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Comparison of Two Methods Used to Determine Apparent Heat Transfer Coefficient for Pouches Pasteurized in a Combination Oven

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Apparent heat transfer coefficients between pouch and heating medium in a combination oven on Vario-steaming mode were determined by comparing the experimental and simulated temperature histories and by the least square and optimization methods. Temperature histories and related P_{70} values from experiments and simulation were compared. One stage approximation of the heating process resulted in large mean square-rooted deviations (MSRDs) in simulated temperature histories, 2.6 ± 0.4°C and 2.8 ± 0.4°C, and also large errors in predicted mean P_{70}, −21.5% and −11.3%, using h values determined by the least square and optimization methods, respectively. According to heat transfer mechanisms the heating process was divided into two stages, i.e. air and mixture of steam and air heating. MSRDs were reduced to 0.6 ± 0.3°C for both methods and errors in predicted mean P_{70} were reduced to 4.3% and 3.0% for the least square and optimization methods, respectively. The differences in h values, MSRDs and mean P_{70} produced by the two methods became negligible.

Introduction

Over the last 20 years *sous vide* food products have been progressively accepted by consumers and caterers due to their convenience, high sensory quality and relatively long chilled shelf-life. In 1993 there were 67 large scale *sous vide* producers in France, where the process originated, with a further 41 producers throughout Belgium, the Netherlands, Ireland, Germany, Spain and the U.K. (1). In 1990 the market for *sous vide* foods in Canada was approximately US$20 million (2). Currently, in the U.K., *sous vide* pouches are usually thermally processed in a combination oven and heated by a mixture of air and steam at temperatures below 100°C.

In the mathematical modelling and subsequent design and optimization of the pouch sterilization process, the heat transfer coefficient (h) between pouch and process medium is one of the critical parameters (3), particularly for conduction heated pouches (4). This is also the case with the pasteurization of *sous vide* foods. Large unknown variations in the h values could actually cause a potential health hazard (5).

The heat transfer coefficient between a can and steam is considered near infinite, but this is not the case for pouches in either pressurized water or steam–air mixture (5). Peterson and Adams (5) and Adams *et al.* (6) used the equation developed by Ball and Olson (7) based on the slope index of the heating curve applied to infinite slab geometry to determine apparent heat transfer coefficients under varied retort heating medium and recirculation rate regimens. The term apparent is used to describe the value because the external heat transfer coefficient between the media and the pouch and between the rack and pouch material are included. For infinite or semi-infinite objects of simple geometry and heated at constant temperature, heat transfer coefficients can be determined by using the analytical solutions of the heat conduction equation (8,9). Heat transfer coefficients can also be estimated from dimensionless number equations but this approach is not suitable for pouches because of the external thermal resistance of the pouch material. For objects with finite geometry heated at variable temperatures, currently two methods can be used: the least square method (10) and the optimization method (11). Both use numerical methods to simulate temperature histories of the objects studied and heat transfer coefficients are determined by comparing these to experimental temperature histories. The only difference between them is the principle used in the determination of the h value from these comparisons. The least square method minimizes the difference between simulated and experimental temperature histories using iterative technique, i.e. changing the h_L value while other parameters are kept unchanged until the difference between the two temperature histories become statistically negligible (10). In the optimization method, which was developed by Lebowitz and Bhowmik (11), a temperature *vs.* time plot is converted to a temperature *vs.* temperature plot, i.e. the simulated and experimental temperatures are located on the x and y axes, respectively. Using linear regression, which is based on the modified least squares analysis (Eqn [1]), the slope index b can be calculated. Similar to the least square method the h_o is determined by changing its value until the slope index reaches unity.

$$b = \frac{\sum_{i=1}^{n} y_i x_i}{\sum_{i=1}^{n} x_i^2} \qquad \text{Eqn [1]}$$

The purpose of this investigation was to compare these two methods through a comparison of h values and the accuracy of the simulated temperature histories and predicted process lethality for conduction heated pouches pasteurized in a combination oven on Vario-steaming mode.

