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On the conversion factors in thermal processes

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Summary

Converting experimental or assumed heating parameters of one container size to another using the so-called conversion factor, CF, is an important practical step in the initial design of thermal processes. However, the current prevailing approach for conversion is limited to cans where the two containers are of metal and are processed essentially in the same heating medium. The present study develops the theoretical equations, verified experimentally, for the conversion factors in a broader spectrum of containers (e.g., glass jars to metal cans and vice versa) and different processing media (e.g., water to steam and vice versa). The developed relationships enable the thermal process engineer to use conversion factors in a simple manner for most practical processing conditions.

Introduction

Converting experimental or derived heating parameters of one container size to the heating parameters for another container size is an important practical step in the design and monitoring of thermal sterilization processes. Presently, the prevailing approach for such a procedure, using the so-called conversion factor, CF, is essentially based on the Schultz & Olson (1938) analysis for convection heating and the Ball & Olson (1957) analysis for conduction heating.

The approach to conversion factors divides the processed foods into two categories: those heated primarily by a convection mechanism and those heated primarily by conduction. Using this overall approach analysis, for convective heating products Schultz & Olson (1938) suggested that the heating rates (i.e., the temperature response parameters, f) for the same product packed in two different container sizes will be proportional to their respective volume/area

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ratio. For conduction heating, the Ball & Olson analysis suggests that the temperature response parameter, f, in any direction of the major axes of the body, can be derived from the expression $\frac{f\alpha}{R^2} = N_{Bi}$. The theory and analysis for conversion factors is fully delineated by Ball & Olson (1957). Using the above approach, conversion factors for a matrix of can sizes for conduction and convection heating were calculated and tabulated (Ball & Olson, 1957).

The limitation of the developed conversion factors is that they are valid only if the two containers are of metal and are processed essentially in the same heat transfer medium. Processing situations theoretically cannot be handled through the present conversion factor system where two different heating media are involved (e.g., water *vs* steam) or when the two containers are of a different type materal (e.g., glass jar *vs* metal container). Therefore, there is a need to develop conversion factor equations, especially for products heated primarily by convection, which will account for processing parameters such as different heating media or different container materials.

The purpose of this study is to: (a) discuss, in general terms, the conversion factor for conduction heating products and (b) develop from a theoretical basis the convection conversion factor equations or a wide spectrum of conditions as well as verify that these developed conversion factors give accurate results.

Analysis and discussion

Conversion factors for conducting heating

The theory of conversion factors for conduction-heated food products is well delineated by Ball & Olson (1957). The temperature response parameter, f, can be derived from $\frac{f\alpha}{R^2}$, which is a function of the N_{Bi}. In the range of N_{Bi} prevailing for conduction heating food products processed either in steam or agitated water, the $\frac{f\alpha}{R^2}$ for a cylindrical container (a finite cylinder) or a rectangular container (a finite slab) will assume a constant value. This constant value of $\frac{f\alpha}{R^2}$ is derived from similar $\frac{f\alpha}{R^2}$ constants for each specific one-dimensional configuration that defines the body. Since the $\frac{f\alpha}{R^2}$ for a given uniform body heated by conduction will assume a constant value whether processed in steam or agitated water, the respective conversion factor between these two media (for the same container size and type) will be approximately one. This assumes that the heated body as a whole (i.e., the product plus the container) has uniform thermal properties. In the case of food products packed in metal cans (and to some extent also in flexible pouches), this assumption is reasonably accurate since the wall, due to its thickness, has a small temperature gradient across it as well as little effect on the overall heat capacitance of the system.

The situation is slightly different for glass jars. The thermal conductivity of glass is larger than that of food materials, and food materials have a smaller respective heat capacity. (The thermal conductivity of glass is about twice that of water and the respective heat capacity is approximately half, leading to a 4:1 ratio in thermal diffusivity.) An observation of a qualitative nature is that the converted f-value, based upon the jar's exterior dimensions and the thermal properties of the entire body taken uniformly to be that of the packed food, will probably result in a slightly larger (though close) f-value compared to the experimental value. The data given by Townsend *et al.* (1949) for conduction heating products packed in metal cans and glass jars substantiate this approach. Thus, it seems safe that one can convert heating data from metal cans to glass jars by assuming the glass wall to have the thermal properties of the packed food, i.e., to assume the jar with its external dimensions to be solid food.

