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Mathematical modeling and optimization of pasteurization for the internal pressure and physical quality of canned beer

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ABSTRACT

Globally, beer is the most popular alcoholic beverage. To accomplish microbial stabilization and extend the shelf life of beer, it is typically subjected to in-package pasteurization using a tunnel pasteurizer. However, high internal pressure can cause can bulging during pasteurization, leading to significant product loss. In this study, an empirical mathematical model was constructed to describe the effects of can thickness (0.245–0.270 mm), fill volume (320–338 mL), carbon dioxide content (5.70–6.10 g/L), and pasteurization temperature (59–66 °C) on the internal pressure inside canned beer. A laboratory-scale pasteurization setup was used to pasteurize samples based on the worst-case scenario of commercial pasteurization. The mathematical model ($R^2 = 0.90$) showed that all parameters significantly influenced the internal pressure of pasteurized canned beer ($p < 0.05$). Additionally, the physical, chemical, and biological properties of pasteurized canned beer were assessed. All values fell within an acceptable range of industrial standards. A simplified 2^{nd}-order polynomial equation ($R^2 = 0.90$) was created and verified for industrial use. The data are well represented by the simplified model, which suggests that it could be used for optimization of product- and process parameters to reduce the occurrence of can bulging in commercial pasteurization of canned beer.

1. Introduction

Beer is the most consumed alcoholic beverage worldwide [1], with a market share of 38.3 % in 2021 [2]. Pasteurization is a common heat treatment used in commercial brewery processes to eliminate pathogens and the majority of spoilage microorganisms that can cause negative effects on the product's safety and quality and to stabilize the product's properties, extending its shelf life and maintaining its desired characteristics [3,4].

For commercial beer production, beer can be pasteurized without packaging, as in the case of flash pasteurization or through in-package pasteurization [5,6]. In flash pasteurization, beer is heated prior to being packed aseptically in a sterilized package. Since the heating time is short, the quality of beer pasteurized using this technique is superior [7]. On the other hand, beer and packaging can be pasteurized simultaneously using in-package pasteurization. The latter method is favorable since the process can prevent

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Table 1
Pasteurization conditions assigned by RSM with Box-Behnken design and the corresponding internal pressures* and qualities* of pasteurized canned beer.

Condition	Can thickness (mm)	Fill volume (mL)	Carbon dioxide (CO_2) content (g/L)	Pasteurization temperature (°C)	Internal pressure (bar)	Physical properties				
						Color (EBC[b])	Foam stability (sec)	Chill haze (EBC)	Permanent haze (EBC)	Alcohol (%v/v)
1	0.245 (−)	329 (0)	5.70 (−)	62.5 (0)	6.33 ± 0.12	6.017 ± 0.202	224 ± 10	0.12 ± 0.05	0.25 ± 0.04	5.01 ± 0.05
2	0.270 (+)	329 (0)	5.70 (−)	62.5 (0)	5.96 ± 0.13	5.936 ± 0.199	223 ± 2	0.07 ± 0.01	0.21 ± 0.03	5.02 ± 0.04
3	0.255 (0)	320 (−)	5.70 (−)	62.5 (0)	5.92 ± 0.12	5.997 ± 0.185	220 ± 8	0.11 ± 0.00	0.23 ± 0.01	5.00 ± 0.01
4[a]	0.255 (0)	338 (+)	5.70 (−)	62.5 (0)	6.49 ± 0.11	6.140 ± 0.294	236 ± 12	0.10 ± 0.02	0.24 ± 0.04	5.03 ± 0.05
5	0.255 (0)	329 (0)	5.70 (−)	59.0 (−)	6.05 ± 0.03	6.130 ± 0.042	229 ± 5	0.07 ± 0.02	0.20 ± 0.01	5.01 ± 0.01
6[a]	0.255 (0)	329 (0)	5.70 (−)	66.0 (+)	6.50 ± 0.12	6.324 ± 0.097	242 ± 13	0.13 ± 0.06	0.27 ± 0.03	5.08 ± 0.01
7	0.245 (−)	320 (−)	5.90 (0)	62.5 (0)	5.90 ± 0.04	5.895 ± 0.180	221 ± 15	0.13 ± 0.05	0.23 ± 0.04	4.94 ± 0.12
8	0.270 (+)	320 (−)	5.90 (0)	62.5 (0)	5.75 ± 0.11	5.968 ± 0.293	221 ± 18	0.06 ± 0.02	0.19 ± 0.01	4.79 ± 0.02
9[a]	0.245 (−)	338 (+)	5.90 (0)	62.5 (0)	6.51 ± 0.13	5.697 ± 0.488	227 ± 12	0.07 ± 0.01	0.18 ± 0.03	4.73 ± 0.05
10	0.270 (+)	338 (+)	5.90 (0)	62.5 (0)	6.31 ± 0.06	5.844 ± 0.344	229 ± 11	0.09 ± 0.03	0.21 ± 0.03	4.85 ± 0.11
11	0.255 (0)	329 (0)	5.90 (0)	62.5 (0)	6.39 ± 0.02	5.607 ± 0.292	213 ± 12	0.11 ± 0.05	0.21 ± 0.05	4.74 ± 0.08
12	0.255 (0)	329 (0)	5.90 (0)	62.5 (0)	6.26 ± 0.12	5.831 ± 0.157	216 ± 17	0.13 ± 0.06	0.22 ± 0.03	4.91 ± 0.13
13	0.255 (0)	329 (0)	5.90 (0)	62.5 (0)	6.28 ± 0.10	5.941 ± 0.607	216 ± 9	0.11 ± 0.07	0.23 ± 0.08	4.84 ± 0.11
14	0.245 (−)	329 (0)	5.90 (0)	59.0 (−)	6.00 ± 0.10	5.726 ± 0.482	224 ± 11	0.07 ± 0.01	0.19 ± 0.01	4.82 ± 0.08
15	0.270 (+)	329 (0)	5.90 (0)	59.0 (−)	5.90 ± 0.02	5.607 ± 0.280	214 ± 12	0.05 ± 0.01	0.17 ± 0.03	4.76 ± 0.04
16	0.255 (0)	320 (−)	5.90 (0)	59.0 (−)	5.70 ± 0.11	5.782 ± 0.499	227 ± 10	0.07 ± 0.03	0.18 ± 0.03	4.78 ± 0.03
17[a]	0.255 (0)	338 (+)	5.90 (0)	59.0 (−)	6.31 ± 0.05	5.829 ± 0.234	221 ± 4	0.08 ± 0.03	0.20 ± 0.03	4.84 ± 0.10
18[a]	0.245 (−)	329 (0)	5.90 (0)	66.0 (+)	6.54 ± 0.11	5.960 ± 0.044	211 ± 12	0.08 ± 0.03	0.18 ± 0.05	4.84 ± 0.11
19	0.270 (+)	329 (0)	5.90 (0)	66.0 (+)	6.32 ± 0.09	5.716 ± 0.329	215 ± 2	0.08 ± 0.03	0.19 ± 0.04	4.78 ± 0.06
20	0.255 (0)	320 (−)	5.90 (0)	66.0 (+)	6.26 ± 0.06	5.537 ± 0.168	211 ± 4	0.11 ± 0.02	0.19 ± 0.02	4.74 ± 0.03
21[a]	0.255 (0)	338 (+)	5.90 (0)	66.0 (+)	6.57 ± 0.03	5.868 ± 0.193	236 ± 29	0.12 ± 0.02	0.25 ± 0.02	4.87 ± 0.07

