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Hot-fill Pasteurization of Cucumber Pickle Spears: An Alternative to Tunnel Pasteurization

ABSTRACT

For commercial production of acidified vegetable products, a tunnel pasteurizer is typically used for thermal processes. To help reduce energy costs and use of water, we developed a hot-fill method for pasteurization of cucumber pickle spears in 0.7 liter (24 oz) jars. The method required refilling jars three times with 70°C to 85°C brine. Initial cucumber spear temperatures up to 60°C were tested with insulated or uninsulated pickle jars. The data showed that for cucumber spears with an initial targeted temperature of 40°C or 60°C, a hot fill method could achieve or exceed a temperature of 73.9°C (165°F) for up to 13.9 min. These conditions exceed published 5-log reduction values (F_{160} of 5.6 min) for food pathogens and were sufficient to meet typical industry processing conditions of 10 or more min at 73.9°C, to destroy spoilage bacteria and inhibit cucumber softening enzymes. A simulation model was developed that may be useful for the optimization of brine temperatures and processing times. Although further development of processing equipment may be needed for inverting and refilling jars, the in-jar pasteurization process has potential application for cucumber spears and related products.

INTRODUCTION

Thermal processes for pasteurization of acidified cucumbers were introduced in the early 1940s *(8, 9)*. Typical processing parameters used in industry include temperatures up to 73.9°C (165°F) for 10 to 15 min, depending on product type, ingredients, jar size and other factors *(14)*. These processes exceed the minimum times and temperatures needed for safety, F_{160} = 5.6 min, for 160°F, or 71.1°C, at pH 4.6 or below, with a z value of 9.3°C (16.7°F) *(4)*. U.S. acidified food regulations 21 CFR part 114 and, in general, the Food Safety Modernization Act *(12, 13)* require killing vegetative microorganisms of public health significance, as well as preventing growth of spoilage bacteria (lactic acid bacteria and yeasts). For commercial producers of acidified

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vegetables, however, the objectives of pasteurization also include inactivation of softening enzymes such as pectinases *(14, 17)*. Spore-forming organisms are not killed by pasteurization temperatures, although spores are prevented from germination in fermented or acidified vegetables if pH values remain at or below pH 4.6 *(15)*.

The vegetative pathogenic bacteria of concern in acidified vegetables include *Escherichia coli* O157:H7, *Salmonella enterica* and *Listeria monocytogenes (2)*. A 5-log reduction (CFU/ml or g) standard for vegetative pathogens is used for FDA process filings. FDA process filing forms require log-linear model parameters for thermal processes, D (decimal log reduction times), F (processing time at a reference temperature), and z (change in D value with temperature) values *(1, 4)*. These parameters have been determined for acidified vegetable products with pH values at or below 4.1 *(5)*, the pH values of most acidified products, and for products at or below pH 4.6 *(4)*. Products with a pH above 4.6 are considered low-acid foods and were not considered in these studies. Acidified cucumber juice or acidified cucumber products were used for these studies, but these studies may be applicable to a variety of brined acidified vegetables, because cucumbers have no known antimicrobial properties that would contribute to acid and heat killing. The use of cucumber juice or cucumbers in brine for thermal processing studies can therefore represent a 'worst case' scenario, and results of studies with cucumber brines have been used to determine safety for a variety of acidic and acidified food products (F. Arritt, personal communication).

Tunnel pasteurizers are typically used for thermal processing of acidified cucumber pickles on a continuous belt. A hot water bath apparatus may also be used for batch processing. Sliced, acidified cucumbers are packed into jars with a cover liquor typically containing acetic acid, flavored oils, spices, and other ingredients. Glass or plastic jars are then capped and subjected to heating. The required time-temperature conditions must be achieved for the cold spot within the jar *(3)* to assure safety, and models for determining if a desired F value has been met in tunnel pasteurizers have been developed *(7)*. The heat penetration kinetics for cucumbers and jars have been previously determined *(8, 16, 18)*. Tunnel pasteurizers typically use a steam or water spray to sequentially heat and cool jars in stages, to prevent cracking glass jars as they are transported through the pasteurizer on a belt.

