Paper No.: 02

Paper Title: The Principles of the Food Processing & Preservation

Module No. : 07

Module Title: Modes of Heat Transfer, Determining Process Time and Process Lethality

7.0 Introduction

Heat transfer is an operation that occurs repeatedly in the food industry. Whether it is called cooking, baking, drying, sterilizing or freezing, heat transfer is part of the processing of almost every food. An understanding of the principles that govern heat transfer is essential to an understanding of food processing.

Heat transfer is a dynamic process in which heat is transferred spontaneously from one body to another cooler body. The rate of heat transfer depends upon the differences in temperature between the bodies, the greater the difference in temperature, the greater the rate of heat transfer.

Temperature difference between the source of heat and the receiver of heat is therefore the driving force in heat transfer. An increase in the temperature difference, increases the driving force and therefore increases the rate of heat transfer. The heat passing from one body to another travels through some medium which in general offers resistance to the heat flow. Both these factors, the temperature difference and the resistance to heat flow, affect the rate of heat transfer. As with other rate processes, these factors are connected by the general equation:

rate of transfer = driving force / resistance

For heat transfer:

rate of heat transfer = temperature difference/ heat flow resistance of medium

During processing, temperatures may change and therefore the rate of heat transfer will change. This is called unsteady state heat transfer, in contrast to steady state heat transfer when the temperatures do not change. An example of unsteady state heat transfer is the heating and cooling of cans in a retort to sterilize the contents. Unsteady state heat transfer is more complex since an additional variable, time, enters into the rate equations.Heat can be transferred in three ways: by conduction, by radiation and by convection.

In conduction, the molecular energy is directly exchanged, from the hotter to the cooler regions, the molecules with greater energy communicating some of this energy to neighbouring molecules with less energy. An example of conduction is the heat transfer through the solid walls of a refrigerated store.

Radiation is the transfer of heat energy by electromagnetic waves, which transfer heat from one body to another, in the same way as electromagnetic light waves transfer light energy. An example of radiant heat transfer is when a foodstuff is passed below a bank of electric resistance heaters that are red-hot.

Convection is the transfer of heat by the movement of groups of molecules in a fluid. The groups of molecules may be moved by either density changes or by forced motion of the fluid. An example of convection heating is cooking in a jacketed pan: without a stirrer, density changes cause heat transfer by natural convection; with a stirrer, the convection is forced.

In general, heat is transferred in solids by conduction, in fluids by conduction and convection. Heat transfer by radiation occurs through open space, can often be neglected, and is most significant when temperature differences are substantial. In practice, the three types of heat transfer may occur together. For calculations it is often best to consider the mechanisms separately, and then to combine them where necessary.

In the case of heat conduction, the equation, rate = driving force/resistance, can be applied directly. The driving force is the temperature difference per unit length of heat-transfer path, also known as the temperature gradient. Instead of resistance to heat flow, its reciprocal called the **conductance** is used. This changes the form of the general equation to:rate of heat transfer = driving force x conductance,that is:

$$\mathrm{d}Q/\mathrm{d}t = kA\ \mathrm{d}T/\mathrm{d}x$$

where$Q/\mathrm{d}t$ is the rate of heat transfer, the quantity of heat energy transferred per unit of time, A is the area of cross-section of the heat flow path, $\mathrm{d}T/\mathrm{d}x$ is the temperature gradient, that is the rate of change of temperature per unit length of path, and k is the thermal conductivity of the medium. Notice the distinction between thermal conductance, which relates to the actual thickness of a given material (k/x) and **thermal conductivity**, which relates only to unit thickness.

Thermal processing implies the controlled use of heat to increase, or reduce depending on circumstances, the rates of reactions in foods.A common example is the retorting of canned foods to effect sterilization. The object of sterilization is to destroy all microorganisms, that is, bacteria, yeasts and moulds, in the food material to prevent decomposition of the food, which makes it unattractive or inedible. Also, sterilization prevents any pathogenic (disease-producing) organisms from surviving and being eaten with the food. Pathogenic toxins may be produced during storage of the food if certain organisms are still viable. Microorganisms are destroyed by heat, but the amount of heating required for the killing of different organisms varies. Also, many bacteria can exist in two forms, the vegetative or growing form and the spore or dormant form. The spores are much harder to destroy by heat treatment than are the vegetative forms.