(*continued on next page*)

Table 1 (*continued*)

Condition	Can thickness (mm)	Fill volume (mL)	Carbon dioxide (CO_2) content (g/L)	Pasteurization temperature (°C)	Internal pressure (bar)	Physical properties				
						Color (EBC[b])	Foam stability (sec)	Chill haze (EBC)	Permanent haze (EBC)	Alcohol (%v/v)
22[a]	0.245 (−)	329 (0)	6.10 (+)	62.5 (0)	6.62 ± 0.12	6.318 ± 0.465	201 ± 15	0.14 ± 0.01	0.25 ± 0.02	4.97 ± 0.04
23	0.270 (+)	329 (0)	6.10 (+)	62.5 (0)	6.63 ± 0.21	6.181 ± 0.409	203 ± 5	0.15 ± 0.02	0.27 ± 0.03	4.97 ± 0.02
24	0.255 (0)	320 (−)	6.10 (+)	62.5 (0)	6.42 ± 0.23	5.960 ± 0.192	208 ± 17	0.09 ± 0.02	0.23 ± 0.01	4.99 ± 0.02
25[a]	0.255 (0)	338 (+)	6.10 (+)	62.5 (0)	6.72 ± 0.18	6.281 ± 0.244	203 ± 14	0.11 ± 0.02	0.23 ± 0.03	4.99 ± 0.04
26[†]	0.255 (0)	329 (0)	6.10 (+)	59.0 (−)	6.56 ± 0.10	5.879 ± 0.087	209 ± 3	0.10 ± 0.01	0.24 ± 0.01	5.00 ± 0.01
27[a]	0.255 (0)	329 (0)	6.10 (+)	66.0 (+)	6.76 ± 0.05	6.664 ± 0.073	N/A	0.15 ± 0.03	0.23 ± 0.01	4.95 ± 0.01

*Mean ± SD is calculated from the internal pressures and the beer properties of 3 canned beer samples (n = 3).
[a] Condition with ≥3 bulged cans out of 15 samples during pasteurization before pasteurization process was completed.
[b] EBC = European Brewery Convention.

recontamination after filling [8]. Tunnel pasteurizers are often used for in-package pasteurization in commercial production [4–6]. It consists of 3 zones, i.e., preheating zone, heating zone or pasteurization zone, and cooling zone to protect package damage due to abrupt pressure change. The temperature in each zone is controlled by water spray [6]. The pasteurization unit (PU) is a measure of pasteurization efficiency and is a function of the process temperature and processing time. For pasteurized beer, a typical range of PU falls between 15 and 30 (corresponding to a pasteurization temperature of 60 °C maintained for 15–30 min) [5,6,9].

Commercial beer products are typically packaged in either glass bottles or aluminum cans [10]. However, aluminum can increasingly replace glass bottles in beer production due to its superior portability, protection ability, and recyclability [11]. Theoretically, canned beer should not be pasteurized at temperatures higher than 62 °C and the PU values should be 18–20 [4]. The design of aluminum can for carbonated beverages incorporates the ability to withstand high pressure generated in the can's headspace due to the nature of the product and increasing pressure from gas expansion during the heating process. Additionally, the cans are engineered to endure the distribution hazards posed by transportation and storage [12]. During in-package pasteurization of carbonated beverages, internal pressure inside the package increases as gas in the headspace expands. If the internal pressure of the canned product is higher than the pressure resistance of the can, can bulging, one form of the defective can, can occur [4,12–14]. For any carbonated beverage containing carbon dioxide (CO_2), several parameters, e.g., CO_2 concentration, pasteurization temperature, wall thickness of aluminum can, strength of package, and headspace volume, could affect internal pressure in the package [4,12,13,15–17]. Furthermore, undesirable gas production from spoilage microorganisms, or the occurrence of process errors that result in cans being held in the heating zone for longer than usual are also listed as possible causes of can bulging [14,18].

Many studies have also found that pasteurization conditions significantly affect the sensorial, physical, and chemical qualities of beer, such as color, haze (turbidity), pH, alcohol content, and foam stability [8,19–22]. As part of the quality control process for pasteurized beer, two types of haze, i.e., chill haze and permanent haze, are often measured prior to product release. Chill haze (reversible haze) forms when beer is cooled to below 0 °C, and then disappears after the temperature increases [23]. This hazes from a protein–polyphenol complex formed through noncovalent interactions (such as hydrogen bonding) that can change over time to an irreversible form (with covalent bonds) or permanent haze [23,24]. Moreover, permanent haze can also result from oxidation, shaking or aging of beer, the presence of metals in beer, or pasteurization [20]. Mostly, customers prefer beers with clear and bright colors. High stability of foam after pouring is also expected [23,25]. However, it was reported that pasteurization caused haze aggregation [20,26]. Burzul et al. [8] observed significant increases in haze formation in lager beer after heat treatment. Yalcinciray et al. [22] found that the color value of beer was significantly altered after pasteurization. On the other hand, pasteurization improved the stability of beer foam as the process increased foam-promoting protein [27].

Both theoretical and empirical models have been utilized in the process optimization of commercial beer production [5,6]. For example, computational fluid dynamics (CFD) is used to study the effect of can orientation on pasteurization efficiency [5] and to simulate the temperature profile of bottled beer during in-package pasteurization to study the effects of processing time on product temperature and the location of the slowest heat zone [6]. Additionally, Guo et al. [9] simulated a numerical model of the temperature and velocity of liquid inside canned beer during the heating process. For the uses of empirical models, response surface methodology (RSM) is often utilized in the construction of models to describe the impacts of parameters related to the thermal process on microbial inactivation and the quality of beer [28,29] and to optimize the fermentation process of beer [30]. However, an empirical model investigating and depicting the effects of parameters related to pasteurization on can bulging incidents has never been constructed.

