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Research Paper

The effects of solid fraction and container pressure on carbonate drinks pasteurization

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ABSTRACT

Thermal pasteurization is a food preservation process that deactivates or eliminates bacteria, extending shelf life. Thermal pasteurization is based on the temperature-controlled variation of the food for a specific duration. In this work, three carbonate fluids with different solid contents were tested through a complete thermal pasteurization cycle (mimicking a continuous industrial process using a tunnel machine) under two container conditions: unsealed (ambient pressure) and sealed (pressurized). Based on comparisons between the unsealed and sealed containers, the results show that the trends in the heat transfer coefficient, drink temperature, and internal pressure differ with respect to internal pressure and food solid fraction. Solid content interacts with the gas fraction, making the thermal process difficult to predict and measure using industrial (high-production-rate) methods. Understanding the non-linear behavior of carbonate drinks prepared from homogeneous or heterogeneous substances is fundamental to preserving food quality and ensuring food safety.

1. Introduction

Pasteurization is a process applied to certain foods and drinks to minimize health risks from pathogenic microorganisms, increase shelf-life, and reduce or eliminate bacterial content. Pasteurization processes based on temperature variation are recognized as traditional methods for deactivating microorganisms by increasing food temperature [1]. Understanding the thermodynamic behavior of the fluid during the thermal pasteurization cycle enables the cycle to be optimized. It reduces the risk of occurrences that may diminish product quality [2].

To quantify the magnitude of the pasteurization process, a parameter called the pasteurization unit (PU) has been introduced, defined as a function of the product temperature over time. This parameter represents a ten times decrease in bacterial presence and the temperature target above which the PU starts accumulating. The PU value is assessed for each food product through laboratory tests that estimate bacterial content and activity, which serve as the basis for calculating the product's shelf-life. It is not acceptable to lower PU below the target because the process could be incomplete, which would be dangerous for consumers. At the same time, exceeding the PU needed is not adequate because it can compromise the food properties. It could deteriorate the final product's flavor and appearance, making the entire batch unsellable. Measuring systems and virtual assessment, as reported by [3], are continually being designed to better control this fundamental step in the food production chain [4]. Two types of pasteurization processes have been developed, considering the production rate: batch and continuous.

Batch pasteurization is appropriate when a small batch of product needs to be pasteurized (low production rate). It can be helpful when the variability of the product is high (the thermal recipe can be easily adjusted thanks to the lower inertia and complexity of the system).

Continuous pasteurization is divided into two types: flow pasteurization and tunnel pasteurization. Flow pasteurization processes are usually developed using non-thermal technologies [5], even though thermal processes are still used in high-temperature applications. HTST (high-temperature, short-time) pasteurization, also called flash pasteurization, is used in most thermal flow pasteurization processes. In flash pasteurization, before bottling, the product runs through pipes or between two plates and is heated to a high temperature for a short time. By contrast, this methodology requires a well-controlled, sterile filling operation to avoid introducing microorganisms into the product [6]. This results in limited flexibility in the production line, which is designed to achieve a high production rate of the same food product with the same thermal recipe. The tunnel pasteurizer is used to pasteurize bottles, cans, or containers already filled and sealed. The product is conveyed by a belt into an enclosed chamber, typically a large one, and is sprayed with water from nozzles on the upper wall [7], generating a temperature-controlled trend starting with a heating ramp, followed by a holding phase, and then a cooling ramp. In such of applications, the heat exchange

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process involves the three effects: (i) the water impingement coupled with the liquid film at the external wall of the container (that depends on the spray intensity and flow rate) [8], (ii) the conductive mechanisms within the container material (that depends on the container material and wall thickness) [9], and (iii) the natural convention inside the container (that depends on the fluid characteristics, container shape and orientation) [10–14].

Regarding fluid characteristics, viscosity and non-Newtonian effects are the two most important properties of food products [10,15,16]. Natural convection behavior depends on viscosity dissipation, which reduces or modifies the effects of the thermal gradient. In addition, the presence of solid fraction within the fluid matrix (for example, the pulp fraction in juices) could add several non-linear thermal effects on the heat exchange process [17].

Tunnel pasteurization is widely used in beer and carbonated drink production plants. The high production rate and the flexibility of the production plant are suitable for such products. A growing market characterizes these products. One of the fundamental aspects of their success is the effervescence. The release of CO_2 introduced in the product gives rise to effervescence, which increases the attractiveness of the beverage, enhances the mouthfeel, and contributes to acidic preserving action [18,19].

Carbonated drinks can be classified according to the method used to carbonate the liquid. In beer, CO_2 is a yeast fermentation product that dissolves in the liquid. Sparkling water is naturally carbonated, so it does not need further addition. For soft drinks or highly sparkling beverages, a carbon dioxide gas injection is expected [20]. The presence of carbon dioxide must be understood as an equilibrium based on partial pressure. The amounts of dissolved and free gas fractions depend on the liquid's temperature and pressure. This implies that, by imposing a thermal process and thus a temperature trend, the gas fraction changes from dissolved to free (and vice versa), thereby modifying the internal pressure (when the container is sealed) and altering effervescence and liquid-to-gas interactions. The presence of CO_2 could change the behavior during the pasteurization process [21]. The authors in [2] use orange-based soft drinks to assess the effects of thermal treatment on their organoleptic characteristics. Mandarin juice was also used in [22] to analyze the stability of three samples (fruit juices, syrups, and carbonated ready-to-serve drinks) under varying storage conditions and chemical preservative concentrations. Analyses of the inhibitory effect of CO_2 on bacteria are available [23], but several bacteria can grow even at high CO_2 concentrations.

