Journal of Food Process Engineering

Journal of Food Process Engineering ISSN 1745-4530

DESIGN AND PERFORMANCE OF CONVENTIONAL AND FUZZY CONTROLS FOR A HIGH TEMPERATURE SHORT TIME PASTEURIZATION SYSTEM

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Received for Publication November 19, 2010
Accepted for Publication May 6, 2011

doi:10.1111/j.1745-4530.2011.00653.x

ABSTRACT

Fuzzy control was applied in a high-temperature short time (HTST) pasteurization system and experimentally evaluated and compared with proportional-integral-derivative (PID)/feedback and PID/feedback/feedforward controllers. The product, a juice model solution, was pasteurized for 91C/40 s in a three-stage plate heat exchange (regeneration, heating and cooling sections). Hot water and propylene glycol were responsible to heat and cool the product, respectively. A control system was designed to assure the pasteurization temperature manipulating the hot fluid flow rate. Controllers were evaluated by means of dynamic behavior of the pasteurization temperature and performance criteria after the imposed step changes of the product inlet temperature. Configured controllers kept the process temperature within HTST requirements, having a variation of ±0,5C, and the similar values of performance criteria indicate an efficiency for all three tested controllers.

PRACTICAL APPLICATIONS

The continuous need for better food products, standardized within the consumer demands, has expanded the applications and the search for solutions using automation and control techniques. The use of control strategies and automation in chemical, petroleum and other industrial processes are more intensive as compared with the same applications in food industries. The complex execution of experimental tests in lab-scale or pilot plants is the main reason for the great number of simulations in the process control area. Based on the importance of accomplishing experimental errors and uncertainties, this paper results from an extensive research developed in a pilot plant of HTST process. Theoretical methods for tuning controllers were applied and evaluated. Conventional controllers (PID/feedback and PID/feedback/feedforward) were tuned and compared with fuzzy control, one of the most recognized nonconventional controllers. Results showed that the requirements to maintain pasteurization temperature after changes in inlet process conditions were performed in all three strategies, indicating the accomplishment of the research purpose.

INTRODUCTION

Higher processing temperatures for a shorter time are possible if the product is sterilized before it is cold-filled into presterilized containers in a sterile atmosphere. This forms the basis of ultra high temperature processing, also termed aseptic processing. It is used to sterilize a wide range of liquid foods, including milk, fruit juices and concentrates, cream, yogurt, salad dressing, egg and ice cream mixes (Fellows 2000). Orange juice pasteurization studies have been demonstrated that lower temperatures are sufficient to inactivate microorganism activities, although, to prevent the loss of cloudiness,