Therefore, this work focuses on empirical models that rely on experimental observations rather than theoretical models such as those used in computational fluid dynamics and finite elements. The objectives of this research were 1) to assess the effects of product-related and process-related parameters, i.e., can thickness, fill volume, CO_2 content, and pasteurization temperature, on the internal pressure of canned beer during pasteurization and on beer qualities after pasteurization, and 2) to construct empirical mathematical models that can be used as product and process guidelines to optimize canned beer pasteurization. The overarching aim was to minimize can bulging incidents during pasteurization by reducing the internal pressure of canned beer while simultaneously maintaining or improving the important properties of beer impacted by the pasteurization process.

2. Materials and methods

2.1. Design of experiment

Based on information obtained from a literature review and company guidelines, can thickness, fill volume, CO_2 content in beer, and pasteurization temperature were selected as independent parameters for this research. To assess the effects of these parameters on the internal pressure and the quality of pasteurized canned beer, 27 experimental conditions (Table 1) were assigned by response surface methodology (RSM) with Box−Behnken design using the Minitab program (version 20.2, Minitab, LLC, USA). Three levels of the independent parameters corresponding to coding levels −1, 0, and 1 were selected, i.e., can thicknesses of 0.245, 0.255, and 0.270 mm (the current thickness of an aluminum can for commercial beer products is 0.270 mm [31]), fill volumes of 320, 329, and 338 mL (typical fill volumes for 330 mL canned beer are ≥ 320 mL [32]), CO_2 contents of 5.70, 5.90, and 6.10 g/L [33,34], and pasteurization temperatures of 59.0, 62.5, and 66.0 °C (the temperature commonly used for commercial canned beer pasteurization is 60 °C [5,9], while some studies have investigated the process at temperatures exceeding 60 °C [22]). All selected parameter ranges covered values of pasteurization conditions currently used in industrial beer production and potential production conditions. The optimal pasteurization conditions of canned beer were identified based on the constructed mathematical models predicting the internal pressure and selected quality attributes of pasteurized canned beer. The composite desirability analysis was utilized to assess the optimal pasteurization conditions using the Minitab program.

2.2. Preparation of canned beer sample

To prepare the samples, 330 mL aluminum cans (Bangkok Can Manufacturing Co., Ltd. (BCM), Pathum Thani, Thailand) and brewed lager beer (Boonrawd Brewery Co., Ltd, Nakhon Pathom, Thailand) were used. Canned beer samples were prepared based on combinations of can thickness, fill volume, and CO_2 content in beer listed in Table 1. Carbon dioxide was atomized and dissolved in beer along the dissolving path of the carbonization plant [4]. The post-filtrated beer was then carbonated to achieve the designed CO_2 content and subsequently stored in a temperature-controlled tank at 3 ± 1 °C before being filled into cans. The cans were sealed with an easy open end lid (BCM) using a volumetric filling machine and seamer (Modulfill Bloc FS-C, Krones Co., Ltd, Neutraubling, Germany).

For each treatment, canned beer samples were weighed (ED3202S S-CW, Sartorius Lab Instruments GmbH & Co. KG, Goettingen, Germany) and 15 cans with assigned fill volumes (±0.5 mL) were selected for the pasteurization experiment. Another three canned beer samples were selected for CO_2 content measurement using a digital gas content meter (Haffmans Inpack CO_2 Calculator, Pentair plc (PNR), Venlo, Netherlands) according to the European Brewery Convention (EBC) method [35] to monitor and verify the CO_2 content in beer (±0.05 g/L). Moreover, three samples were analyzed for their dissolved oxygen contents according to method 2.28.1.1.2 in MEBAK [36] using an oxygen analyzer (Digox 6.1 K-LC portable, Dr. Thiedig GmbH & Co KG, Berlin, Germany). The oxygen content of beer samples must be lower than 0.1 mg/L [4].

2.3. Laboratory-scale pasteurization setup of canned beer

To imitate the in-package pasteurization of canned beers by a tunnel pasteurizer (Linaflex, Krones AG, Neutraubling, Germany), a laboratory-scale pasteurization unit was set up. The system consisted of a temperature-controlled water bath (Waterbath WTB24, Memmert GmbH, Büchenbach, Germany) and temperature dataloggers (Haffmans Redpost PU-Monitor RPU-351, Pentair plc (PNR), Venlo, Netherlands).

To determine the pasteurization time for the study, an analysis of the company records were conducted [18]. It was found that events involving breakdown due to process errors where canned beers were left in the tunnel pasteurizer for a long period of time often led to significant increases in buldged cans. To replicate the worst-case scenario of commercial beer pasteurization, canned beer samples were pasteurized for 2 h in a laboratory-scale pasteurization unit. This selected duration emulated the complete timeline that commercial canned beer spent in the tunnel pasteurizer, including breakdown periods. The treatment time began after the core temperature of the sample reached the assigned pasteurization temperature (Table 1). All conditions were conducted in 3 replicates.

2.4. Determination of the internal pressure of canned beer after pasteurization

The internal pressure of the headspace inside the canned beer was selected as the response for the model to indicate potential of can bulging. The internal pressure values of 3 canned beer samples, which were randomly selected, were determined immediately after pasteurization using an analog pressure gauge meter (CQTE-06BTC Vacuum/Pressure Gauge, Maitech Engineering Supply Co., Ltd, Pathum Tani, Thailand). For certain pasteurization conditions previously found to cause 100 % can bulging during preliminary experimental runs (Table 1), once can bulging was observed in ≥3 out of 15 canned beer samples, three unbulged cans were removed during treatment, their internal pressures were detected, and the sampling time was recorded.

2.5. Characterization of beer quality after pasteurization

Pasteurized beer samples were characterized for their physical, chemical, and biological qualities to assess the influences of pasteurization conditions on beer qualities. All tests were conducted in 3 replicates.

To prepare the samples for characterization of physical and chemical qualities, beer samples were cooled to 20 °C (Circulating water bath TE-10D Tempette, Techne Inc, New Jersey, USA). Before measuring color and alcohol content, beer was filtered through filter paper (alpha cellulose, diameter of 320 mm, pore size of 12–15 mm, Munktell no.12, Munktell Filter AB, Stockholm, Sweden). The color of pasteurized beer was measured at 430 nm by a spectrophotometer (UVmini-1240 UV–Vis Spectrophotometers, Shimadzu, Tokyo, Japan) as described in EBC method 9.6 [35]. Alcohol content was obtained by an Alcolyzer Plus Beer Analysis System (Anton Paar, Graz, Austria) following EBC Method 9.2.6 [35]. Foam stability was measured according to the method outlined by the EBC analysis committee (method 9.42.1) [35] using a foam stability tester (Haffmans Nibem-T-meter, Pentair plc (PNR), Venlo, Netherlands). Chill haze and permanent haze (indicator of colloidal stablity in beer) were obtained by a turbidimeter (LabScat 2, Sigrist-photometer AG, Nidwalden, Switzerland) at 650 nm, 25 °C and 90 °C, respectively [36].

