5544

Simulation and Control of Glucose Concentration in Hot-Water Blanching of Potatoes

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The methodology for online monitoring and computer control of glucose concentration in potatoes during hot-water blanching is demonstrated. Process conditions, control parameters, and setpoints are determined with the aid of an unsteady-state model. Glucose concentration in the blanch water is monitored and maintained at a setpoint value by adjustment of the fresh water flow rate to the blancher, while the glucose concentration of the potatoes is calculated by mass balance. Control is effected through feedback and anticipatory feedback control. Results indicate that glucose concentration in potatoes exiting the blancher may be maintained within 10% of the setpoint value. The use of computers to control glucose concentration in potatoes should prove useful in the control of the color and therefore the quality of processed potato products.

Introduction

The quality of processed potatoes may be determined by the color, texture, and taste of the final product (Gould and Plimpton, 1985). Off-color results from nonenzymatic browning (Maillard reaction), which involves the reaction of reducing sugars with amino acids. High reducing-sugar content enhances the Maillard reaction. Processed potatoes that result in a dark product are judged unacceptable.

Reducing-sugar content in potatoes depends on the cultivar, cultural practices, handling and temperature changes during transit, and storage history (Talburt and Smith, 1987). Potatoes stored at low temperatures exhibit an increase in reducing sugars.

One strategy processors use to control color is hot-water blanching to leach the components that participate in the Maillard reaction. Blanchers are generally of the screw conveyor type with direct steam injection and are run at residence times of 2–30 min. Fresh water is fed to the blanchers. Two or more blanchers in series may be used. Since blanching is usually carried out at temperatures ranging from 60 to 93 °C, enzymes that cause enzymatic browning and undesirable flavors are deactivated. Blanching also gelatinizes the starch of the potato, improving the texture of the product (Talburt and Smith, 1987).

Color is typically controlled by using the experience of the processor. Samples of the finished product are randomly chosen from the line and tested. If the potatoes are too dark or too light, adjustments are made in the processing conditions of the blancher, such as water flow rate, temperature, or residence time. Because this method of quality control is discontinuous and subject to the experience of the processor, there may be differences in the color of the product from batch to batch due to the variability in the feed potatoes. Feeding the blancher at constant potato and water flow rate results in a buildup of the reducing-sugar concentration in the blanch water and a decrease in the amount of sugar in the potatoes over time to a steady-state level (Kozempel et al., 1981). The sugar concentration of the blanch water must be maintained to yield potatoes leached to a sufficiently low sugar concentration level. This means that the flow of water to the blancher must continually be adjusted so that the concentration of reducing sugars in the potato is maintained. An automatic control system that senses the reducing-sugar concentrations and adjusts the water flow rate to the blancher would aid the processor in color and quality control and in lowering utility costs.

Computer Control of Food Processes

The introduction of advanced chemical sensors has made possible the online implementation by computer of conventional and advanced control strategies in the chemical process industries. These strategies have not yet been fully implemented in the food process industries for compositional or quality control because of the lack of sensors, physical property data, and mathematical models. The feed stream to a unit operation consists typically of cut or whole pieces of a fruit or vegetable composed of approximately 80% water and a matrix of carbohydrates, pectins, minerals, and sugars. Sensors are available for online moisture determination in the solid foodstuff, but none are available for the direct online determination of solid composition. These analyses are done offline where the concentration of a component can only be determined by first extracting it from the fruit or vegetable and then performing the analysis. Sensors are available for the determination of a component in the liquid stream. A knowledge of the composition of the feed and the concentration of the constituent to be controlled in the liquid would allow the concentration of the component in the solid to be calculated online by mass balance. Knowledge of the feed composition allows optimal process conditions, such as water flow rate and temperature, to be selected.

It is the purpose of this study to demonstrate how glucose concentration of potatoes in the blancher may be controlled with a personal computer using a commercial glucose analyzer, mass balance equations, and a mathematical model.

