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Effect of Residence Time Distribution in Flash Pasteurizers on the Thermal Death of Microorganisms

To date the calculation of the applied heat load in flash pasteurization plants in terms of Pasteurization Units (PUs) implies several inaccuracies. In this study, the residence time distribution (RTD), which is neglected in practice, was analyzed. Commonly for the determination of PUs the theoretical mean value of the residence time is used. This research investigates, exemplary in a pilot plant, the influence of the RTD on the resulting reduction of the cell count. RTDs were measured with model liquids for beverages (low viscosity) at different flow velocities and for syrups and beverage compounds (high viscosity). The data were used to estimate the microbial inactivation effect by calculations, considering the microbial inactivation kinetics following a first order reaction. For comparison also the survival kinetics were calculated from the mean holding time as result of the residence time distribution. A change in the flow rate, while still ensuring turbulence, leads to a decrease of the count reduction by up to 1.4 orders of magnitudes induced by the RTD. For laminar flows, due to high viscosities, a reduction of 5 orders of magnitudes was obtained, corresponding to a PU reduction of 20 % assuming a $D_{60\,°C}$-value of 1 min. In practice, safety margins in the PU parameterization can now better be adjusted with the knowledge about the RTD impact. The PUs can be individually adapted to the plant and to the product resulting in a safer and a more gentle processing combined with possible energy savings. Thus, the RTD provides a relevant mean for the practice of pasteurization in the case of low Re numbers and small D-values. The impact of RTD is hence not generally negligible.

Descriptors: flash pasteurization, residence time distribution, Pasteurization Unit

1 Introduction

Flash pasteurization is a common method for achieving a microbiologically stabile beverage. Hereby the beverage is heated in a heat exchanger, the fluid then flows through an insulated holding tube and can optionally be cooled in a second heat exchanger. Two factors of this process influence the thermal inactivation of microorganisms, time and temperature. The applied heat dosage is expressed with the Pasteurization Unit (PU) and calculated for a specific temperature for a definite holding time. In practice, the holding time is difficult to measure and thus recalculated from the theoretically mean residence (holding) time τ in the holding tube, which is determined from the measured flow rate $\dot{V}$ and the holding tube volume V according to

$$\tau = \frac{V}{\dot{V}} \qquad 1$$

In addition, the measurement of the effective temperature is difficult in practice. Usually the temperature (ϑ) is only detected at the holding tube's outlet. PUs determined in this way, are only a rough approximation, because neither the exact mean holding time nor the residence time distribution (RTD), nor the impact of the heating and cooling section and the exact effective mean temperature, are known. This paper intends to investigate exemplary the effect of the RTD.

Kalinowski [1] stated that often the theoretical holding time, which usually is applied in the control equipment of pasteurization plants, does not correspond to the real mean holding time. The reasons for this deviation are uncertainties in the calculation of the active volume (flooded volume without recirculation and stagnation). Neglected connecting pieces between plate heat exchanger and holding tube, neglected tube bows and varying diameters of the tubes can decrease the calculated volume of the holding tube. For example, *Sancho* and *Rao* [2] determined experimentally a 10 to 20 % higher average holding time compared to the theoretical mean residence time. In a recent study, *Aguiar* et al. [3] ascertained, for a laboratory pasteurization plant, a substantial increase of the lethal effect in the connecting pieces between heat exchangers and holding tube. This neglected thermal impact can impair the taste of the product. The realization of the residence time reduction by shortening the tube or a higher flow rate would reduce the negative effects and save costs.

Furthermore, the mean residence time can be influenced by fouling or channeling. For instance, *Gutierrez* et al. and *Torres* et al. [4, 5] found a 10–23 % lower mean residence time than derived from the flow rate and tube volume. Thereby the mean residence time was

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determined from residence time distribution measurements. This deviation was due to the decrease of the active volume caused by the existence of internal recirculation and dead leg areas [3, 6]; thus, the experimental mean residence time was smaller than the theoretical one.