To evaluate pasteurization efficacy, enumeration of selected microorganisms in beer samples was performed according to the membrane filtration method [37]. The membrane used was mixed cellulose esters (MCE; 0.45 μm, Merck & Co., Inc, Massachusetts, USA). For brewer's yeast and wild yeast, wort agar (Millipore, Darmstadt, Germany) was utilized. After incubation at 28 °C for 5 days, white–cream colonies were counted as brewer's yeast [38,39]. Other colonies were identified as wild yeast. To detect *Escherichia coli* (*E. coli*) and coliforms, chromogenic agar (ChromID Coli agar, bioMerieux SA, Marcy l'Etoile, France) was used. After incubation at 37 °C for 18–24 h, pink to red colonies and dark blue/violet colonies were specified as *E. coli* and coliforms, respectively [40].

2.6. Data analysis

To construct the mathematical models describing the effects of product- and process parameters, collected data on internal pressures and selected physical qualities (color, foam stability, chill haze, and permanent haze) of canned beer were analyzed using the Minitab program (Version 20.2, Minitab, LLC., Pennsylvania, USA). All obtained data were utilized without any adjustment or transformation, except for encoding the independent parameters. The predictive models were created using a 2nd-order polynomial equation (Eq. (1)). The significance level of hypothesis testing to determine the affecting parameters was based on a type I error (α) of 0.05.

$$y=\beta_0+\beta_1x_1+\beta_2x_2+\beta_3x_3+\beta_4x_4+\beta_{11}x_1^2+\beta_{22}x_2^2+\beta_{33}x_3^2+\beta_{44}x_4^2+\beta_{12}x_1x_2+\beta_{13}x_1x_3+\beta_{14}x_1x_4+\beta_{23}x_2x_3+\beta_{24}x_2x_4+\beta_{34}x_3x_4+\varepsilon \tag{1}$$

where y is the estimated response, i.e., internal pressure of canned beer during pasteurization (bar) or selected physical quality of pasteurized beer (color (EBC), foam stability (sec), chill haze (EBC), or permanent haze (EBC)); x_1, x_2, x_3, and x_4 are the coded values of can thickness (mm), fill volume (mL), CO_2 content (g/L), and pasteurization temperature (°C), respectively; x_1^2, x_2^2, x_3^2, and x_4^2 are the coded values of the quadratic effects of can thickness, fill volume, CO_2 content, and pasteurization temperature, respectively; x_1x_2 is the coded values of the interaction effect of can thickness and fill volume; x_1x_3 is the coded values of the interaction effect of can thickness and CO_2 content; x_1x_4 is the coded values of the interaction effect of can thickness and pasteurization temperature; x_2x_3 is the coded values of the interaction effect of fill volume and CO_2 content; x_2x_4 is the coded values of the interaction effect of fill volume and pasteurization temperature; x_3x_4 is the coded values of the interaction effect of CO_2 content and pasteurization temperature; β_0 is the intercept; β_1, β_2, β_3, and β_4 are the linear effects of can thickness, fill volume, CO_2 content, and pasteurization temperature, respectively; β_{11}, β_{22}, β_{33}, and β_{44} are the quadratic effects of can thickness, fill volume, CO_2 content, and pasteurization temperature, respectively; $\beta_1\beta_2$ is the interaction effect of can thickness and fill volume; $\beta_1\beta_3$ is the interaction effect of can thickness and CO_2 content; $\beta_1\beta_4$ is the interaction effect of can thickness and pasteurization temperature; $\beta_2\beta_3$ is the interaction effect of fill volume and CO_2 content; $\beta_2\beta_4$ is the interaction effect of fill volume and pasteurization temperature; and $\beta_3\beta_4$ is the interaction effect of CO_2 content and pasteurization temperature; and ε is the residual error.

For subsequent uses of the constructed models, the assessment of each model's residual plots was performed. The model later included in the optimization of canned beer pasteurization exhibited the following characteristics in its residual analysis: a normally distributed residual histogram, a normal probability plot displaying a linear trend, a random scatter of residuals in the residual versus fit plot, a lack of discernible patterns in the residual versus order plot, and a nonsignificance lack of fit (p value of ≥ 0.05). The model that met these criteria was subsequently validated by comparing its predicted values against additional randomly selected testing conditions. Specifically, for the model predicting internal pressure during pasteurization, four additional conditions were assigned, and for the models predicting the properties of pasteurized beer, three random conditions were assigned.

3. Results and discussion

3.1. Effects of can thickness, fill volume, CO_2 content, and pasteurization temperature on the internal pressure of pasteurized canned beer

Numbers of studies have identified elevated internal pressure as the primary factor of can bulging subsequent to the pasteurization process [4,12,13,15,16]. Consequently, internal pressure was chosen as the response variable for RSM analysis. The obtained data from assigned conditions (Table 1) were analyzed and used to construct a mathematical model describing the effects of can thickness, fill volume, CO_2 content, and pasteurization temperature on internal pressure in canned beer during pasteurization. Parameter estimates of the model ($R^2 = 0.90$) are listed in Table 2. Can thickness, fill volume, CO_2 content, and pasteurization temperature significantly affected the internal pressure of the samples ($p < 0.05$). The internal pressure increased when the fill volume, CO_2 content, or pasteurization temperature increased. Conversely, it decreased as the thickness increased. The interactions of CO_2 content with other parameters significantly influenced internal pressure ($p < 0.05$). Additionally, the interaction between fill volume and pasteurization temperature had a significant effect on altering pressure inside canned beer (Table 2).

