that contribute substantially to thermal degradation. The simple procedure is as follows: (1) Consider the temperature for each operation in a process. (2) Consider the time in each operation. (3) Calculate C_0 using $C_0 = 10^{(T-100)/33.2}$ × time for each operation. (4) Add C_0 values from each operation to get the total C_0 value for the process. If the z' value of the specific constituent is known (or can be calculated from Q_{10}), that value should be used in place of the $z' = 33.2$ °C which is a general average value when the exact data are lacking.

Once the operations with large contributions to thermal degradation are known, alternatives for reducing the degradation in these operations become a matter of economic and practical considerations.

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Equivalent-Point Method for Thermal Evaluation of Continuous-Flow Systems[1]

Kenneth R. Swartzel

The use of continuous thermal processing and aseptic packaging for preserving fluid foods is growing. Compared to in-can processing, continuous thermal processing offers reduced energy and packaging costs and favors product quality retention. Thermal treatments simultaneously produce beneficial and undesirable changes in products. Microbial destruction and enzyme inactivation are generally desirable, whereas quality factor changes such as with taste, color, and nutrient value are generally undesirable. Continuous thermal processes are described in terms of reaction rate kinetics. The usefulness of an equivalent-point method for optimizing the thermal treatments to achieve the desired changes with minimum undesired changes is discussed. Design criteria are examined with specific examples given.

INTRODUCTION

Continuous thermal processes associated with aseptic packaging have commonly been referred to as ultrahigh temperature (UHT). Contrary to batch heating (retorting), where exposure times can be lengthy (several minutes), UHT processes require only a few seconds. Determining the time and temperature requirement depends upon destruction of spoilage- and disease-causing microbial spores while minimizing undesirable physical, chemical, and biological transformations that occur within the product.

Desirable changes that occur during UHT processing are inactivation of biologically viable materials such as enzymes, microorganisms, and their spores. Undesirable changes are associated with loss of product quality (taste, color, nutrients, etc.). Designing for thermal optimization (maximum desirable changes and minimum undesirable changes) requires knowledge of reaction kinetics. Increased

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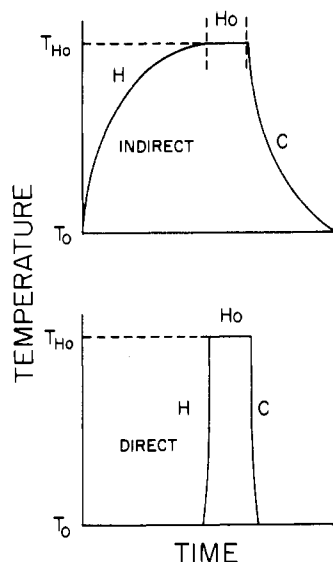
process temperature combined with decreased holding time can give the required lethal effect on microorganisms and simultaneously reduce the thermal effect on chemical reactions associated with loss of product quality, e.g. nutrient degradation. In these respects, optimization favors UHT processing.

In this paper, continuous thermal processes will be described. Process design will be discussed as it relates to reaction rate principles, and optimization of thermal treatments is examined by making use of an equivalent-point method for thermal evaluation.

CONTINUOUS-FLOW SYSTEMS

Two types of commercial continuous-flow processing systems are available: the direct and indirect heating units (Figure 1). With the indirect unit, product is heated via a heat-conducting surface, which separates the heating medium from the product. After the desired processing temperature is attained, the product is maintained at this temperature during the holding time. Cooling occurs in a separate heat exchanger, with product and cooling medium being separated again by a heat-conducting barrier. With the direct unit, product is mixed with saturated steam under pressure. This allows rapid heating of the product as the steam condenses. Again, product is held at the desired processing temperature for a given hold time.

Figure 1. Typical heating (H), holding (H$_0$), and cooling (C) time–temperature patterns for direct and indirect UHT processing.

Cooling occurs in the direct unit by vacuum treatment. This vacuum removes water added due to condensing steam and flash cools the product. In the direct-heating system, virtually all of the product constituent change occurs in the holding tube. The rapid steam heating and flash cooling contributes negligible change to the constituent. However, substantial change can occur during heating and cooling in an indirect unit.