A rather conservative method to size a holding tube, which often is applied in milk processes, is to take the shortest holding time determined with the salt test [7, 8, 9, 10]. For this purpose, a salt solution is injected at the beginning of the holding tube. The first increase of the conductivity, which is measured at the end of the holding tube, identifies the shortest holding time. For this kind of experiments, it is important that the used test fluid has similar rheological properties as the product. Otherwise, changes in the flow pattern may influence the minimal holding time [11, 12].

The pasteurization effect is not only influenced by the mean residence time, but also by the residence time distribution, which depends on fluid internal friction and wall frictions. The residence time distribution depends on the fluid properties (viscosity, particles) and on the plant properties (tube diameter, tube length, number of bends and flow rate) [5, 11]. Slower volume elements near the tube wall (longer residence times) do not necessarily compensate other volume parts at the center of the tube with a higher flow (shorter residence times). This is due to the logarithmic dependency of the thermal death kinetics [7, 13]. Thus, the residence time distribution (RTD) causes a deterioration of the microbial inactivation effect to an unknown extent [13]. Various research articles deal with the mathematical prediction of the residence time distribution from the flow conditions [14, 15, 16, 17, 18]. For this purpose, the fluid and plant properties have to be known exactly; but the described deviations show that the prediction models must be regarded as a rough approximation. The measurement of the residence time distribution seems to be a sufficient tool to determine the mean residence time and the active volume accurately.

The Reynolds number (Re) is a proper figure for the description of the flow pattern. In difference to laminar flows, with a typical parabolic flow pattern, turbulent flows tend to form a plug flow pattern because of a greater impulse and material exchange orthogonally to the main flow direction. A higher Re number provokes a narrower RTD. Torres et al. provided a detailed overview of the conducted research projects in the field of residence time distribution [19]. Sometimes for economic reasons shorter holding tubes with larger diameter are installed with lower Re numbers [1]. This may negatively affect the achieved PU. *Veerkamp* et al. [20] measured the impact of a turbulent and a laminar flow, respectively, with same mean residence times, on the microbial inactivation during the pasteurization of an egg-product. They found a decrease of the decimal count reduction of approximately 55 % caused by the broader RTD of the laminar flow.

The objective of this paper is to investigate the RTD in beverage pasteurizers and its effect on the thermal inactivation of the microbes. For this purpose, the influence of various flow rates and viscosities in a pilot plant were investigated and the resulting count reduction and PUs calculated.

2 Mathematical description of the thermal death of microorganisms

The thermal inactivation kinetics of microorganisms vary; *Xiong* et al. and *Peleg* characterized some of them [21, 22]. In standard textbooks thermal inactivation of microorganisms are mostly described as first order reaction [23], this represents a good and simple approximation especially for vegetative microorganisms [24]. The first order reaction, as common approach for the inactivation kinetics of vegetative microorganisms, is the basis of the PU calculation [25, 26, 27] according to the following equation [25, 27]

$$-\frac{dN}{dt} = k \cdot N \qquad 2$$

N is the number of microorganisms and k is the temperature dependent inactivation constant for the thermal inactivation of the cells; k is here called the specific death rate. The solution of equation 2 for the boundary condition $N(t = 0) = N_0$ is

$$N(t) = N_0 \cdot e^{-k \cdot t} \qquad 3$$

Traditionally in microbiology the decimal reduction degree is used by calculating the rate of heat inactivation on the basis of ^{10}log as

$$lg\left(\frac{N_0}{N(t)}\right) = \frac{k \cdot t}{ln10} \qquad 4$$

The decimal reduction time (D-value) is defined as time needed to reduce the microorganism count by one order of magnitude ($lg(N_0/N) = 1$) and is derived for a constant temperature from equation 4

$$t = D = \frac{ln10}{k} \qquad 5$$

The Arrhenius equation describes the temperature dependency of the reaction. The specific death rate k, and thus the D-value, are calculated for different temperatures from the Arrhenius equation [28] according to

