Verification for ATS Method of New Sterilizing–Value–Estimation–Method

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Since the Ball Formula Method was proposed in 1923, the development of sterilizing–value–estimation–methods has a history of about 100 years. Even today, the Formula Method at an early stage is widely used in food manufacturing because of its ease of use. However, due to advances in thermal processing systems, the range in which this Formula Method can be used has been limited in recent years. To overcome this problem, author proposed the Ambient Temperature Slide method based on a new idea in 2006. The correlation equation, which includes two parameters, heat–transfer coefficient and delay–time, was theoretically obtained using two hypotheses from the expansion of the heat–balance equation. The purpose of this time is to verify the hypothesis of the delay–time δ left behind in the previous third report and finally complete the ATS method theory, and to compare and verify it with Ball Formula Method which represents conventional methods. Both use common sterilizing data that can be investigated for versatility. In this case, the result of the latter comparative verification is also the verification of the former. The ATS method has now been verified for versatility been based on accuracy, confirming all of its outstanding accuracy, versatility, and simplicity.

Keywords: thermal processing, sterilizing value (F_p-value), Ball Formula Method, Ambient Temperature Slide method (ATS method), curve–fitting

1. Introduction

The development of the sterilizing–value–estimation–method for thermal processing has a history of about 100 years since the Ball Formula Method was proposed in 1923. The original Ball Formula Method was widely spread and it is still used in manufacturing sites of the food. This Ball Formula Method uses the parameters f and j obtained from the heat–penetration–curve analysis found in textbooks on sterilizing technology [1–3]. The estimation–methods proposed after Ball have been almost all constructed using the parameters f and j except the ATS method. It is the same in all the conventional methods such as Gillespy’s Method, Hayakawa’s Method, Stumbo’s Method, Pham’s Method, Teixeira’s Time–Shift Method and Noronha’s Apparent–Position–Numerical–Solution [4–17]. At present, none of these methods have shown practical utility in the food industry. As a result, only the Ball Formula Method (hereafter simply referred to as the Formula Method) has been popular and settled worldwide.

Since the environment of sterilizing technology has changed in recent years, the range of use of this Formula Method has been greatly limited. Today, retort sterilizers have been dramatically improved by the addition of water–cascade and water–spray types to the original steam and water–immersion types in order to improve food quality. The author paid attention to the above Formula Method and developed the ATS method with the aim of creating the estimation–method of sterilizing value that exceeds that performance [18–20]. The purpose of this time is to carry out the verification of the hypothesis left behind in the previous third report that there is a delay–time in the ambient temperature and finally complete the ATS method theory. And it is to compare and verify it with the Formula Method which represents conventional methods.

The ATS method was developed based on the idea of a processing system for food in a package containing air. In short, it was created by switching the gas phase temperature to the central–part temperature of solid/liquid in the correlation–equation used for temperature–estimation of that processing system. The central–part temperature described here refers to the coldest spot temperature in a container to be exact. The correlation–equation is extremely simple as follows:

\[ T_{p,n} = T_{p,n-1} + \tau \times (T_{w,n-1} - T_{p,n-1}) \]  \hspace{1cm} (2-1)

Here, \[ T_{w}(t) = T_{w}(t-\delta) \]

Therefore, the parameters that the ATS method utilizes are only the \( \tau \) and \( \delta \) involved in the correlation–equa-
These parameters \( \tau \) and \( \delta \) have the same physical characteristics as the parameters \( f \) and \( j \) of the heat-penetration-curve analysis, but since they are greatly different in terms of concreteness, a comparative study will be made this time.

This correlation-equation (2-1) was theoretically obtained using two hypotheses from the expansion of the heat-balance equation for a finite object, as described in the next section. The verification of the hypothesis of delay-time \( \delta \) left behind at the previous third report is completed by the result of comparative verification with the Formula Method described below. This is because both have the same requirements for versatility confirmation, so the result of the latter comparative verification become the former verification. In particular, the former hypothesis has the character of being verified by accumulating many proofs of good versatility.