If more accurate results are required, a quantitative approach should be used where in the food product packed in a glass jar is represented by a body with multilayer thermal properties. Analysis of such multilayer transient conduction systems requires special mathematical techniques, mainly numerical methods, such as a finite difference or finite elements. A complete analysis of the transient conduction heat transfer in such a case (leading to, among other things, the determination of appropriate conversion factors) is in progress by our group.

Conversion factors for convection heating

Convection heating is assumed for products with viscosities not greatly different from water heated in a non-agitated mode (e.g., juices, thin soups, and small particles in liquid such as peas in brine, etc.) and for products with a higher viscosity for agitated processes (e.g., thick soups, cream style corn, etc.). Under such conditions it is assumed that the container and its contents are heated in (or close to) a Newtonian manner (i.e., small, negligible temperature gradients within the product). Under such conditions the heat flow through the container to the product can be derived in the following lumped-sum form:

$$MC_p \frac{dT}{dt} = A\ U\,(T - T_1) \tag{1}$$

where

$$\frac{1}{U} = \frac{1}{h_o} + \frac{l}{k} + \frac{1}{h_i}. \tag{2}$$

Rearranging eqn (1) integrating it between the boundary conditions ($T = T_o$ at

$t=0$) and converting the logarithm from natural to base 10 yields:

$$2.303 \log \frac{T_1 - T}{T_1 - T_o} = \frac{A}{MC_p} U\,t. \tag{3}$$

Equation 3 yields a straight line on a semilogarithmic scale. Defining the temperature response parameter, f, to be the time required for the unaccomplished dimensionless temperature value $(T_1 - T)/(T_1 - T_o)$ to traverse one log cycle, one gets:

$$2.303 \log 10 = \frac{A}{MC_p} U f \tag{4}$$

or

$$f = \frac{2.303\, MC_p}{A} \frac{1}{U}. \tag{5}$$

Substituting the value of U (eqn 2) into eqn 5 yields:

$$f = \frac{2.303\, MC_p}{A} \left(\frac{1}{h_o} + \frac{l}{k} + \frac{1}{h_i} \right). \tag{6}$$

Equation (6) is the overall expression for the temperature response parameter, f, in convection heating, with the ratio between any two f-values being the respective conversion factor. Before proceeding, it is worthwhile to analyze the significance of the MC_p, l, and the A parameters in eqn (6).

The heat capacity, MC_p, represents the total heat capacity of the heated body, i.e., the container plus its contents. In the case of a metal container or a flexible pouch the heat capacity of the container is obviously negligible compared to that of the contents (for example, the heat capacity of a 303 × 406 can filled with an aqueous solution is approximately 0.01 and 1.1 Btu/lb°F for the container and contents respectively.) However, in cases where products are packed in glass jars, the container heat capacity is not negligible and should be taken into account. (For example, the heat capacity of a 303 × 508 glass jar filled with an aqueous solution is approximately 0.087 and 1.08 Btu/lb°F for the glass jar and contents respectively.)

The thickness of the glass, l, a major resistance to heat flow, is not uniform throughout the jar and may vary by as much as 30%. From the basic heat transfer equation, $Q = \frac{k}{l} A \Delta T$ (ΔT is the temperature gradient across the glass), it can easily be shown that the average thickness, l, is more acurately described as $A/l = \frac{1}{n} \sum_{i=1}^{n} (A/l)_i$, or if equally spaced across the glass surface, $1/l = \frac{1}{n} \sum_{i=1}^{n} 1/l_i$, rather than the usually taken arithmetic average of $l = \frac{1}{n} \sum_{i=1}^{n} l_i$.

The area A, represents the surface available for the transfer of heat. In computing the heat transfer surface one must resolve whether the compared heat transfer area of the containers should (or should not) include the top (i.e., $A = \pi DH + 2\pi D^2/4$ *vs* $A = \pi DH + \pi D^2/4$). There is significant evidence indicating that the heat transfer coefficients through the headspace (i.e., the top) are much smaller than those through the areas in direct contact with the internal fluid. This is especially true for convective heating systems where he heat transfer coefficient through the headspace is from 2 to 10 Btu/hr ft^2 °F and where the heat transfer coefficient through the internal liquid is approximately 100 Btu/hr ft^2 °F (Blaisdell, 1963: Evan & Board, 1954; Hidding, 1975). This suggests that when dealing with vertically-positioned nonagitated containers, the area of comparison should probably exclude the top (i.e., $A = \pi DH + \pi D^2/4$). On the other hand, for agitated processes or horizontally-positioned containers (e.g. Hydrostatic and Hydrolock retort systems) the considered area should include both the top and bottom surfaces. However, for most cases (excluding shallow containers) the method of area selection will have a relatively small effect on the conversion factors.