Materials and Methods

Freshly purchased ESTIMA baking potato was chosen as the food sample. Its physical and thermal properties are given in **Table 1**. Disc shapes were prepared with size 72 × 24 mm ($D \times L$) and vacuum-packaged immediately in 140 × 200 mm Cryovac Z101 laminated plastic pouches to prevent moisture loss. A Gastrovac A300/42 packaging machine (Multivac UK Ltd, Swindon, U.K.) with an evacuation time of 15 s was used for vacuum sealing. The average weight of the potato discs was 109.0 ± 1.3 g. For the test packs, i.e. the packaged discs with thermocouples inserted, great care was taken to ensure the discs were packaged properly. A small hole was punctured by a stainless steel needle (0.8 mm in diameter) in a bottom corner of the pouch and a thermocouple was inserted through the hole. The hole was then carefully sealed around the thermocouple lead using ARALDITE adhesive. To accelerate adhesive hardening these pouches were heated by hot air in an oven for 60 min at 90°C. The potato disc was also punctured by the needle from its curved side to the centre and then the thermocouple junction was inserted into the disc centre. The pouch was then vacuum-sealed. After each run these packages were carefully inspected to ensure there was no vacuum loss and the discs were sectioned to verify the correct location of the thermocouple junction. The packaged discs were stored in a chill cabinet at 3°C overnight to stabilize temperatures prior to heating.

Table 1 Physical properties of potato

Physical properties	Value
Density	1071.0 kg/m^3
Specific heat, C_p[a]	3517.0 J/(kg·K)
Thermal conductivity, k[b]	0.54 W/(m·K)
Thermal diffusivity, a[b]	1.44×10^{-7} m^2/s

[a]Mohsenin (12).
[b]Dickerson and Reed (13).

A Rational CC6 electric six-grid computerized combination oven (Rational UK Ltd, Luton, U.K.) was used for the heating process. All six shelves were loaded. Eight pouches were evenly placed on each shelf with no package overlap and a total of 48 pouches were used in each run. In this investigation only the potato discs on shelf No. 4, which was located at the middle of the cabinet, were tested and triplicate runs were conducted. In each run 16 thermocouples were used, half being in disc centres and half fixed by wire on shelf No. 5, the one above the test shelf. The thermocouple junctions were 12.5 mm above the pouch surface, i.e. the mid-point between the pouch surface and the shelf above, to measure the heating medium temperatures. The oven was set on Vario-steaming mode which operates at temperatures no higher than 99°C and is used commercially for heating *sous vide* pouches. The oven temperature was set at 95°C and the total heating time was 32 min. All temperatures were measured by T-type (Cu/Con) fine wire thermocouples of 0.315 mm diameter (Labfacility Ltd, Teddington, U.K.) and recorded at 1-min time intervals by a Squirrel 1205 16-channel data logger (Grant Instrument Ltd, Cambridge, U.K.).

Theoretical Calculation

Transient heat conduction into an isotropic and homogeneous finite cylinder is governed by the following partial differential equation. This is a two-dimensional equation in cylindrical co-ordinates:

$$\frac{\partial T}{\partial t} = \frac{k}{\rho C_p}\left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial y^2}\right) \qquad \text{Eqn [2]}$$

The initial and boundary conditions used in this study are shown as follows:

initial condition:

$T(r,y) = T_0$ at $t = 0$

convective boundary condition:

$$\frac{\partial T}{\partial n} = \frac{h}{k}\,(T_h - T_b) \qquad \text{Eqn [3]}$$

The differential equation was converted to finite difference equations and numerically solved using the Crank–Nicolson method, which has shown unconditional stability and convergence to the exact solution (14). For the balance of accuracy and computing time, a time increment of 2.5 s and distance increment of 2.4 mm were used in the numerical calculation. The pasteurizing value (P_{Tr}) was estimated by:

$$P_{Tr} = \int_0^t 10^{\frac{T-T_r}{z}}\,dt \qquad \text{Eqn [4]}$$

Simpson's integration method was used to calculate the pasteurizing value P_{70} with a reference temperature of

70°C and z value of 9.1°C (15) from temperature histories.