3.1.1. Effects of carbon dioxide content and its interactions

The expansion of gaseous CO_2 in the headspace of canned beer leads to an increase in internal pressure, potentially causing bulging during the pasteurization process if the resulting pressure surpasses the critical pressure resistance of the packaging. When considering the same fill volume and/or pasteurization temperature, a higher CO_2 content in the beer resulted in a significantly elevated internal pressure ($p < 0.05$) (Tables 1 and 2). This correlated with the increase in solubilized CO_2. Consequently, a larger number of CO_2 molecules were released into the headspace, leading to a corresponding rise in internal pressure (Fig. 1A and B). The result agreed with the study by Liger-Belair [17]. At specific temperatures, the pressures in carbonated water with CO_2 contents of 3.25, 4.53, and 6.87 g/L were recorded as 1.04, 1.46, and 2.21 bars, respectively. As per Henry's law, the solubility of CO_2 in beer is influenced by the CO_2 pressure in the packaging's headspace and the temperature of the product during the production process or storage [4]. Higher temperatures reduce the solubility of gaseous CO_2 in beer, leading to the transformation of CO_2 from the solubilized form in the liquid phase to free CO_2 in the gas phase within the headspace. This consequently increased the pressure inside the can [17] (Fig. 1A). During laboratory-scale pasteurization, the maximum internal pressure observed (~6.76 bars) was that of cans containing the highest CO_2 content (6.10 g/L), heated at the highest temperature (66 °C) (Table 1). This observation aligned with the previously mentioned study, indicating an increase in pressure of gaseous CO_2 with rising levels of solubilized CO_2 and temperature. The highest pressure (~5.10 bars) was observed under extreme conditions, i.e., a CO_2 content of 6.87 g/L and heating at 30 °C.

3.1.2. Effects of fill volume and its interactions

As the volume of gas in the can's headspace is inversely proportional to its pressure, the fill volume, which dictates the headspace, can potentially influence can bulging as well [4,15]. Increasing the fill volume results in a reduction of the headspace, rising the internal pressure of the can. Based on preliminary experiments, canned beers with fill volumes of 320, 329, and 338 mL had headspace-to-total volumes of 6.98 ± 0.16 %, 4.47 ± 0.16 %, and 1.95 ± 0.15 %, respectively. Canned beer samples with larger fill volumes exhibited higher internal pressures at equivalent pasteurization temperature and/or CO_2 content (Table 1; Fig. 1C and D). For example, in canned beer samples with a can thickness of 0.270 mm, filled with a CO_2 content of 5.90 g/L at volumes of 320 mL and 338 mL, both treated at 62.5 °C, the observed internal pressures were 5.75 ± 0.11 and 6.31 ± 0.06 bars, respectively (Table 1). The results

Table 2
Parameter estimates of the 2nd-order polynomial model for the internal pressure during canned beer pasteurization.

R^2	0.8973				
Adjusted R^2	0.8755				
Predicted R^2	0.8446				
Parameter	**Estimate**	**Standard error**	**T-value**	**F-value**	**P-value**
Constant[a]	6.3067	0.0364	173.23		<0.0001*
Can thickness	−0.0861	0.0182	−4.73	22.38	<0.0001*
Fill volume	0.2450	0.0182	13.46	181.16	<0.0001*
CO_2 content	0.2050	0.0182	11.26	126.83	<0.0001*
Pasteurization temperature	0.2028	0.0182	11.14	124.10	<0.0001*
Can thickness*Can thickness	−0.1000	0.0273	−3.66	13.41	<0.0001*
Fill volume*Fill volume	−0.0900	0.0273	−3.30	10.86	0.002*
CO_2 content*CO_2 content	0.1750	0.0273	6.41	41.08	<0.0001*
Pasteurization temperature*Pasteurization temperature	−0.0133	0.0273	−0.49	0.24	0.627
Can thickness*Fill volume	−0.0125	0.0315	−0.40	0.16	0.693
Can thickness*CO_2 content	0.0950	0.0315	3.01	9.08	0.004*
Can thickness*Pasteurization temperature	−0.0292	0.0315	−0.93	0.86	0.358
Fill volume*CO_2 content	−0.0675	0.0315	−2.14	4.58	0.036*
Fill volume*Pasteurization temperature	−0.0733	0.0315	−2.33	5.41	0.023*
CO_2 content*Pasteurization temperature	−0.0642	0.0315	−2.04	4.14	0.046*
Lack of Fit				0.88	0.558

*Significant at p value of <0.05, analyzed using a two-tailed test.
[a] Constant = Intercept.

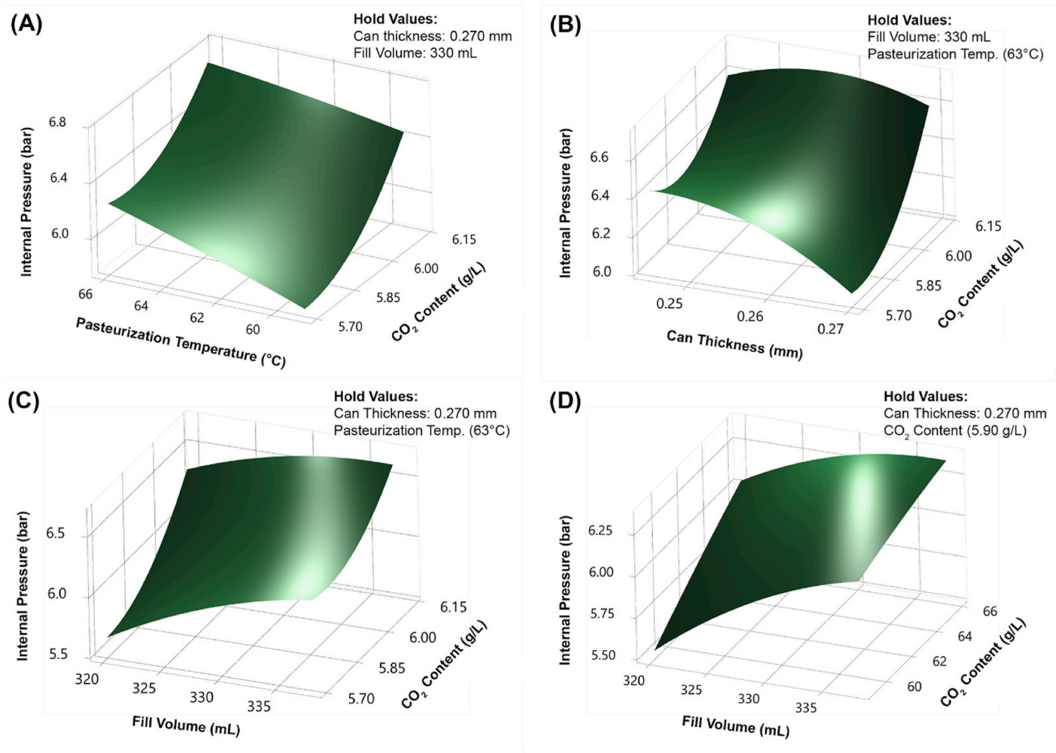

Fig. 1. Response surface plots describing interaction effects of (A) CO_2 content and pasteurization temperature; (B) CO_2 content and can thickness; (C) CO_2 content and fill volume; and (D) fill volume and pasteurization temperature on the internal pressure (bar) of canned beer during pasteurization.

also agreed with Kuntzleman and Sturgis [16], who reported that the burst pressure (the pressure at which the package burst) of plastic bottles containing carbonated beverages at the same CO_2 content and temperature corresponded with the percentage of headspace-to-total volume. At the lowest percentage (6.5 %), the beverage bottle burst at pressure of 9.7 ± 0.3 bars. Furthermore, Kunze [4] suggested that maintaining a headspace of ≥4 % of the total package volume in bottled beer could be crucial in minimizing bottle breakage.