In order to evaluate the new sterilizing-value-estimation-method, the ATS method, the performance was compared with the Formula Method, which is currently the most practical. In this case, it is essential to select sterilizing data in consideration of versatility. Here as the Formula Method, Ball's empirical formula was adopted in order to be able to draw the central-part-temperature curve \([3, 21]\). And the author first made it possible to visually on the graph compare the accuracy of the estimation. In order to satisfy the versatility survey aimed at by these two verifications, eight sterilizing data samples with different combinations of food heat-transfer properties and processing systems were selected by careful examination. As a result, it was confirmed that the ATS method is far superior to the Formula Method in terms of accuracy, versatility, and simplicity.

2. Theory

Here, the theory of the finally completed ATS method is explained. The ATS method is developed based on the four premise conditions composed with the assumptions and verification results described below. I will describe them in a schematic diagram (Fig. 1) of heat-transfer model in retort processing.

Premise condition 1: \( L (=V/A) \) is assumed as the distance from surface to central part of packaged food.

Premise condition 2: Surface temperature of packaged food \( (T_s) \) is assumed to be equal to ambient temperature \( (T_w) \).

Premise condition 3: Temperature gradient from surface to central part of packaged food is assumed as linear.

Premise condition 4: Two difference values, \( \Delta T_p^* \) and \( \Delta T_p \), are assumed to be equal. This is because it was verified by the previous third report that curves of space-mean temperature \( (T_p^*) \) and central-part temperature \( (T_p) \) had similarity relationship and are very closer to each other. Here, the similarity relationship was obtained from the verification of the hypothesis that the space-mean temperature also has a delay-time.

The fundamental equations regarding heat transfer in ATS method under above premise conditions are developed as follows. Quantity of heat \( (\Delta Q_T) \) that transfers from the outside to the inside of packaged food during small time increment \( (\Delta t) \) is expressed as the following equation.

\[
\Delta Q_T = (kA)(T_w n-1-T_p n-1)(\frac{\Delta t}{L})
\]

(2-2)

Here, \( k \) and \( A \) indicate thermal conductivity and surface area, respectively. The quantity of heat flowing into the packaged food during the small time-increment becomes
equal to amount of change in the heat capacity of food (ΔQ_B). Here, ρ, c_p and V mean density, specific heat and volume, respectively. ΔQ_B is expressed as follows:

\[ \Delta Q_B = (\rho c_p V)(T_p^* - T_p^{n-1}) \]  

(2-3)

As it is assumed that ΔQ_T = ΔQ_B, an equation is established as follows:

\[ (\rho c_p V)(T_p^* - T_p^{n-1}) = (kA)(T_w^{n-1} - T_p^{n-1}) \left( \frac{\Delta t}{L^2} \right) \]

Then, k/(ρc_p) can be replaced by thermal diffusivity (α), and space-mean temperature (T_p^*) after a small time-increment is described as follows:

\[ T_p^* = T_p^{n-1} + \frac{\alpha \Delta t}{L^2}(T_w^{n-1} - T_p^{n-1}) \]  

(2-4)

ΔT_p = ΔT_p of premise condition 4 is rewritten in the next equation.

\[ T_p^* - T_p^{n-1} = T_p^{n} - T_p^{n-1} \]  

(2-5)

So, equation 2-4 can be replaced by the next equation 2-6.

\[ T_p^{n} = T_p^{n-1} + \left( \frac{\alpha \Delta t}{L^2} \right)(T_w^{n-1} - T_p^{n-1}) \]  

(2-6)

If the relationship between τ and α is defined as \( \tau = \frac{\alpha \Delta t}{L^2} \), then the central part-temperature (T_p) can be expressed as follows:

\[ \tau = \frac{\alpha \Delta t}{L^2} \]

(2-7)

\[ T_p^{n} = T_p^{n-1} + \tau (T_w^{n-1} - T_p^{n-1}) \]  

(2-8)

Here, τ is in the form of a proportional coefficient, that is, a dimensionless heat-transfer coefficient.