1.1. Aim of the paper and novelty

In this work, an experimental investigation was conducted to assess the thermal behavior of different carbonate drinks during heating and cooling. Different solid percentages are considered to investigate the temperature trends during thermal pasteurization in the presence of solid fraction within the fluid matrix. The fluid selection covers soft and alcohol-based beverages. Tests were performed with sealed (pressurized container) and unsealed (constant pressure in equilibrium with the ambient) samples. The sealed condition represents pasteurization, bringing heat transfer coefficient values closer to those that characterize the actual condition of the products. The literature lacks information and general data on the effects of internal pressure on the thermal behavior of carbonate drinks, especially when a liquid-gas mixture is added to a solid fraction. The novelty of the present study lies in generalizing the thermal behavior during heating and cooling for carbonate drinks, where the presence of a solid fraction can alter the temperature-time trends. The results are interpreted to enable comparative considerations that can extend the present findings to several applications. The definition of the thermal behavior of carbonate drinks with respect to container condition (sealed or unsealed) and the presence of the solid fraction could help manage the thermal efficiency of the pasteurization process and improve the quality of thermally treated food.

2. Materials and methods

To understand the influence of the solid fraction and the container's internal pressure during pasteurization, a matrix of three different carbonate drinks and two container types (sealed and unsealed) has been designed. A representative thermal cycle has been defined for each product based on a typical production process. Usually, a tunnel pasteurizer is divided into three macro-areas, each of which is further subdivided into zones. In the first area, the product is heated until it reaches the target temperature, above the pasteurization threshold. In the central area, the product maintains the specified temperature and undergoes pasteurization. Finally, in the last area, it is cooled to bring it close to room temperature [6]. Each area can be divided into several zones, each of which receives water from a nozzle at a constant temperature. Such division into zones is necessary to avoid excessive temperature differences between the water sprayed and the bottle temperature, and to prevent the bottle from breaking and causing thermal shock to the food products. The duration of each zone depends on the thermal recipe and the filling temperature, which determine the initial food temperature at the entry zone (the first area where the food product is heated) of the tunnel.

To define the experimental strategy, an analysis of the internal mechanisms of the heat exchanger process must be conducted. During heating and cooling, convective phenomena are triggered inside the container, setting the liquid in motion. Natural convection is generated by a thermal gradient that develops radially inside the container. The water spray imposes a specific temperature on the container's external wall, carried by conduction and convection from the outside diameter to the container axis [8]. Boundary effects at the container's bottom and top determine the local thermal phenomena that, coupled with convective cells, generate a zone with low movement (and thus low thermal energy). Inside this zone is a point called the *cold spot*, characterized by the most significant thermal inertia [24]. The *cold spot* is a critical point because it is where the desired temperature is reached most slowly during heating. Therefore, by monitoring this point, it is possible to detect the container temperature, which helps compute the PU value, ensuring that each part of the food product has undergone the proper thermal process. The spot is located along the bottle's downward central axis, and its exact height depends on the process time. The characteristics of the fluid drive the internal heat transfer processes within the container. The properties of the fluid (i.e., density and viscosity) determine the relative importance of conduction and convection in heat transfer. Increasing the solid fraction within the fluid tends to observe a more significant impact of conduction on heat exchange [17,25,26].

Given this evidence, the fluid selection reported in Table 1 has been done. In the Table 1, the main characteristics of the carbonate drinks are reported. The strategy is to define a set composed of carbonate drinks without a solid fraction (a simple mixture between liquid and gas) and with a solid fraction (a mixture between liquid, gas, and solid). The data reported in Table 1 refers to the available data on the food nameplate and sets a reference for the present study. In particular, 'solid' refers to the amount of juice used per recipe. The mixing process (pulp and liquid fractions) and, thus, the final mixture's characteristics were controlled by the manufacturer during the filling process. A lager beer (identified by the handler *Beer* in the present work) has been considered as a mixture of liquid and a gas fraction. The rheology of such a fluid can be interpreted as that of a water-like medium [27] with a viscosity closer to that of water.

A blonde beer with tomato juice that is a typical refreshing Mexican drink (identified by the handler *Beer-Tomato* in the present work) and a soft drink with mango juice that is promoted as an energy drink (identified by the handler *Mango* in the present work) have been considered as a mixture of liquid, solid, and gas fractions. The solid fraction refers to juices such as tomato and mango, which are commonly used in the food industry to create preparations that have a refreshing taste. For example, energy drinks and other preparations are formulated by combining

Table 1
Fluid characteristics (values are intended for 100 ml of fluid).

Description (handler)	Solid [%]	Alcohol [%]	Calories [kJ]	Carbohydrates [g]	$\mu_{@100s^{-1}}$ [Pa s]
Larger beer (*Beer*)	0.0	4.7	160	3	0.001
Blonde beer + tomato (*Beer-Tomato*)	7.5	3.5	40	49	1
Soft drink + mango (*Mango*)	9.0	0.0	211	12	0.1

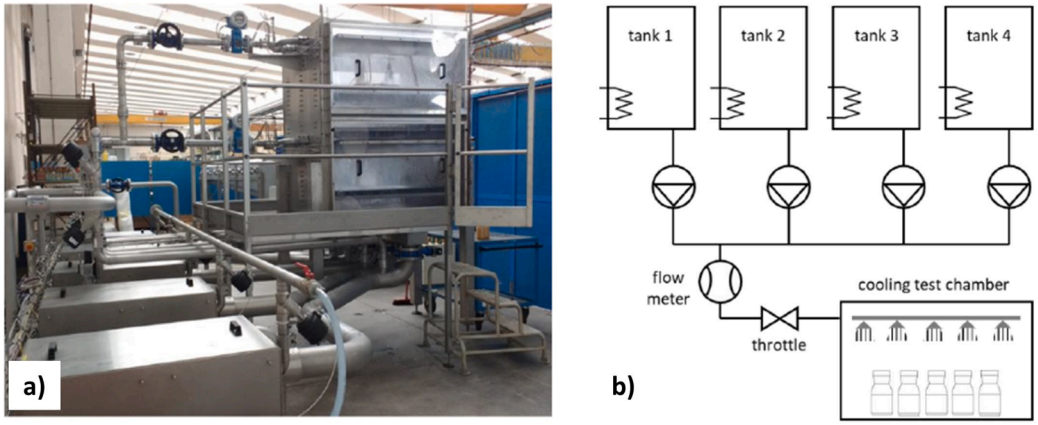


Fig. 1. Experimental test cell: a) actual installation and b) sketch of the test bench.

