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Flash Pasteurization of Beer – a Critical Review

The pasteurization of beer and in particular the flash pasteurization is a widely used technique for the biological product stabilization. In spite of the large extend of experience with the pasteurization the way how it is used in practice is a comparably rough method of low precision. In order to precisely adjust the two core process parameters temperature and exposition time detailed knowledge about the individual microbiological inactivation kinetics as well as about specific process and equipment characteristics is required. The article first considers the questions of the biologically demanded thermal load in terms of "required Pasteurization Units (PU)". The assumed underlying thermal death kinetics and the determination of the necessary logarithmic cell count reduction are discussed. Every claim demanding for a particular target PU for specific kinds of beers (or other beverages) base naturally upon simplifications and assumptions concerning the initial and target cell counts and the D-values of present microorganism. The necessity of both species/strain and matrix specific D-values are pointed out.

In the second step the recalculation of the actually applied thermal load in terms of "effective PU" is critically reviewed. The origin of the questionable so called beer formula is revealed indicating the evident deviations to realistic calculations. In contrast to the assumption in the beer formula the z-value, describing the heat dependency of the D-value, is constant 7°C, it varies in a wide range with species and matrix. This leads to miscalculation of the "effective PU". Furthermore the both parameters of the pasteurization process time and temperature are commonly simplified to average sizes. Investigations on residence time distributions (RTD) are evaluated and combined with thermal death kinetics of microorganism in order to show the relevance of RTD for the effectively applied thermal load and the "effective PU" respectively. Since the common way to determine the actual thermal effect (effective PU) are microbiological count reduction tests with a comparably low accuracy alternative approaches for an correct determination of the inactivation effect are proposed.

Descriptors: flash pasteurization/HTST, Pasteurization Units (PU), D and z-values, residence time distribution

1 Introduction

The shelf-life requirements of beer have been become more demanding within the last decades due to longer distribution channels [1]. This is finally caused by an industrialization of the beer production accompanied by concentration and centralization processes in the brewing industry. At the same time a higher sensitivity of consumers in safe products has been established. Furthermore new beer products with decreased stability and highly heat sensitive ingredients demand a more accurate determination of the process parameter. The longer shelf-life concerns three distinguishable kinds of stabilities: the microbiological, colloidal and flavor stability. This review focuses on the microbiological stability, in particular realized by heat treatment (pasteurization), beside sterile filtration the most common technique to reduce microorganisms.

The aim of the pasteurization is not to obtain a sterile but a stable product. The difference is that an only stable product tolerates the survival of non-beer-spoiling microorganism (organism incapable to grow in the beer matrix). Because neither bacterial spores nor other microorganisms with notably high heat resistance is known as beer spoiling this allows a comparably gentle treatment of the product in contrast to a real sterilization.

The Pasteurization can be performed by continuous systems such as plate pasteurizer (High temperature short time, HTST also referred as flash pasteurization) before filling or by tunnel pasteurization of bottled products. The decision whether HTST or tunnel pasteurization is applied or neither depends on the microbiological product sensitivity, the kind of package, the general hygiene state in the brewery, the distribution channel and the safety and quality demands of the brewery [2]. While HTST pasteurization is remarkably cheaper [3, 4, 5, 6], the pasteurization step before filling leads, even in a sterile filling station, to the risk of recontamination. In contrast tunnel pasteurization takes place after filling. The already sealed product is pasteurized together with packing and closures and there is no risk of recontamination after the process [4, 7, 8, 9].

Beside some of the discussed aspects can be applied at HTST and tunnel pasteurization this article aims to get to the bottom of the current flash pasteurization practice and to reveal critical aspects of its determination by a time temperature course.