Note: equation 2-8 itself cannot express the history of the temperature in the central part of food accurately. Because the central part of the food is separated from the surface by distance L, that temperature change always lags behind. Thus, a hypothesis that the delay-time (δ) always exists in ambient temperature was formulated (This time, this hypothesis that existed from the beginning was verified.). To introduce the effect of delay-time into the calculating equation, hypothetical ambient temperature (T_w^†) that was delayed for δ seconds is expressed as follows:

\[ T_w^†(t) = T_w(t - \delta) \]  

(2-9)

If this equation is used instead of T_w in equation 2-8,

\[ T_p^{n} = T_p^{n-1} + \tau (T_w^{n-1} - T_p^{n-1}) \]  

(2-10)

This equation 2-10 is identical to equation 2-1 and the correlation-equation of this model, which is the central-part-temperature curve-estimation equation utilized the two parameters, τ and δ. The construction of this correlation-equation 2-10 can be easily seen in Fig. 2.

In fact, this figure was the first concept of the ATS method, which was intuitively imagined from the processing system for food in a package containing air described in the previous section. This visually represents the correlation-equation including the delay-time (δ) of the ambient-temperature curve and the heat-transfer coefficient (τ). Therefore, it can be said that the basis of the ATS method is a heat-transfer algorithm-equation between two points. Since it is an equation between two points, it can easily handle large changes in the physical properties of food during the process. In that case, the heat-transfer coefficient τ should be switched to appropriate values at appropriate times according to changes in physical properties.

Thermal diffusivity (α) is a parameter required to know ease of temperature penetration inside the material, and controls the heat-conduction equation. In the ATS method, the α (to be exact, apparent thermal diffusivity) is calculated back by next equation 2-11 with parameter τ that was provided by curve-fitting.

\[ \alpha_{cal} = \frac{\tau L^2}{\Delta t} \]  

(2-11)

Although a total of 10 theoretical developed equations are shown here, only the correlation-equation 2-10 is used in the estimation of the central-part temperature.

3. Experimental Procedure

As described in Section 1, this comparative verification
was performed between the ATS method and the Formula method. In order to enhance the investigation of versatility based on accuracy, extensive experimental data was collected (Table 1). This time, foods with large heat denaturation were avoided to facilitate comparative verification. In other words, the estimation was limited to the range in which the heat-transfer coefficient $\tau$ could be treated as each constant during the heating and cooling phases. As the container, one type of can, three types of pouches, and one type of plastic container were selected. In this case, the silicone rubber of food model is not packaged. The processing systems are the retorts of two kinds of steam type, two kinds of water-immersion type, three kinds of water-spray type and one kind of water-cascade type. A total of eight heat-transfer bodies (four conduction, three convection and one convection/conduction) were selected.

In order to enable quantitative evaluation of the difference in accuracy between the two estimation-methods, the numerical criteria in the table below was established (Table 2). The criteria were originally created for the curve fitting of ATS method. Here, $\text{Dev}(T_p)$ is the deviation ratio of the central-part-temperature curve, and $\text{Dev}(F_p)$ is the deviation ratio of the sterilizing value.

The verification this time is to investigate to what extent the measured central–part–temperature curves obtained from the processing experiments of the above eight samples can be reproduced by the estimation of both methods. Originally, the experiment for obtaining the parameters used for the simulation of the production operation was positioned as a preliminary experiment. It is, this means that all of the experimental verification this time will be conducted in preliminary experiments.

The reproducibility of the ATS method is confirmed by direct curve–fitting of the measured central–part–temperature curve using the correlation–equation 2–10. In that case, the parameters $\tau$ and $\delta$ are uniquely determined by the two–stage convergence calculation, and the estimated central–part–temperature curve is already drawn. In the Formula Method used for comparison with the ATS method, first, the parameters $f$ and $j$ are obtained by heat–penetration–curve analysis of the above preliminary experimental data. Then, using a series of numerical expressions, the central–part temperature is simulated from the measured ambient temperature of the preliminary experiment, and the reproducibility is confirmed by drawing an estimated central–part–temperature curve. Therefore, the accuracy of the two methods is compared by comparing the former curve–fitting result with the latter simulation result. In this case, the