liquid and solid ingredients to enhance flavor and nutritional benefits. The rheology of such fluids is complex to define due to the presence of a separate solid fraction within the fluid matrix. To increase the completeness of this work, the data related to the juice is highlighted. The viscosity of tomato juice is 1 Pa s (value obtained at 100 s^{-1}). The viscosity of the mango juice is 0.1 Pa s (value obtained at 100 s^{-1}). As can be seen from the Table 1, the solid fraction of the latter two fluids (*Beer-Tomato* and *Mango*) is comparable and lower than 10 %. The presence of the solid fraction generates a two-phase fluid that interacts with the internal pressure of the container, generated by the release and dissolution of CO_2. The thermal-fluid behavior is evaluated for the as-received container. The fluid samples were obtained from the market (in sealed containers) to enhance the generalization and reproducibility of this study and its related results. The beverages bought were already pasteurized, so they were chemically stable.

The test bench represents a portion of an in-line pasteurizer and has a footprint area of 2.0 m x 2.0 m and a height of 3.5 m. The actual installation and the sketch of its layout are reported in Fig. 1a and b, respectively. The type and number of nozzles, as well as the water flow rate, are the same as those used in full-size machines. The containers are placed under the nozzles inside the pasteurization chamber. To reproduce the conveyor belt's path, five tanks are introduced that contain water at different temperatures, which are sprayed onto the product. The flow rate is kept constant through a valve positioned before the nozzles, named throttle in Fig. 1a. Linked to the test bench are T-type rod thermocouples used to measure the temperature of the water spray. Fig. 1 shows a schematic diagram of the system. The test bench and its setup were already used to study the cooling process and the thermodynamic characteristics of several juice samples in [17]. The present test bench and its control system maintain a constant water spray temperature with a variation of less than 1.5 °C over time.

2.1. Experimental strategy

A specific strategy has been adopted to determine the fluid thermal behavior. Since the heat-exchange process assessment may depend on the container, the drinks were kept in the same container [10]. The container used was a 330 ml glass bottle with a crown cap, which seems to dominate the market for high-quality adult-oriented products in the following years, as reported by [28]. The container weighs 225 g, has a diameter of 60 mm, and a total height of 225 mm.

The duration of each test is 30 minutes, and the target temperature to be reached during the heating phase varies depending on the drink: 65 °C for the *Beer*, 74 °C for the *Beer-Tomato*, and 70 °C for *Mango*. As a result, shower temperatures vary depending on the product. The fluids' characteristics are summarized in Table 1. The results refer to the average values obtained with three independent tests. For each test, the following samples were used: two at ambient pressure (unsealed container) containing the beverage, one at ambient pressure (unsealed container) containing water, and one at higher pressure (sealed container) containing the beverage. The unsealed container allows gas exchange with the atmosphere, but the cap design prevents the entrainment of water from the tunnel machine's spray. This strategy evaluates the effects of pressure and gas-induced effervescence on the drink's thermal behavior. During the industrial process, containers are sealed, and pasteurization occurs after filling and sealing operations. At the same time, to monitor the thermal process and the reliability of the tunnel machine, operators periodically (more times per production day) control the thermal cycle using a portable device that monitors the internal temperature of the products, named red-post. In that case, the containers can be opened or kept closed according to the red-post design and producers' reference strategy. This means that carbonate drinks can also be monitored using simpler instrumentation, coupled with unsealed containers, to reduce monitoring effort and time waste. In the present investigation, the internal temperatures of unsealed and sealed containers were measured using a purpose-designed device. To monitor the unsealed containers, a temperature probe was inserted using a unique cap to prevent drink contamination from water spray. The temperature probe is a T-type thermocouple with mineral insulation. The probe tip was positioned in the cold spot of the container described in the following paragraph. The temperature probe was calibrated, and the extended uncertainty is estimated to be equal to ± 0.55 °C. This estimation accounts for uncertainty sources related to gain, offset, nonlinearity, and cold-junction compensation.

Sealed containers (and thus pressurized containers) require a different setup. The REDPOST RPU (Haffmans, Netherlands) shown in Fig. 2a was used for the sealed sample. The instrument measures the internal temperature, the external temperature (i.e., the water spray), and the pressure inside the container. The manufacturer provided a reference strategy for installing the temperature probe and pressure transducer

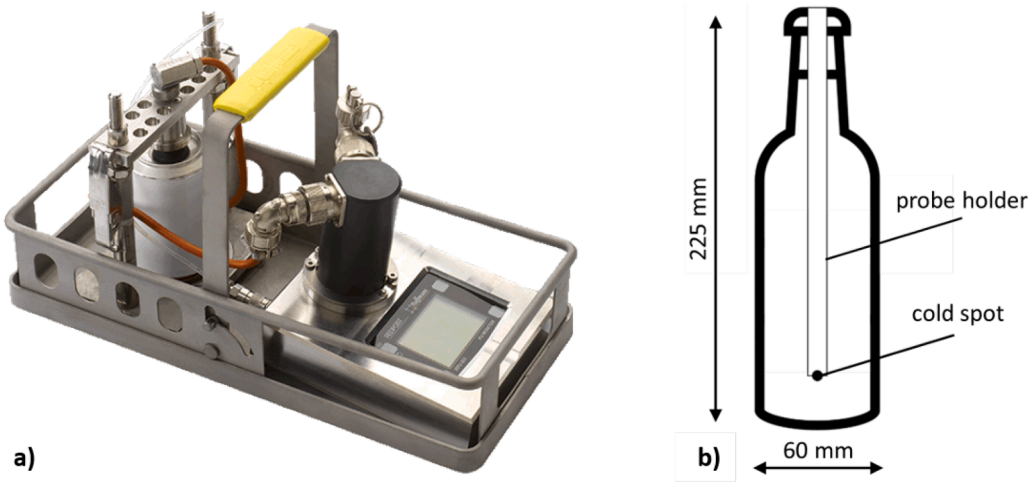


Fig. 2. Internal temperature measurement system: a) the REDPOST RPU, b) position at which the measurements were taken in the bottle.