7.1 Thermal Death Time

It has been found that microorganisms, including *C. botulinum*, are destroyed by heat at rates which depend on the temperature, higher temperatures killing spores more quickly. At any given temperature, the spores are killed at different times, some spores being apparently more resistant to heat than other spores. If a graph is drawn, the number of surviving spores against time of holding at any chosen temperature, it is found experimentally that the number of surviving spores fall asymptotically to zero. Methods of handling process kinetics are well developed and if the standard methods are applied to such results, it is found that thermal death of microorganisms follows, for practical purposes, what is called a first-order process at a constant temperature.

This implies that the fractional destruction in any fixed time interval, is constant. It is thus not possible, in theory at least, to take the time when all of the organisms are actually destroyed. Instead it is practicable, and very useful, to consider the time needed for a particular fraction of the organisms to be killed.

The rates of destruction can in this way be related to:

(1) The numbers of viable organisms in the initial container or batch of containers.
(2) The number of viable organisms which can safely be allowed to survive.

Of course the surviving number must be small indeed, very much less than one, to ensure adequate safety. However, this concept, which includes the admissibility of survival numbers of much less than one per container, has been found to be very useful. From such considerations, the ratio of the

initial to the final number of surviving organisms becomes the criterion that determines adequate treatment. A combination of historical reasons and extensive practical experience has led to this number being set, for *C. botulinum*, at 10^{12}:1. For other organisms, and under other circumstances, it may well be different.

The results of experiments to determine the times needed to reduce actual spore counts from 10^{12} to 1 (the lower, open, circles) or to 0 (the upper, closed, circles) are shown in **Fig. 1**.

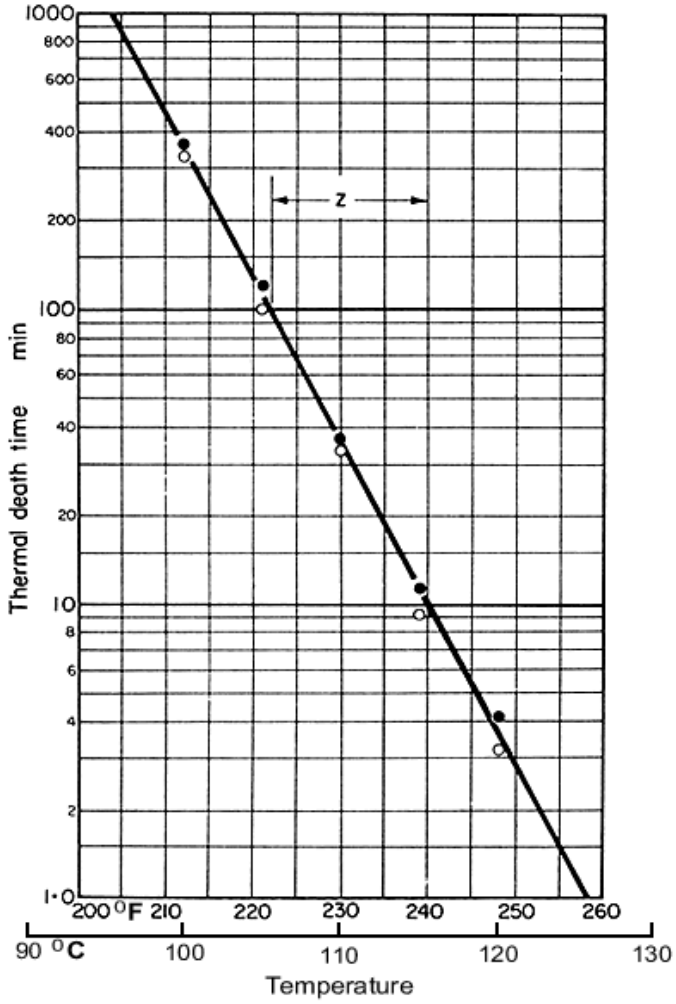

Figure.1. Thermal death time curve for *Clostridium botulinum*

In this graph, these times are plotted against the different temperatures and it shows that when the logarithms of these times are plotted against temperatures, the resulting graph is a straight line. The mean times on this graph are called thermal death times for the corresponding temperatures. Note that these thermal death times do not represent complete sterilization, but a mathematical concept which can be considered as effective sterilization, which is in fact a survival ratio of $1:10^{12}$, and which has been found adequate for safety.