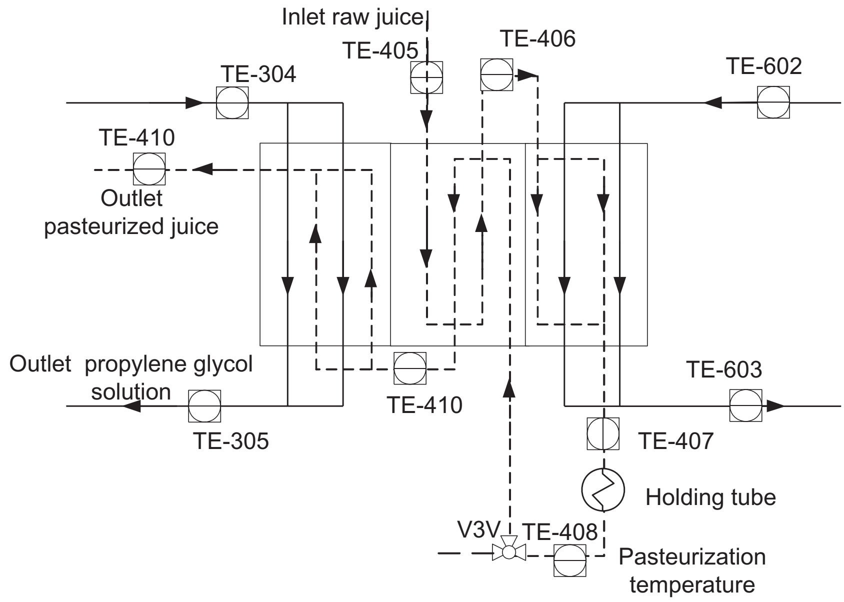

FIG. 1. PLATE HEAT EXCHANGER FLOW CONFIGURATION

higher temperatures are required. This loss has been directly related to the activity of the pectin methyl esterase enzyme, which is generally used as an indicator of the pasteurization effectiveness, because its heat resistance is higher than in common microorganisms (Basak and Ramaswamy 1996; Collet *et al.* 2005). The temperature/time combination used in this study was 91C/40 s, as already used in other applications (Eargman and Rouse 1976; Kimball 1991; Corrêa and Faria 2004). There are many papers about controller in pasteurization processes that have been written, although they are mostly focused on milk pasteurization and on the use of conventional controllers with feedback strategy (Shieh *et al.* 1992; Negiz *et al.* 1996, 1998; Schlesser *et al.* 1997; Ibarrola *et al.* 1998) Recent papers are focused on comparing the efficiency of soft controlling strategies. The application of fuzzy control in product quality of the food industry has been considered pertinent by several authors; nevertheless, few reviews on this topic are available (Perrot *et al.* 2006). Applied fuzzy control, model adaptive fuzzy control and neural network technologies were used to control the thermal heat treatment of milk in a plate heat exchanger (Riverol *et al.* 2008).

According to the Federal Code of Regulations (USDA-FSIS 2000) the recording accuracy of temperature and time recording devices shall be equal to or better than a 1F (0.5C) variation of process temperature. Based on this assumption, the aim of this paper was to implement and compare the efficiency of the strategies, namely PID/feedback/, PID/feedback/feedforward and fuzzy/PID, to maintain the pasteurization temperature of the high-temperature short time (HTST) process within this temperature variation even after changes were made in the product inlet temperature.

MATERIALS AND METHODS

Description of the Plant

Experiments were carried out in the Control and Automation of Food Process Laboratory, Food Engineering Department, Faculty of Food Engineering, State University of Campinas in Campinas, São Paulo, Brazil. The pilot plant consists of a pasteurization system, with a three-stage plate heat exchanger (regeneration, heating and cooling) linked with the secondary fluid systems and a holding tube (GEA Tuchennhagen do Brazil Ltda, Campinas, São Paulo, Brazil). The three fluid lines (product, hot water and cooling solution) were equipped with temperature, pressure and flow sensors and variable speed pumps. The instrumentation, automation and the control system used were hybrid, equipped with both analogical and fieldbus foundation technologies. Aimax for Windows® was the supervising man–machine interface used for the remote supervision of the process. Figure 1 shows the flow configuration of the plate heat exchanger pasteurizer used.

The product, having a 150 L/h flow rate was treated at the HTST pilot plant for 91C/40 s, with the same intensity applied to the pasteurization process of orange juice at 12°Brix (Eargman and Rouse 1976; Kimball 1991; Corrêa and Faria 2004). A diagram of the plant is shown in Fig. 2. The raw product was stored in tanks, TQ-401 and TQ-402, from where it was pumped to the pasteurizer. Regeneration was the first stage where the raw product was heated to an intermediate temperature using wasted energy from the finished pasteurized product. In the second stage, the warmed up product was heated to the pasteurization temperature using hot water