$$k = k_0 \cdot e^{\left(\frac{-E_A}{R \cdot T}\right)} \qquad 6$$

The frequency factor k_0 is the reaction rate at an infinitely high temperature ($1/T = 0$), the activation energy E_A describes the temperature dependency of the death rate, R is the ideal gas constant (8.314 J/mol K) and T is the absolute temperature in K. E_A and k_0 are influenced by the kind of microorganism (strain) and the habitat conditions. In microbiology, the decimal reduction time D- and the z-value are the commonly used empirical parameters to describe the reduction of living cells. The z-value (Eq. 12) is derived from equation 6 in several steps by comparing two inactivation settings with an equal lethal effect ($N_0/N(t)$) in terms of two time-temperature combinations as

$$t_1 \cdot k_1(T_1) = t_2 \cdot k_2(T_2) \qquad 7$$

Combining the Arrhenius equation (Eq. 6) yields

$$t_1 \cdot k_0 \cdot e^{\frac{-E_A}{R \cdot T_1}} = t_2 \cdot k_0 \cdot e^{\frac{-E_A}{R \cdot T_2}} \qquad 8$$

which is transferred by logarithmic conversion to

$$ln\frac{t_1}{t_2} = -\frac{E_A}{R}\left(\frac{1}{T_2} - \frac{1}{T_1}\right) = -\frac{E_A}{R}\left(\frac{T_1 - T_2}{T_2 \cdot T_1}\right) \quad 9$$

A common approach in pasteurization is to use a reference point (T_{ref}, t_{ref}) for describing the same effects for different time-temperature combinations:

$$ln\frac{t}{t_{ref}} = -\frac{E_A}{R}\left(\frac{1}{T_{ref}} - \frac{1}{T}\right) = -\frac{E_A}{R}\left(\frac{T - T_{ref}}{T_{ref} \cdot T}\right) \quad 10$$

Presenting equation 10 on the basis of ^{10}log results in

$$lg\frac{t}{t_{ref}} = -\frac{E_A}{ln10 \cdot R \cdot T_{ref} \cdot T}\left(T - T_{ref}\right) \quad 11$$

which allows to calculate the same degree of sterility for all time-temperature combinations. The z-value defines the temperature increase ($T–T_{ref}$) which provokes a decrease of the D-value by one order of magnitude ($lg(t/t_{ref}) = –1$). Thus the z-value can be obtained by

$$\frac{1}{z} = \frac{E_A}{ln10 \cdot R \cdot T_{ref} \cdot T} \quad 12$$

The z-value allows to translate a known D-value (at a reference temperature, D_{ref}) into other D-values for different temperatures from equation 11 and 12 by substituting the time figures t and t_{ref} by the decimal reduction times (D-values) D and D_{ref} according to

$$D = \frac{D_{ref}}{10^{\frac{\vartheta - \vartheta_{ref}}{z}}} \quad 13$$

Referred to equations 4 and 5, the decimal cell count reduction can be expressed with the D-value by

$$lg\left(\frac{N_0}{N(t)}\right) = \frac{t}{D} \quad 14$$

The PU is the pasteurization time at a defined temperature. In practice, the reference system is adapted to the characteristics of the beverage. For beer the reference temperature is 60 °C and for fruit juice beverages 80 °C. The PU is the pasteurization time at a defined temperature. Inserting equation 13 into 14, the subsequent equation follows

$$D_{ref} \cdot lg\left(\frac{N_0}{N(t)}\right) = t \cdot 10^{\frac{\vartheta - \vartheta_{ref}}{z}} = PU \quad 15$$

Equation 15 explains the relation of the PU with the first order reaction and the Arrhenius relation and represents the lethal effect as Pasteurization Units (PU) for a specific pasteurization temperature. A particular amount of PUs accords to the same inactivation effect independent of the time (t)-temperature (ϑ) combination. This is valid as long as the temperature is above the lowest lethal temperature. In beer breweries, according to the so-called beer formula 1 PU is equivalent to an exposure time of 1 min at 60 °C. Here a z-value of 7 °C is assumed to achieve a 10-fold reduction of the D-value.