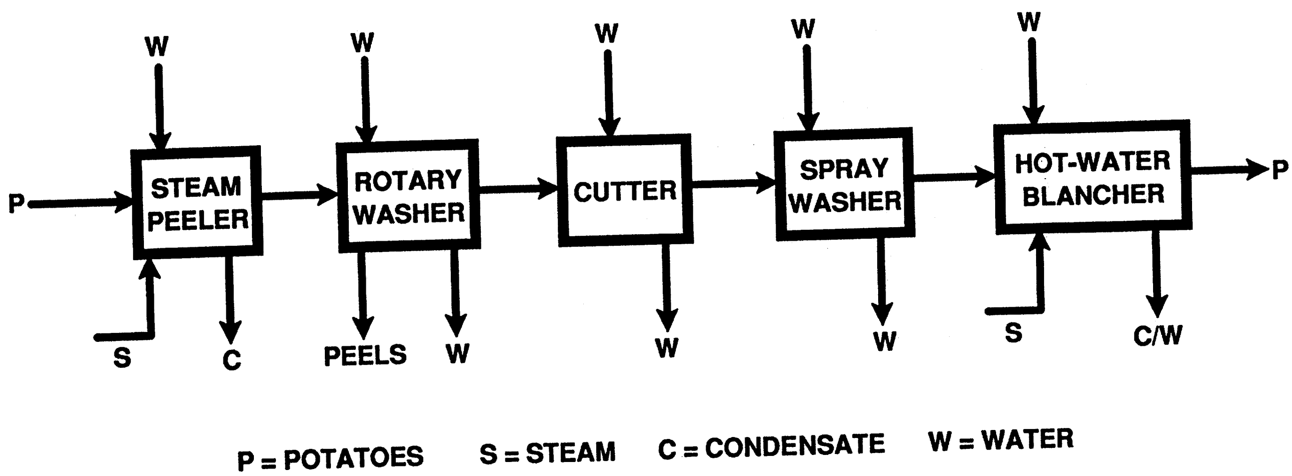

Figure 1. Block diagram for blanching control experiments.

Experimental Procedures

The process flowsheet of Figure 1 shows the pilot plant equipment. Potatoes were peeled in a DSA 45 Kunz 45 L high-pressure steam peeler at 1750 kPa for 15 s, washed in a rod/reel washer to remove the loosened peels, cut into 1-cm dice with an Urschel slicer model G-A, and spray-washed (Robins Vibro-Flo washer) to remove surface sugars and starch. The potatoes were then blanched for 18 min in a 3-m long Rietz thermoscrew hot-water blancher, Model TL-36-K2210, with a 0.9-m diameter screw. The distance between the flights is 0.3 m. The blancher is hypothetically sectioned into nine zones where each zone is defined by the distance between the flights. The height of water and potatoes was maintained at 0.3 m.

Either Maine Russet Burbank or Maine Shepody potatoes, harvested in October 1988 and stored at 3–4 °C, with specific gravities of 1.084 and 1.074, respectively, were used. Blancher temperature was controlled from zone 5 with a Taylor 440R on/off controller. The setpoint temperature was 83 °C in all experiments. Steam was fed to each zone of the precooker to maintain temperature. Thermocouples were installed in eight of the nine zones of the blancher. Potato flow rate was held constant at 200 kg/h.

The process control loop for glucose control is shown in the block diagram of Figure 2. The concentration of glucose in the blancher, and therefore in the potato, is adjusted through manipulation of the valve controlling the flow rate of water to the blancher. The concentration of glucose in the exit blanch water was determined online by using a YSI Model 2000 glucose and L-lactate analyzer equipped with a RS-232C port (YSI Inc., Yellow Springs, OH). The YSI was interfaced to a Compaq Deskpro 386 personal computer with an analog output interface board (Metrabyte Corporation, Model DDA-06). This signal was converted to a pneumatic signal by using a Foxboro Model E69F transducer. The air signal was directed to a 3–15-psi Series V-1 Foxboro control valve.