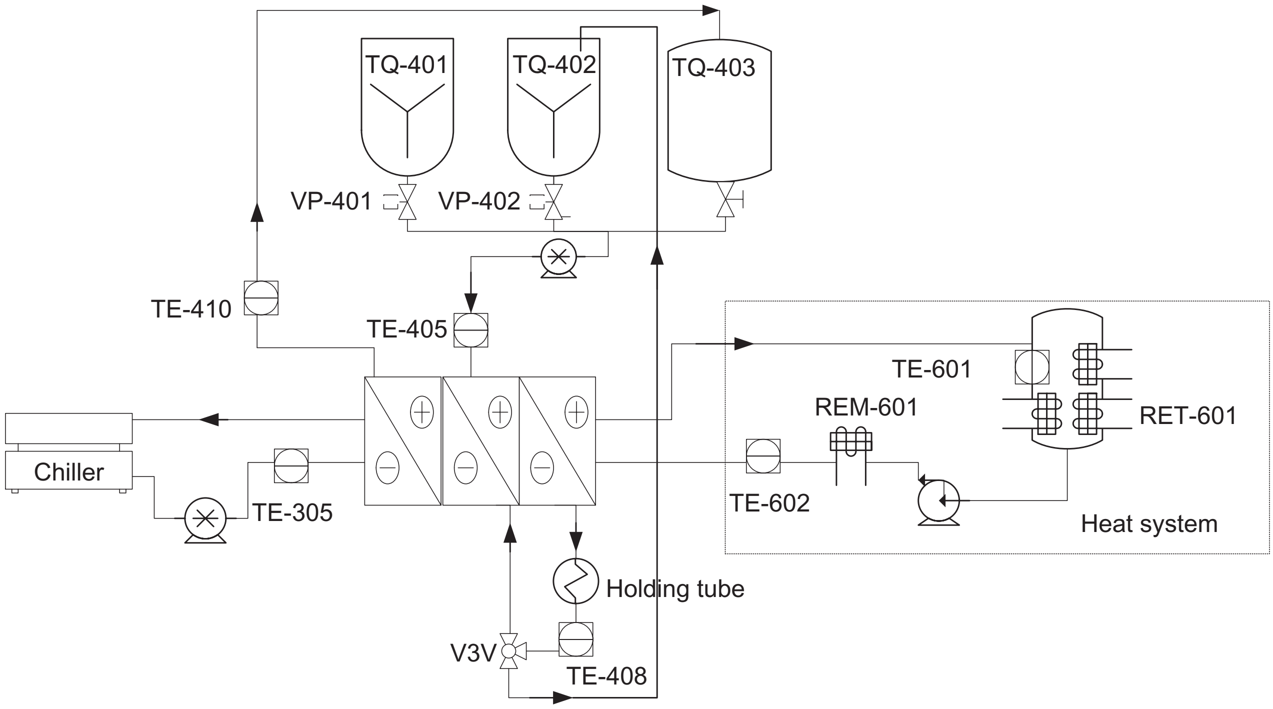

FIG. 2. PROCESS DIAGRAM

coming from a closed circuit made up of a tank equipped with electrical resistances. In the holding tube, thermally insulated, the product was kept at the pasteurization temperature during the residence time (40 s). If the product temperature, verified by the sensor installed at the end of this holding tube (TE408), was below the set point, a diverting valve (V3V) would return the product to the raw material tank. The pasteurized product, whose temperature was above the set point, was sent back to the other side of the regeneration section to be cooled off. The last stage is the cooling section, where propylene glycol at 50% m/m coming from a chiller (Silva *et al.* 2006) was responsible to cool the product down to storage temperature. The final product was stored in tank TQ-403.

Two controllers were previously configured to keep the set point of the hot water temperature in the heat system (Berto and Silveira Junior 2004). The first one maintains the tank's hot water temperature (TE601) within a ±2C variation, switching to on/off the status of an electrical resistance (RET601) placed in the water tank. The second one is a PID controller that kept the water temperature (TE602) on its set point by adjusting the power of a 2,500-W resistance (REM-601) placed 20 cm from the inlet of the heating stage.