Public Safety Considerations. For the public's safety, a holding tube sized to hold the fastest moving particle for a minimum specified time is the prevailing design factor. One method is to assume laminar flow. Since the characteristics of laminar flow are well-known, the holding tube length may be calculated by

$$L = 7.07 \times 10^{-7}(Qt_f/d^2) \qquad (1)$$

as given by Dickerson et al. (1968) with unit conversion.

Product Quality Considerations. When other than public health considerations are of interest, the determination of the holding-time standard must be based on mean velocity rather than fastest particle velocity. The measured mean residence time is twice the residence time for the fastest particle to travel through the holding tube under laminar flow conditions or by the unit conversion of eq 1:

$$t_m = 2.82 \times 10^6(Ld^2/Q) \qquad (2)$$

Heating and cooling of product are usually not considered as part of the thermal treatment from a public health standpoint. However, substantial alteration of quality can be realized in this part of an indirect heating process. To consider constituent changes due to the total thermal treatment, the design must take the heating and cooling sections into consideration. Several methods are available to do this (i.e., Deindoerfer and Humphrey, 1959; Richards, 1965; Renner, 1977; Hallström and Dejmek, 1977). They all depend on adequately defining the heating and cooling curves.

Time–Temperature Relationships. Actual bulk mean temperature measurements with calculated or measured residence times generate excellent time–temperature curves. In systems where bulk mean temperature measurements are difficult to obtain, the time–temperature curves may be deduced (Deindoerfer and Humphrey, 1959). The following equation applies to the general case
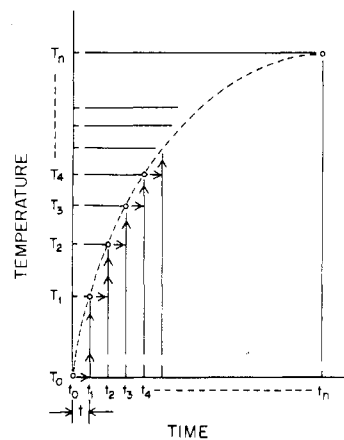

Figure 2. Graphical representation of time–temperature iteration procedure.

of isothermal exponential heating or cooling and gives the temperature T as a function of the time t

$$T = T_{(H,C)}[1 + b \exp(-Jt)] \qquad (3)$$

where

$$b = (T_o - T_{(H,C)})/T_{(H,C)} \qquad (4)$$

and

$$J = U_t A/\omega_p c_p \qquad (5)$$

Deindoerfer and Humphrey (1959) tabulated relationships for various types of heating and cooling. Identification of the heating and cooling system, physical properties, and required input and discharged temperatures would result in a temperature–time profile. However, physical properties (k_p, c_p, η_p, ρ_p, etc.) for most fluid foods in the UHT range are not know. For those fluids where properties are known, a graphical iteration may be performed to generate the required time–temperature curve (Swartzel, 1982) as shown in Figure 2. Initial parameter values are established at T_0, resulting in the determination of U_1. With U_1 a time interval t is selected. At t_1, T_1 is determined. With T_1, a new set of parameter values are used to determine U_2 and the iteration continues until the time–temperature curve emerges.

Thermal Evaluation. With reliable, complete thermal curves the task of incorporating defined kinetic data is at hand. Bigelow et al. (1920) and Ball (1923) pioneered the technology of thermal evaluation with developments related to the theory and practice of sterilization of canned foods. These evaluation techniques were based solely on empirically derived graphs for the killing of microorganisms. The development of rate laws for the degradation of constituents in food products during thermal treatment has been advanced by several investigators. These include Charm (1958), Johnson, et al. (1959), Deindoerfer and Humphrey (1959), Herrmann (1976), and Hallström (1977). Generally the rate low for degradation of a constituent under changing temperatures is as given by Deindoerfer and Humphrey (1959).

$$\ln (N/N_0) = -B \int \exp(-E_a/RT) \, dt \qquad (6)$$

At constant temperature, eq 6 becomes

$$\ln (N/N_0) = -Bt \exp(-E_a/RT) \qquad (7)$$

With changing temperatures (as in the heating or cooling sections of a heat exchanger) the fraction of population or constituent concentration active after the thermal treatment is more difficult to determine as will be demonstrated. With changing or constant temperature, reliable

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kinetic parameters in some form must be known.

