Journal of Food Engineering **30** (1996) 327–338

0260-8774/96 $15.00 + 0.00

ELSEVIER

PII: S0260-8774(96)00057-X

Evaluation of Process Deviations, Consisting of Drops in Rotational Speed, during Thermal Processing of Foods in Rotary Water Cascading Retorts

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(Received 20 August 1995; accepted 2 August 1996)

ABSTRACT

Taking into account the similarities of broken-line heating curves and heat-penetration curves obtained when a product undergoes a drop in rotational speed during thermal processing in a rotary water cascading retort, a semi-empirical method used for handling broken-line heating behaviour is suggested as a method of dealing with this type of process deviation. For this purpose, the possibility of extrapolating the empirical heating rate parameter f_h, determined on the heat-penetration curve of white beans in brine processed in a still retort, to the 'still' conditions associated with a rotational speed drop in a rotary water cascading retort, was investigated. Following this approach, safe product temperature predictions were obtained. The main criterion influencing the quality of the evalution was the determination of the correct empirical parametric value to be used. This means, when determining this parametric value, care is required when selecting the correct temperature interval on the heat-penetration curve. Copyright © 1996 Elsevier Science Limited

NOTATION

f_h Time required for the difference between the retort and the product temperature to change by a factor of 10 (min); subscripts 1 and 2 refer to the first and the second linear part of a broken-line heating curve, respectively

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j_h	Lag factor in heat-penetration curves
R	Can radius (m)
r	Can radial distance (m)
x_{bh}	Break point time (min)
α	Thermal diffusivity (m^2/s)

INTRODUCTION

Agitation increases the rate of heat transfer during thermal processing of packed liquid foods or liquid foods with particulates. Using rotary (axial or end-over-end) retorts, some products that normally heat by mixed conduction/convection may benefit from induced convection currents, a fact that gives a faster heating rate, allowing for shorter processing times (Clifcorn *et al.*, 1950; Conley *et al.*, 1951; Berry *et al.*, 1979; Berry & Bradshaw, 1980, 1982; Naveh & Kopelman, 1980; Berry & Dickerson, 1981). Furthermore, burn-on at the surface of low viscosity foods can be substantially eliminated by inducing agitation (Berry & Kohnhorst, 1985). Therefore, for low viscosity foods, rotation allows the application of higher processing temperatures and, since the principle of high temperature, short time (HTST) holds here (Lund, 1977), it leads to improved quality of the food (assuming agitation does not cause product damage). Rotational speed, being a critical variable in the process, needs to be continuously monitored to guarantee that the scheduled process is delivered.

Obviously, a drop in the rotational speed during a rotary process leads to a decrease of the rate of heat transfer in the product being processed. In industry, when this deviation is established, the required processing time is calculated assuming that the entire process was carried out in a still mode. This is a conservative evaluation of the deviation and leads to an overprocessing of the product, and consequently to a decrease of the product quality. Improvements in evaluating this deviation would thus favour product quality.

A drop in rotational speed during processing in a rotary retort causes the product heating rate to decrease; this results in a need to handle the process as a deviation. When heat-penetration data from this type of deviation is plotted in the classical inverse log–linear coordinates (Ball & Olson, 1957), the heat-penetration curves show a resemblance to broken-line heating curves. The graph shows a lag period and two segments each being asymptotic to a distinct straight line. Therefore, this type of heating curve can be described as an 'induced' broken-line heating curve, and can be characterized using the empirical broken-line heating parameters (a lag factor, j_h, two heating rate indices, f_{h1} and f_{h2}, for the first and second linear segments, respectively, and the break point time, x_{bh}), as defined by Ball & Olson (1957).

For calculation of product temperature profiles during thermal processing of straight-line heating (both conduction and convection), Noronha *et al.* (1995) suggested a semi-empirical procedure based on the numerical solution for heat transfer in conductive heating foods. The numerical procedure allows the handling of variable retort temperatures and changes in any of the model specific variables. Empirical parameters (j_h and f_h) are incorporated as numerical variables. This model was extended to handle broken heating, by incorporating the variables j_h, f_{h1}, f_{h2} and x_{bh} (Denys *et al.*, 1995).

