorporated directly into the actual control program, which was also written in C.

Fuzz-C uses four components that the developers refer to as "blocks". The ***LINGUISTIC*** block is the actual fuzzy variable. Included in the ***LINGUISTIC*** block are the upper and lower range limits which define the domain of discourse for the variable. The ***FUZZYSET*** block comprises the fuzzy numbers that describe or characterize a ***LINGUISTIC*** block. The ***FUZZY*** block allows rules to be written and loaded into the preprocessor, and a ***CONSEQUENCE*** block calls the defuzzification process for the rule firings.

The Fuzz-C preprocessor uses "degree of membership" (DOM) as a summing variable for rule firings. Its singleton consequents correspond to the centre of gravity of an "equivalent" geometrical shape, and thus the final outcome is the same as if centre of gravity defuzzification was used. However, the DOM summation neatly addresses repeated overlapping areas, a problem with centre of gravity calculations in the geometric approach to defuzzification described by Kosko (1993).

In the development stages it was discovered that the version of Fuzz-C available could not handle floating point numbers as inputs for the fuzzy number memberships. It was therefore necessary to scale some values (e.g., multiply by ten). The scaled numbers were converted back to actual values when passed to other functions, such as screen display in the control program.

Fuzzy variables and corresponding fuzzy number memberships

Four fuzzy variables were used in the control scheme. In setting out the basic operating concept for the roaster controller, the bulk grain temperature was the obvious process variable. The manipulated variable was the change in temperature setpoint for the infrared heating panels. The product flow rate can be considered as a load disturbance. The rate of change in product temperature also plays a role in determining controller behaviour, because there should be a differential or anticipatory action to the control. For example, if the bulk grain temperature is below the PV setpoint but is rising quickly, a zero panel temperature control action is called for (i.e., no change). Negative control action results if the temperature is at the setpoint but is rising.

Fuzzy sets were established within the domain of discourse for each variable. Memberships in these sets were based on:

1. the perceptions and experience of the operators,
2. the characterization of the process and observation of the human controller while product was being manufactured, and
3. the designers' judgement on the nature of control action that the fuzzy memberships would evoke.

Trapezoidal memberships, with adjacent memberships intersecting at a truth value of 0.5, were employed as shown in Figs. 1 to 3.

Product flow rate

Figure 1 gives the values and corresponding sets for the fuzzy variable for product flow rate (abbreviated as "PROD"). The four fuzzy numbers used to describe this variable were:

LOW - low flow rate
MOD - moderate flow rate, should be higher
GOOD - a good or normal flow rate
HIGH - high flow rate, difficult to maintain

Table 1. Singleton values for adjustments in IR panel temperature setpoint (DTP).

Fuzzy number for DTP	Setpoint change (°C)
NVL: Negative Very Large	-50
NL: Negative Large	-30
NM: Negative Medium	-15
NS: negative Small	-5
Z: Zero	0
PS: Positive Small	5
PM: Positive Medium	15
PL: Positive Large	30
PVL: Positive Very Large	50

Table 2. Rule matrix for a low product flow rate (LOW).

Change in grain temperature	Grain temperature			
	LO	MD	HI	VH
	IR panel temperature setpoint adjustment			
DNL	PVL	PVL	PS	NS
DNS	PVL	PL	PS	NM
DZ	PL	PM	Z	NL
DPS	PS	PS	NS	NVL
DPL	Z	Z	NS	NVL

The GOOD fuzzy set is centred about a production rate of 1.1 t/h. In this case, the "good" production rate was consistent with the operator's opinion that 1.1 t/h was the maximum throughput that could be sustained by the grinding and blending equipment over a complete shift.

Bulk grain temperature

The operator indicated that a 90°C bulk grain temperature was "high" while 70°C was too low, and tried to keep the values between 80 and 90°C. The fuzzy variable of bulk grain temperature (TB) was constructed accordingly. Four fuzzy numbers comprise the TB set complement:

LO - low temperature, inadequate roasting
MD - moderate temperature, satisfactory
HI - high temperature, good roast
VH - very high temperature, dark roast

Change in product temperature

The third variable, the change in grain bulk temperature (DTB) is depicted in Fig. 3. Five numbers were selected for this variable. Zero is not a single-value set, and changes in bulk temperature of up to ±3° are considered to have membership in the fuzzy "zero" number. The fuzzy numbers employed in the characterization of DTB are:

DNL - Negative Large
DNS - Negative Small
DZ - Zero
DPS - Positive Small
DPL - Positive Large

Table 3. Rule matrix for a moderate product flow rate (MOD).