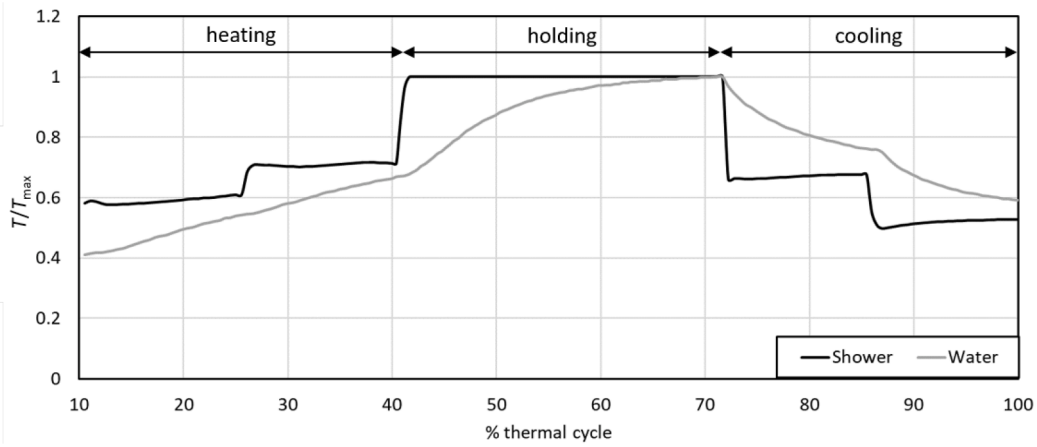


Fig. 3. The trend lines $\frac{T}{T_{max}}$ of nozzle and water temperature.

in the container without compromising the container's sealing characteristics. The measuring unit has a control panel connected to the temperature and pressure probes with a single cable. The container under examination was positioned far from the control unit to avoid affecting the interaction between the container and the water spray. Such a device is commonly used in industry to monitor daily thermal pasteurization. The temperature probe was calibrated similarly to the previous one. In this case, the extended uncertainty is $\pm$ 0.5 °C. Therefore, each drink reported in the Table 1 was heat-treated using sealed and unsealed containers, following the temperature trend of heating, holding, and cooling intervals. The thermal behavior differs from that of a heating-to-cooling ramp, and the presence of solid and gas fractions in the heat-treated container determines the variation of temperature-to-time relations. The results reported in [17] show that the solid fraction modifies the natural convection mechanisms characteristics of the fluid that reacts differently to the same thermal input. To evaluate the heat transfer coefficient, regardless of the shower temperature and the duration of holding at a given temperature, the K coefficient was introduced:

$$K = \frac{60}{t_{zone}} \cdot \ln\left(\frac{T_{start} - T_{nozzle}}{T_{end} - T_{nozzle}}\right) \cdot 1000 \quad (1)$$

where t_{zone} is the duration of holding at a given temperature, T_{start} and T_{end} are the temperatures at which the product enters and leaves a given zone, and T_{nozzle} is the nozzle temperature, kept constant within the zone. The definition of the K coefficient is based on the formulation of [24] and is commonly used in the food and beverage industry to assess heat exchange throughout the entire tunnel machine. In fact, the K parameter allows the comparison of the thermal behavior, making independent considerations from the temperature of the food product. The formulation is based on the temperature difference between the product and the water spray. The K parameter represents how fast the food product reacts to a specific thermal input provided by the water spray. In this way, the heat-exchange process can be compared across different food products and spray temperatures independently of the temperature and the condition of the food products. Therefore, higher K parameter values indicate a faster heat exchanger process and greater coupling between shower temperature and the food product. Even if the formulation of K parameter is general, an additional step can be done. By evaluating the $\frac{K}{K_w}$ ratio, it is possible to compare the difference in K of the product with that of water. In this way, the proposed results are entirely free from the container influence. Sampled drinks and water are stored in the same container, and thus, when the ratio tends to unity, the food product exhibits a thermal behavior similar to that of water. Conversely, for values of the ratio below unity, the food product has greater inertia than water in responding to the thermal input from the water spray. As reported earlier, a water sample has been used as a reference in each test, with K_w serving as a normalization factor for sealed and unsealed containers. This methodology generates a robust data set,

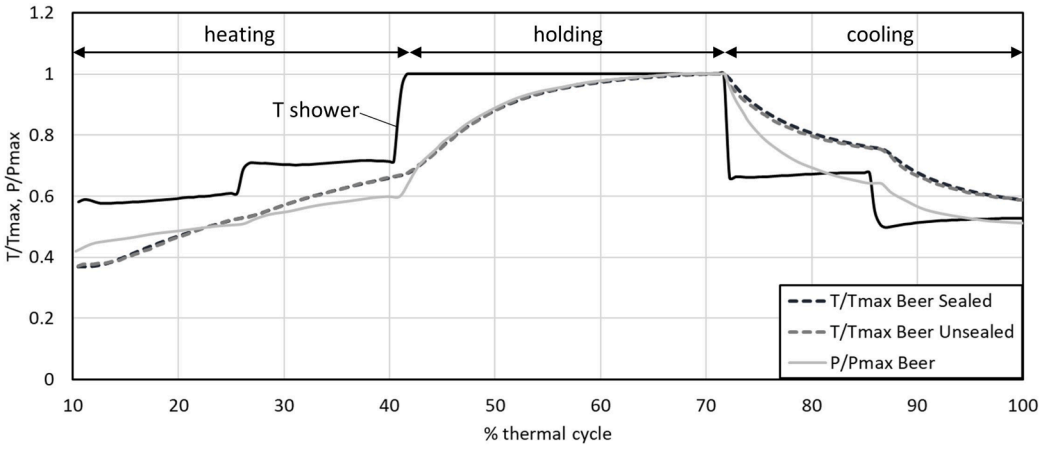


Fig. 4. The trend lines $\frac{T}{T_{max}}$ of *Beer* sample.

overcoming the effects of variation in shower temperature, container position/shape, and container temperature. As a result, the temperature data for the samples were synchronized and recorded at the same sample rate (1 s).