Simulation Model

The following information must be available in order to control glucose concentration in the potatoes exiting the blancher: (1) an estimate of the glucose concentration of the potatoes entering the blancher and (2) a mathematical model which relates the concentration of glucose in the blanch water to that in the inlet potatoes and the flow rate of water to the blancher as a function of time.

In a commercial situation, the glucose concentration of the inlet potatoes may or may not be known. Storage data may be used to estimate the concentration. Storage data for Maine Russet Burbank potatoes used in these experiments are shown in Figure 3. When potatoes are analyzed for glucose, it is found that the location of the potatoes in the storage bins determines the concentration. The potatoes of Figure 3 generally came from the top of the bins. These data were used in the steady-state and unsteady-state leaching models described next.

A steady-state model that relates the composition of a species in the blanch water to the inlet composition and water flow rate to the blancher has already been developed by Kozempel et al. (1981, 1982, 1985) for the leaching of potatoes. The unsteady-state counterpart of this model has been presented by Tomasula and Kozempel (1989).

These models were extended here to account for the plug-flow behavior exhibited in pilot-plant and commercial hot-water blanchers. The concentration of a species in the blanch water, S_z, in any zone of the blancher can then be calculated by using the following equation:

$$S_{z+1} = -\frac{(PC_zE + W_zS_z - PMS_0E - (W_z + W_t)S_0)}{PMS + W_z + W_t} \times \exp\frac{-(PME + W_z + W_t)\theta}{V/Z_t + PM\tau E} + \frac{(PC_zE + W_zS_z)}{PME + W_z + W_t} \quad (1)$$

where z represents the current blancher zone and $z + 1$, the following zone. E is given by

$$E = 1 - \frac{8}{\Pi^2}\sum_{N=0}^{\infty}\frac{\exp(-D(2N+1)^2\Pi^2\tau/L^2)}{(2N+1)^2} \quad (2)$$

The concentration of a species in the potato may be obtained by mass balance:

$$C_{z+1} = (PC_z + W_zS_z - (W_z + W_t)S_{z+1})/P \quad (3)$$

The diffusion coefficients were evaluated at the zone temperatures by using the equations given by Tomasula and Kozempel (1989). The temperature of the potato pieces may be assumed to be that of the blanch water if blanching is carried out over 6 min.

The ideal steam flow rate to each zone was calculated by an energy balance about each zone. Evaporation losses were neglected because the blancher was covered. The ideal steam flow rate calculated in this manner agreed well with the experimentally measured value of approximately 90 kg/h.

Figure 4 demonstrates the performance of the unsteady-state model given by eqs 1 and 2. The results for the last zone of the blancher are shown. The glucose concentration in the blanch water increases to a steady-state value while that of the potatoes decreases to a steady-state value. The