Taking into account the existing resemblance of broken-line heating curves and heat-penetration curves for a convection heated product, when a drop in rotational speed occurs, the extended model is suggested as an approach to deal with this kind of process deviation. The objective of this paper is to verify whether the knowledge of the empirical parameters, describing heat-penetration curves for products processed in still conditions, can be used to predict the product temperature response when rotational speed drops during a rotary water cascading process. White beans in brine were considered as a case study. It was necessary to investigate whether the empirical f_h parametric value, determined in the classical graphical way on heat-penetration curves for still-processed beans, could be incorporated in the extended semi-empirical model in order to yield a safe evaluation of the process deviation.

MATERIALS AND METHODS

Materials

Heat-penetration experiments were carried out with dried white beans (*Phaseolus vulgaris*) stored dry at 15°C, and soaked in distilled water at 15°C for at least 16 h before processing. Glass jars (600 ml in volume, 172 mm in height, 81 mm in diameter, about 2·6 mm in wall thickness; Carnaud-Giralt, Laporta, Spain) were filled with 450 g of beans; before weighing the beans, the excess water was removed by letting the beans stand in a sieve for approximately 1 min. Distilled water was added to a final gross headspace of 10 mm.

Still and end-over-end rotary (10, 15 and 25 rpm) processes were simulated in a modified Barriquand Steriflow process simulator (microflow type 911R No. 877, Barriquand, Roanne, France). During heating, as well as in the cooling step, water cascading was used. Type T (copper–constantan) thermocouples (Ellab, Copenhagen, Denmark) were used to measure retort and product temperatures. The thermocouples were calibrated in ice water (0°C) and at the temperature of the retort to be used during the heat-penetration tests (115 or 121°C). All thermocouples could measure temperature with a maximum deviation of $\pm 0{\cdot}1$°C. For rotational processes, a slip-ring contact (DCS85-12, Ellab, Copenhagen, Denmark) was used. Data acquisition was performed with a CMC-92 multi-channel data acquisition system (TR9216, Ellab, Copenhagen, Denmark), connected to a personal computer for storing and manipulating the data.

Heat penetration

Heat-penetration experiments at different rotational speeds (0, 10, 15 and 25 rpm) were conducted to examine the nature of the heat-penetration curves. The retort heating profile used consisted of an equilibration phase at 40°C, followed by a linear coming-up-time (CUT) of 7·5–8·5 min and a holding phase of 15 min at 121°C. Temperatures inside two (rotary processes) or four (still process) glass jars were measured 2–3 cm from the bottom. This location was determined as the coldest spot during the still process. Van Loey *et al.* (1994) reported that an increase in rotational speed moves the coldest spot from the bottom towards the centre of the jar. In the logic of the strategy followed, for both the still and the rotary processes, product temperatures were measured at the same position in the glass jar.

At each rotational speed (10, 15 and 25 rpm), a process deviation, consisting of a drop in the rotational speed to 0 rpm was simulated. Thereby, the same retort temperature profile as described above was used. The deviations were programmed to occur 5 min after CUT.

For processes executed at a rotational speed of 15 rpm, the influence of the time when a rotational deviation occurred was also investigated. Therefore, two more processes were simulated with deviations occuring 1 and 7 min after CUT, respectively. The retort temperature profile used here was composed of an equilibration period at 20°C, followed by a CUT of 8·5 min up to 115°C and a holding phase until the difference between retort and product temperature reached 0·5°C. Four glass jars were processed during each process, and temperatures measured 2–3 cm from the bottom