To reduce the energy costs and use of water associated with a tunnel pasteurizer, we investigated a hot fill method for products containing acidified cucumber spears in jars. This method may reduce overheating the exterior of the jars by applying heat directly to the vegetable material, as previously proposed by Morawicki and Schmalko *(18)*. We proposed that repeated hot fill thermal processes may deliver sufficient heat to achieve established pasteurization time temperature treatments for cucumber spear acidified products. Processing equipment for using the in-jar method with cucumber spears will likely require only off-the-shelf technology for filling and handling jars and may offer the advantage of reduced water and energy use compared with a tunnel pasteurizer. We report here the brine temperatures, filling regimen, and holding times needed for a hot fill process to achieve thermal processing parameters similar with a tunnel pasteurizer process for cucumber spear products.

MATERIALS AND METHODS

Cucumber spears and jars

Fresh size 3A pickling cucumbers (3.8 cm to 4.4 cm in diameter) were obtained from a commercial source. Cucumbers free of obvious physical damage were washed prior to use, to remove dirt or other debris. Cucumbers were sliced longitudinally into four sections (spears) and were preheated to various initial temperatures (20°C, 40°C, and 60°C) in a water bath *(Fig. 1A)*. Approximately 10 spears were hand packed into 0.7 liter (24 oz) glass pickle jars obtained from a commercial manufacturer. Jars were prepared with and without a 5 cm thick insulation material (Corning "Pink" fiberglass R-6.7, Owens Corning Insulating Systems, LLC, Toledo OH) cut to surround the jars and held in place with tape *(Fig. 1B)*. One large cucumber spear was placed in the center of the jar, while another large spear was located in the outside perimeter with geometry as shown *(Fig. 2)*. Smaller spears were tightly packed in the jar to keep the larger spears in place.

Five holes were drilled on each metal lid pickle jar lid (obtained from a commercial supplier) to provide access for four type T thermocouples and a PVC tube (Nalgene, 3.2 mm internal diameter, #8000-0010, Nalge Nunc Intl. Corp. Rochester, NY). After the lid was closed, two thermocouples were inserted through the holes to reach approximately the center of the two larger pickle spears (center and periphery). The thermocouples were held in place with a silicon putty *(Fig. 1B)*, and the tubing used to fill and empty the jars was inserted through a larger hole and extended to the bottom of the jar. Two additional thermocouples were inserted into the jars to record the temperature of the brine near the center of the jar and at the periphery. A reversible peristaltic pump was used to add and remove the hot brine solution (0.86% NaCl) through the PVC tube at a flow rate of approximately 0.3 liter/min with 70°C, 80°C or 85°C brine. Experiments used three repeated fills, for total processing times of 16 min to 45 min as indicated. The average values of pickle jar contents were 10.0 +/- 0.9 spears, weighing 412.5 +/- 31.5 g, with jar weights of 351.8 +/- 4.0 g, and brine weight of 268.3 +/- 42.3 g. Spears were made from cucumbers with a diameter value of approximately 44 mm (size 3A cucumbers), typical of commercial practice.

Heat transfer modeling

Heat transfer between the pickles and hot brine was numerically evaluated with commercial software, COMSOL

1A *1B*

Figure 1. Apparatus used for cucumber processing. A. Cucumber spears in the water bath apparatus for heating prior to in-jar pasteurization. B. Insulated and uninsulated jars with type T thermocouples inserted through holes in the jar lid.