| No. | Materials           | Package form and size (mm) | Heat-transfer properties | Processing system (Retort type) | Process conditions |
|-----|---------------------|----------------------------|--------------------------|--------------------------------|-------------------|
| 1   | Canned tuna in oil  | Tuna can No. 2             | conduction               | Steam                          | 120 ℃ × 98 min    |
| 2   | Liquid egg          | 400g pouch                 | convection               | Water-spray/swing              | 55 ℃ × 37 min     |
| 3   | 5% Cornstarch liquid| 220g pouch                 | convection & conduction  | Steam/pressurized              | 120.5 ℃ × 20 min  |
| 4   | Transfuse-liquid pouch| 2000ml pouch               | convection               | Water-spray                    | 116 ℃ × 44 min    |
| 5   | Consommé            | 150cc semirigid Container (PP)| convection             | Water-immersion/rotary         | 120 ℃ × 21 min    |
| 6   | Silicone rubber     | Unpackaged (130×170×20(H)) | conduction               | Water-immersion               | 120 ℃ × 20 min    |
| 7   | Silicone rubber     | Unpackaged (130×170×20(H)) | conduction               | Water-spray                   | 120 ℃ × 21 min    |
| 8   | Silicone rubber     | Unpackaged (130×170×20(H)) | conduction               | Water-cascade                 | 120 ℃ × 18 min    |

Table 2 Numerical criteria for accuracy evaluation.

| Symbol | Grade of evaluation | $\text{Dev}(T_p)$ | $\text{Dev}(F_p)$ |
|--------|---------------------|-------------------|-------------------|
| ◎      | Excellent           | under 1.0%        | between ± 1%      |
| ○      | Good                | under 2.0%        | between ± 5%      |
| △      | Medium              | under 3.0%        | between ± 15%     |
| ▲      | Low                 | 3.0% and over     | ± 15% and beyond  |
sterilizing value is calculated using the General Method from the estimated central-part-temperature curve drawn by both methods [3].

In the heat-penetration-curve analysis used in the Formula Method, a measured central-part-temperature curve is first drawn on a semi-logarithmic graph. Then straight-line-fitting is performed to obtain the slope-index parameter $f$ and the intercept-coefficient parameter $j$.

4. Results

Comparison charts of the estimated central-part-temperature curve were shown so that the results of both methods could be visually verified (Figs. 3 to 10). The ambient-temperature curve ($T_w$) and the central-part-temperature curve ($T_p$) are the measured values in preliminary experiments. Using this measured $T_w$, two central-part-temperature curves are estimated and compared. The estimated central-part-temperature curve of the ATS method is shown as ($T_{p\text{ cal1}}$), and the estimated central-part-temperature curve of the Formula Method is shown as ($T_{p\text{ cal2}}$). The accuracy of the estimated curve is indicated by four judgment symbols such as ($▲△:\bigcirc\bigcirc$). The previous two symbols ($▲△$) indicate the deviation ratio in the heating and cooling phases of the central-part-temperature curve. The latter two symbols ($\bigcirc\bigcirc$) indicate the deviation ratio in the heating and cooling phases of the sterilizing value.

Figure 3 is the comparison made in the classic combination of solid’s canned food and steam retort. In this case, the CUT (come-up time to process-temperature) and CDT (come-down time to minimum cooling-temperature) are very small. There is no problem because the estimated value of ATS method is accurate ($\bigcirc\bigcirc:\bigcirc\bigcirc$). Regarding the ATS method, this comment will be repeated in the following figures. Therefore, this comment was omitted in the following figures. In this case, the Formula Method was able to calculate the estimated value fairly accurately ($▲△:\bigcirc\bigcirc$). The temperature drop at the start of processing in the Formula Method is caused by the CUT-correction operation. So it is present in all of the following figures but varying degrees.

Figure 4 is the comparison made in the combination of liquid with low fluidity and water-spray/swing type retort. This is a typical pasteurization. In this case the CDT is quite large. The Formula Method cannot simulate the cooling phase at all.