Change in grain temperature	Grain temperature			
	LO	MD	HI	VH
	IR panel temperature setpoint adjustment			
DNL	PVL	PVL	PS	NS
DNS	PVL	PL	PS	NM
DZ	PL	PM	Z	NL
DPS	PS	PS	NS	NVL
DPL	PS	Z	NM	NVL

Change in IR heater panel setpoint temperature

The manipulated (output) variable is the change in infrared heater panel temperature (DTP), since this controller uses a velocity form of control action. The magnitude and direction of change to the panel temperature is a consequent of the values for the first three fuzzy variables: production rate, bulk grain temperature, and change in bulk grain temperature. Singleton values, consistent with the Fuzz-C scheme for rule consequents, were chosen to represent the DTP fuzzy sets as illustrated in Table 1.

Due to the velocity form of the controller output, a maximum panel setpoint temperature had to be established in the control logic. The maximum allowable temperature of 810°C was established by the operator, who observed that a higher panel temperature frequently caused scorching in the roaster.

The mid-range values (i.e., "Medium" and "Small") were derived directly from the actions taken by the human operator during production. Specifically, a change of about 15°C was considered to be a "Medium" or moderate change, while a 5° change was a "Small" adjustment according to the operator. Corresponding changes in grain bulk temperature for these adjustments with a normal rate of grain flow were observed to be of the order 1.5 to 3.0°C and 0.5 to 1.0°C, respectively. The "Large" and "Very Large" changes were necessary to allow the system to ramp up or down rapidly under a transient condition of system operation. "Large" was defined as twice the magnitude of medium. "Very Large" was quantified subjectively as being the greatest possible adjustment that would likely ever be made to the panel temperature (either positive or negative) during normal operation. Usually the operator would only make an adjustment of such a magnitude while starting up or shutting down the process. The DTP singleton value for the fuzzy number "Zero" was zero or no change.

Fuzzy rules and rule combinations

Eighty rules were used in this controller; 20 for each of the four product flow rate fuzzy numbers. This corresponds to a three-dimensional rule matrix, but the rules are more clearly depicted as four two-dimensional matrices, as shown in Tables 2 to 5. Each rule possesses three antecedent conditions relating PROD, TB, and DTB, and one consequent, which is the control action taken on the panel temperature (DTP). The rules take the form:

IF (PROD is X) and IF (TB is Y) and IF (DTB is Z) THEN DTP is A

Table 4. Rule matrix for a good product flow rate (GOOD).

Change in grain temperature	Grain temperature			
	LO	MD	HI	VH
	IR panel temperature setpoint adjustment			
DNL	PVL	PVL	PS	NM
DNS	PVL	PVL	PS	NM
DZ	PVL	PL	Z	NL
DPS	PL	PM	NS	NVL
DPL	PM	PM	NM	NVL

Table 5. Rule matrix for a high product flow rate (HIGH).

Change in grain temperature	Grain temperature			
	LO	MD	HI	VH
	IR panel temperature setpoint adjustment			
DNL	PVL	PVL	PS	NM
DNS	PVL	PVL	PS	NM
DZ	PVL	PL	Z	NL
DPS	PL	PL	NS	NVL
DPL	PM	PM	NM	NVL

The rules are numbered by successive columns in each table. For example, Rule 1 is at the top and Rule 5 at the bottom of the first (LO) column in the LO production rate (Table 2); Rule 10 is at the bottom of the second (MD) column, etc. Examination of the rule matrices reveals a quiescent node at the row-3, column-3 position in each table (i.e., Rules 13, 33, 53, and 73 for the LOW, MOD, GOOD, and HIGH fuzzy numbers, respectively). This position represents a “high” bulk grain temperature, “zero” change in bulk grain temperature, and calls for “zero” change in panel setpoint. It is the implicit setpoint for the controller, and corresponds to a crisp value of between 88 and 92°C, based on the memberships given in Fig. 2. To change the implicit grain temperature setpoint would involve altering either the control rules or the grade memberships. It is easier and faster to change memberships in our system.

Localized symmetry occurs about the zero point for IR panel temperature change. In the HI column, the setpoint is bordered on the low side by a "small" change and on the high side by a "negative small" command (see Tables 2 to 5). A comparable symmetry exists in the zero (DZ) row, but only for the two highest production numbers (GOOD and HIGH). This was because a medium (versus large) upward adjustment was desired for lower mass flowrates in order to suppress overshooting; large was felt to be too great a change when smaller amounts of material were being roasted.