Evaluation of process deviations consisting of drops in rotational speed

Heat-transfer model and parameter determination

The numerical solution for a conductive heating sphere with infinite surface heat-transfer coefficient was chosen to simulate heating curves with any j_h, f_{h1}, f_{h2} and x_{bh} values. These empirical parameters, classically used for the description of broken-line heating curves (Ball & Olson, 1957), were incorporated in the model as numerical variables. Equation (1) was used to determine the position in the sphere that was characteristic of the j value. The 'apparent' thermal diffusivity, α, that results in a certain f_h value was calculated from eqn (2) (Ball & Olson, 1957). Changes in the f_h value (f_{h1} to f_{h2}) were performed by changing the apparent thermal diffusivity at the moment the break occurs (x_{bh}).

$$j(r) = \frac{2R}{\pi r} \sin\left(\frac{\pi r}{R}\right) \tag{1}$$

$$f_h = \frac{\ln(10)R^2}{\pi^2 \alpha} \tag{2}$$

A procedure allowing the simultaneous determination of the 'corrected' j_h and f_h parameters of an experimental straight-line heat-penetration curve, independently of the boundary conditions (e.g. the retort temperature profile), was presented by Noronha *et al.* (1995), and was extended for broken-line heating curves (Denys *et al.*, 1995). The procedure uses an optimization method (a modified version of Box's COMPLEX method; Saguy, 1983) for searching for the 'correct" j_h, f_{h1}, f_{h2} and x_{bh} values, by varying these parameters and minimizing the sum of squares of the differences between the experimental and the predicted product temperatures.

Evaluation of process deviations

The above-described semi-empirical heat-penetration model for broken-line heating products was applied to predict the product temperature response for white beans in brine, undergoing a drop in the rotational speed in a rotary water cascading retort. This approach is flow charted in Fig. 1. The 'corrected' j_h and f_{h1} values, obtained with the above-described optimization procedure, were used to describe the product temperatures in normal rotary conditions (before the deviation occurs). After a drop in rotational speed, the f_h value, determined graphically from the heat-penetration curve of still-processed beans, was incorporated into the model as f_{h2}, to predict the product temperatures after the deviation. Naturally, the 'deviation time' (time when the deviation occurs) was incorporated in the model in analogy to the break point time, x_{bh}.

RESULTS AND DISCUSSION

Heat penetration and nature of the heat-penetration curves

Heat-penetration curves for white beans in brine, processed at different rotational speeds, are shown on semi-logarithmic coordinates in Fig. 2. On this figure, the