3 Materials and methods

3.1 Measurement of the residence time distribution (RTD)

For a precise determination of the thermal load, or rather the Pasteurization Units (PU; Eq. 15) it is necessary to include the distribution of the residence time into the calculation, instead of the common used theoretical mean residence time (Eq. 1). Therefore the RTDs were measured within the holding tube of a semi-technical flash pasteurization plant (Fig. 1). The holding section consisted of 5 insulated tube loops (24 m total length) with an inner diameter of 0.015 m and connecting pieces with diameters from 0.015 to 0.025 m (4.2 m length) which together result in a holding section volume of about 5.2 L. The heating and cooling sections contain a volume of 3 L, respectively.

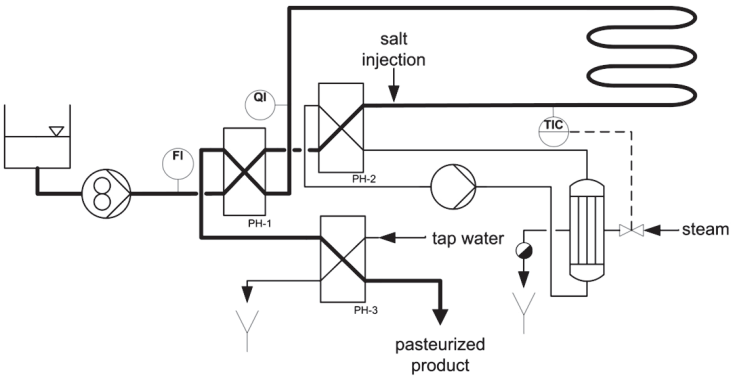

Fig. 1 Simplified flow chart of the flash pasteurization plant modified for the measurement of the residence time distribution. The quality indication (QI) is the measurement of the conductivity, the bold line marks the track of the product, PH-1 to PH-3 indicate the recuperation, heating and cooling sections of the three-stage plate heat exchanger

For the determination of the RTD a saturated sodium chloride solution was used as tracer. A quantity of 5 mL of this solution was pulse-injected instantly within one second through a septum at the inlet port of the holding tube (Fig. 1). The concentration of the tracer was measured inline at the end of the holding tube, by means of the conductivity meter, with an inductive sensor (Bürkert, Type 8226; 10 s^{-1}).

The recording of the conductivity started in the moment when half the volume (2.5 mL) was injected and stopped when the initial base-level conductivity was reached again (i_{max}), i = 1 marks the start time. The time distribution function $E(t_i)$ results from the concentration of the tracer plotted against the residence time. The RTD function describes the fraction that is leaving the system at each point in time $c(t_i)$ in relation to the total injected sodium chloride solution according to

$$E(t_i) = \frac{c(t_i)}{\sum_{i=1}^{i_{max}} c(t_i) \cdot \Delta t} \quad 16$$

Because the conductivity sensor records signals at a rate of 10 s^{-1} a discrete residence time distribution function was calculated for intervals of 0.1 s. The area below the function is 1. The resulting mean residence time was calculated weighted with the discontinuous residence time density (Eq. 16). Thereby the residence time intervals, in which bigger amounts of the salt solution are leaving the holding tube, are more pronounced. The weighted mean residence time $\bar{t}$ is thus calculated as

$$\bar{t} = \sum_{i=1}^{i_{max}} t_i \cdot E(t_i) \cdot \Delta t \quad 17$$

The flow rate is measured with an electronic flow meter (Krohne, Optiflux 6100) on the cold side just before heating. Different flow rates were set with a controlled pump. Most of the experiments

were performed with water as product simulant. Because syrups and beverage compounds with high viscosities are pasteurized in beverage industry too, the RTD of a fluid with a viscosity of a 50 $\%_{(w/w)}$ sugar solution was additionally measured. Due to the decrease of the electric conductivity with increasing sugar concentration the experiments could not be performed with a 50 % sugar solution, therefore a solution of 12.5 $\%_{(w/w)}$ sucrose and 0.25 $\%_{(w/w)}$ methylcellulose was used to increase the viscosity and to simulate the flow characteristics of a 50 % sucrose solution.