Hallström (1977) noted that, by combining kinetic models for biological, chemical, and physical changes in the fluid with the established time–temperature relationship for the thermal process, evaluation may be accomplished. He defined three common kinetic models that have been incorporated into the time–temperature equation for process evaluations. The first model was an integrated form of the Arrhenius equation, as

$$k = B \int \exp(-E_a/RT) \, dt \qquad (8)$$

Hallström evaluated a direct and an indirect commercial UHT process and established a log (k/B) vs. E_a/R relationship to give a total thermal description of the processes over a broad kinetic range. He then utilized a second and third model where both incorporated the slope index (z value) of the thermal death–time curve. These expressions are well-known for calculating the lethal effect (F) and the effect on sensory changes (C = cook value), as

$$F_{(T^*,z)} \text{ or } C_{(T^*,z)} = \int 10^{(T-T^*)/z} \, dt \qquad (9)$$

or

$$\log (N/N_0) = \frac{-1}{D_T^*} \int 10^{(T-T^*)/z} \, dt \qquad (10)$$

To use eq 9 or 10 the z value has to be constant with the temperature range in question. $F_{(T^*,z)}$ and $C_{(T^*,z)}$ values alone do not give a complete thermal description of the process. However, data in this form, as shown later, can be used to generate a complete description of the thermal process. Also a plot of log (k/B) vs. (E_a/R) adquately defines the process and aids in making process comparisons. Since actual values of E_a and B are not required for this method, a thermal description for a given time–temperature relationship can be obtained.

In 1982, Swartzel extended the previous work by developing thermal reduction relationships (G values). For the heating or cooling time–temperature curve G was established as

$$G_{(H,C)} = \frac{1}{2.303J}\left[E_1\left(\frac{r}{1+b}\right) - E_1\left(\frac{r}{1+be^{-Jt_m'}}\right)\right] - \frac{e^{-r}}{2.303J}\left[E_1\left(\frac{r}{1+b} - r\right) - E_1\left(\frac{r}{1+be^{-Jt_m'}} - r\right)\right] \qquad (11)$$

where

$$r = E_a/RT_{(H,C)} \qquad (12)$$

J is from eq 5 and

$$G = \log (N_0/N)/B \qquad (13)$$

A different and distinct G for each different heating or cooling section (thermal curve) can be determined for each arbitrarily selected E_a value. G has also been defined for a holding section as

$$G_{Ho} = (t/2.303) \exp(-E_a/RT) \qquad (14)$$

For each selected E_a value, G values can be determined for the heating, holding, and cooling sections by eq 11–14. Recognizing that cumulative thermal effects of reactions can be summed by superposition, G values for the three sections are totaled for each selected E_a value. This total G value (G_{TOT}) is substituted into eq 14 along with the originally selected E_a value. Infinite time–temperature conditions would satisfy the equation. By plotting log t vs. T, a straight line results. By repeating the process for the same thermal curve (eq 3) with different selected E_a values, new log t vs. T lines emerge. Swartzel (1982)

Table I. $F_{(T^*,z)}$ and $C_{(T^*,z)}$ Values for Direct- and Indirect-Heating Systems (Hallström, 1977)

constituent	direct, min	indirect, min
destruction of microorganisms	$F_{(121°C,8.5°C)} = 14.6$	$F_{(121°C,8.5°C)} = 16.7$
	$F_{(121°C,10°C)} = 6.8$	$F_{(121°C,10°C)} = 8.7$
browning reaction	$C_{(100°C,21°C)} = 7.2$	$C_{(100°C,21°C)} = 14.7$
average chemical (nutrient) changes	$C_{(100°C,25°C)} = 3.5$	$C_{(100°C,25°C)} = 7.9$

demonstrated that these lines, representing different E_a values for a given indirect heating system, all tend to intersect at one unique point. He assumed any accumulated error in the process (thermocouple calibration, data acquistion, determination of exponential integrals in eq 8, etc.) would be indicative by imperfect intersections with three of more log t vs. T lines. The intersection points of these lines may be evaluated by regression analysis to determine statistically the most error-free intersection point for all lines. Although a detailed analysis of the error involved with the intersection has not been done, more information concerning the statisticaly analysis of the intersection is given in the literature (Swartzel and Jones, 1984). This intersection represents the equivalent time (t_E) and temperature (T_E) where the heat treatment described by the thermal curve is totally defined for determining reduction levels of any constituent for the mass average flow and referred to as the equivalent point. This equivalent point can be used to determine the thermal change of any constituent since it is independent of the E_a value. Therefore, each different process characterized by a heating, holding, and cooling curve can be described by one unique equivalent time and temperature. By combining eq 13 and 14 with t and T values replaced by t_E and T_E values, log reduction values for any constituent of interest may be determined with known E_a and B values, as