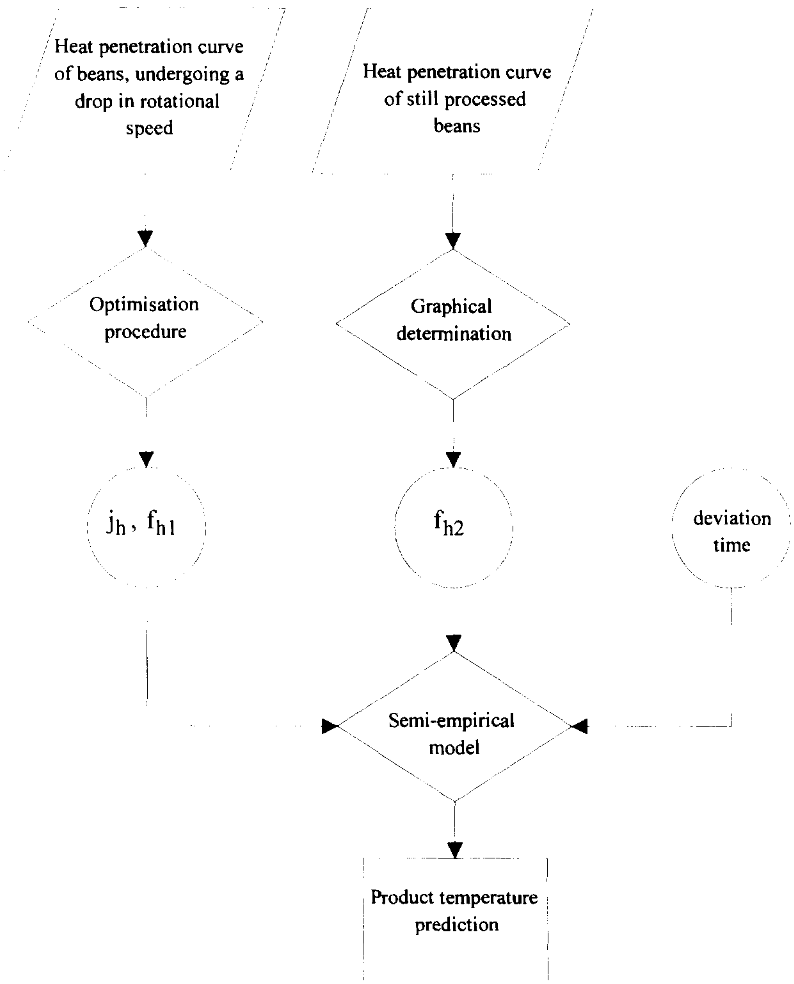

Fig. 1. Flow chart of the strategy followed to evaluate process deviations consisting of drops in rotational speed.

positive influence of introducing a rotation on the heating rate of the product is visible. Furthermore, increasing the rotational speed leads to a faster heating of the product, this effect being smaller than the effect of introducing the rotation. This was also reported by Van Loey *et al.* (1994).

Figure 3 shows heat-penetration curves on semi-logarithmic coordinates obtained for the processes at different rotational speeds with a deviation drop in rotational speed occurring 5 min after CUT (i.e. at a process time of 12·5 min). The sudden decrease of the product heating rate, causing 'induced broken-line heating curves', reveals itself in Fig. 3.

When processing white beans in still conditions, the heating rate of the product slowly decreased during the process, resulting in a curved heat-penetration curve on semi-logaritmic coordinates, rather than a straight line as obtained when processing in rotary conditions (Fig. 2). This implies an important consequence for the strategy followed. Given the curved nature of a heat-penetration curve for white beans processed in still conditions, graphical determination of the empirical parameter f_h from different temperature intervals of this heat-penetration curve will result in different values. This is visualized in Fig. 2, where two temperature intervals were

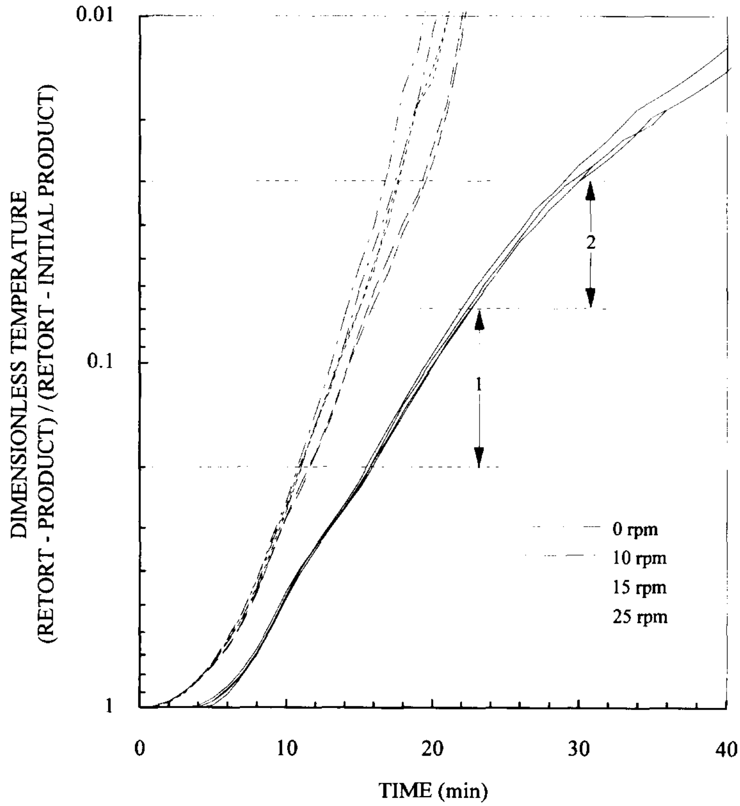

Fig. 2. Log–linear temperature profiles for white beans processed at different rotational speeds.

considered on a dimensionless temperature scale. Within these intervals, the f_h values were graphically determined on the heat-penetration curves for still conditions. The dimensionless temperature interval between 0·2 and 0·07 (interval 1) led to an average f_h (of the four curves) of 14·8 min, while an interval between 0·07 and 0·03 (interval 2) resulted in a value of 20·1 min. Within each temperature interval, the heat-penetration curves can be considered as straight lines.