Solutions for conversion factors in convective heating are derived below for several practical cases. In general, the conversion factors deal with the same product packed in two different containers but exposed to a similar mode of turbulence-promoting forces (natural or forced). Under such circumstances one can assume that the internal heat transfer coefficient, h_i(primarily dominated by viscosity and sheer forces), has similar values in both containers.

The relationship between the f-values of a convective heating product packed in two different containers can therefore be derived by extracting the value, $\frac{1}{h_i}$ (eqn 6), from the equation for the first container (Index 1) and substituting into the quation for the second container (Index 2) yielding the general, overall relationship (eqn 7).

$$f_2 = \left(\frac{2.303\ MC_p}{A}\right)_2 \left[\left(\frac{fA}{2.303\ MC_p}\right)_1 + \left(\frac{l}{k}\right)_2 - \left(\frac{l}{k}\right)_1 + \left(\frac{1}{h_o}\right)_2 - \left(\frac{1}{h_o}\right)_1\right] \quad (7)$$

Equation 7 is the overall relationship between the f-values of two containers (the conversion factor being the respective ratio), taking into account the container wall properties (l/k) and the processing medium heat transfer coefficient, h_o

Metal can to metal can

Processing two metal cans (or flexible pouches) in the same heating medium means the exterior heat transfer coefficients, h_o, are equivalent. The value of l/k

for metal is always negligible. Therefore, eqn (7) will become:

$$f_2 = \left(\frac{2.303\ MC_p}{A}\right)_2 \left(\frac{fA}{2.303\ MC_p}\right)_1 \tag{8}$$

or

$$CF = \frac{f_2}{f_1} = \frac{(MC_p/A)_2}{(MC_p/A)_1}. \tag{9}$$

Neglecting the heat capacitance of the metal, eqn 9 will yield:

$$CF = \frac{f_1}{f_2} = \frac{(V/A)_1}{(V/A)_2}. \tag{10}$$

Equation (10) is in the classical form expressed by Schultz & Olson (1938). The ratio (V/A) in eqn 10 can be expressed in terms of the linear dimensions for any given shape of a body.

Metal can to glass jar (and vice versa)

If the metal can and the glass jar are processed in the same heating medium, one can assume that the value of $1/h_0$ will be about the same. (The value of l/k for metal is negligible.) Eqn (7) is thus reduced to eqn (11), the conversion factor then being f_G/f_M. (G and M indicate glass and metal respectively).

$$f_G = \left(\frac{2.303\ MC_p}{A}\right)_G \left[\left(\frac{fA}{2.303\ MC_p}\right)_M + \left(\frac{l}{k}\right)_G\right] \tag{11}$$

The method of conversion from a glass jar to a metal can is performed in a similar manner, thus arriving with eqn 12:

$$f_M = \left(\frac{2.303\ MC_p}{A}\right)_M \left[\left(\frac{fA}{2.303\ MC_p}\right) - \left(\frac{l}{k}\right)_G\right]. \tag{12}$$

Glass jar to glass jar

If two glass jars have the same wall thickness and are processed in the same heating medium, the ratio of the f-values becomes trivial and is identical to the expression in conversion from metal to metal. That is,

$$\frac{f_1}{f_2} = \frac{(MC_p)_1/A_1}{(MC_p)_2/A_2} \tag{13}$$

where the MC_p represents the entire heat capacity (i.e., the heat capacity of the jar plus that of the contents) for the respective jars.

Conversion factor for two different processing media

When two containers are processed in two different media, the exterior heat transfer coefficient, h_o, should be taken into account. Clearly, the film heat transfer coefficient for condensing steam ($h_o > 3{,}000$ Btu/hr ft^2 °F) is at least one order of magnitude larger than that of agitated water ($h_o \sim 175$ to 400 Btu/hr ft^2 °F—Merril, 1948; Cowell *et al.*, 1959); therefore, the value, $1/h_o$, for steam can be neglected. The actual value of h_o for water should be selected based on experimental data, available correlations, or on an acceptable value from the literature.