In general, the rule matrices are asymmetrical; the rules are more liberal at turning temperatures up from the "low" fuzzy set versus permitting temperature to remain "very high". The rules

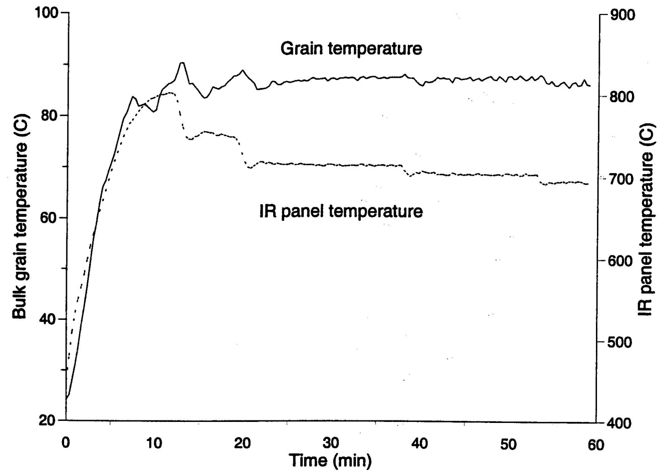

Fig. 4. Start-up and control of the infrared roaster with the fuzzy controller, 85°C setpoint.

also call for stronger action when the grain flow rate is greater (i.e., more thermal inertia in the system).

The truth values of the three antecedent conditions (i.e. the three inputs) in each rule are subjected to the fuzzy "and" logical operator. This results in the minimum truth value of the three arguments being passed to the consequent singleton number that is called for by that particular rule (DTP). In most instances, more than one rule fires. In this controller, an aggregated or accumulated weighted average of all of the associated rule consequents was employed to yield the final defuzzified output.

RESULTS and DISCUSSION

Several tests of the fuzzy control system hardware and software were made in the plant with 100% cracked wheat. The pure wheat test material was felt to be sufficiently representative of the 3-grain cereal for controller testing purposes. This was done because interruptions and temperature deviations during the testing of the system would cause a portion of the product to be off-spec and thus unsuitable for sale as cereal for human consumption. Deleting the more expensive flax component gave a substantial cost savings.

A cold-start control system run with a bulk grain temperature setpoint of 85°C is illustrated in Fig. 4. The grain flow rate for that test was 0.8 t/h. It took less than 10 min for the roaster to attain operating temperature. The rise time was similar to that normally required for a manual cold-start procedure. After about 20 min, the controller operation was quite stable around the implicit setpoint temperature. Maximum and minimum recorded bulk grain temperatures from that point until the end of the run were 88.2 and 85.6°C, respectively.

A second test was run to observe the servo-response of the system as the implicit bulk grain temperature setpoint was increased. This was accomplished by disabling the controller and re-initializing it with a different definition of the fuzzy number “high” centred around 90°C. The response of the system is illustrated in Fig. 5. Grain flow rate for this test was 1.0 t/h. The initial dip in bulk grain temperature was due to the controller being offline for a few minutes while the setpoint was

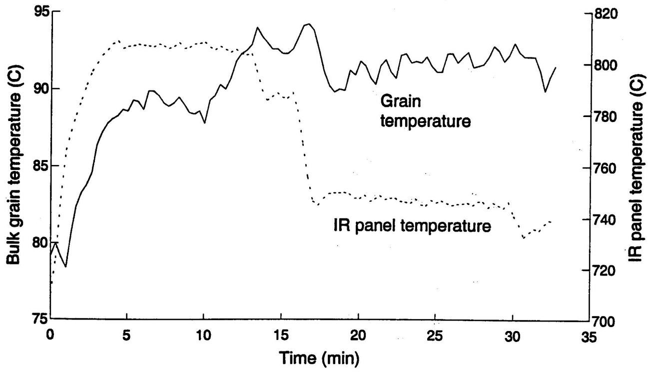

Fig. 5. Ramp up and control of the infrared roaster with the fuzzy controller, 90°C setpoint.

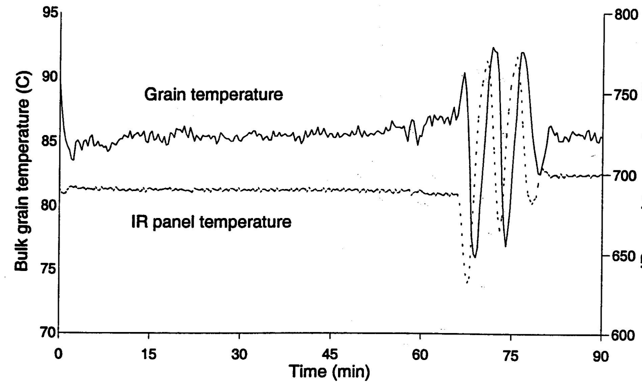

Fig. 6. Hot start and load disturbances with fuzzy controller, 85°C setpoint.

changed. Panel temperature then rose quickly to over 800°C as the grain bulk temperature rose toward the new setpoint value. There was some overshoot of grain temperature and controller action stepped the IR panel temperature down in two stages, eventually stabilizing at about 750°C. The grain temperature response for this test was not as smooth as in the earlier test because the plant had difficulty maintaining the grain flow at the higher production rate (1.0 t/h).