Evaluation of process deviations consisting of drops in rotational speed

As described before, the extended semi-empirical model was used to predict the heat-penetration curves (Fig. 3) for the three processes with deviations. The 'corrected' j_h and f_{h1} values obtained with the optimization procedure, working on the heat-penetration data of each glass jar, were used to generate the product temperature profile for this particular jar from the beginning of the process up to the time of the deviation. At this time, the f_h value determined from the heat-penetration curve of still-processed beans (f_{h2}) was incorporated into the model as a parameter to predict the product temperatures after the deviation.

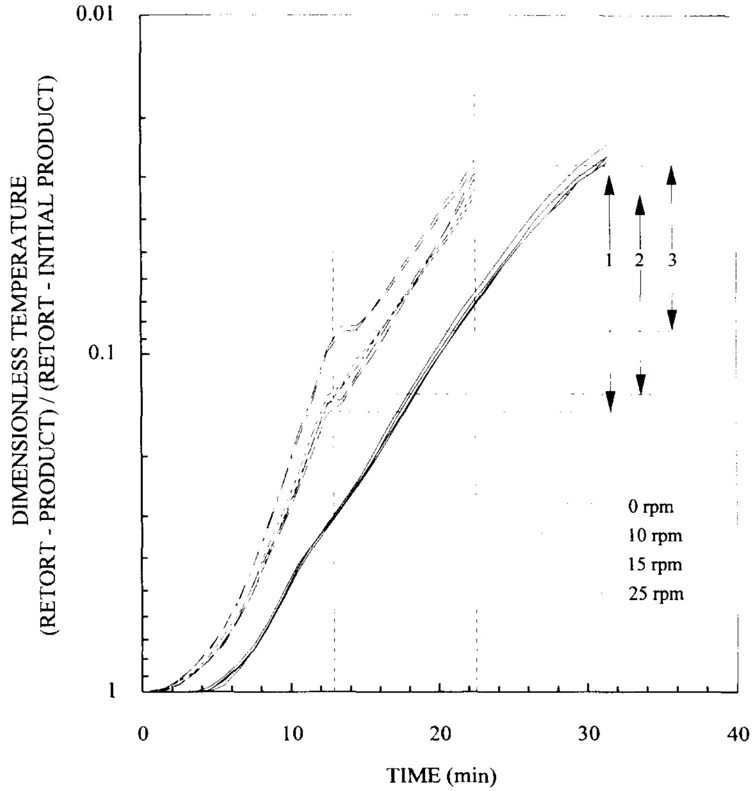

Fig. 3. Log–linear temperature profiles for white beans processed at different rotational speeds; a drop in rotational speed occurs at time 12·5 min.

TABLE 1
Various f_h Values, Graphically Determined on Heat-penetration Curves of Still-processed Beans, Considering Different Temperature Intervals

Considered temperature interval (Fig. 3)	*f_h (min)*		*Used to evaluate process deviation (rpm)*
	Minimum	*Maximum*	
1	18.83	19.45	10–0 rpm
2	19.26	19.92	15–0 rpm
3	20.54	21.07	25–0 rpm

Obviously, the process deviation can occur at any product temperature during a rotary process, and its impact is dependent on the process time when it happens and on the characteristic heating rate of the product (i.e. the rotational speed of the retort). In view of the non-linearity of heat-penetration curves for still-processed beans, f_{h2} was determined from the temperature interval between the deviation time and the end of heating. This procedure is visualized in Fig. 3 where, on a dimensionless scale, the temperature intervals 1, 2 and 3 are shown, corresponding to the intervals from the respective temperatures at the deviation time up to the respective final temperatures reached in the product. Table 1 presents the minimum and maximum values of f_h, graphically determined on the four heat-penetration curves for the still process, within these temperature intervals. As expected, due to the continuous concave curved nature of the heat-penetration curve, lower f_h values were obtained when considering lower temperature intervals (i.e. temperature intervals starting sooner in the process).