Figure 5 is the comparison made in the combination of liquid to be heated/gelatinized and a steam/pressurized type retort. The CDT is considerably larger in this case too. The Formula Method cannot simulate the cooling phase well.

Figure 6 is the comparison made in the combination of liquid having a large convective-heat-transfer element and water-spray retort. This is a typical overshoot control operation. In this case, both CUT and CDT are considerably large. The Formula Method could not simulate all phases of heating and cooling well.
Figure 7 is the comparison made in the combination of a cup-packed soup having headspace, and water-immersion/rotary type retort. A processing system for packed food containing air is also used here. In this case, both CUT and CDT are quite large. In the Formula Method, the estimated central-part temperature deviates significantly from the measured central-part temperature of the whole phase.

Figure 8 is the comparison using a water-immersion retort having a small CUT and CDT with a food model silicone rubber (CUT: 6.925 min, CDT: 1.55 min). The Formula Method can estimate the central-part-temperature curve fairly accurately. However, the accuracy of the estimated sterilizing value is not very good.

Figure 9 is the comparison using a water-spray retort having a medium CUT and CDT with a food model silicone rubber (CUT: 8.15 min, CDT: 15.2 min). The Formula Method cannot simulate the cooling phase at all. In this case, it is becoming difficult to estimate the sterilizing value.

Figure 10 is the comparison using a water-cascade retort having a large CUT and CDT with a food model silicone rubber (CUT: 25.5 min, CDT: 25.35 min). In the Formula Method the estimated temperature at the start of processing shows abnormally low value. Moreover, all the simulation of heating and cooling phases is completely failed state. In this case, the estimation itself is not valid because there is a contradiction in the estimated central-part temperature of the cooling phase that the temperature is reversed.

The estimated results of the ATS method were excel-
lent to all experimental data this time (〇〇:〇〇). On the other hand, in the Formula Method, there was no evaluation, and ▲ was the majority. It was observed that the accuracy became worse as the CUT and CDT became larger.

Next, the accuracy of the estimated sterilizing-value of both methods was compared (Table 3). For 55 ℃ processing of liquid egg, the reference values of the pasteurization (reference temperature: 85 ℃, reference z value: 7.8 ℃) were used. All of the sterilizing values of the ATS method show 100% reproducibility, and there is no problem in accuracy. On the other hand, in the Formula method, the sterilizing values other than the canned tuna in oil fluctuate greatly over and under the actual value. The deviation ratio of the canned tuna in oil is within +3.5%, which is within the practical range. In this case, the CUT and CDT are much smaller than the other samples, so that it is considered that the accuracy was obtained in the Formula Method.

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Next, using the characteristics of the processing system, the results of investigating the difference in parameters due to the difference in the size of CUT and CDT are shown (Table 4). The parameters used in both estimation-methods are completely different in absolute values and units. The parameters τ and δ obtained by the ATS method are heat-transfer coefficient which is the Fourier number (-) subdivided to the sampling cycle (Δt), and the delay-time (sec). On the other hand, f and j obtained by the heat-penetration-curve analysis, which is the basis of the Formula Method, are defined as follows.

The former is the time (min) that the straight line when straight-line-fitting crosses one logarithmic cycle. And the latter is the intersection (-) of the straight line with the vertical axis of the heating or cooling start point (CUT-corrected start point in the case of heating). In this case, the larger the CUT and CDT, the shorter the linear part of the heat-penetration curve, making straight-line-fitting difficult. Therefore, it was predicted