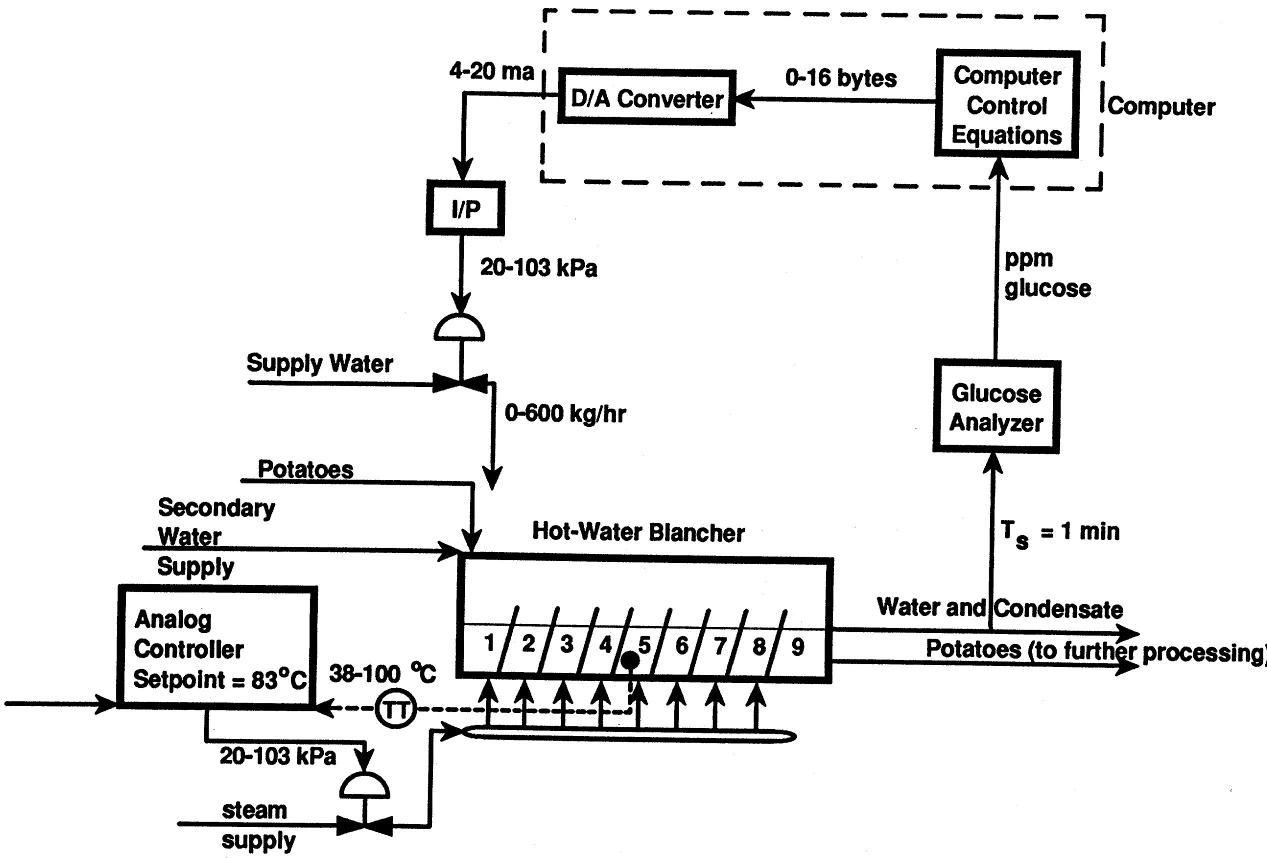

Figure 2. Schematic drawing of the glucose analyzing and control system.

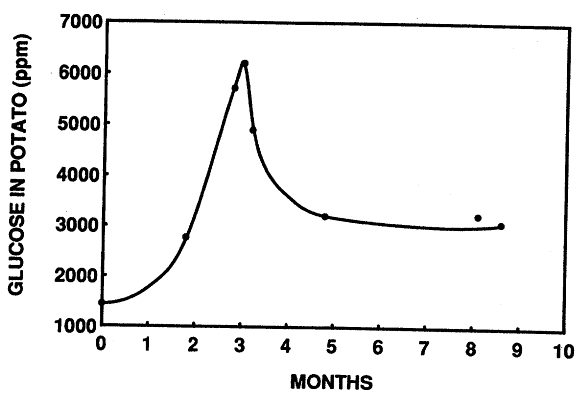

Figure 3. Storage data for Maine Russet Burbank potatoes stored at 3 °C.