$$G_{TOT} = M/B = (t_E/2.303) \exp(-E_a/RT_E) \qquad (15)$$

$$\log (N_0/N) = (Bt_E/2.303) \exp(-E_a/RT_E) \qquad (16)$$

Therefore, with the determination of t_E and T_E for any thermal system described by definable heating, holding, and cooling curves, changes of any constituent may be determined.

As stated above, Hallström (1977) defined $F_{(T^*,z)}$ and $C_{(T^*,z)}$ values for an indirect- and a direct-heating UHT system. Three types of constituents were examined for various $F_{(T^*,z)}$ and $C_{(T^*,z)}$ values are noted in Table I. Examining the data in Table I alone makes comparing the two thermal systems difficult and may result in misleading conclusions. By plotting these data as in Figure 3, t_E and T_E values may be obtained. Similarity exists at low z values for both systems; however, the systems are very dissimilar at high z values. By describing each system with its particular t_E and T_E values, changes in any constituent (any z or E_a value) may be easily obtained by use of eq 16.

For design purposes, eq 15 and 16 and the method that utilizes them can be useful in several ways as described in the following sections.

DESIGN

Public health consideration must always be met first in the design of any thermal food process.

As stated earlier, since thermal destruction is logarithmic, total destruction theoretically cannot be accomplished. Therefore, to what nonzero level should the probability of survival be reduced? Lund (1975) discussed this point in relation to the reduction of *Clostridium botulinum*. Citing several historical references, a minimum
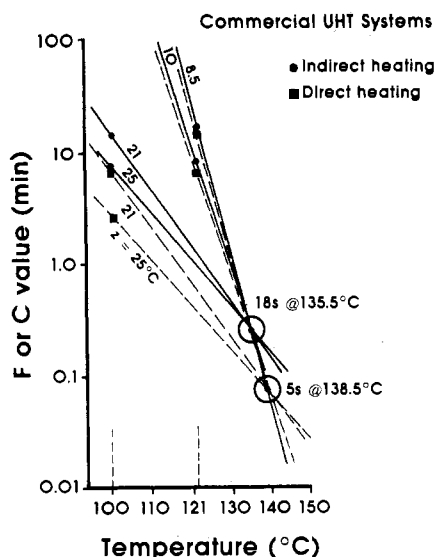
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Figure 3. Derivation of equivalent time and temperature values from $F_{(T^*_z)}$ and $C_{(T^*_z)}$ values for direct- and indirect-heating systems. Values for $F_{(T^*_z)}$ and $C_{(T^*_z)}$ are from Hallström (1977).
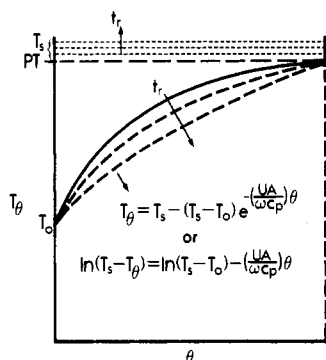

Figure 4. Typical heating time–temperature curves for indirect UHT processing. The arrow direction of t_r indicates the direction that the heating curve moves from time zero (solid line) as fouling deposit increases during run time.

design criterion of F_0 = 2.45 min as a 12-D destruction "bot cook" was established. However, spoilage is generally due to the survival of spores more heat resistant than *C. botulinum*. To balance destruction rates of these heat-resistant spore-forming bacteria with the heat-induced physical and chemical changes in the product, an F_0 = 5 min has been generally accepted for low-acid, aseptically processed and packaged foods. Nonetheless, for all aseptic processing the Process Authority establishes the required F_0 value, which is recommended to the Food and Drug Administration for acceptance. Process Authorities are organizations recognized as being able to determine whether a process satisfies all applicable regulations and will produce safe products for the public.