3.2 Incorporation of the residence time distribution (RTD) in the prediction of the cell count reduction

The effect of the RTD on the reduction of the cell count and thus the Pasteurization Units can be calculated for each case as described subsequently. Assuming that each volume element is exposed to the same mean temperature but to different residence times, the cell count $N(t_i)$ for each residence time t_i can be calculated based on an initial cell count N_0 by integrating equation 6 into equation 3 as

$$N(t_i) = N_0 \cdot e^{-k_0 \cdot exp\left(\frac{-E_A}{R \cdot T}\right) \cdot t_i} \quad 18$$

The total volume of the pasteurized beverage is considered to consist of discrete small volume elements characterized by a constant residence time t_i within a time interval Δt. The time interval is 0.1 s due to the discrete measurement of the RTD. The sum of the final cell counts in all discretely calculated volume elements provides the total final cell count N_{RTD} according to

$$N_{RTD} = \sum_{i=1}^{i_{max}} N(t_i) \cdot E(t_i) \cdot \Delta t \quad 19$$

Here, $i = 1$ and i_{max} represent the start and end of the RTD measurement and thus the volume elements with the shortest ($i = 1$) and longest residence time (i_{max}). Each volume element is weighted by the residence time density (Eq. 16). For this purpose, $N(t_i)$ is multiplied with the area below the RTD density function in the interval Δt for the corresponding t_i. This is expressed by the product of $E(t_i)$ and the interval's width Δt obtained from the conductivity measurement. Equation 19 completed with equation 18 yields

$$N_{RTD} = \sum_{i=1}^{i_{max}} \left(N_0 \cdot e^{-k_0 \cdot exp\left(\frac{-E_A}{R \cdot T}\right) \cdot t_i}\right) \cdot E(t_i) \cdot \Delta t \quad 20$$

Figure 2 clarifies schematically the incorporation of the RTD in the prediction of the cell count reduction by means of a sum of discrete time intervals, as well as the relation of the RTD function and the inactivation kinetics of microorganisms. Longer residence times cannot compensate shorter residence times with decreased cell reductions.

For its application, equation 20 requires realistic kinetic inactivation parameters (k_0 and E_A) of the spoiling microorganism. Here we therefore applied kinetic data accepted by convention in the brewing industry for beer; the z-value was set to 7 °C and the reference temperature ϑ_{ref} for the PU calculation of beer was 60 °C [13]. The reference D-value ($D_{\vartheta_{ref}}$) was set to 1 min according to the average of published data for obligate beer spoiling microorganisms [24, 29, 30, 31]. The activation energy E_A results from equation 12. According to *Kessler* [28] the z-value was translated to the activation energy for the reference temperature $T = T_{ref}$ by

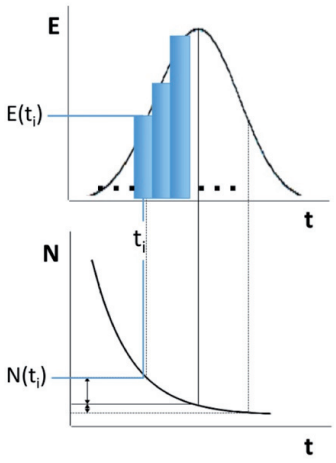

Fig. 2 **Schematic illustration of the RTD and its relation to the inactivation kinetics of microorganisms by a first order reaction. For the calculation of the total inactivation effect the inactivation ratio of discrete residence times (t_i) are summed up along the entire span of residence times and weighted by the RTD (area of the RTD density function)**