Predicted data for the three processes (at different rotational speeds), considering only one container, are presented in Fig. 4. Both minimum and maximum f_h values given in Table 1 were used to generate product temperature profiles. Good predictions were obtained for the cases where rotational speed dropped from 15 and 25 rpm to still conditions. For the process at 10 rpm, predicted temperatures were lower compared with the experimental ones after the rotation stops. Nevertheless, this implies an underestimation of the cumulated letality, and consequently is conservative. Note that the semi-empirical model could not handle the sudden temperature drop appearing in each of the heat-penetration curves right after the deviations in the rotational speed. This phenomenon is caused by a temperature gradient from the bottom to the centre of the glass jar, as the coldest spot moves from the centre (rotary condition) to the bottom (still condition).

Heat-penetration curves for white beans processed at 15 rpm with a simulated drop in rotational speed occurring 1 and 7 min after CUT, respectively, are shown in Fig. 5. Only one glass jar was used for illustration purposes. Minimum and maximum f_h values, determined from the heat-penetration curves for the still process within the corresponding temperature intervals from the respective deviation time up to the end of the process ('large intervals' 1 and 2, as shown in Fig. 5), are given in Table 2. Applying the same strategy as for the former cases, predicted product temperature profiles using minimum and maximum f_h values were generated and are presented in Fig. 6(a), (b) (full lines). The differences between experimental and predicted temperatures after the deviation were larger compared with the former cases, resulting in a larger underprediction of the product temperatures. This can be explained by the curved nature of the heat-penetration curves for the still-processed beans within these large intervals. As in Fig. 5, these heat-penetration curves still showed a gradual decrease of the slope in the considered interval. In Fig. 6(a), (b), predictions using an f_h determined in a smaller 'lower temperature' interval (intervals 3 and 4 shown in Fig. 5) are also presented (dotted lines). In these intervals, the heat-penetration curves of the still-processed beans can be considered as straight lines. Minimum and maximum f_h values used here are also given in Table 2. As expected, a slight overprediction of the product temperatures was obtained (Fig. 6(a), (b). Note that the process with a deviation simulated 7 min after CUT is comparable with one of the former cases (15–0 rpm, 5 min after CUT). This expresses itself in the f_h values obtained within interval 4 (Table 2); they were in the same range as the f_h values obtained within interval 2 of Fig. 3 (Table 1).

Two remarks should be made here. Firstly, additional research is needed to determine if the approach presented in this paper can be applied to other rotary retorts. Secondly, a consideration should be made of further possibilities of the