Another test was conducted to evaluate the controller response to the load disturbances. Implicit grain temperature setpoint was 85°C for that test. Grain flow rate to the roaster was initially 1.0 t/h. It was decreased briefly, then increased, and then reset to its original value. The effects of the flow disturbances are evident in Fig 6. The first disturbance occurred at about the 70 minute mark, when the grain temperature is seen to rise suddenly. The controller responded with a rapid decrease in IR panel temperature, down to a minimum of 630°C. After a few minutes the combined effects of the controller overshoot and the increased grain flow of the second disturbance prompted a sudden increase in IR panel temperature. With consistent grain flow restored, the controller regained stability after only one more oscillation. IR panel temperature levelled out at 700°C and the grain temperature settled to about 85°C.

In all of the in-plant tests, the fuzzy controller reacted rapidly and performed predictably, and acted much as the operator would have in the same situations. One advantage of the controller over manual control was consistency - it reacted in the same way each time a disturbance was repeated. The consistency of grain roast was observed to be better under automatic control. Also, no fires occurred in the roaster during the fuzzy controller tests.

Fires were not uncommon during a cold start or when load disturbances occurred under manual control. In those situations, anticipating a problem, the operator was compelled to swing the IR heating panels up and away from the roaster bed to observe the condition of the grain. However, that action itself resulted in drastic swings in panel temperature and subsequent large grain temperature deviations when the panels were returned to the closed position. With the fuzzy controller regulating panel temperature, the operator did not feel the need to observe the grain condition. Consequently, grain was not overheated and no fires were experienced.

CONCLUSIONS

A fuzzy rule-based control system for an electric infrared roaster of cereal grain was developed. Control rules were created from observations of the process and interviews with the system operator. The control system was tested in-plant while roasting cracked wheat. The following conclusions were drawn from the results:

1. A combination of fuzzy process variables and control rule matrices provided a simple and effective means to synthesize knowledge for a process dominated by heuristic control information.
2. The Fuzz-C pre-processor software was a convenient tool to develop and implement the control strategy within a shell program that monitored the process, logged data, and communicated with the operator and the low-level control hardware (i.e., the addressable PID controllers and shaft encoder).
3. The fuzzy control system provided reliable and robust control of the infrared roaster under both setpoint and load disturbances experienced in a process plant situation.
4. The approach of capturing the operator's responses to process and load disturbances, rather than modelling the dynamics of the process for control, was effective for this infrared roasting system.

The ease with which a controller was developed for this process indicates that the same approach can be used for other process applications that are typically under manual control. In this case, the fuzzy controller as developed performed well and required little tuning. It was apparent from the steps involved in changing the implicit grain temperature setpoint that, if required, tuning of the controller would be easily done.

REFERENCES

Bremner, H. and B.E. Postlethwaite. 1997. An application of model-based fuzzy control to an industrial grain dryer. *Transactions of the Institute of Measurement and Control* 19(4):185-191.

Brown, R.B. and V.J. Davidson. 1996. Infrared treatment of grain for disinfestation and improved quality and the development of a control strategy for maintaining process consistency and efficiency: Volume I - Process characteristics and treatment efficacy. Report to Maple Leaf Grocery Products, Mississauga, ON.

Davidson, V.J., S. Martineau and R.B. Brown. 1996. Quality based control for drying of food materials. In *Proceedings of NAFIPS '96*, 114-117. Berkeley, CA.

Davidson, V.J., R.B. Brown and J.J. Landman. 1999. Fuzzy control system for peanut roasting. *Journal of Food Engineering* 41:141-146.

Kosko, B. 1993. *Fuzzy Thinking: The New Science of Fuzzy Logic*. New York, NY: Hyperion.

Moreira, R.G. and F.W. Bakker-Arkema. 1992. Grain dryer controls: A review. *Cereal Chemistry* 69(4): 390-396.

Postlethwaite, B. 1994. A model-based fuzzy controller. *Chemical Engineering Research and Design* 72(1): 38-46.

Zhang, Q. and J.B. Litchfield. 1991. Knowledge representation in a grain dryer fuzzy logic controller. ASAE Paper No. 91-6059. St. Joseph, MI: ASAE.