2 Technical Requirements

Before looking for the calculation of the "needed and effective PU" some basic aspects of the technical requirements which are characteristic for HTST to get a safe pasteurization should be considered. First of all we have to deal with the fact, that an

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Figures see Appendix

unconcealed product is pasteurized. This can lead to a recontamination after the pasteurization at three critical control points (CCP). As mentioned before the filling has to take place in a controlled, sterile filling operation [10]. Container and closures have to be pasteurized separately. However already in the cooling zone a recontamination can take place. While the rapid heating and cooling through plate heat exchanger pasteurized and unpasteurized product flow parallel only separated through a thin plate. Corrosion, capillary cracks or other leaks can cause a recontamination of pasteurized beverage through unpasteurized in the heat exchanger. The corrosion in the great majority of cases is caused by chloride ions [11, 12]. To minimize the risk of recontamination of the pasteurized beer the pressure on the pasteurized side is higher than on the unpasteurized side, even though this cannot eliminate this risk completely [11]. Furthermore the pressure of the beer has to be above the temperature dependent CO_2 pressure at any time, otherwise CO_2 bubbles will occur. Free flowing bubbles have a reduced heat transfer thus the chance of survival inside a bubble is increased. On the other hand bubbles adhere to the wall reduce the free volume followed by a reduction of the residence time. Both effects lead to surviving microorganisms [13].

Another hazard to deal with is fouling. It means the deposition of organic material in consequence of high temperature differences. If fouling appears in a flash pasteurizer it could be an origin of uncompleted pasteurization. This can happen by a decrease of residence time due to reduced free volume, a reduced thermal conductivity causing decreased maximum temperatures. After holding time the fouling layer even can be the origin of microorganisms. In consequence the equipment has to be good cleanable and a regularly cleaning is essential [14].

3 Thermal Death Theory and Pasteurization Units

Beer is a matrix with a low risk of growth of pathogenic organisms, mainly due to the low pH of beer the carbon dioxide followed by alcohol and humulene content [4, 15]. *Ment et al.* found no growth or survival of foodborne pathogens in beer with ethanol levels above 1 %vol or pH values below 4.0 [16]. But microorganisms have been revealed, which are capable to grow and spoil beer in terms of turbidity and off-flavors. In order to achieve a microbiological stabile product it is necessary to inactivate yeasts, specific species of Lactobacillus, Pedicococus, Megasphera and Pectinatus [4, 1, 17]. Detail lists of microorganism which can occur in the different phases of beer production have made among others *Vaughan et al.* and *Back* [18, 19].

Pasteurization owes its name from Louis Pasteur who 1866 discovered, that yeast occurring in wine can be destroyed by approximately 30 min. at 63 °C [20, 3]. Since this time pasteurization has changed to shorter time and higher temperature to achieve better quality. There are different courses of the thermal inactivation of microorganisms over time, a summery is given by *Xiong et al.* [21] and can be seen in figure 1.

The shoulder-shaped inactivation (curve E) occurs mainly in presence of spores. In spite of the greater meaning of bacterial endospores also beer spoiling ascospores may cause such a shoulder-delay. The thermal inactivation of vegetative cells correspondents in most frequently to a first order reaction (Eq.(1)) as shown with curve A in figure 1.

$$N = N_0 e^{-kt} \qquad (1)$$

N_0 is the initial viable cell count, N the cell count after a time t and k is the temperature depended reaction rate constant. For practical purposes the decimal reduction time (D-value) replaces the reaction rate constant k. The D-value represents the time that is needed to decrease the viable cell count by 90 % at a defined temperature. The D-value is defined by the subsequent equation:

$$D = \frac{ln10}{k} \qquad (2)$$

In beverage engineering, the needed intensity of heat treatment is expressed in pasteurization units (PU).The required PU (PU_{re}) is derived from the formula:

$$PU_{re} = D \cdot lg\frac{N_0}{N} \qquad (3)$$

Since the D-value depends on the temperature and the temperature in practical application is a parameter to be set, a relation between PU and temperature is required. Derived from the Arrhenius relation a second important organism specific value is known: the z-value. The z-value can be interpreted as the temperature change from a reference temperature (ϑ_R) at which the D-value is known from experiments to the temperature ϑ in order to change the D-value by the factor 10. The z-value depends in the first instance on the activation energy (E_a) (R=universal gas constant):

$$z = \frac{ln10 \cdot R \cdot \vartheta_R \cdot \vartheta}{E_a} \qquad (4)$$

To determine the D- and z-value for a microorganism species or strain death challenge experiments are necessary. These experiments need to be carried out under clearly defined conditions such as physiological properties of the organism (e.g. growing phase of the culture, cultivation conditions), environmental conditions during the thermal death time experiments [22] and numerous other parameters D- and z-values depends on. Cells which are in the stationary phase are more heat resistant than cells which are growing [23] furthermore pH, alcohol carbon dioxide and hop contents influences the heat resistance [5]. *O´Conner-Cox et al.* [23] described detailed the factors affecting heat resistance of an organism. A review about the existing D- and z-values of different microorganism can be found in the Lemgo Database for D- and z-values [24, 25].