$$E_A = \frac{ln10 \cdot R \cdot T_{ref}^2}{z} \quad 21$$

which results in an activation energy of 304 kJ/mol. For the determination of the frequency factor k_0 of the Arrhenius equation the determined activation energy and the $D_{60\,°C}$-value is used. The reaction rate constant k_{ref} for the reference temperature is derived from equation 5

$$k_{ref} = \frac{ln10}{D_{ref}} \quad 22$$

The temperature independent frequency factor k_0 was calculated by inserting the determined E_A and $k_{ref}(60\,°C)$ values in equation 6. The reaction rate constant can be calculated with known k_0 and E_A for varying temperatures (Eq. 6). In the following, a pasteurization temperature of 70 °C is assumed which results in a k (70 °C) of 56 min^{-1}.

The logarithm of the surviving cell count ratio (the decimal reduction degree) $lg\left(\frac{N_0}{N(t)}\right)$ is calculated from the RTD and the mean residence time to examine the impact of the RTD on the pasteurization effect. With a D_{ref} = 1 min the decimal reduction degree corresponds to the calculated PUs (Eq. 15).

4 Results and discussion

Figure 3 illustrates the RTDs, measured with water at 70 °C in a semi-technical pilot flash pasteurizer. Three different flow rates are shown representing different Re numbers. Pasteurization parameters related to the practice were correspondingly adjusted (70 °C and holding times between 45 and 75 s).

Even though all three RTDs in figure 3 represent turbulent flow patterns (Reynolds numbers of 15,000, 19,000 and 24,000), a rising flow rate corresponds to a narrower distribution of the residence times. The effect of these variations in the RTD on the cell count reduction can be calculated with the weighted expected surviving cell count (N_{RTD}, Eq. 20). In table 1 the effect of the RTD on the

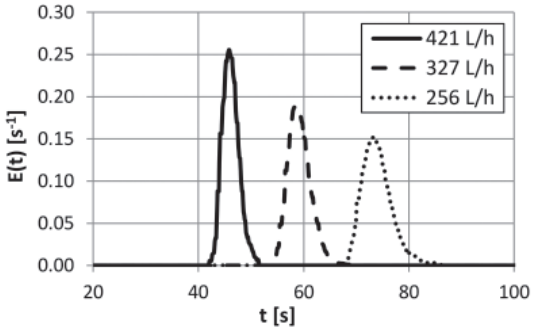

Fig. 3 Exemplary residence time distributions measured in the holding tube of the described pasteurization pilot plant for different flow rates at 70 °C. The Reynolds numbers ranged between 15,000 and 24,000

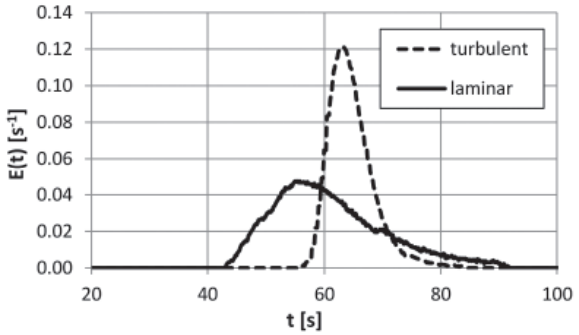

Fig. 4 Residence time distribution of a model liquid for a beverage compound or syrup (solution consisting of 12.5 $\%_{(w/w)}$ sucrose and 0.25 $\%_{(w/w)}$ methylcellulose in water) and water as a low viscous beverage simulant in a holding tube of a semi-technical pilot plant. The Re numbers were 0.5 and 7100, respectively

calculated cell count reduction is shown for different flow rates. The calculation with the help of the equations 21 and 22 as described above is based on commonly used specific inactivation figures. It is necessary to set an initial cell count N_0 by definition to start the calculation workflow, which however will not influence the final decimal reduction degree [$\lg\left(\frac{N_0}{N_{RTD}}\right)$].