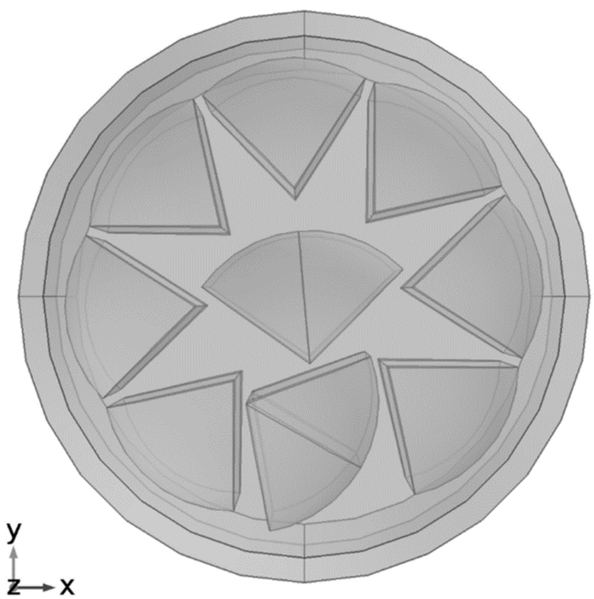


Figure 2. Cross-sectional geometry of the packed pickle jars. The approximate geometry of a central cross-section of the 0.7 L pickle jars. The diameter was 90 mm. Typical packing included 7 to 10 small spears and 2 large spears arranged as shown. The T type thermocouples were inserted into the center of the large spears.

5.2a (Comsol Inc., Burlington, MA). A 3D model was set up with the conjugate heat transfer interface within the heat transfer module, which contained the following continuity, momentum, heat equations for fluids and solids:

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho u) = 0$$

$$\rho \frac{\partial u}{\partial t} + \rho u.\nabla u = -\nabla p + \nabla.(\mu(\nabla u + (\nabla u)^T) - \frac{2}{3}\mu(\nabla.u)I) + F$$

$$\rho C_p \left(\frac{\partial T}{\partial t} + (u.\nabla)T \right) = -(\nabla.q) + \tau:S - \frac{T\rho\partial}{\rho\partial T}\Big|_p \left(\frac{\partial p}{\partial t} + (u.\nabla)p \right) + Q$$

$$\rho C_p \frac{\partial T}{\partial t} = -(\nabla.q) - T\frac{\partial E}{\partial t} + Q$$

with: *ρ*, the density (kg m^{-3}); *t*, time (s); *u*, the velocity vector (m s^{-1}); *p*, pressure (Pa); *μ*, the dynamic viscosity; *F* the body force vector; *Cp*, specific heat capacity at constant pressure (J kg^{-1} K^{-1}); *T*, absolute temperature (K); *q*, the heat flux by conduction (W m^{-2}); τ, the viscous stress tensor (Pa); *S*, the strain-rate tensor (s^{-1}); *Q*, the heat source (W m^{-3}); and *E*, the elastic contribution to entropy (J m^{-3} K^{-1}). For further details about the equations, readers are referred to Comsol Multiphysics *(6)*. Two experimental cases were used to validate the model, with 9 spears having initial temperatures of 21°C or 35°C packed into insulated and uninsulated jars.

The thermo-physical properties of cucumbers described by Fasina and Fleming *(11)* were used. To model the temperature equilibration in jars, temperature-dependent water properties for hot brine and laminar flow were used with initial brine temperatures of 70°C, 80°C, and 85°C. Holding times between the filling and refilling steps varied from 4 to 16 min to allow for temperature equilibration. No slip boundary conditions were selected for cucumber surfaces and inner walls of the jar. For modeling uninsulated jar temperatures, ambient room temperature and a heat transfer coefficient of 0 W/m^2k were applied to the outer walls of the jar to incorporate heat loss to the environment. To replicate the three-stage heating, the simulation was run with the same boundary conditions three times. While the experimentally measured temperature values were used for the first simulation, temperature distribution of the pickles and the jar from the last fill step were imported to the subsequent refill simulation as the initial values. The geometry was meshed with free tetrahedral elements. There was no change in temperature values after the element number was increased to 1917322. The models were solved with a time step of 0.1 s and assumed to be fully converged when residuals were below 10^{-6}. The time-temperature history obtained from the experiments and numerical studies were used to evaluate the effectiveness of the proposed method in terms of lethality values achieved in the center of the two larger spears. Safe processing conditions were defined with a reference temperature of 71.1°C for 5.6 min (F_{160}), and a z value of 9.28°C (16.7°F), based on Breidt et al. *(4)*.