3.1.3. Effects of can thickness and its interactions

In this study, it was found that the thickness of the aluminum can was inversely related to the internal pressure of the sample (Table 2), i.e., reducing the can thickness significantly increased the pressure inside the can (Fig. 1B). This can be attributed to the thermal expansion characteristics of aluminum [41]. The increase in temperature causes thermal expansion due to the anharmonicity of latticed molecule vibrations [42]. At a given temperature, aluminum cans with greater mass (thicker walls) can expand to a larger extent, subsequently increasing the headspace volume within the can compared to that of cans with a thinner wall. Preliminary experiment collaborated on this observation. The cans with thicker walls had significantly higher mass than the cans with thinner walls ($p < 0.05$). The cans with thicknesses of 0.245, 0.255, and 0.270 mm exhibited expansion percentage of 0.16 ± 0.16 %, 0.18 ± 0.15 %, and 0.44 ± 0.34 %, respectively. Moreover, the interaction between can thickness and CO_2 content in beer had significant effects on the internal pressure of canned beer (Table 2; Fig. 1B). As the temperature increased, the random movement of CO_2 molecules accelerate [43], transferring kinetic energy to aluminum molecules throughout the can wall. This leads to an increase in can expansion and a corresponding reduction in internal pressure of the can [42].

Based on the findings in Table 1, the maximum internal pressure of the samples measured immediately after pasteurization exceeded the critical pressure resistance value of aluminum can (6.20 bars) provided by the supplier [31]. Under certain extreme experimental conditions, especially involving high pasteurization temperatures, fill volumes, and/or CO_2 contents, instances of can bulging were observed during pasteurization (Table 1).

3.2. Simplified mathematical model of canned beer pasteurization for beer industry application

A full mathematical model explaining the correlations between can thickness, fill volume, CO_2 content in beer, and pasteurization temperature and their effects on the internal pressure of pasteurized canned beers was constructed (Table 2) and discussed in the previous section. However, the model was overly complicated due to several negligible terms. Consequently, a simplified mathematical model was introduced (Table 3). The R^2 of the model was 0.90. Removal of insignificant terms resulted in the predictive R^2 of the simplified model (0.85) being slightly higher than that of the full mathematical model (0.84), indicating that the simplified model exhibits greater accuracy in predicting the corresponding internal pressure, based on given pasteurization conditions.

Table 4 shows four additional random combinations of canned beer pasteurization for validation of the simplified mathematical model (Table 3). The actual pressures obtained fell within the range of the predicted internal pressure for all conditions. This indicated that the simplified model was reliable and can be utilized for internal pressure prediction of canned beer pasteurization within the studied range of can thickness (0.245–0.270 mm), fill volume (320–338 mL), CO_2 content (5.70–6.10 g/L), and pasteurization temperature (59.0–66.0 °C). The simplified model (Table 3) can also be used as a guideline to prevent and/or minimize bulging incidents during in-package pasteurization.

3.3. Effects of can thickness, fill volume, CO_2 content, and pasteurization temperature on the quality of pasteurized canned beer

In beer production, pasteurization is used to ensure the product's safety and extend its shelf life, with minimum effect on the product's quality [44]. In this study, all physical and chemical properties of canned beer obtained (Table 1) fell within the acceptable ranges of company standards [45]. The effects of all independent parameters on color, foam stability, chill haze, and permanent haze were shown in Tables 5 and 6.

3.3.1. Effects of independent variables on beer color

Burzul et al. [8] and Yalcinciray et al. [22] observed significant differences in beer color before and after pasteurization (pasteurization conditions used were 60 °C and 15 min and 65 °C and 45 min). However, in this study, pasteurization temperature showed no significant effect on beer color ($p > 0.05$; Table 5). Similarly, can thickness did not significantly influence the color of canned beer even though cans with different wall thicknesses are known to have different rates of heat penetration [9]. However, since the variations in can thickness used in this work were small (i.e., maximum variation of 0.025 mm), the differences in temperature profiles between varying can thicknesses might be negligible.

3.3.2. Effects of independent variables on foam stability

The CO_2 content in beer had strong and significantly inversing effect on the foam stability of beer ($p < 0.05$; Table 5). The highest foam stability (~242 s) was observed in canned samples filled with 329 mL of beer, with a CO_2 content of 5.70 g/L, and treated at 66 °C (Table 1). The result aligned with studies conducted by Lynch and Bamforth [25] and Bamforth [46]. At the same temperature, beer samples with higher CO_2 content exhibited both an increased quantity of foam and larger bubble size. This led to destabilization of the beer's foam stability [25,46,47]. According to the results presented in Table 5, there were significant effects of fill volume and pasteurization temperature on the foam stability of beer ($p < 0.05$), i.e., as the fill volume and/or pasteurization temperature increased, a corresponding rise in foam stability was observed. This can be attributed to the escalated severity of the pasteurization process, influenced by the increases of both parameters (Table 1). Bech et al. [27] reported an increase in the foaming stability of beer following thermal processing, due to the presence of foam stabilizing species, such as lipid-transfer protein 1. Additionally, He et al. [48] reported a significant effect of pasteurization on the protein content ($p \leq 0.001$), resulting in a more stabilized beer foam during storage.

3.3.3. Effects of independent variables on chill haze and permanent haze

Based on the findings in Table 6, the pasteurization temperature significantly influenced both chill haze ($p < 0.05$) and permanent haze ($p < 0.05$). These results were consistent with a study performed by Tajchakavit et al. [49], who observed an increase in haze

Table 3
Parameter estimates of the 2nd-order simplified polynomial model for the internal pressure during canned beer pasteurization.