Table 1 Influence of the RTD of different flow rates on the microorganism reduction level. The data are based on $D_{60\,°C}$ = 1 min and z = 7 °C but were calculated from the corresponding E_A and k_0 at 70 °C. $N_{\bar{t}}$ is the microorganism count calculated with the mean residence time $\bar{t}$ and N_{RTD} is the microorganism count under consideration of the residence time distribution

flow rate $\dot{V}$ [L/h]	Reynolds number Re	$\lg\left(\frac{N_0}{N_{\bar{t}}}\right)$	$\lg\left(\frac{N_0}{N_{RTD}}\right)$
421	24,000	18.8	18.4
327	19,000	24.1	23.4
256	15,000	30.1	29.1

The RTDs for the used parameters (distinctly turbulent flow) slightly influence the thermal inactivation. The decimal reduction degree $\lg\left(\frac{N_0}{N_{RTD}}\right)$ calculated under consideration of the residence time distribution (RTD) is lower than the $\lg\left(\frac{N_0}{N_{\bar{t}}}\right)$ calculated with the mean residence time. A maximal difference of one order of magnitude was found. In order to learn more about the influence of the viscosity the RTDs were also measured at 20 °C (data not shown) – simulating a moderately more viscous product – even if lethal effects cannot be expected at this temperature. As a conclusion, the microbial reduction degree resulted in a 1.4 orders of magnitude lower reduction degree by application of the RTD measurement compared to the calculations where the mean residence time was used, the application of the theoretical mean residence time, which is the widely accepted procedure, could lead to further inaccuracies. Therefore can be concluded that in these standard cases the inactivation effect is underestimated.

In addition, the mean residence time $\bar{t}$ is influenced by the flow rate. It is evident that the nominal volume of the holding tube is not ideally mixed as assumed for the calculation of the theoretical mean residence time τ (Eq. 1). A higher flow rate leads to a better impulse and mass exchange and consequently to a higher active volume of the tube system. This can be demonstrated by the recalculation of the volume from the flow rate and the mean residence time $\bar{t}$ determined by the RTD. The rise of the flow rate from 260 to 420 L/h causes an increase of the active volume by about 3 %.

In the beverage industry not only low viscous products are pasteurized, but also syrups and beverage compounds with high viscosities. The deviation of a laminar flow pattern in difference to a turbulent one was investigated with a high viscous simulant with a viscosity corresponding to a 50 $\%_{(w/w)}$- sucrose solution and a low viscous fluid (water) at 20 °C. In figure 4 the RTDs of both are shown. The high viscous fluid with a laminar flow pattern (Re = 0.5) causes a significantly wider RTD. This broader RTD provokes a stronger effect on the predicted cell count reduction as shown in table 2. The RTD of the high viscous fluid decreases the cell count reduction by 5 orders of magnitudes while in case of the low viscous liquid the RTD decreases the count reduction by 1.4 orders of magnitude. This significant reduction during laminar flow is not only caused by the broader RTD, but also by the reduced active volume. The mean residence time of the high viscous fluid is shorter and consequently there is a decrease of the decimal reduction $\lg\left(\frac{N_0}{N_{\bar{t}}}\right)$ calculated from the mean residence time, too (shown in Table 2).

Table 2 Influence of the residence time distribution on the calculated degree of cell count reduction for different viscosities (η) calculated with a first order reaction based on a z-value of 7 °C and a $D_{60\,°C}$-value of 1 min; assumed pasteurization temperature 70 °C; holding time 65 s

flow rate $\dot{V}$ [L/h]	viscosity η [mPa s]	Reynolds number	$\lg\left(\frac{N_{RTD}}{N_{\bar{t}}}\right)$	$\lg\left(\frac{N_0}{N_{RTD}}\right)$
300	1.0×10^{-3}	7100	26.2	24.8
300	13	0.5	24.7	19.7

The effect of the RTD is due to the logarithmic function of the thermal inactivation of microorganisms [13]. The lowering effect of the lethal efficacy depends on the residence time distribution breadth and on the D- and z-values. Both, the RTD and the inactivation kinetics characteristically interact with each other: a comparably broad RTD function covers a wider range of the logarithmic thermal inactivation curve than a narrow RTD and thus increases the inactivation effect of the logarithmic kinetic; and the D-value defines the extent of the inactivation curve bending.