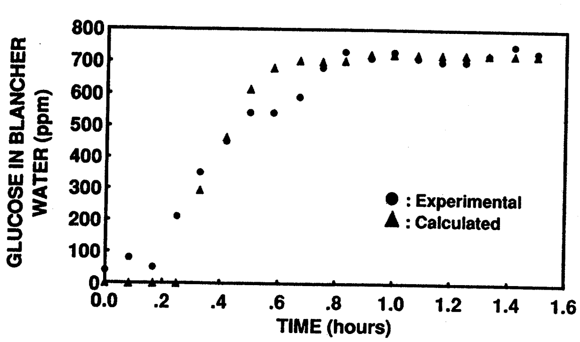

Figure 4. Comparison of experimental and calculated results in the blanching of Maine Shepody potatoes, from eq 1.

average absolute percent error between the experimental and calculated values for glucose in the blanch water is 7.0%. The average absolute error between the experimental and calculated values for glucose in the potato is 9.0%, indicating that the simulation model provides an excellent representation of the experimental data.

Computer Program

The computer program used for control consists of a main program written in QUICKBASIC 4.5 that performs the following functions: monitors the RS-232 port of the computer for the current glucose concentration in the exit water of the blancher and compares it to the setpoint, writes it to the D/A board where it is converted to a milliamp signal, and provides a graphical and digital display on the monitor. The monitor shows current values of all control parameters and plots the simulated values of glucose in the blanch water along with the experimental ones in real time. The simulated values are calculated by using eqs 1 and 2 in a secondary program, which is linked to the main program and written in FORTRAN. This program also performs the energy balances and the material balances given by eq 3.

Results and Discussion

The influence of temperature on the leaching of glucose was investigated to make sure that there was no interaction between the two independent control systems. The flow rate of water to the blancher was held constant at 340 kg/h and the flow rate of potatoes at 200 kg/h, and the blancher temperature was set to 83 °C. When steady state was reached as indicated by a constant glucose concentration in the blancher, the temperature was increased to 86 °C and then to 89 °C when the second steady state was reached. The results are plotted in Figure 5 and indicate that the increase in the amount of glucose leached as the temperature is increased from 83 to 86 °C is insignificant. Moreover, the concentration of glucose in the potato held constant at approximately 2500 ppm. This is to be

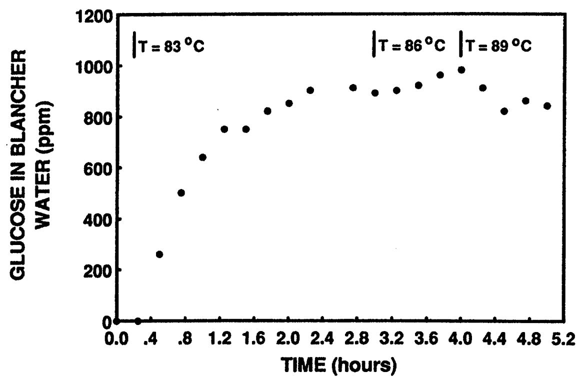

Figure 5. Variation of glucose composition of blanch water with temperature for Maine Russet Burbank potatoes.

expected because the effective diffusion coefficients of glucose are nearly constant over this range. Increasing the temperature, though, from 86 to 89 °C resulted in a slight decrease of glucose in the blancher due to the increased steam flow rate but a negligible change in the amount of glucose in the potato. In all cases, the changes in glucose composition in the potato are too small to be detected. In addition, differences in the glucose concentration of the potato feed contribute to the variation of glucose seen in the water and in the potato. A single lot of potatoes may show glucose concentrations with a range of 500 ppm.

Runs were also made where the setpoint temperature of the blancher was set to 83 °C and the water flow rate suddenly increased by 200 kg/h. The temperature of the exit blanch water typically deviates from the setpoint by 1 °C when this occurs.

The computer program read in a new value of glucose concentration, y_{exp}, every minute. Control action took place as often. Two feedback control strategies were investigated, feedback and feedback with anticipatory control.