To select a process that provides the F_0 for microorganism destruction and keeps quality deterioration within acceptable limits requires consideration of thermal effects during heating and cooling. Since cooling processes are generally rapid and contribute much less than heating to the thermal treatment, it will be omitted in this discussion. However, if process cooling is slow, the cooling curve may need to be considered.

In the heating section, fouling may occur and change the thermal treatment (Figure 4) (Swartzel, 1983b). Deposit of food on the heat-transfer surface increases the resistance to heat flow into the product. Normally process controls are set to maintain a constant product discharge tem-
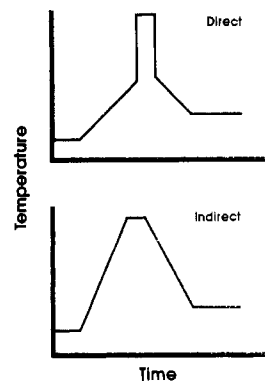

Figure 5. Comparison of linear heating curves for direct and indirect systems, representing the minimum thermal treatment for public health considerations.

perature from a heat exchanger. As fouling increases, the most severe case would ultimately result in a linear relationship between temperature and time in the heat exchanger (Figure 5). Although it may be theoretically possible to have a process that would generate a concave upward curve, realistic food-processing situations do not produce this effect. In fact, the limit of the heating system is generally reached (when maintaining a constant temperature at the end of heating section is no longer possible) much before the linear relationship develops. In practice, the minimum heat treatment available for pathogenic spore destruction results when the temperature–time curve is linear. Process design for microbial safety should be based on linear time–temperature relationships during heating (and cooling).

Deindoerfer and Humphrey (1959) solved the linear heating curve. With modification their solution becomes

$$G_{(H,C)} = \frac{E_a}{2.303RS} \left[E_1\left(\frac{E_a}{R(T_0 + St)}\right) + E_2\left(\frac{E_a}{RT_0}\right) \right] \tag{17}$$

The fastest particle's residence time in the heat exchanger is utilized to satisfy the requirement that all particles are heated for at least the minimum time. G_{TOT} values for selected E_a values are determined from eq 14. G_H values representing the linear heating portion of the thermal treatment are then determined from eq 17 for the same E_a values used in eq 14. If G_H is less than G_{TOT}, then additional thermal treatment is required by the addition of a holding section. Should the G_H value for the heating section be greater than the G_{TOT} value (based on T_E and t_E for F_0 = 5), a holding section is not required. The thermal treatment may be reduced in the heating portion until G_H values equal G_{TOT} values.

For quality considerations, G_H values are the largest for the initial (t_r = 0) thermal curve before fouling and should be used for design purposes. As fouling occurs, the thermal treatment is reduced, providing less constituent change; therefore, generally less quality reduction, is realized. However, for some quality factors (e.g., flavor) erosion of fouled material into the product may be more detrimental than the higher thermal treatment at t_r = 0. In calculating G_{Ho}, it is appropriate to use mean residence time for accessing quality deterioration.

Examples. The equivalent-point evaluation method will be used to study two examples of continuous thermal processing relating reaction kinetics and process design. Figure 6 indicates pasteurization design criteria for the production of extended shelf life refrigerated liquid whole egg (LWE) (Hamid-Samimi and Swartzel, 1985). Public
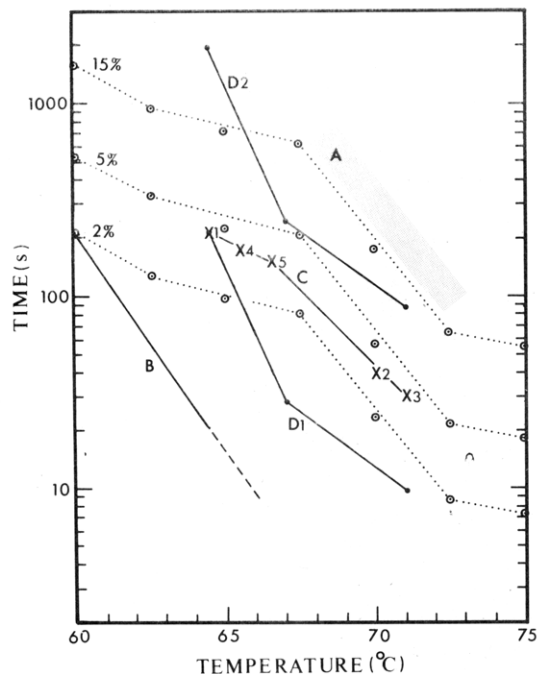
Figure 6. Constant soluble protein loss (SPL) levels in liquid whole egg (LWE) (dotted lines): A, coagulation region; B, 9-D inactivation curve for *Salmonella* in LWE; C, functionality curve (×1–×5 indicates different data point source); D1 and D2, 1-D and 9-D inactivation curves for *S. faecalis* var. *zymogenes* in LWE (Hamid-Samimi and Swartzel, 1985).