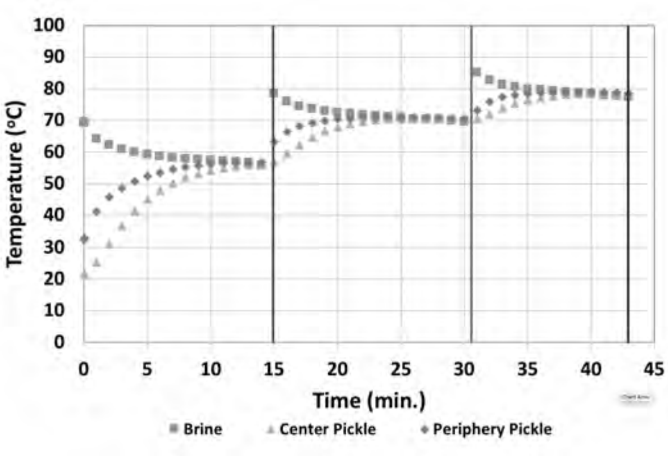
Statistical analysis

Reheating experiments were done with two or more independent replications. The mean values for replicated experiments were reported with the standard deviation. For simulation results, numerical values were compared with experimental values based on root mean square error (RMSE) for model validation.

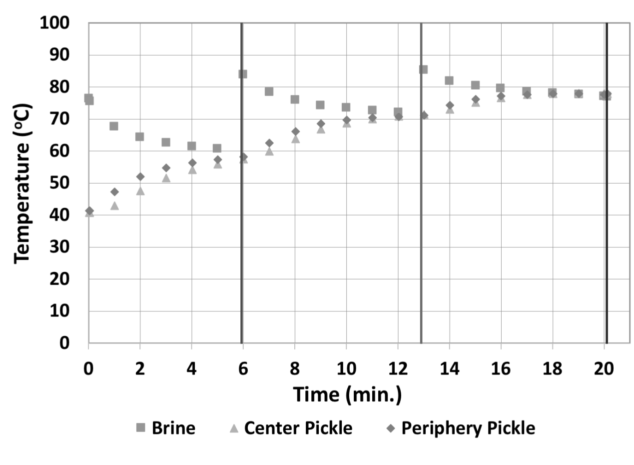
RESULTS

Time-temperature profiles

For development of a reheating process for in-jar pasteurization, representative time-temperature profiles were generated, using spears preheated to 20°C, 40°C, and 60°C, as shown in *Fig. 3A* through 3C, respectively. To prevent glass breakage due to thermal shock, the jars were filled with brine heated to 70°C, 80°C, and 85°C at the beginning of the first, second, and third fill-hold steps, respectively. Brine and spear temperatures were similar after approximately 15 min for the initial fill with cucumbers at an initial temperature of 20°C *(Fig. 3A)*. For subsequent filling, the difference between the temperature of the brine and that of the spears was approximately 1°C at the end of each fill-hold step. When cucumbers were preheated to 40°C or 60°C (*Figs. 3B* and *3C*, respectively), the time between fill steps was 13 min or less. It was apparent that convergence of brine and cucumber temperatures occurred more rapidly in the 2nd and 3rd fill for all three treatments than in the first. Interestingly, in most cases the center spear had a lower temperature than the periphery spear.

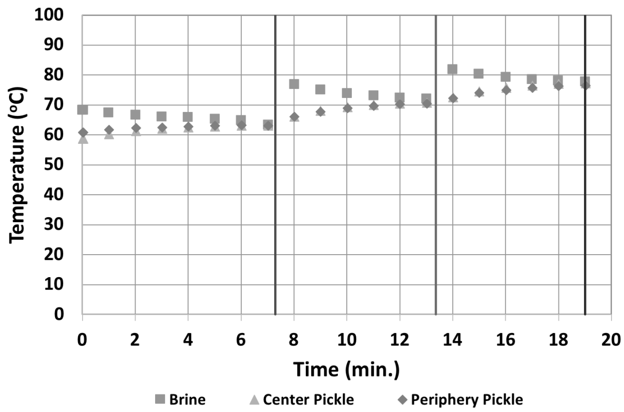


3A. Cucumbers with an initial temperature of 20°C



3B. Cucumbers with an initial temperature of 40°C

Figure 3. Time-temperature profile brine and cucumber spears. The time vs. temperature profiles of the brine (squares), center spear (triangles), and periphery pickle (diamonds) for three successive fills (insulted jars). Cucumbers were pre-heated to 20°C (A); 40°C (B); 60°C (C) in a water bath. The bold vertical lines represent the end time for each successive re-filling of the jars.