Table 1 shows fluid flow rates, fluid thermophysical properties and temperatures, and the exchanged enthalpy in each section, under steady state conditions. Model solution density was experimentally determined at 20C (1,054.72 ± 1.97 kg/m^3) while specific heat at 20C (3.87 kJ/kg C) was calculated according to the temperature and composition of the solution (Choi and Okos 1986). The density and the specific heat of hot water at 90C used were 967 kg/m^3 and 4,212 kJ/kg

TABLE 1. HIGH-TEMPERATURE SHORT TIME OPERATIONAL CONDITIONS UNDER STEADY STATE

	Regeneration stage		Heat stage		Cooling stage	
Product	Raw product	Pasteurized product	Preheated product	Heating water	Propylene glycol solution	Cooled product
Density (kg/m^3)	1,054.72	1,054.72	1,054.72	967.0	1,046.1	1,054.72
Specific Heat (kJ/kg C)	3.87	3.87	3.87	4.212	3.470	3.870
Flow rate (L/h)	150	150	150	483	1,920	150
Flow rate (kg/s)	0.044	0.044	0.044	0.130	0.558	0.044
Inlet temperature (C)	26.2 (TE405)	91.0 (TE408)	61.8 (TE406)	96.2 (TE602)	–1.7 (TE304)	54.3 (TE409)
Outlet temperature (C)	61.8 (TE406)	54.3 (TE409)	91.5 (TE407)	87.2 (TE603)	2.5 (TE305)	8.9 (TE410)
Heat Exchanged (W)	6,092.0	–6,249.3	5,057.3	–4,928.0	8,132.3	–7,730.7

C, respectively (Choi and Okos 1986). The density and the specific heat values of propylene glycol solution (50% m/m) at 0C used were 1,046.1 kg/m^3 and 3.47 kJ/kg C, respectively (Ashrae 1972).Differences between delivered and absorbed heat was because of the uninsulated plate heat exchanger.

Because of extensive number of assays, water was used in the experiments carried out to configure controller setting parameters. Controller performance was evaluated using a 12°Brix sucrose solution, which has the same soluble solid contents, and similar thermophysical and rheological properties of an orange juice beverage.

Controller Tuning Methodology

To prevent the influence of the regeneration stage during the tuning assays, the divert valve was kept closed and the pasteurized product was sent to tank TQ-403 after passing through the holding tube. This procedure prevented it from returning to the other side of regeneration stage, after passing through the holding tube. The product was warmed up to 61.8C in tank 401, the same inlet temperature of steady state conditions (Table 1).

PID/Feedback Tuning. The objective of this tuning was to calculate appropriate values for the PID parameters (K_c, τ_i, e, τ_d), which are used to set the output variable, $c(t)$, according to the calculated error of the system, $e(t)$ (Eqs. 1 and 2).

$$c(t) = K_c \left\{ e(t) + \frac{1}{\tau_i} \int_0^t e(t)\,dt + \tau_d \frac{de(t)}{dt} \right\} \tag{1}$$

$$e(t) = TE408(t) - Tsp \tag{2}$$

PID/feedback tuning methodology (Aström and Hägglund 1984) consisted of imposing oscillations to the manipulated variable (secondary fluid flow rate) and record the process variable behavior (pasteurization temperature, TE408). The critical gain (K_{cr}) and the critical period (P_{cr}) obtained from these assays were used to calculate the suggested PID parameters (K_c, τ_i, e, τ_d).

In the heat section, an oscillation of $\pm$95 L/h brought about to the set point of the hot water flow rate (483 L/h) for a period of 30 s. During these tests, a PID controller kept the changes in the inlet hot water temperature within the change of $\pm$0.5C (Berto and Silveira Junior 2004).