All the temperatures of the drinks were measured in the cold spot, which was estimated according to the shape of the container. The position at which the measurements were taken is shown in Fig. 2b. The detection point is approximately 1 inch from the bottom of the container, in agreement with [24]. Such a measure serves as a standard in the food and beverage industry and is the only measurement point adopted in daily operations. It is important to note that, according to the literature [17], containers exhibit different thermal behavior depending on the food's rheology. In particular, natural convection and/or conduction processes influence the temperature distribution inside the container. The definition of the cold spot allows a simple measurement to ensure that the entire container has been correctly thermally treated. Such a strategy avoids the application of the averaging methodology (between two or more measuring points) or the selection of multiple temperature trends, making thermal process validation or invalidation complex and difficult to justify.

3. Results

The measured variables (temperature and pressure) were normalized to the maximum values observed during the tests, since the food products require different thermal treatments (see the previous paragraph for reference). The non-dimensional temperature (calculated as $\frac{T}{T_{max}}$) is calculated, where T is the temperature of the product and T_{max} is the maximum temperature reached by the product during the thermal cycle. Similarly, the non-dimensional pressure is defined as ($\frac{P}{P_{max}}$), where P is the pressure inside the sealed bottle and P_{max} is the maximum pressure reached inside the bottle during its thermal cycle.

Fig. 3 shows the temperature trends of the water spray and the sample filled with water during a representative thermal cycle. As shown in the thermal trends, the heating and cooling zones were divided into two steps of water spray temperature, allowing for progressive increases and decreases in temperature to and from the holding zone. The holding phase accounts for almost one-third of the thermal cycle's duration and is maintained at a constant water spray temperature. As highlighted, the thermal cycle is approximately 30 min long, while the maximum temperature varies from sample to sample, as reported in the previous paragraph.

Fig. 4 shows a comparison between $\frac{T}{T_{max}}$ of *Beer* in sealed and unsealed containers. The minimum difference between the two trends can be observed, leading to a minimum difference in the evaluation of the coefficient K (reported in the next section). Looking at the temperature trend, *Beer* sample clearly shows the step imposed by the water spray. The *Beer* sample reacts immediately to the temperature variation imposed at the container wall by the water spray, showing a typical trend of a water-like medium (see Fig. 3 for comparison). In the same figure, the trend of $\frac{P}{P_{max}}$ is reported. The internal pressure increases during heating and holding, and decreases as the fluid temperature decreases. Sealed and unsealed containers do not show appreciable differences in temperature trends, and both containers (sealed and not) show the same reaction to the thermal input. Looking at the pressure trend, it can be noted that a more significant increment occurs at the beginning of the holding region, with the maximum value obtained at its end.

Fig. 5 shows a comparison between $\frac{T}{T_{max}}$ and the $\frac{P}{P_{max}}$ of *Beer-Tomato* in sealed and unsealed containers. The trends show that the sealed product is significantly slower to raise its temperature during heating or lower its temperature during cooling than the unsealed product. In this case, the thermal behavior of the sealed and unsealed containers differs, showing that the sealing condition, i.e., the internal pressure, imposes greater thermal inertia. The reaction of the internal drink temperature to the external water spray appears slow, with a smooth temperature variation rather than the expected step. The unsealing condition changes the thermal behavior of the food product. In particular, according to [29], the internal pressure appears to shift the thermal process from a convective to a conduction-convective mechanism. The constant slope of the temperature-to-time trend indicates that the heat exchange process is approximately constant over time. This means that the convective cells, which develop from the start to the end of the heating and/or cooling process, are absent. Comparing the temperature trend of sealed containers from Fig. 4 and Fig. 5, the effects of solid fraction (and thus the product rheology) are visible. A solid fraction imposes greater thermal inertia, generated by internal pressure.

The coefficient $\frac{P}{P_{max}}$ reaches its peak in the holding zone and then decreases, even as the fluid temperature continues to rise. The gas release process does not follow a monotonous trend during heating, as highlighted for the *Beer* in the previous analysis. The presence of a solid fraction seems to alter the gas release process with an interruption during the holding phase (the pressure does not rise, instead of the presence of positive thermal input) at approximately 55 % of the thermal cycle (see Fig. 4). Temperature and pressure trends are influenced by the solid fraction, altering the drinks' rheology and gas release process.

Fig. 6 shows a comparison between $\frac{T}{T_{max}}$, and the $\frac{P}{P_{max}}$ of *Mango* in sealed and unsealed containers. The graph shows that the heating process is similar for the two container types (sealed and unsealed). The thermal inertia during the heating and holding phases appears similar, with a constant slope in the temperature-time trend. Looking at the cooling process, the unsealed container shows greater inertia, as evidenced by the temperature steps imposed by the water spray. The sealed con-