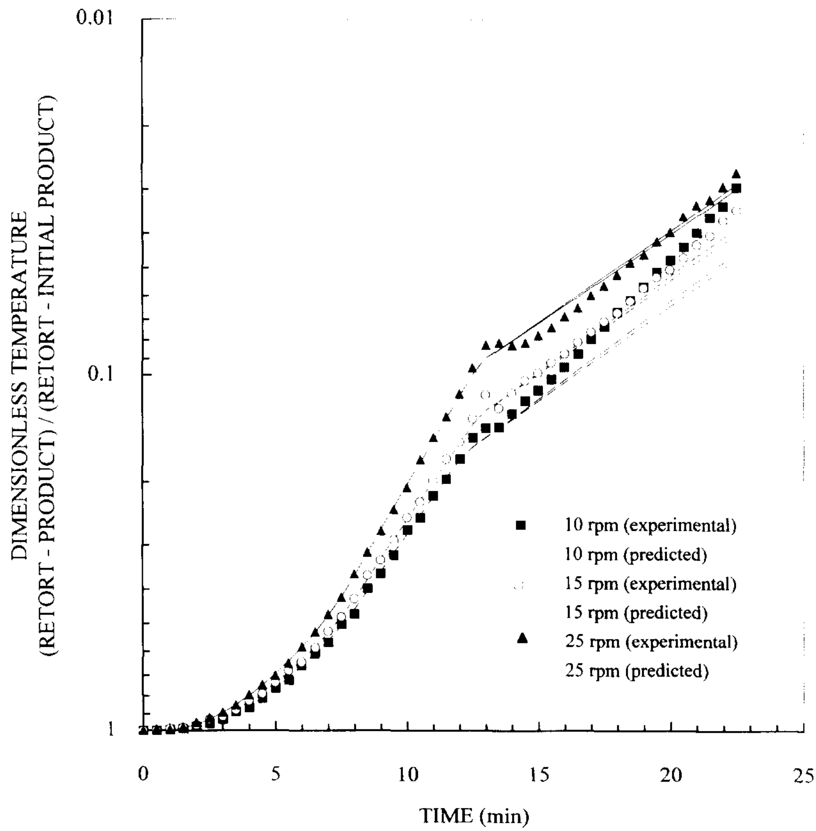

Fig. 4. Evaluation of process deviations consisting of a drop in rotational speed using minimum and maximum f_h values.

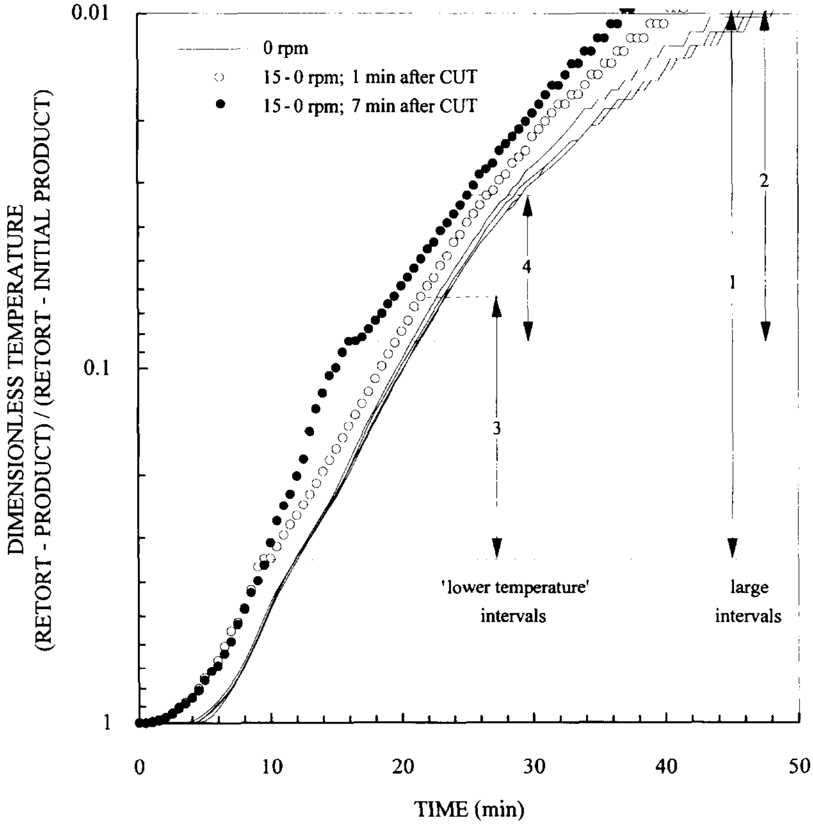

Fig. 5. Log–linear temperature profiles for white beans processed at 15 rpm; a drop in the rotational speed occurs at time 9·5 min and 15·5 min, respectively.