With the z-value the effective PU (PU_{ef}) can be recalculated from any time-temperature-combination by the following equation:

$$PU_{ef} = \int 10^{\frac{\vartheta - \vartheta_R}{z}} dt \qquad (5)$$

In instances such as flash pasteurization when the temperature can be considered to be constant the equation can do without the integral.

$$PU_{ef} = t \cdot 10^{\frac{\vartheta - \vartheta_{reference}}{z}} \qquad (6)$$

In the brewing industry the equation is commonly farther simplified. For calculating the PU_{ef} the so called beer formula (Eq. (7)) is still in practice. This formula uses a fixed z-value of 6.9 °C for all microorganisms and conditions. It is based upon publications in the 1950s by *Del Vecchio et al.* [26, 27, 28]. They found by survival-death experiments a z-value of 12.5 °F, 6.9 °C respectively [26]. They use 60 °C as reference temperature for the calculation of PU.

$$PU_{ef} = t \cdot 1{,}393^{(\vartheta - 60°C)} \qquad (7)$$

So the effect of one PU refers to the effect of heat exposure for one minute at 60 °C.

4 Critical review of the required Pasteurization Units (PU_{re})

The PU_{re} represents the heat load to be applied to stabilize the product. The required time-temperature combination (and thus PU_{re}) in pasteurization processes depends on the initial cell count, the target viable cell count, the properties of the matrix, the physiological state of organisms and the kind of microorganism.

Ignoring the wide range of D-values within beer spoiling microorganisms the general recommendations for the required PU are given. In case of normal gravity beers 15 PU_{ef} and more are accepted in the industrial practice [5, 29, 30, 31, 32, 33]. This value is finally due to the same set of publications by Del Vecchio et al. from 1951 [26, 27, 28], responsible for the beer formula. They stated that 15 min at 60 °C was the universally accepted standard for beer pasteurization as long as conditions were normal. However the investigations of Del Vecchio et al. [26] employed more or less unspecific mixtures of species without indication of an initial cell count. He found in particular an abnormal yeast to be the most heat resistant brewing species. This yeast is supposed to require 5.6 PU for a complete inactivation of all cells in their experiments. An initial cell count is not published. Large safety margins for the possible occurrence of more of those heat resistant organisms led to recommendation for practical applications of 15 to 20 PU [5].

Since the publication of Del Vecchio other publications dealt with the question how to determine PU_{re} more precise. *Dallyn et al.* [34] found that vegetative yeast cells can be inactivated by 1 PU or less even in large numbers. If ascospores in low quantities are present they recommend a PU-value of 10–12. Higher numbers of extraordinary heat resistant yeasts or ascospores only occurs referring to Dallyn et al. when the initial number of cells is high (especially aged cells). Several researchers attempt to determine a sensible PU value based up on extraordinary heat resistant microorganism [34, 35, 36, 26] however, these microorganisms rarely appear in breweries. To save energy and avoid off-flavors due to too large safety margins [37, 38, 29, 39, 40] O´Connor-Cox et al. [5] recommend to use the results of the microbial control of finished beer prior to pasteurization to determine how many and which organisms occur regularly in the respective beer. A collection of D- and z-values of beer spoiling microorganisms measured in beer and other matrices can be found at the Lemgo D- and z-value Database for Food [25].

Not only the D-value and the initial cell count determine the PU_{re}. According to equation (3) the target cell count is essential too. It must be considered that as a result of the exponential death characteristics it is impossible to achieve survival cell counts of zero [41]. The target degree of sterility (survival cell count) is an individual commercial decision for each brewery. Possible values of the target degree of sterility named in published papers range between 1 cell per 1000 mL and 1 cell per 500 hl [35, 42]. It seems to be more sensible to relate the cell count to the case depending bottle volume because the statistical incidence of a microorganism finding is related to the container. If one beer spoiling microorganisms occurs in 10,000 L statistically one of 40,000 0.25-liter bottles or one of 200 50-liter barrels is contaminated, respectively. From this the accepted risk of spoiled containers leads to the target cell count N after the pasteurization.