Proportional feedback control was accomplished by using the steady-state solution of eq 1 to define the relationship between glucose concentration in the water and milliamp signal. At the beginning of a control experiment, the initial concentration of the potato and the flow rate of potatoes to the blancher were entered in the computer control program described above. Values of $y_{water,ss}$ were then calculated for a range of water flow rates to the precooker. The water flow rates used ranged from valve fully opened to fully closed. Table I shows a list of the results for potatoes with an average C_0 of 1580 ppm. Because linear relationships in output and input signals exist for the control valve, I/P converter, and D/A board, the relationship between $y_{water,ss}$ and milliamp signal is easily established. This relationship is never constant because it depends on C_0. The relationship between milliamp signal and error is given by the proportional control equation:

$$\text{ma} = K\cdot\text{Err} + \text{constant} \qquad (4)$$

where K is the proportional control constant and Err is the error between the setpoint value of glucose in the blanch water, y_{set}, and the experimental value, y_{exp}:

$$\text{Err} = y_{set} - y_{exp} \qquad (5)$$

A value of Err of ±30 ppm was considered as agreement between y_{set} and y_{exp}, due to the variability of the potato feed and the neligible impact on the concentration of glucose in the potato.

The 18-min delay between control action and the sensing of glucose in the blancher water was accounted for in the computer program.

Table I. Steady-State Simulation Values[a]

water flow rate, kg/h	$y_{water,ss}$, ppm	$y_{potato,ss}$, ppm
0.0	1374.0	1439.7
141.6	626.3	1047.5
283.2	388.5	959.3
424.8	280.8	921.6
566.4	219.6	900.8
708.0	180.3	887.5
849.5	152.9	878.4

[a] C_0 = 1580 ppm.

Figure 6 shows a process control run employing proportional feedback control where the setpoint of glucose in the blancher water was set to 300 ppm and the desired potato outlet concentration to 550 ppm. Proportional control was used only in the first 2 h of this experiment.

The results indicate that once the setpoint is reached, the glucose concentration in the potato has also reached the setpoint value. However, with proportional feedback control, the control valve opens to the value ultimately calculated by using eq 4 to keep the glucose concentration at the setpoint, but the glucose that has built up in the blancher is washed out in one residence time. One more hour must elapse until the setpoint is again approached. Because the proportional feedback controller was found to overreact, a control action based on anticipation was used next, at times greater than 2 h (shown in Figure 6) and in further experiments.

A period is noted at the beginning of the control experiments where it is impossible to effect glucose control. This period is termed the leaching period and is the time needed for the setpoint concentration to be reached. Part of this time is represented by the residence time of the blancher. After the potatoes fill the blancher, there is a rapid increase in the glucose concentration in the blanch water corresponding to a rapid decrease in the glucose concentration of the potato.

Anticipatory control was next combined with feedback proportional control. The control strategy is based on anticipating and acting on any process disturbances before they are felt by the system. It is ideal for systems such as this, where there is a delay time of 18 min before previous control action is felt at the exit of the blancher and, in some cases, a rapid rise in glucose in the blanch water when the rate of leaching is high. The only disturbance to the process, which is leaching of glucose from potatoes, occurs excessively in the first hour of operation of the blancher and is easily controlled at times past this when glucose content has reached the setpoint.

In order to anticipate this point, the simulation model given by eqs 1–3 was again used. Values of $y_{water,ss}$ were generated by using C_0 and a range of flow rates. Because the control valve is nearly closed when the potatoes first fill the blancher, the system has the tendency to approach the value of $y_{water,ss}$ at zero flow of feed water. $y_{water,ss}$ is the maximum value of S_9, the glucose concentration in the exit blanch water. The flow rate of water which gives steady-state values of S_9 and C_9, the glucose concentration in the exit potatoes, that most closely corresponds to the setpoints chosen for a particular run is then used during the leaching period until the setpoint is reached. The time it takes for the setpoint to be reached is easily estimated from the unsteady-state model.