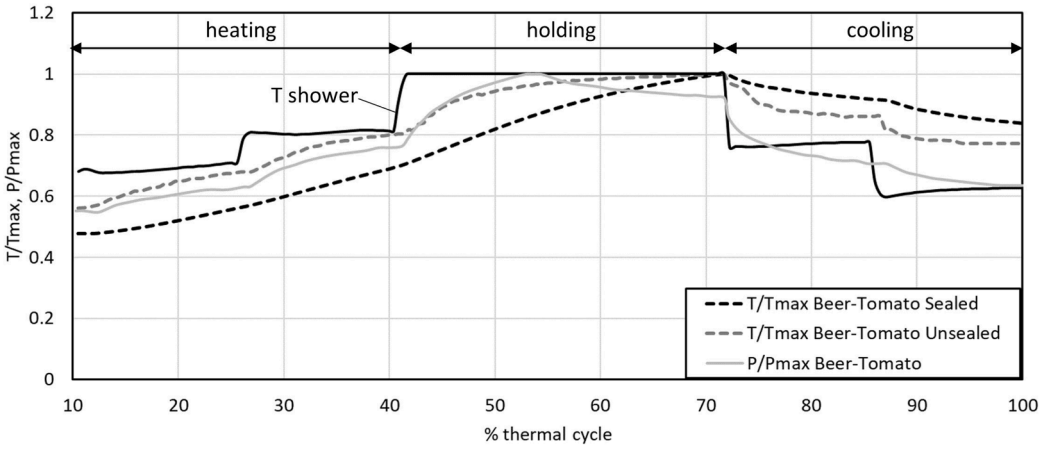


Fig. 5. The trend lines $\frac{T}{T_{max}}$ of *Beer-Tomato* sample.

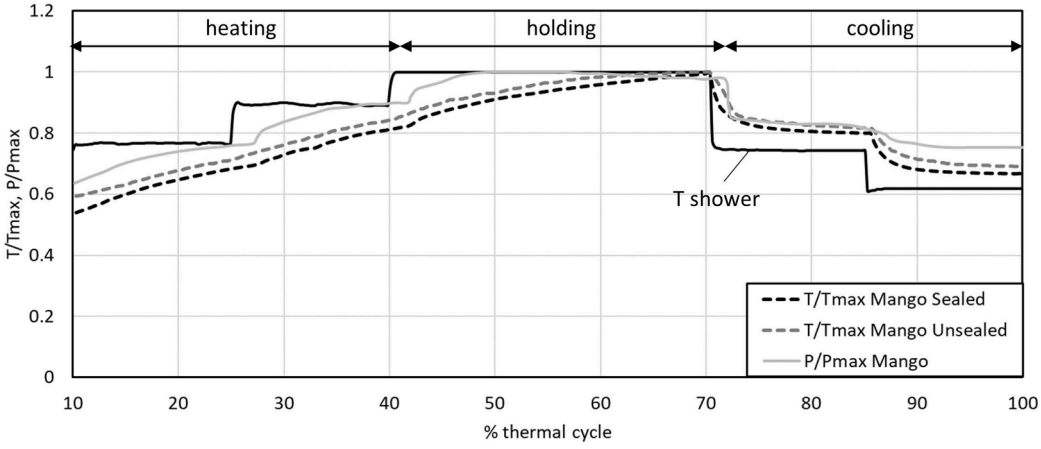


Fig. 6. The trend lines $\frac{T}{T_{max}}$ of *Mango* sample.

tainer shows greater capability to follow the stepwise variation in the water spray temperature. Thus, the solid fraction, the mango juice's rheology, and its internal pressure impose thermal effects different from those in the previous case (see Fig. 5). These findings show that nonlinear effects characterized each case and condition for the same multiphase flow type (liquid-gas mixture and solid fraction).

Similarly to the previous case (see Fig. 5), the coefficient $\frac{P}{P_{max}}$ reaches its peak during the holding zone. After that, it starts to slow down despite the increasing temperature trend. This confirms that the solid fraction changes the gas release process. The monotonous trend obtained for the heating and holding phases in the case of *Beer* (see Fig. 4 for more details) can not be assessed for the other two drink types, characterized by a specific amount of solid fraction. In the thermodynamic process, higher temperature leads to a greater gas-free fraction, resulting in greater pressure on the container. The solid fraction reduces or hinders this behavior, altering the container's pressure conditions. At the same time, the presence of a solid fraction results in a steeper pressure-to-time trend, increasing the interval during which the container remains at the highest pressure.

Based on the temperature measurements obtained during the experimental tests, it was possible to calculate the coefficient K, according to the definition reported in Eq. 1. The coefficient K embodies the effects of fluid characteristics and containers on the thermal behavior of food products. In particular, the coefficient K is calculated for each interval characterized by a constant water spray temperature. Therefore, in this section, five values of the coefficient K are computed for each sample.

Figs. 7, 8, and 10 show the $\frac{K}{K_w}$ trends for the *Beer*, *Beer-Tomato*, and *Mango*, respectively. From Fig. 7, it can be seen that there is a slight variation in the sealed and unsealed case behavior for *Beer*. Both containers show that the cooling phase is characterized by greater heat transfer ($\frac{K}{K_w}$ is greater than 1). The $\frac{K}{K_w}$ calculated in the two cases is similar. The variations can be estimated as equal to 0.5 % during the heating, 4 % during the holding, and 5 % during the cooling phases. Therefore, in the *Beer* case, or more in general, when the drink is composed of only the liquid and gas fraction, the thermal behavior of the drink can be assessed using the sealed or the unsealed container without diminishing the validity and the accuracy of the measurement process. Due to several checks during production, the possibility of using an easy-to-use redpost that cannot withstand internal pressure reduces the operator's effort without compromising the control process's reliability. At the same time, even with the control system able to keep the container sealed, the positioning phase and the installation of the container and the internal probe on the redpost unit required a trained operator and more effort to achieve a reliable measurement.