PID/Feedback/Feedforward Tuning. PID/feedback/feedforward controller was tuned according Lead/Lag Unit (LLU) (Ogunnaike and Ray 1994). This methodology is based on the following steps:

(1) To obtain process reaction curves for (a) the response of the process output (pasteurization temperature) to a step change in the manipulated variable, u (secondary fluid flow rate) and (b) the response to a step change in the disturbance d (inlet product raw temperature), with $u = 0$. The magnitude of these steps must be as small as possible to make a measurable change in the controlled variable

(2) To characterize each response by their respective steady-state gains (K_u and K_d), effective time constants (τ_u and τ_d) and time delays (td_u and td_d).

(3) To estimate the lead/lag unit parameters, gain term and associated delay, from parameters previously obtained, according Eqs. (3) and (4):

$$K_{ff} = \frac{K_d}{K_u}, \tag{3}$$

$$td_{ff} = td_u - td_d. \tag{4}$$

The design of the PID/feedback/feedforward, in the fieldbus system, consists of specifying the parameters K_c, τ_i, e, τ_d of feedback strategy, and the term K_{ff} of the feedforward strategy, calculated according to Eq. (3).

Feedforward controller tuning was made using the process reaction curves obtained after the step changes of 96.7 L/h in the hot water flow rate (u) and +10.1C in the inlet product temperature (d).

Fuzzy/PID Tuning. In spite of the wide range of applicability of fuzzy control, the tuning process needs a skilful operator's experience and usually requires more simulations and fine tunings before the system is ready to run (Riverol *et al.* 2008). The purpose of this paper was to evaluate the methodology proposed by Li (1997), which do not require the operator's skill.

This methodology consists in designing and tuning the scaling gains of the fuzzy controller based on its well-tuned linear PID controller. As PID controller has proportional, integral and derivative gains, the fuzzy three-term controller also has fuzzy proportional, integral and derivative gains. This methodology created the concept called "fuzzy transfer function" to connect these fuzzy gains with the corresponding scaling gains. This paper used the settled PID/feedback parameters to obtain fuzzy scaling gains.

Performance Criteria

Mathematical criteria were calculated using the dynamic responses of the closed loop system. Peak time (t_p) is the moment the controlled temperature reached its maximum value (M_P) while t_s is the time required for the temperature to stabilize within $\pm$ 0.1C of set point. Integral absolute error (IAE), integral time absolute error (ITAE) and integral square error (ISE) were also used for controller evaluation (Ogunnaike and Ray 1994).

TABLE 2. STEP CHANGES IMPOSED IN THE INLET PRODUCT TEMPERATURE

Step change (°C)	PID/ feedback	PID/feedback/ feedforward	Fuzzy/PID/ feedback
Positive step change	8.1	6.8	8.5
Negative step change	–7.9	–6.5	–7,4

The dynamic responses were obtained by imposing the step changes in the inlet product temperature (TE405) showed in Table 2. This change was made by moving the raw product supply from tank 1 to tank 2 through pneumatic valves (VP401 and VP402). Integral performance criteria (Eq. 5) were calculated based on the magnitude (A) of the step change imposed, which were not the same because of experimental difficulties in the control of the temperature in the jacket of the raw product tank.

$$IE_{\mathrm{R}} = \frac{IE}{|A|} \tag{5}$$

In the case of the controlled temperature diverged in more than ±0.5C settled controller parameters were modified.

RESULTS AND DISCUSSION

Controller Tuning

Feedback Controller. An oscillation of ±95 L/h was imposed to the set point of the hot water flow rate (483 L/h) in a time interval of 30 s. Table 3 shows the critical gain (K_{cr}), the critical period (P_{cr}) and the calculated values of PID parameters K_c, τ_i and τ_d. Preliminary assays carried out with these PID parameters led to oscillations in the pasteurization temperature of above 0.5C. Therefore the calculated K_c was decreased to minimize these oscillations. These retuned procedures showed that the tuning methodology of Aström and Hägglund (1984) is quite efficient, because it was necessary to modify only the proportional gain.