Figure 7. Limiting lines for the destruction of spores and effects on other constituents of whole milk.

health considerations are satisfied by line B, indicating a 9-D destruction level for *Salmonella* in LWE. Line C indicates the thermal level where functionality and product performance has not been seriously affected. This line does not allow for heating or cooling. Curve D1 represents 90% reduction for *Salmonella faecalis* var. zymogenes in LWE. Curve D2 corresponds to a 9-D inactivation curve for the same organism. Soluble protein loss (SPL) levels have been correlated to product performance, with 2–5% loss being considered normal for the total thermal treatment. Therefore, the upper limit of processing is established at the 5% SPL level. The region marked "A" represents the coagulation boundary—an area to be avoided. A region is shown rather than a line to indicate the variability in time of coagulation at a constant temperature. The preferred operating region would have a lower boundary of approximately 2% SPL with an upper boundary of 5% SPL. The times and temperatures in these regions may be considered as t_E and T_E values. Incorporation of the above kinetic data into the actual process design should be done as described earlier.

Kessler (1981) presented several design graphs for thermal treatment of milk. Figure 7 indicates the limiting lines for the destruction of spores and constituent changes of whole milk. Kessler concluded that a lower limiting line would be applicable to thermophilic spores with a thermal death value of 9 (9-D process). This he felt would give a "satisfactory spore destruction", even for a large daily production volume. This line also corresponds to the F_0 value of 5 min noted as the minimum design criterion above. He established a 3% loss of thiamine as an upper quality limit. Denny (1979) established decimal reduction values (D values) for a composite spore suspension of *C. botulinum* containing equal numbers of four strains of type B and four strains of type A at an inoculum level of 10^6 spores/mL of 1.5% fat milk. These are shown on Figure 7 as "bot cook", although values above 113 °C were ex-
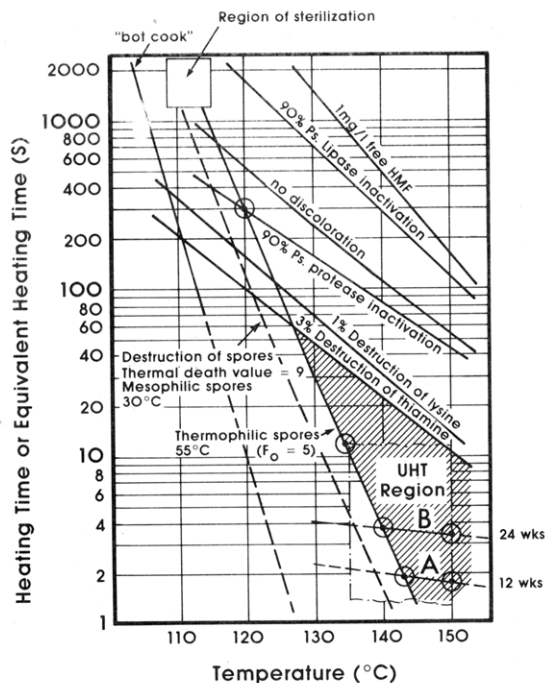
trapolated and, therefore, subject to question. Lines A and B were added to the Kessler graph to indicate the thermal aseptic treatment of whole milk for which the onset of gelation was 12 and 24 weeks, respectively (Swartzel, 1983a).