3C. Cucumbers with an initial temperature of 60°C

Insulation and initial temperature

The spears with initial temperatures of 20°C, 40°C, or 60°C were heated with and without insulation of the jars *(Fig. 4)*. These experiments used a variety of holding times after each fill, as indicated in *Table 1*. For each fill step, regardless of initial temperature, the mean temperatures between fills for all experiments were not significantly different between insulated and uninsulated jars ($P > 0.05$), suggesting that insulation may not be necessary to achieve desired processing temperatures. For cucumbers with an initial temperature of 20°C, the first filling step resulted in a mean temperature increase of 42.3°C and 48.9°C (for uninsulated and insulated jars, respectively). After three filling steps, the mean temperatures were 66.7°C and 73.5°C (for uninsulated and insulated jars, respectively). For cucumbers preheated to higher temperatures (40°C or 60°C), final temperatures were greater than or equal to 71.7°C and 76.7°C, respectively. These data indicate that processing temperatures typically used for assuring safety and product quality (at or above 160°F) can be achieved by the repeated filling method for initial cucumber temperatures of 40°C or above.

Processing times

Accumulated processing times for selected refilling regimens *(Table 1)* at or above 71.1°C (160°F), the reference temperature typically used for pathogen reduction, or 73.9°C(165°F) as referenced by Etchells and

TABLE 1. Average values of pickle jar contents

Temp.[1]		Fill Hold Step (min.)[3]			Time[4]	71.1°C[5]	73.9°C[6]
(°C)	Trt.[2]	1	2	3	(min.)	(min)	(min.)
20	Ins	14	16	15	45	14.6 +/- 0.4	13.4 +/- 1.2
20	Ins	12	9	8	29	na[7]	Na
20	Unins	7	7	9	23	na	Na
20	Unins	11	10	8	29	na	Na
40	Ins	11	13	13	37	18.9 +/- 3.1	13.9 +/- 5.2
40	Unins	6	7	7	20	10.0 +/- 0.4	6.0 +/- 0.3
40	Unins	10	5	7	22	8.4[8]	Na
60	Ins	7	6	10	24	11.4 +/- 0.2	8.8 +/- 0.2
60	Ins	7	4	4	16	9.6 +/- 0.4	4.8 +/- 0.5
60	Unins	8	6	8	21	10.8 +/- 0.2	8.9 +/- 0.5
60	Unins	7	6	4	17	6.0 +/- 0.1	4.5 +/- 0.1

[1]Temp., initial temperature of the cucumbers

[2]Trt., jar treatment, Ins, insulated; Unins, uninsulated

[3]Fill Hold Step., the time (min.) between each fill and hold

[4]Time, total time of processing

[5]71.1°C, mean time (min.) above 71.1°C for center and periphery cucumbers

[6]73.9°C, mean time (min.) 73.9°C for center and periphery cucumbers

[7]na, not applicable, because the indicated F value was not met

[8]only center cucumber data available

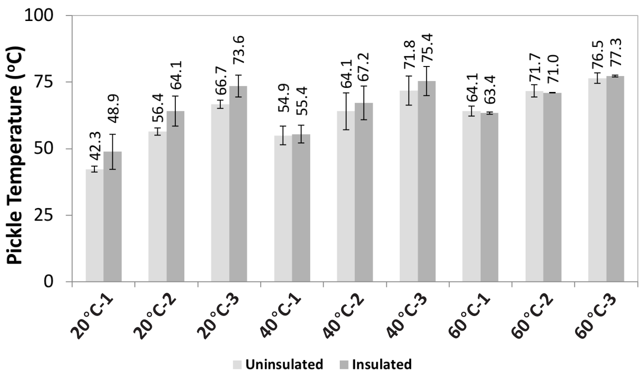


Figure 4. Temperatures after filling for insulated and un-insulated jars. The temperatures (in degrees C) resulting from the three filling steps for uninsulated (light gray bars) and insulated (dark gray bars) jars are shown for the indicated initial cucumber temperatures (20°C, 40°C, or 60°C) and fill steps (1-3). For all treatments, there was no significant difference between insulated and uninsulated jars (P > 0.05).