Any canning process must be considered then from the standpoint of effective sterilization. This is done by combining the thermal death time data with the time-temperature relationships at the point in the can that heats slowest. Generally, this point is on the axis of the can and somewhere close to the geometric centre. Using either the unsteady-state heating curves or experimental measurements with a thermocouple at the slowest heating point in a can, the temperature-time graph for the can under the chosen conditions can be plotted. This curve has then to be evaluated in terms of its effectiveness in destroying *C. botulinum* or any other critical organism, such as thermophilic spore

formers, which are important in industry. In this way the engineering data, which provides the temperatures within the container as the process is carried out, are combined with kinetic data to evaluate the effect of processing on the product.

The standard reference temperature is generally selected as 121.1°C (250 °F), and the relative time (in minutes) required to sterilize, effectively, any selected organism at 121°C is spoken of as the ***F*value** of that organism. For any process that is different from a steady holding at 121°C, our standard process, the actual attained *F* values can be worked out by stepwise integration. If the total *F* value so found is below 2.8 min, then sterilization is not sufficient; if above 2.8 min, the heat treatment is more drastic than it needs to be.

7.2 Equivalent Killing Power at Other Temperatures

The other factor that must be determined, so that the equivalent killing powers at temperatures different from 121°C can be evaluated, is the dependence of thermal death time on temperature. Experimentally, it has been found that if the logarithm of *t*, the thermal death time, is plotted against the temperature, a straight-line relationship is obtained. This is shown in Fig. 6.4 and more explicitly in **Fig. 2.**

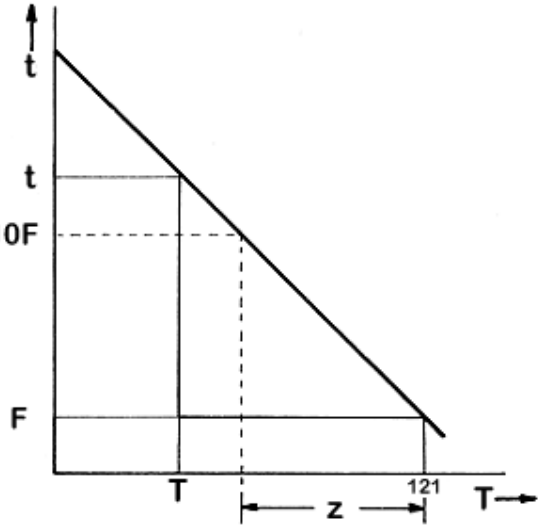

Figure.2: Thermal death time/temperature relationships

We can then write from the graph

$$\log t - \log F = m(121 - T) = \log t/F$$

where *t* is the thermal death time at temperature *T, F* is the thermal death time at temperature 121°C and *m* is the slope of the graph.Also, if we define the ***z*** value as the number of degrees below 121°C at which *t* increases by a factor of 10, that is by one cycle on a logarithmic graph,

$$t = 10F \text{ when } T = (121 - z)$$

so that, $\log 10F - \log F = \log (10F/F) = 1 = m[121 - (121 - z)]$

and so $z = 1/m$

Therefore $\log (t/F) = (121 - T)/z$

or $t = F \times 10^{(121-T)/z}$

Now, the fraction of the process towards reaching thermal death, dS, accomplished in time dt is given by $(1/t_1)$dt, where t_1 is the thermal death time at temperature T_1, assuming that the destruction is additive.