The use of this conversion factor will be discussed with the following example of frequently-occurring situation. The heating parameter is required for a product packed in a glass jar to be processed in water. The heating data are available for the product packed in a metal can processed in steam. The following conversion equation is derived from eqn 7:

$$f_G = \left(\frac{2.303\ MC_p}{A}\right)_G \left[\left(\frac{fA}{2.303\ MC_p}\right)_M + \left(\frac{l}{k}\right)_G + \left(\frac{1}{h_o}\right)_G\right] \qquad (14)$$

Thus, the f-value or the conversion factor for other possible cases can easily be obtained by substituting the appropriate values into eqn 7.

Extensive experimental heat penetration data were reported by Townsend *et al.* (1949) for several products in many sizes of glass jars and metal containers processed in water and steam. We have used these data to verify our proposed derived conversion factor equations. Sets of data were tested using the appropriate conversion factor equations by inserting the appropriate thermal properties and correcting for the container dimensions (for headspace, can rims, double seams—see examples 1 and 2), as well as the glass thickness of jars (average of 2.0 mm for 202 × 309 or smaller and 2.3 mm for 208 × 401 or larger). The results (Table 1) indicate that good agreement exists between the converted f_h-values and the experimental values including converted f_h-values calculated over a wide range of container sizes, as well as simultaneously changing from one heating medium and container type to another.

Example 1. The f_h for a 401 × 411 metal can (A2-1/2), filled with 1% bentonite (convective heating) and processed in water, was reported by Townsend *et al.* (1949) to be 6.5 min. It is desired to predict the f_h for a smiliar-sized 401 × 411 jar filled with the same material and processed under similar conditions.

The thermal properties of the 1% bentonite solution were taken as those of water. Thermal conductivity of 0.6 and 9.25 Btu/hr ft^2 °F, specific heat of 0.2 and 0.12 Btu/lb °F, and density of 2.23 and 7.9 were used for glass and steel respectively. Corrections for headspace were taken to be 0.4 and 0.24 inches for the glass jar and the metal can respectively. Values of 0.25 and 0.13 inches were subtracted from the metal can's 401 × 411 nominal dimensions, reflecting rim correction for the height and thickness correction (of the double seam and of the wall) for the diameter to estimate the dimensions of the solution in the can.

Table 1. f_h Predicted based upon conversion factor equations

	Reference container				Desired Container						
								f_h, min.			
No.	Size	Heating medium	Type	f_h* Reported (min)	Size	Heating medium	Type	Predicted	Reported*	Percentage difference	Eqn used
1	202 × 214	Steam	Metal	4.5	202 × 309	Water	Glass	9.5	8.3	+ 10	14
2	211 × 210	"	"	4.1	208 × 401	"	"	10.5	10.2	+ 3	"
3	307 × 409	"	"	5.1	303 × 411	"	"	12.6	14.6	− 14	"
4	401 × 411	"	"	5.8	202 × 309	"	"	7.8	8.3	− 6	"
5	"	"	"	"	208 × 401	"	"	9.8	10.2	− 4	"
6	"	"	"	"	303 × 411	"	"	12.5	14.6	− 14	"
7	202 × 214	Water	"	3.2	202 × 309	"	"	7.0	6.9	+ 7	11
8	211 × 210	"	"	4.4	208 × 401	"	"	9.3	8.8	+ 6	"
9	202 × 214	"	"	3.2	202 × 309	"	"	6.9	6.9	0	"
10	"	"	"	1.8	"	"	"	5.4	6.0	− 10	"
11	"	"	"	2.8	"	"	"	6.5	7.1	− 8	"
12	211 × 210	"	"	3.4	208 × 401	"	"	8.4	8.9	− 6	"
13	401 × 411	"	"	6.5	401 × 411	"	"	13.3	13.8	− 4	"
14	"	"	"	5.5	"	"	"	12.3	13.4	− 8	"
15	208 × 401	"	Glass	8.9	211 × 210	"	Metal can	3.95	3.9	+ 1	12
16	"	"	"	"	202 × 214	"	"	3.3	3.8	− 13	"
17	401 × 411	"	"	13.4	401 × 411	"	"	6.11	6.0	+ 2	"
18	202 × 309	"	"	8.3	208 × 401	"	Glass jar	9.7	9.5	"	13
19	208 × 401	"	"	8.8	401 × 411	"	"	13.7	13.4	"	"
20	401 × 411	"	"	13.4	202 × 309	"	"	7.2	7.0	+ 3	"

*Data reported by Townsend *et al.*, (1949) Knowing the glass wall thickness of the 401 × 411 glass jar ($l = 2.3$ mm) and using eqn (11), the predicted f_h was found to be 13.3 min, 4% less than the experimental value of 13.8 min reported by Townsend *et. al.*, 1949) (example 13, Table 1).