The shaded area representing the UHT region is bounded by a lower limit established for microbial safety and an upper limit defined by a quality deterioration. As described previously, the t_E and T_E values for the fastest particle (assuming laminar flow and linear heating and holding sections) should satisfy the lower limit. The t_E and T_E values associated with the initial mass mean heating temperature profile and holding section should not be above the upper limit. Future research may indicate that the upper limit may need to be reduced due to increased knowledge of kinetics as applied to flavor components.

Summary. Continuous-flow thermal processing and aseptic packaging of foods are techniques growing in use in the food industry. With increased use come new questions for the food engineer. To help answer these questions, the engineer needs tools to help design processes and processing systems. These tools consist of models and kinetic parameters that describe changes in constituents of foods as a result of the thermal processing. Such tools are used to improve or optimize existing processes and develop control systems for processing operations.

This work describes an equivalent-point method for thermal evaluation of continuous-flow systems. This method or tool is a technique that defines the thermal treatment with one time and one temperature, independent of activation energies. It offers a complete kinetic description of the thermal system. It depends on accurate thermal histories. The usefulness of the method is described with specific evaluation and design examples given.

Present work involves (1) evaluating the error limits on the equivalent point intersection, (2) utilizing the method to generate kinetic data during continuous flow and at high temperatures simulating actual process conditions, and (3) investigating the use of the method to evaluate constituents that may be used as thermal system evaluation calibration materials.

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NOTATION

A	heat-transfer surface area (m^2)
b	$(T_0 - T_{(H,C)}/T_{(H,C)}$ (dimensionless)
B	Arrhenius frequency constant (s^{-1})
c_p	product specific heat (J/kg K)
$C_{(T^*,z)}$	chemical (sensory changes) evaluated at z and T^* (min)
d	holding tube diameter (m)
D_T	thermal resistance value or decimal reduction value (DRT) at temperature T to reduce population or concentration by 90% (min; s)
E_a	activation energy (J/mol; kcal/mol)
$E_{1(\alpha)}$	$\int_\alpha^\infty (e^{-t}/t)\, dt$; exponential integral of order 1 with compliment α
$E_{2(\alpha)}$	$\int_\alpha^\infty (e^{-t}/t^2)\, dt$; exponential integral of order 2 with compliment α
$F_{(T^*,z)}$	equivalent time at T^* delivered to the product evaluated at z (min)
F_0	number of equivalent minutes of $T = 121$ °C delivered to a product using a z value of 10 °C (min)
$G_{(H,H_0,C)}$	product constituent reduction relation (H, heating; H$_0$, holding; C, cooling) (s)
G_{TOT}	product constituent reduction relation for total system (s)
J	$U_t A/c_p w_p$ (s^{-1})
k	rate constant (s^{-1})
k_p	thermal conductivity of product (W/m K)
L	holding tube length (m)
M	reduction expondent (substrate concentration reduced by a factor 10^M) (dimensionless)
N	constituent population or concentration (amount/volume)
N_0	initial population or concentration (amount/volume)
N/N_0	fraction of population or concentration active after thermal treatment
Q	fluid flow rate (1/h)
r	$E_a/RT_{(H,C)}$ (dimensionless)
R	universal gas constant (8.314) (J/mol K)
S	slope of linear heating or cooling time–temperature relationship (°C/s)
SPL	soluble protein loss (%)
t	time (s)
t_E	equivalent time (s)
t_f	fastest particle residence time (laminar flow) (s)
t_m	mean product residence time (s)
t_m'	total mean residence time (s)
t_r	process run time (h)
T	temperature (K; °C)
T^*	reference temperature (K; °C)
$T_{(H,C)}$	temperature of heating media T_H or cooling media T_C (K; °C)
T_E	equivalent temperature (K; °C)
T_0	initial or inlet temperature (K; °C)
U_t	overall heat transfer coefficient at processing run time t; when t is numerical, a time sequence is indicated as on Figure 3 (J/m^2 h K)
UHT	ultrahigh temperature (generally refers to continuous aseptic thermal treatment)
V_m	mean fluid velocity (m/s)
z	temperature increment to reduce thermal death time 10-fold or to cause the F or D value to change by a factor of 10 (K; °C)
η_p	absolute viscosity of product (Pa s)
ρ_p	density of product (kg/m^3)
ω_p	mass of flowing product in heat exchanger (kg)
θ	mean residence time through the heat exchangers, also used as a subscript (s) (Figure 4)

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