TABLE 2
Various f_h Values, Graphically Determined on Heat-Penetration Curves of Still-Processed Beans, Considering Different Temperature Intervals

Considered temperature interval (Fig. 5)	*f_h (min)*		*Used to evaluate process deviation*
	Minimum	*Maximum*	
1	20.86	22.58	15–0 rpm,
3	14.24	15.57	1 min after CUT
2	26.69	30.18	15–0 rpm,
4	17.82	22.01	7 min after CUT

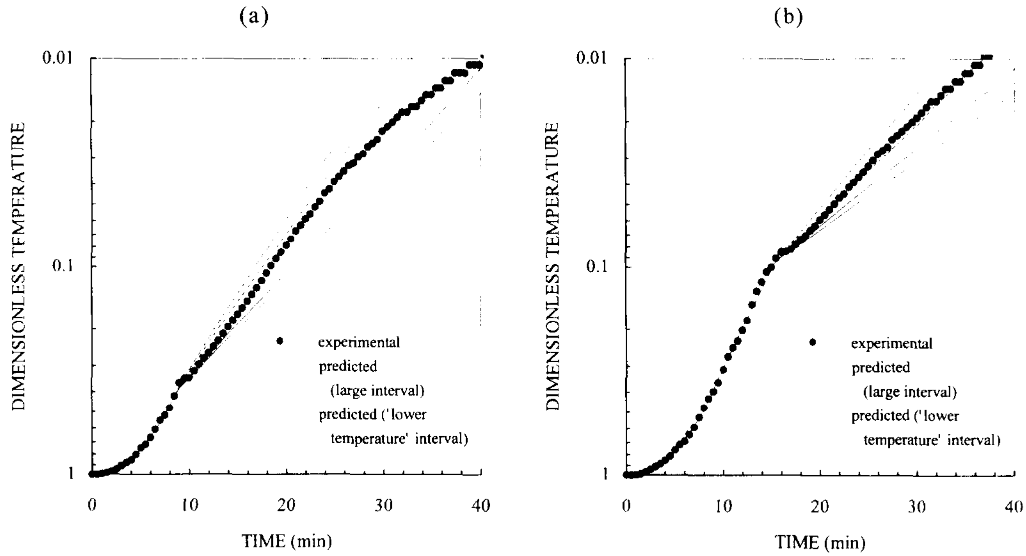

Fig. 6. Evaluation of process deviations consisting of a drop in rotational speed occurring at two different times.

semi-empirical method. If the model was extended in a way so that more than one change of the heating rate could be incorporated, by importing successive f_h values in the numerical solution at successive 'break point times', a more complex heat-penetration curve could be modelled. Better fitting predictions are obtained when a large temperature interval was considered on the heat-penetration curves for still-processed beans. Within temperature interval 1 of Fig. 5, heat-penetration curves for still-processed beans could empirically be described by two or three successive f_h values. Using these values for the prediction of product temperatures after the deviation, as shown in Fig. 6(a), the predicted heat-penetration curve is expected to fit the experimental curve better. However, further research is needed to investigate whether this proposed method also leads to a safe evaluation of process deviations consisting of drops in rotational speed.

CONCLUSIONS

A methodology was presented for dealing with drops in rotational speed during thermal processing of foods in rotary water cascading retorts. A semi-empirical method for simulating temperature profiles during thermal processing of broken-line heating products under variable retort temperatures was suggested. The approach consisted of an extrapolation of the empirical heating rate parameter f_h from a still process to the conditions after the deviation, and provides a tool for safe evaluation. The main criterion determining the safety of the method was the determination of the correct empirical parametric value to be used. Given the non-linear nature of heat-penetration curves for still-processed beans, this heavily depends on the selection of the correct temperature interval on this experimental heat-penetration curve. Obviously, for products exhibiting straight-line heating curves for both still and rotary processes, the selection of a particular temperature interval is not required. Note that white beans were presented here as a case study. Simular results were obtained for whole kernel corn in brine. Experiments with different products and retorts should also be performed in order to test further the proposed method for the evaluation of process deviations consisting of drops in the rotational speed.

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