5 Critical view on the recalculation of the applied (effective) Pasteurization Units (PU_{ef})

The beer formula (7) has been generally accepted in the brewing industry for determining pasteurization regimes, using the constant z-value of 6.9 °C [43] from the mentioned experiments of Del Vecchio et.al. [26]. Since it has been verified that z-values (as D-values) strongly depend on species of microorganism and further parameters this kind of calculation implicate a wide simplification.

An example how pregnant the influence of the z-value is shows the example from *Roesicke et al.* [44]. Even if the z-value ranges only between 6 and 8 °C the recalculated PU in case of a time-temperature combination 30 s and 70 °C would result in span of 24 PU (z = 8 °C) and 9 PU (z = 6 °C). *Molzahn et al.* [45] found even z-values between 3.7 and 7.4 °C for different yeast species and 12.4 °C for *L. brevis*. *Oliver-Daumen* [46] referred actually a z-value about 52 °C for *Lactobacillus lindneri* in alcohol-free beer.

Figure 2 illustrates how the z-value influences the D-value at temperatures unequal the reference temperature. The D-value is plotted versus the temperature T. A and B represents two cases (e. g. two species) with the calculated D-values at different temperatures which differ in their z-value. At the reference temperature T_{60} both microorganisms have the same D-value. At higher temperatures D-values of species A (low z-value) are below those of species B (high z-value), that means in consequence shorter time to apply one PU_{ef}. It is thus of great importance to be aware of the impact of the z- value and to acquire knowledge about the z-values of all occurring organism. Otherwise the calculated PU from pasteurizers is wrong or at least only a rough estimation.

In consequence of this Molzahn et al. [45] recommend to use the z-value of the most thermo resistant microorganism. However, figure 2 shows that it depends on the pasteurization temperature whether higher or lower z-value leads to high D-values. Below T_{60} the effect is vice versa.

6 Importance of D- and z- values experiments

It was already shown that D- and z- values are important in order to precisely design a pasteurization process. Beside the mentioned results of Del Vecchio et al. [28, 27, 26] many more indications of thermal death characteristics are published in regard to the beer pasteurization [47, 36, 27, 25]. However, the most of them did not use realistic beer matrices in regard to alcohol or carbon dioxide content. *Garrick et al.* [47] showed the influence of the pH-value, the carbon dioxide and alcohol content on the thermal death characteristics. The D-value decreases with lower pH, higher content of carbon dioxide and alcohol concentration considerably. The influence of the alcohol was reconfirmed by *Adams et al.* [48]. Experiments have shown that for example of alcohol content affects D-values as well as z-values. While the D-value increases with a lower alcohol content the z-value decreases. Thus in difference to the common assumption a high z-value does not generally indicate a higher heat resistance [36, 45, 47, 49]. This means that a precise calculation of both the necessary PU (D-value) and the applied PU (z-value) would require specific experiments.

To avoid the use of inaccurate z-values *Tsang et al.* [36] introduce another model related to equation (3), the Inactivation Factor (IF) to determine the required time temperature combination.

$$\text{IF} = \text{degree of sterilty} * N_0 \qquad (8)$$

N_0 means the initial viable cell count and degree of sterility is the volume in which one organism may occur after a time t. IF thus indicates the number of decades to be reduced. The time needed at a given temperature is given by the following equation

$$IF = 10^{\frac{t}{D'}} \qquad (9)$$

where D′ is the D value at the pasteurizer temperature. The equation is only valid for one temperature and the corresponding D-value has to be known.

7 Impact of the residence time distributions

An advantage of the flash pasteurization is the rapid heating and cooling through heat exchangers while a holding tube ensures the desired holding time at processing temperature [50, 51, 52]. The effect of pasteurization does thereby depend on the design of the equipment and technical process parameter. Each element of a fluid takes a different route through the processing [53].The residence time of each volume part can differ. The variable residence time results in a residence time distribution (RTD).