The trends reported in Fig. 8 show that the behavior of the *Beer-Tomato* is different when sealed and unsealed. The $\frac{K}{K_w}$ drops by 77 % during the heating, 74 % during the holding, and 11 % during cooling using a sealed container. The trends for the sealed container appear constant during the heating and holding zones, while slightly increasing during the cooling phase. Conversely, the unsealed container shows a greater heat exchange during heating. After that, the holding and cooling phases are characterized by a lower value of coefficient K. Such a

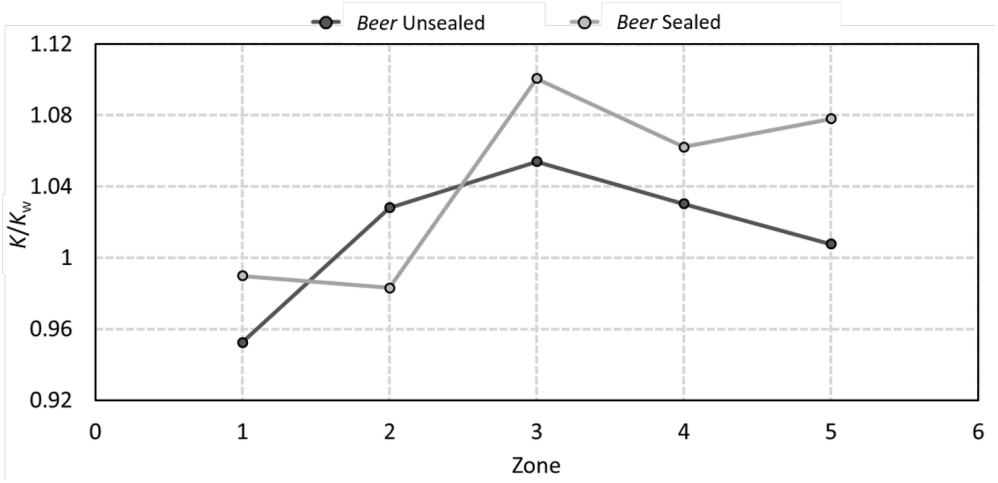


Fig. 7. The trend lines $\frac{K}{K_w}$ for *Beer* sample.

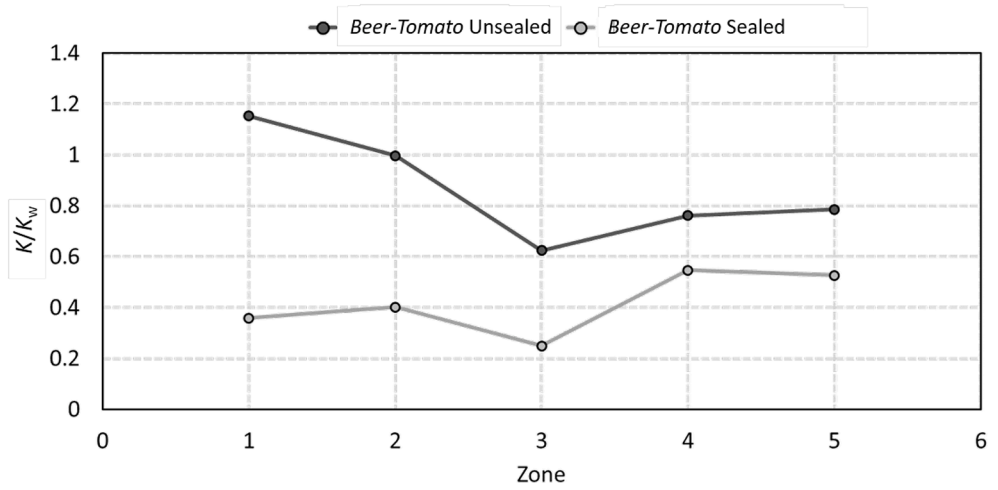


Fig. 8. The trend lines $\frac{K}{K_w}$ for *Beer-Tomato* sample.

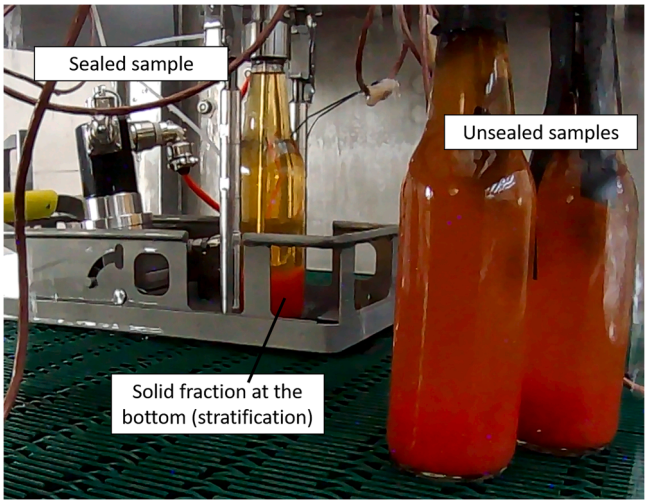


Fig. 9. Frame of the video taken during the test of *Beer-Tomato* sample in sealed and unsealed conditions.

comparison shows how the solid fraction changes the thermal process according to (i) the mixture (see Fig. 7, in which no solid fraction was present) and (ii) the heating and cooling phases.

The different thermal behavior of the unsealed and sealed containers can be explained using the video recorder during pasteurization. A video was taken during the test, and a visual comparison of the containers, kept sealed and unsealed, allows assessment of the mixing process inside the container. A frame of the video in which the mixing process between liquid and solid fractions can be appreciated is shown in Fig. 9. The unsealed container undergoes effervescence driven by the thermal input from the water spray. The heating and the holding phases are characterized by the increment in the gas release process (the temperature of the dink is still increasing, see Fig. 5) that generates a natural mixing process inside the container in addition to the natural convection mechanisms (internal convective cell as reported in [24]). As can be seen from the video frame in Fig. 9, the sealed container, and thus the absence of effervescence from the bottom to the top, impose a concentration of the solid fraction at the cold spot of the container. This stratification indicates that evaluating the pasteurization process at a single point at the container bottom may be affected by mixing driven by the temperature gradient and internal pressure, which are not easily predicted.