In the second control run, this strategy was used. The steady-state values, $y_{water,ss}$ and $y_{potato,ss}$, for some water flow rates at C_0 have already been shown in Table I. Since the objective was to maintain the glucose concentration in the potatoes, C_9, at 900 ppm and S_9 at 300 ppm, the control valve was opened so that the flow rate of water to

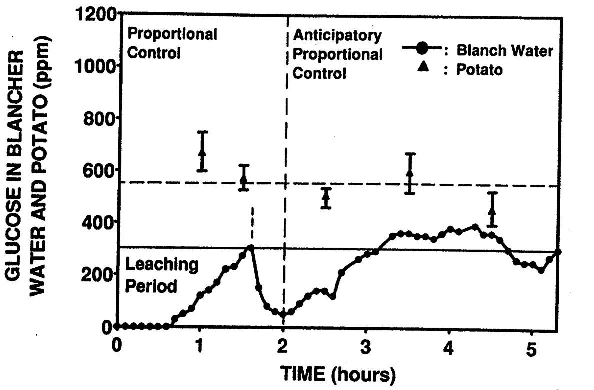

Figure 6. Process control run for glucose. C_0 = 2000 ppm; Set_{water} = 300 ppm; Set_{potato} = 550 ppm.

the blancher was approximately 400 kg/h while the blancher was filled with potatoes and held at this value until the setpoint was reached. Calculations using the unsteady-state model indicated that the setpoint would be reached in an hour. To avoid washing out glucose once the setpoint was reached, the control valve was closed a residence time before the setpoint was estimated to be reached. The results are plotted in Figure 7. No washing out of glucose occurs. The concentration of glucose in the blanch water oscillates about the setpoint due to the variability of the feed potatoes. The data were simulated by using eqs 1 and 2 and actual process conditions and are plotted in Figure 7. These values are lower than those used to anticipate the setpoint, where ideal process conditions were used.

In Table II, the experimental values of the glucose concentrations of the potatoes are compared to the setpoint value and the simulated ones. The agreement is good considering the variability in the feed.

Anticipatory with feedback proportional control was also used to control glucose at times greater than 2 h, as shown in Figure 6.

Next, the ability of the control system to respond to the loading of potatoes high in glucose, to changes in the potato feed composition, and to changes in the setpoint for glucose concentration in the potato was tested. The procedure leading to the development of the data of Figure 7 was repeated here. Maine Russet Burbank potatoes with a concentration of glucose of 4500 ppm were first fed to the blancher. After 2.5 h, potatoes with a concentration of 1390 ppm were fed to the blancher. Results are plotted in Figure 8.

The leaching period for high-sugar potatoes is as long as it is for potatoes of lower sugar concentration, but the glucose concentration in the blanch water overshot the 600 ppm setpoint and recovered in 0.5 h. When low-sugar potatoes were added and the blanch water and potato setpoints were changed to 200 and 700 ppm, respectively, setpoint values were reached in less than 1 h.

The results of Figure 8 indicate that the control system did not anticipate the rapid rise in glucose concentration during the leaching period. This is because it was thought on the day of the experiments that the average glucose concentration of the potatoes was about 3000 ppm as indicated by storage data and not 4500 ppm as more analysis showed. An online system that detects glucose concentration in the feed potatoes would eliminate this uncertainty.

The simulated values of the exit concentration of glucose in the blanch water are plotted in Figure 8 for comparison with the experimental ones. Table III compares the

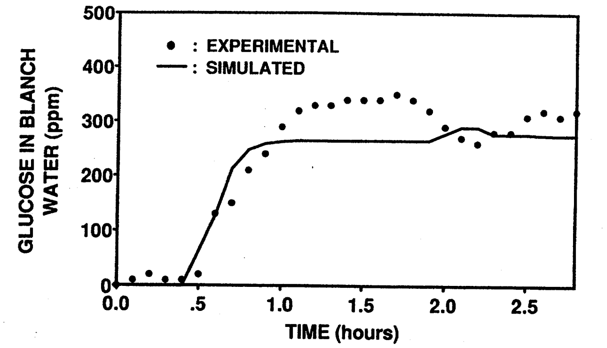

Figure 7. Simulation of process control run for glucose. C_0 = 1580 ppm; Set_{water} = 300 ppm.