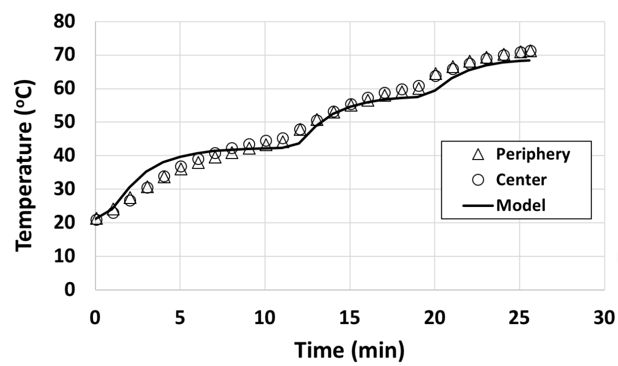
Jones *(9, 10)* for processing to achieve quality factors, were reported. The accumulated processing times were presented as a mean value for center and periphery cucumbers. For experiments at 40°C or 60°C, although total processing times varied from 16 min to 37 min, all treatments achieved the F_{160} (71.1°C) of 5.6 min or longer, indicating that minimum safe processing parameters were achieved by the process. For trials with a 20°C initial temperature, however, this F_{160} value was achieved only with a total processing time of 45 min *(Table 1)*. Hold times at 73.9°C of 4.5 min up to 13.9 min were achieved, and were found to have a linear trend related to total processing time ($r^2 = 0.646$, data not shown), indicating that optimization of holding times may allow a variety of time-temperature conditions for processing to meet quality objectives.

Numerical analysis

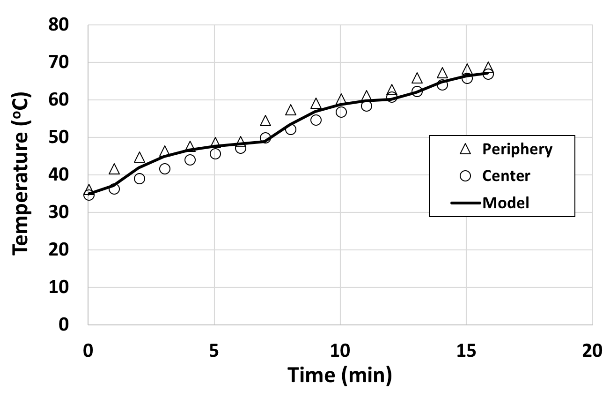
The numerical model was validated for selected time-temperature profiles with insulated and non-insulated jars. *Fig. 5A and 5B* show observed and predicted temperature data for cucumbers in insulated or non-insulated jars with an initial temperature of 21.2°C or 34.9°C (respectively). The estimated temperatures for both uninsulated jars and insulted jars all had RMSE values for numerical vs. experimental data of less than 2.9°C. The estimated temperature distribution at the mid height of the jar during the third fill-hold step with non-insulated jars is shown in *Fig. 6*. Future studies with alternate spear packing density may be helpful to determine how spear packing affects equilibration temperatures.