That is $dS = (1/t_1)dt$

or $= (1/F)10^{-(121-T)/z}\, dt$

When the thermal death time has been reached, that is when effective sterilization has been achieved,

$$\int dS = 1$$

This implies that the sterilization process is complete, that the necessary fraction of the bacteria/spores have been destroyed, when the integral is equal to F. In this way, the factors F and z can be combined with the time-temperature curve and **integrated to evaluate a sterilizing process**.The integral can be evaluated graphically or by stepwise numerical integration. In this latter case the contribution towards F of a period of t min at a temperature T is given by $t \times 10^{-(121-T)/z}$ Breaking up the **temperature-time** curve into t_1 min at T_1, t_2 mm atT_2, etc., the total F is given by

$$F = t_1 \times 10^{-(121-T1)/z} + t_2 \times 10^{-(121-T2)/z} + \text{é é é é ..}$$

This value of F is then compared with the standard value of F for the organism, for example 2.8 min for *C. botulinum* in our example, to decide whether the sterilizing procedure is adequate.

7.3 LETHALITY CALCULATIONS

The general method: In the sterilization of low-acid foods, process lethality is expressed as equivalentminutes at a reference temperature of 121.1°C, and is commonlyexpressed as anFo-value. For example, a particular Fo-value of 6 minutes(Fig. 3) would assume a step-change temperature response where thecold-spot temperature would rise instantaneously to the reference temperature,be held there for 6 minutes and then cool instantaneously. Thisresponse, of course, is not possible for an in-container sterilization process.However, in early work, it was reported that lethalities attained atdifferent temperatures are additive and thus may be accumulated as thetemperature at the cold spot changes through a process. Thus, knowingthe cold-spot temperature history one can determine the rate of lethalityat each time increment, plot the resulting data as a function of time, andintegrate under the curve to obtain the equivalent lethality at the referencetemperature.

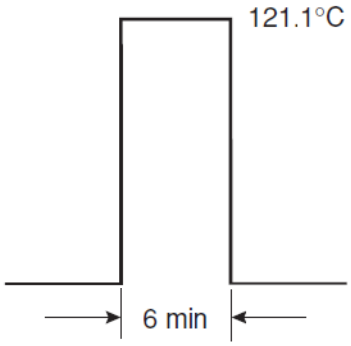

Figure.3: Cold-spot temperature history representing anFo of 6 minutes.

From the work of scientists Esty and Meyer, it is widely recognized that *C.botulinum* spores may be characterized by a z-value of 10 Celsius degrees(18 Fahrenheit degrees) and a D121.1°C of 0.21 minutes. Also, since thermal death time (tdt)data were frequently not available for a specific

product formulation, it was proposed that a unit thermal death time curve should be applied in calculationswhere the F-value is 1 minute. Recognizing that log1 = 0 andcombining this with the death kinetics for *C. botulinum*, Equation for theend-point tdt curve may be expressed as:

$$\log tdt = (1/10)(121.1 - T).$$

Note that the tdt is now the time at a specified product temperature equivalentto Fo minutes at a reference temperature of 121.1°C. The units of the tdt are minutes at T per minute at 121.1°C. It follows that the lethalrate then is 1/tdt, with units of minutes at 121.1°C per minute at theproduct temperature T. Thus the lethal rate, L, is expressed as:

$$L = 1/tdt = 10(T - 121.1)/10$$

where the units are minutes at the reference temperature per minute at theproduct temperature. The process lethality is calculated by integrating Lover the time of the process:

$$F0 = \int L\,dt = \text{process time} \times L$$

and in general:

$$L = 10(T - Tx)/z \quad \text{(Eqn. 3.7)}$$

Thus, a reference temperature and z-value may be assigned to suit theprocess being evaluated. For example, when pasteurizing beer, processesare commonly calculated using a z-value of 10 Celsius degrees and areference temperature of 60°C.

7.4 Conclusion

General method calculations remain the benchmark when determiningthe lethality delivered by a specific thermal process. However, there aremany mathematical models reported in the literature that predict processlethality based on the heating and cooling characteristics of the product,and processing time and temperature data. Finite difference analysis can be applied to determine both deliveredlethality and quality loss during processing. These techniques were publishedas early as 1969, but the software and computer capacity to completethese calculations have only recently become more widely available.