R^2	0.8954				
Adjusted R^2	0.8787				
Predicted R^2	0.8515				
Parameter	**Estimate**	**Standard error**	**T-value**	**F-value**	**P-value**
Constant[a]	6.2948	0.0268	234.98		<0.0001*
Can thickness	−0.0861	0.0180	−4.79	22.96	<0.0001*
Fill volume	0.2450	0.0180	13.63	185.87	<0.0001*
CO_2 content	0.2050	0.0180	11.41	130.13	<0.0001*
Pasteurization temperature	0.2028	0.0180	11.28	127.32	<0.0001*
Can thickness*Can thickness	−0.0956	0.0254	−3.76	14.14	<0.0001*
Fill volume*Fill volume	−0.0856	0.0254	−3.37	11.33	0.001*
CO_2 content*CO_2 content	0.1794	0.0254	7.06	49.85	<0.0001*
Can thickness*CO_2 content	0.0950	0.0311	3.05	9.32	0.003*
Fill volume*CO_2 content	−0.0675	0.0311	−2.17	4.70	0.034*
Fill volume*Pasteurization temperature	−0.0733	0.0311	−2.36	5.55	0.021*
CO_2 content*Pasteurization temperature	−0.0642	0.0311	−2.06	4.25	0.043*
Lack of Fit				0.77	0.687

*Significant at p value of <0.05, analyzed using a two-tailed test.
[a] Constant = Intercept.

Table 4
Validation conditions of the simplified 2nd-order polynomial model for canned beer pasteurization and the corresponding predicted and actual* internal pressures and beer qualities.

Condition	Can thickness (mm)	Fill volume (mL)	CO_2 content (g/L)	Pasteurization temperature (°C)	Internal pressure (bar)		Foam stability (sec)		Permanent haze (EBC)	
					95 % CI range	Results	95 % CI range	Results	95 % CI range	Results
1	0.245	333	5.80	63	6.34–6.48	6.41 ± 0.04	217–229	223 ± 7	0.20–0.23	0.20 ± 0.01
2	0.255	322	6.00	61	6.07–6.19	6.09 ± 0.03	208–218	214 ± 4	–	–
3	0.255	330	5.90	62	6.24–6.35	6.25 ± 0.03	205–216	210 ± 4	0.17–0.21	0.20 ± 0.01
4	0.270	327	5.90	60	5.83–5.96	5.84 ± 0.05	–	–	0.15–0.19	0.17 ± 0.00

*Mean ± SD values were obtained from six replicates (n = 6).
†CI = Confident interval.

formation as the pasteurization temperature increased from 50 to 60 °C. Wang et al. [26] also noted the increasing formation of the protein–polyphenol complex (a primary form of haze in beverages) with rising temperature from 5 to 35 °C. Elevated temperature can lead to the disintegration of the formed linkages into free molecules, which subsequently aggregate with carbohydrates or inorganic materials, resulting in haziness of beer [19]. The interaction between can thickness and pasteurization temperature also significantly influenced the formation of permanent haze ($p < 0.05$; Table 6). Heat treatment can damage the protective coating of the can wall, initiating the aluminum migration. This process contributes to the increased haze formation, as aluminum has been identified as one of the metal ions responsible for haze formation in beer [50,51]. Furthermore, the fill volume had a significant effect on the formation of permanent haze in pasteurized beer ($p < 0.05$; Table 6). The increase of beer volume increased the substances within the beer, resulting in more formation of the haze-inducing complex during the heating process [19,26,49].

The carbon dioxide content also had a significant effect on both types of haze ($p < 0.05$), as increasing solubilized CO_2 in beer increased haze formation (Table 6). Siebert et al. [21] reported that, at intermediate protein and polyphenol concentrations, beverages with pH ~4 exhibited maximum haze formation. While beer generally has a pH of 4.3–4.6 [4], increasing the CO_2 content increases carbonic acid formation, leading to a further reduction in pH [52]. The interaction effect of CO_2 content and pasteurization temperature also had a significant effect on permanent haze (Table 6). As the temperature increased, the solubilized CO_2 level in beer decreased [4]. This increased the pH of beer, resulting in lower haze aggregation. Moreover, the interaction effect of can thickness and CO_2 content significantly affected permanent haze formation in beer ($p < 0.05$; Table 6). With increasing CO_2 content contributing to decreased pH, a higher acidity promotes the presence of additional metal ions in beer due to migration, leading to more haze formation [50,51].

For the biological properties of pasteurized beer, *E. coli*, coliforms, brewer's yeast, and wild yeast were not detected in beer samples from any testing conditions (results not shown). Note that the pasteurization process applied in this study was prolonged to account for the breakdown time (treatment time of 2 h), which gave pasteurization efficiencies of 86, 275, and 877 PU at pasteurization temperatures of 59.0, 62.5 and 66.0 °C, respectively. Therefore, the biological properties of beer should be validated under actual pasteurization conditions before any industrial adaptation.

3.4. Optimization of canned beer pasteurization and industrial implications for commercial canned beer production

In addition to the simplified model for the internal pressure during canned beer pasteurization, the models describing the characteristics of foam stability and permanent haze of beer (Tables 5 and 6, respectively) were selected for the optimization of in-package pasteurization of canned beer based on the criteria of a suitable model stated earlier. Additional information on the R^2, adjusted R^2, and predicted R^2 of both models are available in Tables 5 and 6 Both attributes are also crucial quality indicators that influence consumer acceptance [22,23,25]. Validation results of both models are presented in Table 4.

To reduce product loss during beer production, can bulging incidents can be minimized through the optimization of product specifications and pasteurization conditions. The optimization criteria which are based on the mathematical models of the internal pressure of canned beer during pasteurization (Table 3) and the foam stability and permanent haze of pasteurized beer (Tables 5 and 6, respectively), are listed in Table 7 (Scenario 1). Through composite desirability analysis, to meet the criteria, the fill volume, CO_2 content, and pasteurization temperature used should be low, while the thickness of aluminum can should be high. Currently, aluminum can used in pasteurized beer production is typically 0.270 mm in wall thickness [31]. Commercially, beer is typically pasteurized at 60 °C for 15–30 min, resulting in a pasteurization efficiency of 15–30 PU [3,6]. However, the maximum temperature can rise to 63–65 °C during pasteurization [22,53], potentially leading to can bulging.

Given the current can thickness, canned beer with a typical CO_2 content (≤6.00 g/L) [33,34,54] should maintain a fill volume not exceeding 336 mL, depending on the CO_2 content of the product (Fig. 2) to ensure the internal pressure of the can remains ≤6.20 bars during pasteurization (with a set pasteurization temperature of 63 °C for analysis) (Table 7; Scenario 2). On the other hand, the utilization of cans with thinner walls (0.245 mm and 0.255 mm) as compared to the current commercial usage can be considered to reduce packaging cost, provided specific conditions are met, e.g., a fill volume of 320–333 mL, CO_2 content between 5.70 and 6.00 g/L,

Table 5

Parameter estimates of the 2nd-order polynomial model for the color and foam stability of canned beer after pasteurization.