In this investigation the least square method was modified. The mean square-rooted deviation (MSRD), i.e. the sum of the squared deviations between experimental and simulated temperatures at each time interval divided by the process time and then rooted, replaced the sum of the squared deviations. The advantage of this modification is that MSRD shows the average deviations between two temperature histories more clearly. MSRD was also used to compare the degree of agreement between simulated and experimental temperature histories.

In Lenowitz and Bohwmik's investigation (16) the optimization method was used to calculate h values for whole heating processes (one stage) for retortable pouches heated by hot water under overriding air pressure. They also divided the heating process into two stages: come-up time, i.e. the time required for the retort to reach the desired temperature, and heating time, and determined the h values for each stage. After comparing the h values at the different stages of the thermal process: come-up; heating; combined come-up and heating; and cooling stages, they concluded that at the 95% confidence interval there were no significant differences between any two h values. Similar to the retort heating, there are actually two stages of heating in the Vario-steaming mode of the combination oven. After the oven door is closed the pouches are first heated by hot air while water is being heated in the steam generator. When water reaches the boiling point, steam is injected into the cabinet and the pouches are then heated by a mixture of steam and air. Therefore, in this investigation the heating process was also divided into two stages: (1) air heating which lasts about 3 min and (2) steam and air heating for the rest of the process. h values for each stage were calculated.

In thermal processes the main purpose of food temperature measurement or simulation is to evaluate the process lethality. In this investigation the experimental P_{70} values were compared with those predicted from the simulated temperature histories using the h values determined by the two methods.

Two sample t-tests carried out by the package Minitab 10.2 were used for all the comparisons.

Results and Discussion

Table 2 gives the results of the comparisons between these two methods. The results of t-test indicate that for one stage heating at 95% confidence the h_L determined by the least square method is smaller than the h_o determined by the optimization method. The mean MSRD value based on the h_L is smaller than that based on the h_o, which means that the simulated temperature histories using the h_L agree better with the experimental ones. As an example, **Fig. 1a** shows the effect of h values determined by the two methods on the deviations of the simulated temperature history from the experimental one. The deviations of the cumulative lethality calculated from the simulated temperature histories as a function of heating time are shown in **Fig. 1b**. By contrast, it is found that the cumulative lethality calculated using h_o is closer to the experimental one. The t-test shows that the P_{70} predicted by the least square method is smaller. Compared to the experimental mean P_{70} the errors of predicted mean P_{70} are –21.5% and –11.3% for the least square and optimization methods, respectively.

These differences are mainly caused by one stage heating approximation and the different principles used in these two methods. As mentioned previously, the oven heating actually involves two different heat transfer mechanisms or stages. Using one stage heating approximation, the determined h value must be greater than the true h value during air heating and smaller than that during steam and air heating. As a result the simulated temperatures initially should be greater than those from the experiment. After the two temperature curves cross each other the simulated temperature curve gradually approaches the experimental one from underneath as heating proceeds. This can be observed clearly in **Fig. 1a**. The MSRD is the absolute mean deviation between two temperature histories. When the least square method is applied and the sum of squared deviations or MSRD reaches the minimum the large deviations may distribute in both the low and high temperature regions. The optimization method is different. Lebowitz and Bhowmik (11) applied the linear regression technique by using the modified least square estimation to let the straight line pass through the

Table 2 Comparison of h values, predicted P_{70} values and MSRDs between simulated and experimental temperature histories by using the least square and optimization methods

	Least square				Optimization			
Parameters	One stage mean±c.i[a]	CV(%)	Two stage mean±CI	CV(%)	One stage mean±CI	CV(%)	Two stage meah±CI	CV(%)
h or $h1$ (W/(m²·K))	264.8±20.4	18.9	20.9±2.9	34.9	311.2±30.1	24.2	20.8±3.3	39.4
$h2$ (W/(m²·K))			510.0±52.8	25.9			502.9±57.2	28.4
M.S.R.D (°C)	2.6±0.2	15.3	0.6±0.1	50.0	2.8±0.2	14.3	0.6±0.1	50.0
P_{70} value (min)								
Experiment	1382.7±114.1	20.6	1382.7±114.1	20.6	1382.7±114.1	20.6	1382.7±114.1	20.6
Predicted	1085.7±99.5	22.9	1442.8±131.1	22.7	1227.0±145.7	21.5	1424.8±122.0	21.4
Errors in mean P_{70} (%)	–21.5		4.3		–11.3		3.0	