The case dependent PU_{re} derives from equation (3) will be transferred with equation (6) into time-temperature parameter combinations. To calculate the correct holding time different models describe the flow of the fluid in a tube. A strongly simplified model describes the flow as an ideal plug flow. In this case all parts of the fluid have the identical velocity. Thus the mean residence time is the theoretical mean residence time τ and can be calculated from the flow rate Q and the volume of the tube V_t:

$$\tau = \frac{V_t}{Q} \qquad (10)$$

Because of wall friction, items in the process line, flow parameters and fluid properties a specific residence time distribution occurs [54]. Depending on the velocity and thus the turbulence of the flow, generally two kinds of pattern can be distinguished, the laminar flow (parabolic velocity profile) and the turbulent flow (flat velocity profile) [55, 56]. As indication the Reynolds number (Re) for tubes is used:

$$Re = \frac{dv}{\nu} \qquad (11)$$

Where d is the diameter of the tube, v the velocity of the fluid and ν is the kinematic viscosity of the fluid. Above Re = 2300 turbulent flow takes place. Because of the flat velocity profile the turbulent flow results typically in smaller a RTD compared with laminar flow. The conservative method to calculate the holding time is to assume laminar flow using the minimum residence time, which occurs at the tube center where the velocity is assumed to be twice the average velocity (0,5 τ) [53, 57, 11]. But several researches have pointed to their results, that the fastest elements in laminar flows achieve a residence time of 0.6–0.8 τ [53, 58, 59, 60, 61]. Thus the simplified flow models rarely reflect the holding time of a real tube [53].

Some researches dealt with the prediction of the RTD through models [62, 63, 64, 65, 66, 67] but this cannot include channeling flow in the holding tube like *Gutierrez et al.* and *Torres at al.* have measured [53, 50]. They found a 10–23% lower mean residence time than the theoretical mean residence time τ. This was due to some parts of the tubes where no velocity or even back flow occurs. In contrast to this Martin mentioned that early interruption of an RTD measurement leads to under estimation of the mean residence time. Thus to record eventually tailing effects Martin advised possible measurement periods of the order of 3–5 times the theoretical mean residence time τ [68]. Thus it is highly recommended to measure the exact RTD for each fluid at the specific process parameters.

A comparably low demanding method to determine the residence time distribution is the pulse experiment [69]. A small amount of a tracer is injected at the inlet and its concentration is continuously recorded at the outlet. The concentration of the tracer over time at the outlet characterizes the statistical distribution of the residence time. It is called the E-curve E(t). The distribution function can be obtained from the following equation [70].

$$E(t) = \frac{c(t) - c_0}{\int_0^\infty c(t) - c_0 dt} \qquad (12)$$

c(t) is the tracer concentration continuously recorded at the outlet and c_0 is the tracer background concentration. The area under the curve is one. Then mean residence time t_m is

$$t_m = \int_0^\infty t * E(t)dt \qquad (13)$$

In order to estimate the impact of a residence time distribution the relation to the thermal death kinetics must be taken into account. An exemplary simplified symmetric distribution as assumed in figure 3 reveal that the parts of a fluid with longer residence time cannot compensate those with a shorter time due to the exponential survival function. Realistic RTD as measured by Torres et al. in bended tubes using water as medium are sinister displaced asymmetric [50]. The non-compensating effect must hence be even bigger. *Veerkamp et al.* [71] have investigate the influence of the width of the RTD. They compare a laminar (Re = 860) flow with a turbulent (Re = 5100) one with the same theoretical mean residence time with regard to the inactivation of microorganism. They found a decimal reduction of 1.3 in the laminar flow and 2.3 in the turbulent flow. The gathered information even if not yet related to the flash pasteurization of beer indicates that the RTD have a relevant effect on the actually applied thermal load. The PU determined with the average residence time does not represent the effective thermal load and the PU_{ef} respectively. The PU_{ef} is less than the PU calculated out of the average residence time [72, 73].

From figure 3 it is obvious that particles in the fluid with a very high residence time (tail) don’t influence the risk of surviving microorganisms. Thus Gutierrez et al. and Torres at al. channeling flow [53, 50] with the result of shorter mean residence time is a better description of the pasteurization than the long measurement of *Martin* [68].