DISCUSSION

The US FDA requires thermal processing parameters in process filing forms for acidified foods. Commercial processes must achieve a 5-log unit reduction in bacterial pathogens for production and sale of acidified vegetables in the U.S. The time-temperature relationship for achieving safety of acidified foods are described *(4)* by log-linear model parameters similar to those described by Ball and Olsen *(1)*. While D and z values and F values are clearly defined for sterilization processes, pasteurization of acidified vegetable products does not lead to sterilization. For acidified foods, published thermal processing parameters *(4, 5)* include D (defined for acidified foods as a 5-log_{10} reduction time for vegetative bacterial pathogens), z (temperature change in °F for 1 log_{10} change in D value) and F_{160} values (time in min of processing to achieve a 5-log reduction at 71.1°C, or 160°F). Typically, 71.1°C (160°F) is used as the reference temperature for acidified foods. When these parameters were used, a 5-log reduction in



5A. Observed and predicted temperature data for an insulated jar



5B. Observed and predicted temperature data for a non-insulated jar

Figure 5. Numerical estimates and experimental values thermal treatments of brined spears. The time-temperature data for insulated (A) and uninsulated (B) jars, including spears at the center (circles) or the periphery (triangles) of the jars, are shown. The solid lines represent the numerical estimate for the predicted cucumber temperature (for both periphery and center).

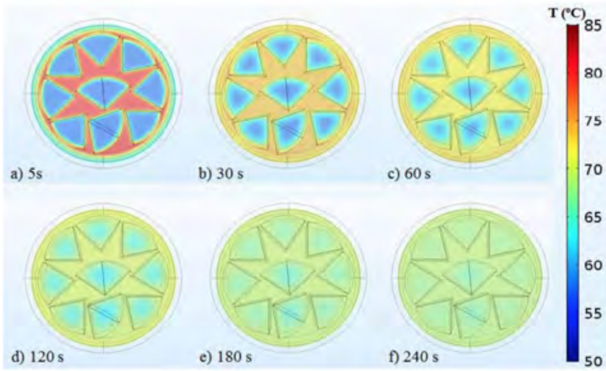


Figure 6. Numerical estimates for temperature distribution in a jar cross section. Numerically calculated temperature distribution at the mid height of the pickle jar for varying times after the start of the third filling for a non-insulated jar with an initial cucumber temperature of 40°C: (a) 5 s; (b) 30 s; (c) 60 s; (d) 120 s; (e) 180 s;(f) 240 s. The colored bar represent the temperature gradient from 50°C (blue) to 85°C (red) as indicated.

pathogenic *Escherichia coli*, *Salmonella enterica*, and *Listeria monocytogenes* was found to require an F_{160} value of 5.6 min, with a z value of 16.7°F *(4)*. These were the minimum thermal processing conditions targeted for the current study. However, the majority of acidified products, including most acidified cucumber spears, have pH values below 4.1, and a 5-log reduction in pathogens can be achieved with an F_{160} of 1.2 min (with a corresponding z value of 19.5°F) *(5)*. The data in *Table 1* showed that, with cucumbers preheated to 40°C or 60°C, three repeated fills were sufficient to achieve a 5-log reduction in vegetative bacterial pathogens. All treatments except for cucumber spears with an initial temperature of 20°C in uninsulated jars exceeded the F_{160} (71.1°C) value of 5.6 min.

Commercial processers also consider quality factors when processing acidified foods *(17)*. These factors may include thermal destruction of softening enzymes. Published processing values to achieve desired quality include processing at temperatures of 73.9°C (165°F) for 15 min or 71.1°C (160°F) for 20 min *(8, 9)*, with an estimated z value of 22.4°C. Based on these recommendations, the differences in processing times for safety vs. quality factors are shown in *Fig. 7*. In addition to requiring a 5-log reduction in bacterial pathogens, acidified food regulations (21 CFR part 114) *(12)* also require that spoilage organisms of non-public health significance do not grow in the product. However, industry practice often varies considerably from published thermal process recommendations for quality factors. Commercial processes typically use the minimal heat process that exceeds processing requirements for safety, prevents spoilage microorganisms from growing, and achieves the desired quality. Time and temperature parameters for thermal processing of acidified vegetables may vary with product type, jar size, the concentration of spices and other ingredients that may have antimicrobial activity, and other factors.