[a]95% confidence interval.

origin. The slope index b is calculated using sum of the products of two temperatures ($y_i\ x_i$) divided by sum of the squared experimental temperatures (x_i^2) at each time interval (Eqn [1]). It is the simulated temperature, not the temperature difference, that affects the slope index. In the high temperature region, a small deviation in the simulated temperature will lead to a large variation of the slope index. As a result, the large deviations are located mainly in the low temperature region (**Fig. 1a**). Because the deviations of the simulated temperature in the high temperature region affect the predicted P_{70} values more significantly this method reduces the error in the predicted P_{70} (**Fig. 1b**), but may increase MSRD.

In **Table 2** it is found that the h_{L2} and h_{o2} values in the second stage are much greater than those in the first stage. This is as expected because of the completely different heat transfer mechanisms involved in these two stages. Although the presence of the uncondensed air deteriorates the condensation process of the steam, the mixture of steam and air still has a much greater heat transfer rate than hot air. These results also indicate that, apart from the external thermal resistance of the pouch material, the one-stage heating approximation is a major factor contributing to the small h value in this kind of thermal process. This finding is different from that reported by Lebowitz and Bhowmik (16) because of the differences in the method used to divide the process and the heat transfer mechanisms involved. In their work, recirculated hot water with constant flow rate was used as the heating medium. The heat transfer mechanisms involved in the two stages are same. The effect of water temperature difference between the two stages on h values is not significant, resulting in similar h values.

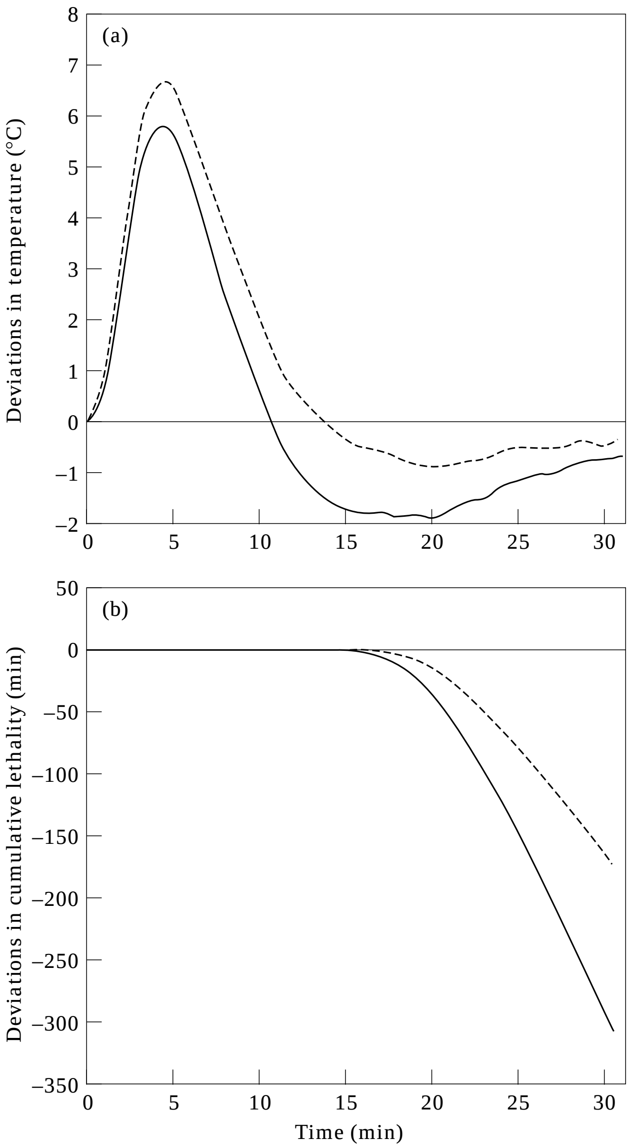

Fig. 1 Comparisons of temperature histories and cumulative lethality between experiment and simulation: (a) the deviations of the simulated temperature history from the experimental one and (b) the deviations of the simulated cumulative lethality from the experimental one by using the least square method (|——|) and the optimization method (|– – – – –|) at one stage heating approximation