The described interaction of RTD and the D-value with the cell count reduction is calculable and illustrated for the mentioned example with two different viscosities in figure 5. The surviving cell count was calculated from the mean residence time (N_t) and the residence time distribution (N_{RTD}). In figure 5 $D_{60\,°C}$-values from 0.2 to 8 min are plotted (the absolute thermal death effect increases exponentially with a decreasing $D_{60\,°C}$-value). These D-values and a z-value at 60 °C of 7 °C were used to determine the reaction parameters E_A, k_0, and k of the first order reaction and thus the cell reductions. The logarithm of the resulting cell count ratio $\lg\left(\frac{N_{RTD}}{N_{\bar{t}}}\right)$ represents the decimal difference in the resulting microorganism count induced through the RTD. Figure 5 reveals that the effect of RTD increases at smaller D-values. Low Re numbers or even laminar flow conditions enhance this effect as in case of syrups, compounds, large pipe diameters or low flow rates.

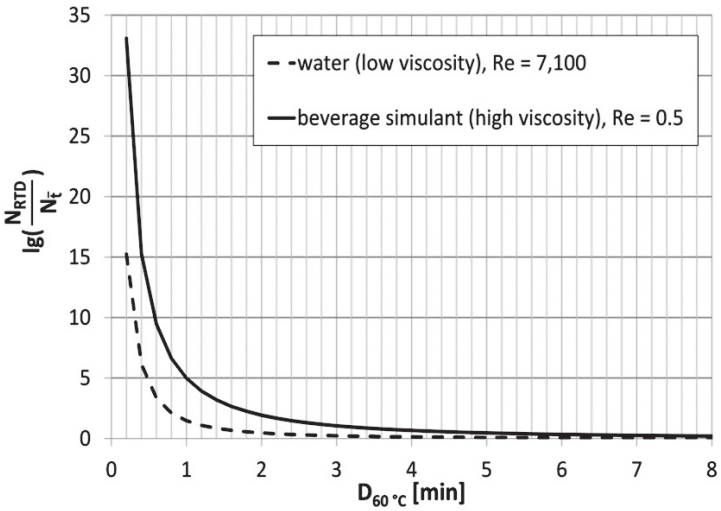

Fig. 5 Effect of the D-value on the influence of the RTD on the resulting cell count N_{RTD} for two viscosities and Re numbers (0.5 and 7,100). Calculations were made based on the logarithm of the ratio of the surviving cell count induced by the residence time distribution N_{RTD} (Eq. 20) to the surviving cell count induced by the mean residence time $N_{\bar{t}}$ (Eq. 17 and 18). A z-value of 7 °C and a pasteurization temperature of 70 °C was assumed. The corresponding RTDs are shown in figure 4

5 Conclusion

The effect of the residence time distributions (RTDs) on the expected microorganism inactivation is influenced by the RTD and the microorganism inactivation kinetics. In case of low Re numbers and small D-values the RTD decreases distinctly the decimal reduction degree. Small Re numbers can especially be expected for syrups and beverage compounds. The widely accepted procedure to determine the PUs with the mean residence time underestimates hence the real inactivation. The applied PUs must then be adapted by increasing the holding time or increasing holding temperature. In the practice of beer pasteurization, the applied PUs imply safety margins so that this decrease of the decimal reduction degree inappreciably affects the shelf life of the product. Furthermore, the volume and the active volume (considering residence time relevant dead legs) are not exactly known in the practice. The active volume can be clarified by RTD measurements even for the conventional PU determination. The RTD measurements provides a more exact determination of the decimal reduction degree. Finally, the impact of RTDs are not generally negligible and it must be recommended to verify their effect case dependent. RTD measurements can be applied with few changes of the plant and the incorporation of the calculations into the degree of sterility is simple to implement.

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