TABLE 3. SETTLED PARAMETERS PID/FEEDBACK CONTROLLER

Parameters	Calculated parameters	Retuned parameters
Critical period – P_{cr} (s)	60.0	
Critical gain K_{cr} (C/Hz)	28.94	
Proportional gain, K_c (C/Hz)	**17.4**	**9.0**
τ_i (s)	30.0	30.0
τ_d (s)	7.5	7.5

Parameters expressed in bold have to be re-tuned.

TABLE 4. SETTLED PARAMETER OF PID/ FEEDFORWARD CONTROLLER

	Calculated values	Re-tuned values
K_{ff}	**2.9**	**0.5**

Parameters expressed in bold have to be re-tuned.

PID/Feedback/Feedforward Controller. The main advantage of feedforward is to compensate the effect of a disturbance before the process is affected. It has proven to be a very powerful process control scheme, especially for disturbance rejection. Given that the process output itself is never measured in this control, the combination with feedback control has proved to be quite advantageous (Ogunnaike and Ray 1994).

Table 4 shows the parameter K_{ff} of the feedforward strategy calculated according to LLU method. Preliminary tests were carried out and K_{ff} had to be reduced six times to avoid considerable temperature oscillations, thus confirming that the higher the term K_{ff} is, the greater are the oscillations on temperature after imposing step changes in the process.

The small value of the retuned K_{ff} (0.5), indicated that the feedback strategy is almost sufficient to maintain the controlled temperatures within the desired safety range. According to this, the imposed disturbances probably were within the disturbance rejection range.

Fuzzy/PID/Feedback. The retuned parameters of conventional feedback/PID showed in Table 3 were used to configure the scaling gains of the fuzzy controller. Preliminary tests with these parameters were not satisfactory to control the system because significant oscillations were detected at pasteurization temperature and hot water flow rate behaviors after the imposed step changes. To minimize this effect, a few experimental tests were made and these parameters were retuned. Table 5 shows calculated and retuned fuzzy scaling gains.

Controller Performance

Figures 3 to 8 illustrate the performance of all three controllers after the step changes described in Table 2 were imposed on the closed loop system. The error process behavior (TE408-Tsp) is linked to the left axis while the imposed devia-

TABLE 5. CALCULATED AND RE-TUNED FUZZY SCALING GAINS

	Calculated	Re-tuned
K_e	1.00	0.30
K_d	15.00	4.50
K_0	0.30	0.35
K_1	7.50	5.25

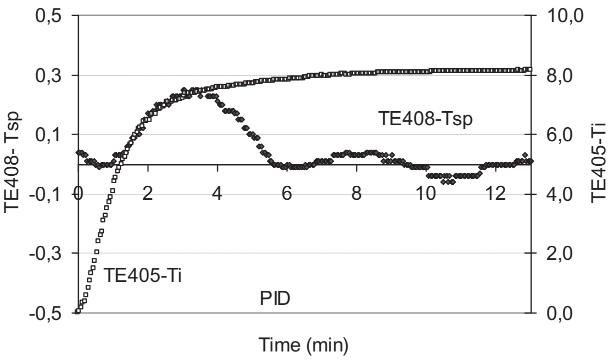

FIG. 3. PID/FEEDBACK PERFORMANCE. ERROR (TE408-TSP) BEHAVIOR AFTER THE STEP CHANGE OF +8.1C IN THE INLET PRODUCT TEMPERATURE (TE405-TI)

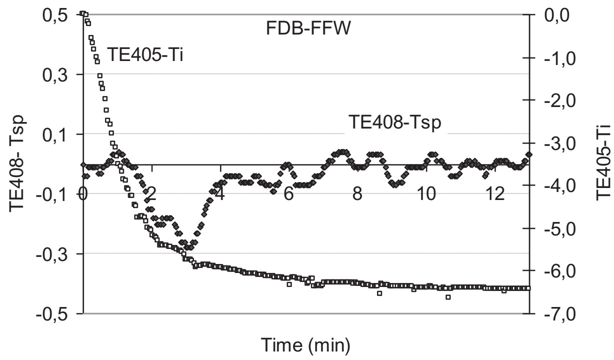

FIG. 6. PID/FEEDBACK/FEEDFORWARD PERFORMANCE. ERROR BEHAVIOR (TE408-TSP) AFTER THE STEP CHANGE OF –6.5C IN THE INLET PRODUCT TEMPERATURE (TE405-TI)