Figure 2a clearly shows the significant improvement in the simulated temperature histories calculated using the h values from two stages, whether determined by the least square or the optimization method. **Table 2** indicates that compared to one stage approximation the mean MSRDs are reduced dramatically, 78.1% and 78.2%, by using h_{L1}, h_{L2} and h_{o1}, h_{o2}. The predicted P_{70} values are also improved significantly (**Fig. 2b**). The errors of the predicted mean P_{70} values are reduced from –21.5% and –11.3% to 4.3% and 3.0%, respectively, but coefficients of variance, CV, remain almost unchanged. t-tests show that at 95% confidence the h values, the simulated temperature histories and predicted P_{70} values calculated using these two methods are not significantly different.

Conclusion

For batch heating in a combination oven on Vario-steaming mode the mean h_L value determined by the least square method is smaller than the mean h_o determined by the optimization method. The simulated temperature histories using the h_L values show better agreement with experimental ones but the errors of the predicted mean P_{70} values are greater. According to the heat transfer mechanisms this process can be divided into two stages. As a result a significant improvement can be made in the process simulation, whichever method is used. The differences in the h values, the simulated temperature histories and the predicted P_{70} values by the two methods are diminished. Therefore, it is concluded that if the process is properly modelled there is no significant difference in process simulation using the least square or optimization method.

Nomenclature

a	thermal diffusivity (m^2/s)
b	slope index
C_p	specific heat (J/(kg.K))

D diameter of a disc (mm)
h apparent heat transfer coefficient (W/(m^2.K))
h_L, h_o apparent heat transfer coefficients for one stage determined by the least square or optimization methods (W/(m^2.K))
h_{L1}, h_{L2} apparent heat transfer coefficients for stage 1 and 2 determined by the least square method (W/(m^2.K))
h_{o1}, h_{o2} apparent heat transfer coefficients for stage 1 and 2 determined by the optimization method (W/(m^2.K))
k thermal conductivity (W/(m.K))
L thickness of disc (mm)
r radial distance of cylinder or disc (m)
t time (s)
T food temperature (°C)
T_b temperature at boundary node point (°C)
T_h process medium temperature (°C)
T_o initial food temperature (°C)
T_r reference temperature (°C)
x_i experimental temperatures (°C)
y vertical distance of a disc (m)
y_i simulated temperatures (°C)
$\partial T/\partial n$ outward normal gradient of temperature (°C/m)
ρ density (kg/m^3)