| No. | Materials | Measured value | Estimated value |
|-----|-----------|----------------|----------------|
|     |           |                | ATS method     | Formula Method |
|     |           |                | Fp Reference Tp/zr | Fp Reproducibility | Fp Reproducibility |
|     |           |                | (min) (℃/℃) | (%) | (min) (%) |
| 1   | Canned tuna in oil | 33.498 | 121.1/10 | 33.497 | 100 | 34.683 | 103.5 |
| 2   | Liquid egg | 0.00375 | 85/7.8 | 0.00375 | 100 | 0.00341 | 91 |
| 3   | 5% Cornstarch liquid | 11.492 | 121.1/10 | 11.49 | 100 | 9.009 | 78.4 |
| 4   | Transfuse-liquid pouch | 10.465 | 121.1/10 | 10.464 | 100 | 12.356 | 118.1 |
| 5   | consommé | 10.373 | 121.1/10 | 10.373 | 100 | 5.421 | 52.3 |
| 6   | Silicone rubber (Water-immersion) | 9.784 | 121.1/10 | 9.78 | 100 | 8.177 | 83.6 |
| 7   | Silicone rubber (Water-spray) | 8.289 | 121.1/10 | 8.288 | 100 | 7.028 | 84.8 |
| 8   | Silicone rubber (Water-cascade) | 10.211 | 121.1/10 | 10.211 | 100 | 5.843 | 54.2 |

| No. | Materials | Heating phase | Cooling phase | Heating phase | Cooling phase |
|-----|-----------|---------------|---------------|---------------|---------------|
| 6   | Silicone rubber (Water-immersion) CUT & CDT: small | τh = 0.003649 (-) | τc = 0.003499 (-) | fh = 10.997 (min) | fc = 8.910(min) |
| 7   | Silicone rubber (Water-spray) CUT & CDT: medium | τh = 0.003669 (-) | τc = 0.003610 (-) | fh = 10.412 (min) | fc = 16.295 (min) |
| 8   | Silicone rubber (Water-cascade) CUT & CDT: large | τh = 0.003664 (-) | τc = 0.003797 (-) | fh = 10.738(min) | fc = 13.857(min) |

Note: The subscripts h and c indicate the heating and cooling phases.
that the reproducibility of the parameters $f$ and $j$ would deteriorate. In Ball’s empirical formula, the assumptions of $f_c = h_c$ and $j_c = 1.41$ are made based on experimental observations. Therefore, the cooling phase parameters in Table 4 were not used to estimate the sterilizing values in Table 3.

In the ATS method the difference between the absolute values of heat-transfer coefficient $\tau_h$ and $\tau_c$ was within $\pm 4.1\%$, and the difference between the absolute values of delay-time $\delta_h$ and $\delta_c$ was within $\pm 32\%$. On the other hand, in the Formula Method, the difference between the absolute values of $h_c$ and $f_c$ of the heat-transfer coefficient characteristics varied up to $\pm 30\%$. And the difference between the absolute values of $j_h$ and $j_c$ of delay-time characteristics varied up to $\pm 87\%$. Here, it was observed that the absolute values of the parameters used in the Formula Method are roughly correlated with the magnitude of CUT and CDT.

5. Discussion

In the comparison charts of the estimated central-part-temperature curves (Figs. 3 to 10), the accuracy of results estimated in the ATS method were excellent (○ ○ ○ ○ ○) for all samples. Also in Table 3, the estimated sterilizing-value of the ATS method showed reproducibility in which all samples have a comparative ratio of almost 100%. Therefore, the ATS method can be said to be the estimation-method of sterilizing value that can respond well to the various processing conditions prepared this time without any problems.

It was found that the Formula Method, which was the subject of the experimental verification, was significantly inferior to the ATS method in accuracy evaluation and reproducibility of the sterilizing value. It was a severe result that only the canned tuna in oil (▲ △ ○ ○ ○), which was a classic processing of combination of steam retort and canned food, was recognized as practical. The feature of the sample that has been recognized for its practicality is that the CUT and CDT are very short compared to other samples. In the case of the other 7 samples, it was visually observed that one or both of CUT and CDT were fairly large. It was also confirmed that the degree of poor performance which is currently a problem was proportional to the size of the CUT or CDT.

In Table 4, it is noticeable that the $j$ value of the Formula Method has a large deviation. As CUT and CDT increase, the $j$ value also increases significantly in correlation with it. In the ATS method, no such correlation is observed in the $(\tau_h$ and $\tau_c$) group and the ($\delta_h$ and $\delta_c$) group, and it is stable. The parameters of the ATS method are almost unaffected by the processing system, that is, CUT or CDT, and enable accurate estimation of the sterilizing value, so it can be said that the parameters have excellent characteristics. In other words, this shows that they can be sufficiently applied to the production operation, which is the original role of the parameter.