Without knowledge of the distributions of residence time big safety margins have to be taken into account to guaranty microbiological stability. On the other hand the precise calculation of PU_{ef} is necessary to minimize the alteration of nutritional and sensorial properties caused by over-processing of the slower particles [50, 74, 53, 59]. *Levenspiel* [75] have introduced an equation to describe a first order reaction (like thermal inactivation of microorganisms) influenced by the RTD of a continuous reactor:

$$\frac{c}{c_0} = \int_0^{\infty} \exp\left(-\frac{2.303t}{D}\right) E(t)dt \qquad (14)$$

c_0 is the initial cell count, c the cell count after the pasteurization and E(t) the statistical distribution of the residence time.

Apart of the flow rate and consequently the Reynolds number there are many other parameters influencing the RTD. Thus there are several aspects to regard when RTD experiments are conducted. RTD experiments have to be conducted with a fluid with physical properties corresponding to the real product to be pasteurized, otherwise the RTD can differ as *Heppell Dickerson* and *Tomasula* [69, 76, 58] showed for water and milk. The measured RTD can be influenced by the choice of the tracer and the way the tracer is injected and measured [77, 78]. If particles are in the food, the particle density, shape and size can influence the RTD [79, 80, 81, 82]. Torres et al. [44] revealed that higher temperature effect smaller RTD for water according to the higher Re number. Heating or cooling can effect a change in the velocity profile [83, 84]. Moreover the RTD is influenced by the geometrics of the tube. Shorter tubes lead to smaller RTD [50] and straight tubes have a smaller RTD than bended tubes [85, 80, 86, 61, 87, 88]. *Vashisth et al.* have reviewed the properties of a bended geometry and shows that the critical Reynolds number increases in curved tubes [89].

8 Impact of the spatial temperature distribution

The temperature is typically controlled at the outlet of the holding tube [57, 30, 90] including immanently a safety margin. Never the less concerning the logarithmic relationship between destruction of microorganisms and temperature, is an accuracy temperature measurement necessary. An inaccuracy of 1 °C effect about 25 % of error in the pasteurization effect [11, 13, 91]. In principle such level of accuracy should be achieved but in practice they are frequently not achieved [11]. In most cases only the influence of the holding tube is observed, but *Wenneberg* has calculated a reduction of some decades of bacterial spores in the heating section of a milk pasteurizer [92].

For the spatial temperature distribution applies analogously what was said about the RTD. A wide distribution leads to an increased risk of microbiological spoiling. However the temperature distribution cannot measure without enormous effort and without influencing other parameters.

9 Measurement of the PU_{ef}

In order to measure the combined effects of residence time and spatial temperature distribution and to perform a pasteurization assessment microbiological count reduction tests are commonly used [54, 93, 94]. A microorganism suspension of predefined concentration is pasteurized and the survival rate is measured. From the reduction the PU_{ef} can be recalculate. The accuracy of this kind of test suffers under the low precision of microbiological survival cell count detection in growth experiments. Another disadvantage is the need to apply high concentrated microorganism suspension to the production line. That is why other methods as the so called time temperature indicators (TTI) were searched. TTIs have to comply with certain requirements. First of all the substances have to be suitable for use in foodstuffs. The measured reaction should be a first order reaction with a temperature dependency. The reaction kinetics should lead to exact results with the same time temperature profile as in the pasteurization process. Overviews of TTI approaches are given by Torres and *Oliveira* [95] and *Hendrickx et al.* [96]. *Reeves et al.* [97] and *Enevoldsen* [98] have investigated the melibiase activity as TTI. For a pasteurize temperature of 60 °C PU-values of 30–125 was possible to measure with an accuracy of ± 20 % [98]. Melibiase is an enzyme that occurs only in the cell walls of brewer´s lager yeasts (*S. carlsbergensis*) [98]. Another disadvantage of this method is the probable sensitivity of melibiase to the matrix just as microorganism. *Miles et al.* [99] investigated Blue #2 at different pH´s. *Ellborg* and *Tragardh* introduce the hydrolysis of dextran for assessing the TTI [100]. The degree of hydrolysis was determined by gel filtration. The more frequent investigated possible TTI is the acid hydrolysis of sucrose [95, 101, 102, 57, 103]. In order to employ the hydrolysis of sucrose for verifying the pasteurization of beer Torres et al. recommend a pH-value below 1 [95]. There is no publication about an industrial application of such a method. The advantage of these methods is that the influence of the heating and cooling zone can be estimated, the analysis is quicker and more precise than microbiological count reduction tests. The disadvantage is that differences in the activation energy did not allow a direct transfer to PU_{ef}. The different z-values of chemical reactions and microbial death have to be taken into account.