tion in the inlet temperature (T405-Ti) is linked to the right axis. Figures 3 and 4 show PID/feedback performance, Figs. 5 and 6 refer to PID/feedback/feedforward performance while Figs. 7 and 8 show fuzzy/PID/feedback scheme.

Table 6 shows the relative performance criteria (ISE_R, IAE_R e $ITAE_R$), and also parameters namely maximum overshoot (M_p), peak time (t_p) and setting time at 0.1C (t_s) of each assay.

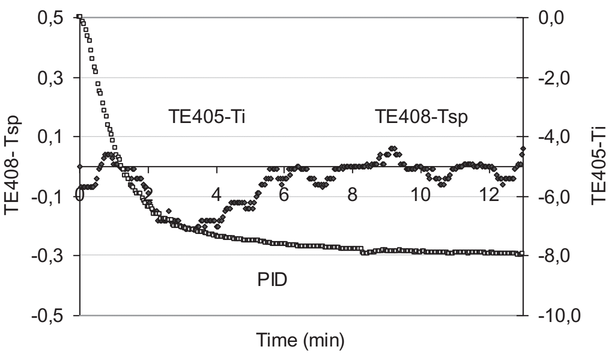

FIG. 4. PID/FEEDBACK PERFORMANCE. ERROR BEHAVIOR (TE408-TSP) AFTER THE STEP CHANGE OF –7,9C IN THE INLET PRODUCT TEMPERATURE (TE405-TI)

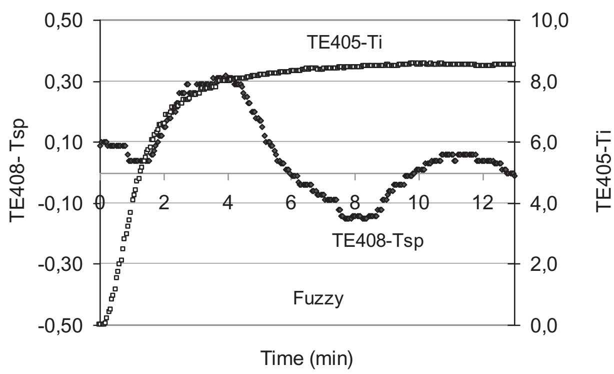

FIG. 7. FUZZY/PID/FEEDBACK PERFORMANCE. ERROR BEHAVIOR (TE408-TSP) AFTER THE STEP CHANGE OF +8.5C IN THE INLET PRODUCT TEMPERATURE (TE405-TI)

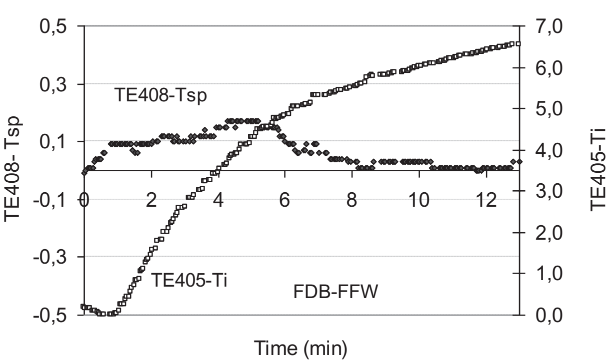

FIG. 5. PID/FEEDBACK/FEEDFORWARD PERFORMANCE. ERROR BEHAVIOR (TE408-TSP) AFTER THE STEP CHANGE OF +6.8C IN THE INLET PRODUCT TEMPERATURE (TE405-TI)