Example 2. The f_h for a 401 × 411 metal A2-1/2 can filled with 1% bentonite processed in steam was reported as 5.8 min (Townsend *et al.*, 1949). It is desired to predict the f_h for a 202 × 309 baby glass jar filled with the same material processed in water.

Substituting the thermal properties (outlined in example 1) and exterior water film coefficient, h_o, of 250 Btu/ft^2 °F into the appropriate equation (eqn 13) yielded an f_h of 7.8 min for the 202 × 309 glass jar as compared to the experimental value of 8.3 min reported by Townsend (Example 4 in Table 1). Though the above conversion was performed over a wide range of sizes (volumetric ratio of 401 × 411 to 202 × 309 is approximately 2:1) as well as when changing the heating medium, only a small difference (about 6% between the 7.8 min predicted and the 8.3 min measured) was determined.

The exterior heat transfer film coefficient in agitated water ranges approximately between 175 and 400 Btu/hr ft^2 °F. The exact value depends primarily upon the degree of turbulence and the body configuration. The selected value of the heat transfer coefficient will obviously affect the computed f_h. A significant decrease in the f-falue is expected when increasing the extermal heat transfer coefficient from 50 (minimum h_o for nonagitated water) to 200 Btu/hr ft^2 °F, after which the f-value rapidly approaches an asymptotic value.

In conclusion, the present study developed the theoretical equations for the conversion factors in a broader spectrum of containers (e.g., glass jar to metal can and vice versa), as well as processing media (e.g., water to steam and vice versa), and verified experimentally that the converted values provide accurate results. The developed equations enable the thermal process engineer to use conversion factors in a simple manner for most pratical processing conditions.

Finally, the application of any type of conversion factor should be used with care. One should bear in mind that for a given product (even processed under similar tubulence-promoting conditions) changes in type of container size, kind of filling, etc. can lead to unaccountable dissimilarities resulting in process deviation. As such, conversion factors should be used only as the preliminary step of process design and by no means should they be interpreted as a substitute for the final experimental validation step of the actual delivered lethality.

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Notations

A: Surface heat transfer area
CF: Conversion factor—the ratio between two heating rate parameters
D: Container diameter
f: The temperature response parameter—the time required for the straight portion of the semilogarithmic curve to traverse one log cycle
H: Container height
h_i: Internal heat transfer coefficient
h_o: External heat transfer coefficient
k: Thermal conductivity of wall material
l: Thickness of wall
MC_p: Heat capacity
N_{Bi}: Biot number
Q: Heat flow
R: Characteristic dimension
t: Time
T: Temperature, variable
T_r: Medium temperature
T_o: Initial temperature
U: Overall heat transfer coefficient
V: Volume of body
α: Thermal diffusivity

References

Ball, C.O. & Olson, F.C.W. (1957) *Sterilization in Food Technology*. McGraw Hill Co., Inc. New York.

Blaisdell, J.L. (1963) Natural Convection Heating of Liquids in Unagitated Food Containers. Ph.D. thesis. Michigan State University (Unpublished).

Cowell, N.D., Evans, H.L., Hicks, E.W. & Mellor, J.D. (1959) *Fd Technol., Champaigne,* **13,** 425.Evans, H.L. & Board, P.W. (1954) Studies in canning processes. 1. effects of headspace on heat penetration in products heating by conduction. *Fd Technol. Champaigne,* **8,** 258.

Hiddink, J. (1975). *Natural Convection Heating of Liquids with Reference to Sterilization of Canned Food.* Ph.D. thesis. Wageningen, Holland.

Merrill, O.G. (1948) *Ind. Eng. Chem.* **40,** 2263.

Schultz, O.T. & Olson, F.C.W. (1938) *J. Fd Sci.* **3,** 647.

Townsend, C.T., Reed, J.M., McConnell, J., Powers, M.J., Esselen, Jr, W.B., Somers, I.I., Dwyer, J.J. & Ball, C.O. (1949) *Fd Technol., Champaigne,* **6,** 212.

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