Data for the equilibration of center and periphery cucumbers *(Fig. 3)* showed that the periphery cucumber spear equilibrated with the brine quicker than the center spear. For the 40°C insulated trial shown in Table 1, this variation was evident by the standard deviation values for the mean value for hold times for center and periphery cucumbers at 71.1°C and 73.9°C (3.13 min and 5.25 min, respectively), with periphery cucumbers being hotter. The reason for these differences in unclear. It is possible this occurred because of convection patterns within the jar *(3)*, and these patterns may have been influenced by the filling tube location for the experiments shown. In some trials, this trend was reversed (data not shown), with the center cucumber spear heating faster. Further research with alternative packing arrangements, or filling mechanisms that may be applicable to commercial processes, may be helpful

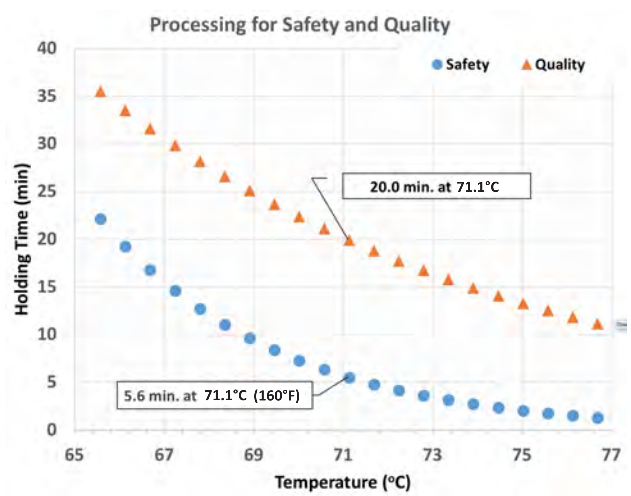


Figure 7. Processing times and temperatures for quality and safety. The estimated times for processing to achieve quality factors (triangles) or safety (circles) are shown. Selected points based on published values (F values) for quality factors at 71.1°C (20 min) or 73.9°C (15 min) or safety at 71.1°C (5.6 min) are indicated with data point labels. The z values for safety and quality were 9.28°C and 22.4°C (respectively).

to determine how these parameters affect heat distribution (both vertical and horizontal) through the jars.

A numerical model was developed for temperature predictions that may be useful for optimization of processes for achieving time-temperature conditions needed for both safety and quality factors. For commercial application, the time needed between filling steps may require holding shunts for jars (allowing jars to accumulate between filling steps) during processing, to establish processing conditions that achieve a selected (cumulative) heat process. For the initial filling steps, it may be possible to use a brine without flavoring ingredients to prevent off flavors due to heating. Brine from the initial filling steps could then be recycled to reduce water and energy usage for processing, with only the final fill containing the flavored cover liquor for the product formulation. Further work may include an analysis of potential energy and water savings and optimization of processing conditions for selected commercial processes.

CONCLUSIONS

A hot-fill pasteurization method consisting of repeated filling of jars containing cucumber spears with preheated brine was investigated. The target F_{160} value for established safe processing of acidified cucumber spears with a reference temperature of 71.1°C (160°F) for 5.6 min was achieved with three sequential fill-hold steps for most of the filling regimens studied. However, achieving this F value required a 45 min process for cucumbers with an initial temperature of 20°C. All filling regimens with cucumber spears at 40°C or 60°C initial temperatures exceeded the F_{160} of 5.6 min. Processing times and temperatures at or above 73.9°C (165°F) for up to 13.4 min were achieved for cucumber spears with initial temperatures of 40°C or 60°C, likely meeting conditions typical of most commercial processes. A numerical model was developed that may be useful for optimizing filling regimens to achieve desired time-temperature conditions. Further research may be needed to allow commercial application of the method, including the development of jar inverters for processing lines, to allow draining of jars with cucumber spears, and sanitary measures consistent with good manufacturing practice would have to be in place to prevent recontamination of jars with pathogens during refilling with brines. It is also likely that a cooling step may be required to prevent over-processing once the repeated fills are completed. We have demonstrated that safe and shelf stable acidified vegetables could be produced with the repeated hot fill method, introducing sufficient heat into the product to attain desired quality and safety parameters, and potentially reducing water use and increasing energy efficiency as an alternative to tunnel pasteurizers.

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