Table II. Exit MRB Potato Stream Glucose Concentration[a]

time, h	experimental, ppm	simulated, ppm	relative % error[b]	relative % error[c]
1	830 ± 60	1000	−20.5	−10
2	730 ± 30	970	−32.9	−20
4	860 ± 30	860	0.0	− 5
5	980 ± 30	860	12.2	8
		average absolute % error =	16.4	11

[a] C_0 = 1580 ppm; setpoint = 900 ppm. [b] Relative % error = (experimental − simulated)/experimental × 100. [c] Relative % error = (experimental − setpoint)/experimental × 100.

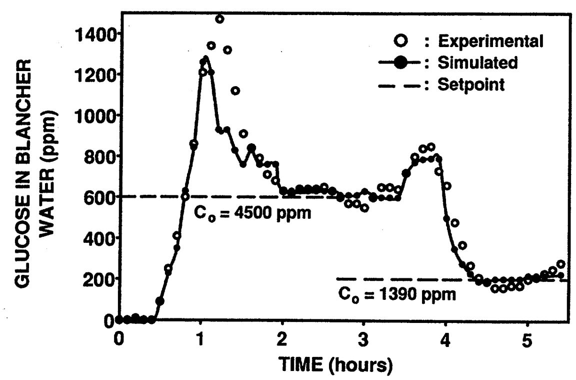

Figure 8. Simulation of process control run for glucose with C_0 = 4500 ppm and C_0 = 1390 ppm.

Table III. Exit MRB Potato Stream Glucose Concentration

time, h	C_0	experimental, ppm	simulated, ppm	relative % error[a]	relative % error[b]
1.5	4500[c]	3400 ± 100	2640	22.4	12
2.0		3000 ± 100	2750	8.3	0
3.0		3330 ± 200	2750	17.4	10
3.5		2950 ± 300	2500	15.3	− 2
4.5	1390[d]	760 ± 30	860	−13.1	8
5.5		610 ± 30	870	−42.6	−15
			average absolute % error =	19.9	8

[a] Relative % error = (experimental − simulated)/experimental × 100. [b] Relative % error = (experimental − setpoint)/experimental × 100. [c] Setpoint of potatoes = 3000 ppm. [d] Setpoint of potatoes = 700 ppm.

experimental values of glucose in the potato with the simulated and the setpoint values. The agreement between both values is good even though there was uncertainty in the feed composition.

Conclusion

Control of glucose concentration in potatoes during hot-water blanching has been demonstrated by using feedback control with a proportional-type computer controller and feedback control that includes anticipatory and proportional control. The simulation of the experimental data with an unsteady-state plug flow model has also been shown and represents the experimental data well. These experiments demonstrate that automatic control of color and quality of processed potatoes is possible; however, experiments must be done to link glucose composition with color.

Notation

C_0	initial concentration of solute in the potato, kg/kg
C_z	concentration of solute in potato at zone z, kg/kg
D	effective diffusion coefficient, m^2/s
K	proportional control constant
L	thickness of the potato piece, m
M	moisture of potato, kg of water/kg of potato
MRB	Maine Russet Burbank potatoes
N	number of terms of eq 2
P	potato flow rate, kg/h
Set	setpoint
S_0	initial concentration of species in blanch water, kg/kg
S_z	concentration of species in blanch water in zone z, kg/kg
T_s	glucose sampling frequency, min.
V	weight of water and potatoes in the blancher, kg
W_t	steam flow rate, kg/h
W_z	water flow rate to zone of blancher, kg/h
y_{exp}	experimental value of glucose in exit water of blancher, ppm
$y_{potato,ss}$	steady-state value of glucose in potato, ppm
y_{set}	setpoint of glucose in exit of blancher, ppm
$y_{water,ss}$	steady-state value of glucose in exit water of blancher, ppm
z	zone of blancher
Z_t	total number of hypothetical zones in the blancher
θ	time spent in z, h
τ	residence time in one zone of the blancher, h

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