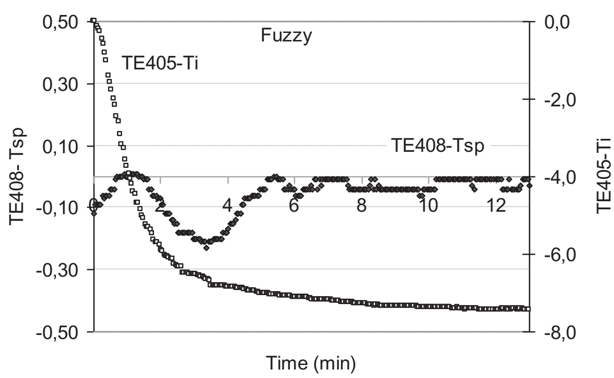

FIG. 8. FUZZY/PID/FEEDBACK PERFORMANCE. ERROR BEHAVIOR (TE408-TSP) AFTER THE STEP CHANGE OF –7.5C IN THE INLET PRODUCT TEMPERATURE (TE405-TI)

TABLE 6. PERFORMANCE CRITERIA TESTED CONTROLLERS

	PID/feedback		PID/feedback feedforward		Fuzzy/PID	
	(+)	(–)	(+)	(–)	(+)	(–)
A (C)	8,2	–6.6	8,0	–7,0	6,5	–7,4
ISE_R (C^2s/C)	0.07	**0.03**	0.08	0.08	**0.06**	0.06
IAE_R (Cs/C)	**6.70**	**4.75**	7.59	7.71	8.94	6.24
$ITAE_R$ (Cs^2/C)	**18.40**	**12.04**	22.29	29.90	45.26	22.41
t_p (min)	2.83	2.45	2.15	2.65	2.50	2.30
*M*p (C/C)	0.04	**–0.03**	0.04	–0.04	**0.03**	**–0.03**
t_s (min/C)	**0.51**	**0.45**	0.51	0.70	0.66	0.69

Parameter expressed in bold refers to the best calculated values.

According to these criteria values and the dynamic responses (Figs. 3 to 8), all three strategies were adequate to keep the pasteurization temperature within the range of a 0.5C change. Integral performance criteria of PID/feedback are suitably lower than the fuzzy/feedback and PID/feedback/feedforward ones. Although, these differences are not great enough to say that this strategy is better than the others. These results agree with Shieh *et al*. (1992) where, at certain temperature ranges, fuzzy logic has controlled the system temperature, as well the PID feedback controller.

Fuzzy logic controllers have been reported to be successfully used for a number of complex and nonlinear processes (Charam *et al*. 2010). Nonlinearity was observed on the dynamic responses of plate heat exchangers after multiple disturbances were made in the process (Berto and Silveira Jr. 2003). The satisfactory performance of the PID/Feedback scheme, after only a single-step temperature change, led to the conclusion that this HTST process, under experimental tested conditions, is practically linear.

Similar values of integral performance criteria support the assumption that all three controllers have an equivalent performance under the tested conditions.

CONCLUSION

PID/feedback, PID/feedback/feedforward and fuzzy/PID/feedback controllers were implemented in a HTST continuous processing plant of fruit juice. The efficiency of controllers was evaluated and compared to maintain the pasteurization temperature after step changes imposed on the inlet raw product temperature. Almost all initial parameters setting, calculated according to tuning methodologies proposed in specialized literature, had to be reduced in value to avoid considerable oscillations in controlled temperature. Relative performance criteria (IAE_R, $ITAE_R$ e ISE_R) were similar for all three controllers, indicating an equivalent performance. While fuzzy performance was not better in controlling the process temperature than conventional tested controllers, it is possible to state that under tested experimental conditions, this HTST process has lower nonlinearity characteristics.

ACKNOWLEDGMENTS

The authors thank The State of São Paulo Research Foundation, FAPESP for financial support (2000/00437–0).

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