In the water-cascade retort with the largest CUT and CDT, the $j$ values of the Formula Method protrude. And the estimated central-part temperature causes to fall below the cooling ambient temperature, resulting in heat-transfer inconsistency. From these, it can be inferred that a large CUT or CDT is the primary cause of the poor performance of the Formula Method. Since the ATS method has already produced good estimation-results, heat-transfer characteristics of foods and processing temperature conditions are not said to be factors causing the poor performance of the Formula Method.

From the above comparative-verification results, it was confirmed that the ATS method really excelled in versatility based on accuracy. In addition, since its performance was confirmed, it can be said that the hypothesis that there is a delay-time in the ambient temperature, which was essential for the completion of the theory of the ATS method, was also verified. This delay-time hypothesis is introduced from the first report. It was dealt with potentially so far but it became a hypothesis that should be verified in the third report.

As described in Section 3, both estimation-methods use the same two-parameter method. However, there are fundamental differences in the physical meaning of the parameters. Of the two parameters obtained using the heat-penetration-curve analysis in the Formula Method, $f$ is the slope index (min) that has the heat-transfer coefficient characteristic, and $j$ is the intercept coefficient (–) that has delay-time characteristic. On the other hand, two types of parameters for the ATS method are the heat-transfer coefficient (–) $\tau$ and the delay-time (sec) $\delta$ obtained by direct curve-fitting, using Equation 2–10. They are very simple. And, for the operation, a total of four parameters are calculated about the heating and cooling phases. It is considered that the direct and simple physical meanings of parameters greatly contribute to the simplicity of the ATS method.

In the ATS method, the above-mentioned curve-fitting has successfully estimated the central-part temperature of the preliminary experiment. On the other hand, in the case of the Formula Method, after getting the parame-
ers the central-part temperature needs to be estimated using the ambient temperature of the preliminary experiment and four numerical expressions. Therefore, when comparing the estimated central-part-temperature curves of both methods, the ATS method is overwhelmingly simpler because there is no follow-up calculation action. By having confirmed the accuracy, the versatility based on accuracy, and the simplicity, which was required for the new estimation-method of sterilizing value, the purpose of the verification of this treatise was fully achieved.

The ATS method overcame the weakness of the conventional method, which has a limited range of use. In there, in the ATS method, there was the decision that the parameters $f$ and $j$ for heat-penetration-curve analysis were not used. It means that the new estimation-method demanded an analysis method freed from dependence on the heat-penetration-curve analysis. On the other hand, conventional methods, including Formula Method, have a common basis for heat-penetration-curve analysis that cannot be removed. That heat-penetration-curve analysis is premised on the unnatural assumption of instantaneous come-up heating (without CUT) and instantaneous come-down cooling (without CDT). Because of that assumption, the accuracy of conventional methods is inevitably expected to decrease with increasing CUT and CDT.

Ball and subsequent process engineers proposed a number of corrective treatments to mitigate the harmful effects of this unnatural assumption. However, these estimation-methods of sterilizing value has lost its practicality and has not been settled in the food industry because it has become complicated due to repeated corrections. Since the ATS method does not use the heat-penetration-curve analysis, it is completely free from the corrective treatment necessary for the conventional methods. Therefore, the ATS method can be said to be a practical new sterilizing-value-estimation-method that can replace the conventional methods, in thermal processing.

6. Conclusion

In comparison with the Formula Method, the ATS method showed overwhelmingly excellent performance. Since the versatility based on accuracy was sufficiently confirmed, the verification of the hypothesis of delay-time $\delta$, which had been left behind until now, was finished. Consequently, the ATS method theory was finally completed.

The ATS method is the sterilizing-value-estimation-method that was freed from the heat-penetration-curve analysis on which most conventional methods are based. Not affected by CUT or CDT, all of its outstanding accuracy, versatility and simplicity were confirmed. It was shown that the ATS method is a practical new sterilizing-value-estimation-method for thermal processing of packaged food.

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