The last analysis refers to the carbonated drink with mango juice, named *Mango*. From Fig. 10, it can be seen that the *Mango* still responds differently to the *Beer-Tomato*. Comparing sealed and unsealed containers, in heating, $\frac{K}{K_w}$ decreases by 28 %, during the holding decrease by 48 % while in cooling, $\frac{K}{K_w}$ increases by 39 %. The drink inside the sealed container cools down faster in the cold spot than the unsealed

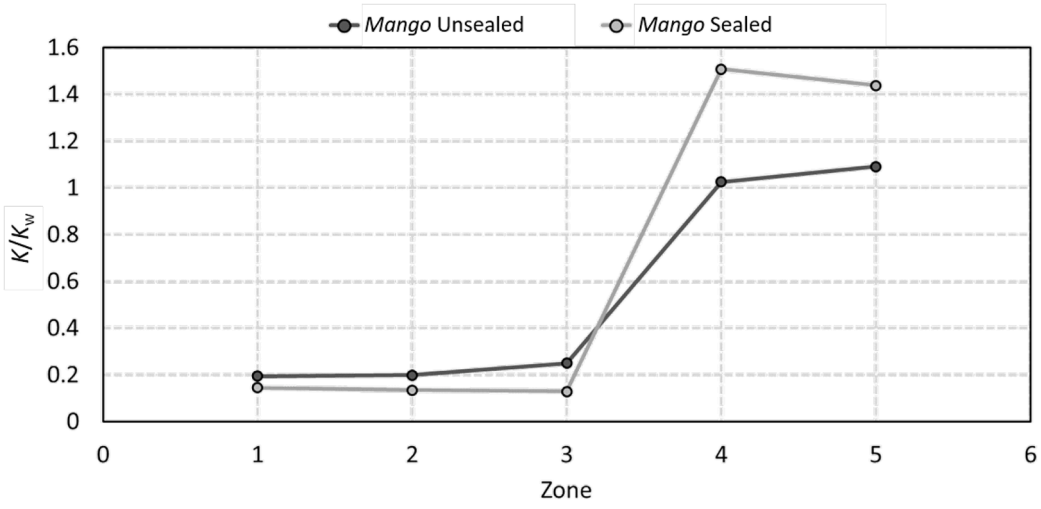


Fig. 10. The trend lines $\frac{K}{K_w}$ for *Mango* sample.

product. The cold spot is the slowest point during heating to raise his temperature, whereas it is not the slowest during cooling ([17]). The solid fraction in the soft drink confirms the thermal effects previously shown. Mango juice, which is the solid fraction in this soft carbonate drink (see Table 1), reduces the capability of the water spray to induce internal convection, especially during the heating and holding phase. As for the *Beer-Tomato*, the sealed container shows reduced capability in the first two phases, while greater heat exchange occurs during the cooling phase. The effects of effervescence appear not detrimental in the case of *Mango* because the juice can not form a stratification at the container bottom but increases the viscosity of the drink, uniformly as reported by [17]. These findings confirm that multiphase fluids obtained using a liquid matrix and a solid fraction exhibit distinct thermal behavior. The non-linear behaviors can be assessed as follows. The sample named *Mango* has a higher solid fraction than *Beer-Tomato* (see Table 1), which could explain the lower values during the heating and holding phase. Conversely, during the cooling phase, the *Mango* sample is faster in an unpredictable manner (with respect to the solid fraction content).

The two fluids with a solid phase in a sealed container showed a decrease in the heat exchange coefficient during heating compared to the unsealed container. Meanwhile, during cooling, the two fluids showed opposite behavior: the beer with tomato juice showed a decreasing trend in the heat transfer coefficient. At the same time, the heat exchanger increases the temperature of the mango soft drink compared to the container at ambient pressure. The main difference between the sealed and unsealed conditions is the presence of effervescence. The effervescence, present in the bottle at ambient pressure, allows the movement of the solid fraction within the mixture, enabling better heat transfer between the product and the water spray. The lack of effervescence within the sealed bottle slows the movement of the solid fraction and allows smaller convective cells to form within the fluid, resulting in reduced heat transfer effectiveness.

4. Conclusions

This paper investigated the behavior of three beverages during a pasteurization cycle in sealed and unsealed containers. The drink selection has involved a beer (intended as a mixture of liquid and gas fractions), a beer with tomato juice, and a soft drink with mango juice (both intended as mixtures of liquid, gas, and solid fractions).

Experimental analyses have shown that the presence of a solid fraction alters the liquid matrix's ability to release and dissolve the gas fraction. This determines differences in the heat transfer coefficient during the heating and cooling phases, which represent the steps of a pasteurization process. In addition, the solid and gas contents interact differently depending on the container status (sealed or unsealed).

In the case of a two-phase substance such as beer (a mixture of liquid and gas without a solid fraction), behavior during the pasteurization cycle varies and appears very similar in sealed and unsealed containers. If the fluid has a solid phase, its behavior during pasteurization may differ significantly when a sealed container is used. The different fluid properties result in variations in the relative influence of conduction and convection on heat transfer between the external spray and the internal food product.

Given that the product undergoes pasteurization in a sealed container during production, determining the correct heat transfer coefficient is fundamental to ensuring proper process execution. Fluids with solid phases exhibit difficult-to-predict trends in the heat transfer coefficient that require punctual evaluation to set the water spray temperature and the duration of the thermal process. Several tests are necessary to detect the specific thermal behavior of each food sample. Heating and cooling phases experience the combined effects of the gas and solid fractions, which can modify the PU value at the end of the pasteurization process. To preserve safety and quality, it is necessary to define the thermal recipe for each sample in its final form (temperature, container, and production parameters).

CRediT authorship contribution statement

Alessio Suman: Writing – original draft, Methodology, Investigation, Data curation; **Nicola Zanini:** Writing – original draft, Methodology, Investigation; **Federico Proni:** Writing – original draft, Investigation; **Michele Pinelli:** Writing – review & editing, Supervision, Project administration.

Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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