10 Summary

The hitherto existing practice of flash pasteurization suffers under the low precise adjustment of the process parameters time and temperature. If either microbiological risk or resources demanding safety margins shall be avoided an exact determination of the "required Pasteurization Units" and a correct calculation of the actually applied "effective Pasteurization Units" are necessary. The knowledge of thermal death kinetics and a risk assessment for the targeted cell count reduction is as well important as information concerning the spatial temperature and residence time distribution of the flash pasteurization equipment.

This paper is part of a research project that aims to investigate novel methods to manage and control the pasteurization process with minimal resources. Experimental results and ensuing proposals will be published.

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Appendix

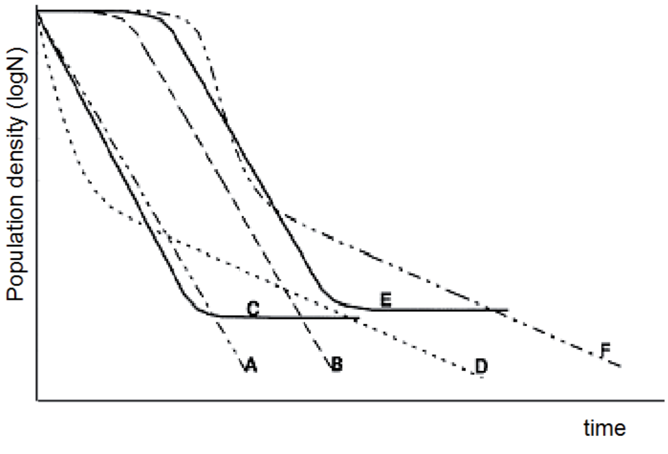

Fig. 1 **Typical survival kinetics of heat treated microorganism by Xiong et al.:**

A = linear decay,

B = linear with shoulder,

C and D = two-phase death kinetics,

E and F = S-shapes curves [21]

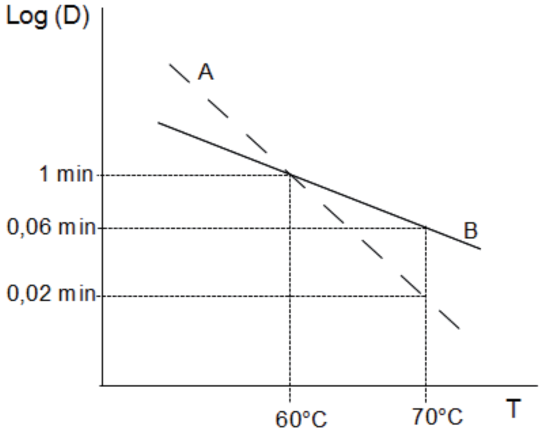

Fig. 2 Scheme of thermal death time curve for two microorganisms, where microorganism A has a higher z-value (z = 6 min) than B (z = 8 min), from *Patino et al.* [41] changed

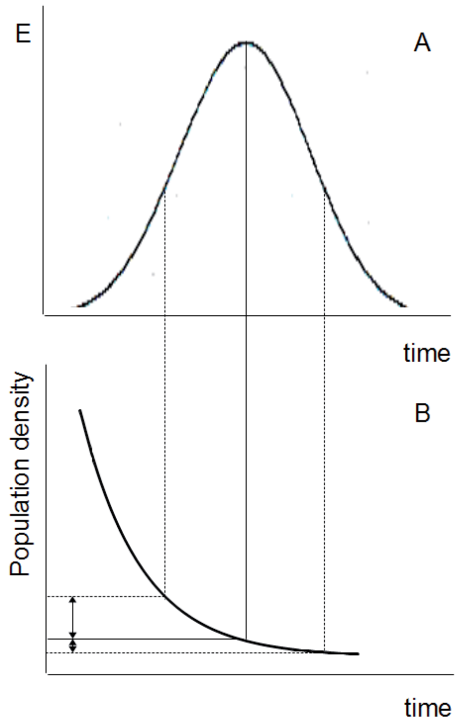

Fig. 3 Influence of the residence time distribution (A) (assuming exemplary a symmetric Gauß determination) on the inactivation of the microorganism (B)