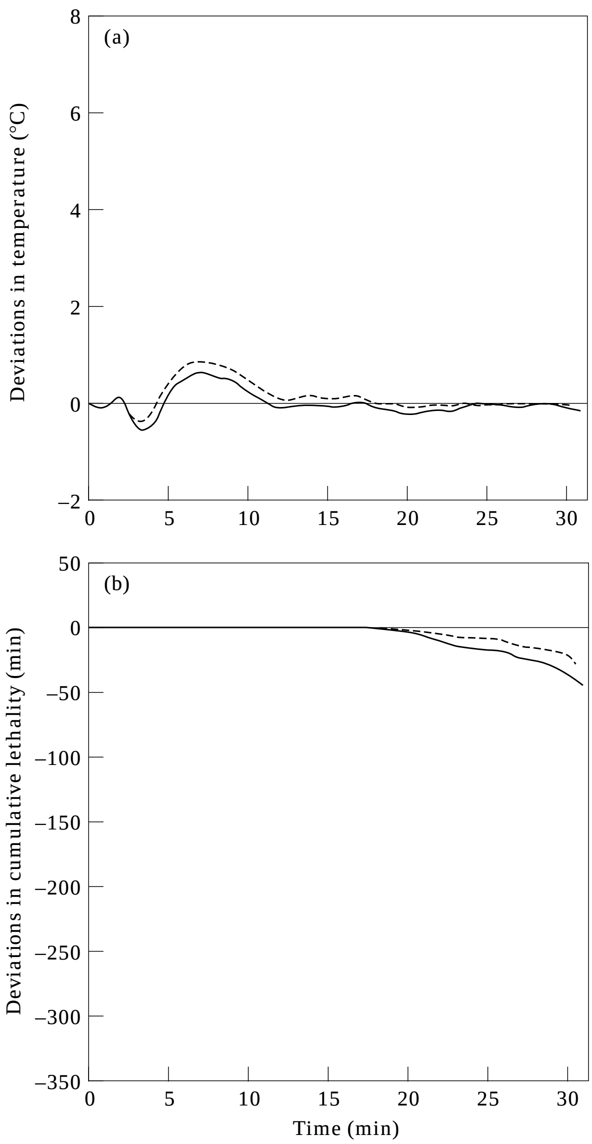

Fig. 2 Comparisons of temperature histories and cumulative lethality between experiment and simulation: (a) the deviations of the simulated temperature histories to the experimental one and (b) the deviations of the simulated cumulative lethality to the experimental one by using the least square method (|——|) and the optimization method (|– – – – –|) at two stage heating

References

1 Martens, T.A. European network of centres of competence in sous vide? *First European Sous Vide Cooking Symposium Proceedings*, pp. 152–159 (1993)
2 Smith, J.P., Ramaswamy, H.S. and Simpson, B.K. Developments in food packaging technology. Part II: storage aspects. *Trends in Food Science and Technology*, **8**, 120–124 (1990)
3 Beverly, R.G., Strasser, J. and Wright, B. Critical factors in filling and sterilizing of institutional pouches. *Food Technology*, **34**, 44–48 (1980)
4 Terashima, Y. Overall heat transmission from the heating medium (steam and water) to the contents of the retortable pouch. *Canner's Journal (Kanzume Jiho)*, **54**, 73–79 (1975)
5 Peterson, W.R. and Adams, J.P. Water velocity effect on heat penetration parameters during institutional size retort pouch processing. *Journal of Food Science*, **48**, 457–459, 464 (1983)
6 Adams, J.P., Peterson, W.R. and Otwell, W.S. Processing of seafood in institutional-sized retort pouches. *Food Technology*, **37**, 123–127, 142 (1983)
7 Ball, C.O. and Olson, F.C.W. *Sterilization in Food Technology*. New York: McGraw-Hill, pp. 215–227 (1957)
8 Mielche, M.M. Effect of different temperature control methods on heating time and certain quality parameters of oven-roasted beef. *Journal of Food Process Engineering*, **15**, 131–142 (1992)
9 Burfoot, D. and Self, K.P. Prediction of heating times for cubes of beef during water cooking. *International Journal of Food Science and Technology*, **23**, 274–257 (1988)
10 Lenz, M.K. and Lund, D.B. The lethality-Fourier number method. Heating rate variations and lethality confidence intervals for forced-convection heated foods in containers. *Journal of Food Process Engineering*, **2**, 227–271 (1978)
11 Lebowitz, S.F. and Bhowmik, S.R. Determination of retortable pouch heat transfer coefficients by optimisation method. *Journal of Food Science*, **54**, 1407–1412 (1989)
12 Mohsenin, N.N. *Thermal Properties of Foods and Agricultural Materials*. London: Gordon and Breach, p. 310 (1980)
13 Dickerson, R.W. and Reed, R.B. Jr. Calculation and measurement of heat transfer in foods. *Food Technology*, **22**, 1533–1543 (1968)
14 Smith, G.D. *Numerical Solution of Partial Differential Equations: Finite Difference Methods*, 2nd Edn. Oxford: Oxford University Press, pp. 75–121 (1978)

15 Gaze, J.E. and Brown, G.D. Determination of the heat resistance of a strain of non-proteolytic *Clostridium botulinum* type B and a strain of type E, heated in cod and carrot over the temperature range 70 to 92°C. *CFDRA Technical Memorandum No.592* (1990)

16 Lebowitz, S.F. and Bhowmik, S.R. Effect on retortable pouch heat transfer coefficients of different thermal processing stages and pouch material. *Journal of Food Science*, **55**, 1421–1424, 1434 (1990)