	Color					Foam stability				
R^2	0.3607					0.6924				
Adjusted R^2	0.2251					0.6027				
Predicted R^2	0.0461					0.4731				
Parameter	**Estimate**	**Standard error**	**T-value**	**F-value**	**P-value**	**Estimate**	**Standard error**	**T-value**	**F-value**	**P-value**
Constant[a]	5.793	0.103	56.00		<0.0001*	210.29	2.78	75.77		<0.0001*
Can thickness	−0.0301	0.0517	−0.58	0.34	0.562	−0.33	1.36	−0.24	0.06	0.809
Fill volume	0.0433	0.0517	0.84	0.70	0.405	5.03	1.44	3.48	12.14	0.001*
CO_2 content	0.0616	0.0517	1.19	1.42	0.238	−11.90	1.54	−7.74	59.93	<0.0001*
Pasteurization temperature	0.0930	0.0517	1.80	3.23	0.077	0.54	1.50	0.36	0.13	0.719
Can thickness*Can thickness	−0.0073	0.0776	−0.09	0.01	0.926	0.07	2.11	0.03	0.00	0.975
Fill volume*Fill volume	−0.0157	0.0776	−0.20	0.04	0.841	6.75	2.12	3.18	10.12	0.003*
CO_2 content*CO_2 content	0.3628	0.0776	4.68	21.87	<0.0001*	6.00	2.15	2.79	7.78	0.008
Pasteurization temperature*Pasteurization temperature	0.0125	0.0776	0.16	0.03	0.873	4.50	2.15	2.09	4.38	0.042*
Can thickness*Fill volume	0.0184	0.0896	0.21	0.04	0.838	2.80	2.47	1.14	1.29	0.262
Can thickness*CO_2 content	−0.0140	0.0896	−0.16	0.02	0.876	0.18	2.34	0.08	0.01	0.939
Can thickness*Pasteurization temperature	−0.0311	0.0896	−0.35	0.12	0.729	1.97	2.23	0.88	0.78	0.382
Fill volume*CO_2 content	0.0444	0.0896	0.50	0.25	0.622	−7.55	2.47	−3.06	9.36	0.004*
Fill volume*Pasteurization temperature	0.0709	0.0896	0.79	0.63	0.431	4.80	2.57	1.87	3.49	0.068
CO_2 content*Pasteurization temperature	0.1477	0.0896	1.65	2.72	0.104	−5.74	2.87	−2.00	4.01	0.051
Lack of Fit				1.42	0.196				1.49	0.187

*Significant at p value of <0.05, analyzed using a two-tailed test.

[a] Constant = Intercept.

Table 6

Parameter estimates of the 2nd-order polynomial model for the chill haze and permanent haze of canned beer after pasteurization.

	Chill haze					Permanent haze				
R^2	0.5905					0.6834				
Adjusted R^2	0.4863					0.6042				
Predicted R^2	0.3306					0.4940				
Parameter	**Estimate**	**Standard error**	**T-value**	**F-value**	**P-value**	**Estimate**	**Standard error**	**T-value**	**F-value**	**P-value**
Constant[a]	0.08500	0.00809	10.51		<0.0001*	0.19000	0.00911	20.85		<0.0001*
Can thickness	−0.00265	0.00358	−0.74	0.55	0.462	0.00039	0.00413	0.09	0.01	0.926
Fill volume	0.00282	0.00347	0.81	0.66	0.419	0.01130	0.00397	2.84	8.09	0.006*
CO_2 content	0.01536	0.00360	4.27	18.21	<0.0001*	0.00381	0.00385	0.99	0.98	0.327
Pasteurization temperature	0.01684	0.00348	4.84	23.45	<0.0001*	0.01129	0.00384	2.94	8.64	0.005*
Can thickness*Can thickness	−0.00344	0.00569	−0.60	0.36	0.549	0.00384	0.00642	0.60	0.36	0.553
Fill volume*Fill volume	0.00586	0.00564	1.04	1.08	0.303	0.00927	0.00636	1.46	2.13	0.150
CO_2 content*CO_2 content	0.02047	0.00569	3.60	12.96	0.001*	0.04645	0.00629	7.39	54.54	<0.0001*
Pasteurization temperature*Pasteurization temperature	−0.00357	0.00563	−0.63	0.40	0.529	−0.00189	0.00629	−0.30	0.09	0.764
Can thickness*Fill volume	0.01949	0.00635	3.07	9.42	0.003*	0.01247	0.00749	1.66	2.77	0.102
Can thickness*CO_2 content	0.00641	0.00635	1.01	1.02	0.317	0.01874	0.00677	2.77	7.66	0.008*
Can thickness*Pasteurization temperature	0.00656	0.00601	1.09	1.19	0.280	0.01808	0.00711	2.54	6.47	0.014*
Fill volume*CO_2 content	0.00510	0.00601	0.85	0.72	0.400	0.00098	0.00677	0.15	0.02	0.885
Fill volume*Pasteurization temperature	0.00167	0.00572	0.29	0.08	0.772	0.01083	0.00644	1.68	2.83	0.098
CO_2 content*Pasteurization temperature	0.00407	0.00631	0.65	0.42	0.521	−0.02083	0.00644	−3.23	10.46	0.002*
Lack of Fit				2.51	0.017				1.59	0.139

*Significant at p value of <0.05, analyzed using a two-tailed test.

[a] Constant = Intercept.

Table 7
Optimization specifications for general guideline of in-package pasteurization of 330 mL canned beer and guidelines for specific cases.

Scenario	Response/Fixed parameter	Specification	Note:
1	Internal pressure	Minimum	General guideline for industrial practice
	Foam stability	Maximum	
	Permanent haze	Minimum	
2	Internal pressure	≤6.20 bars	Optimum fill volume for 330 mL canned beer with current industrial specifications on CO_2 content, can thickness, and pasteurization temperature
	Foam stability	Maximum	
	Permanent haze	Minimum	
	CO_2 content	≤6.00 g/L	
	Can thickness	0.270 nm	
	Pasteurization temperature	63 °C	
3	Internal pressure	≤6.20 bars	Optimum zone for fill volume, CO_2 content, and pasteurization temperature for 330 mL canned beer with reduced can thickness
	Foam stability	Maximum	
	Permanent haze	Minimum	
	Can thickness	0.245 and 0.255 nm	

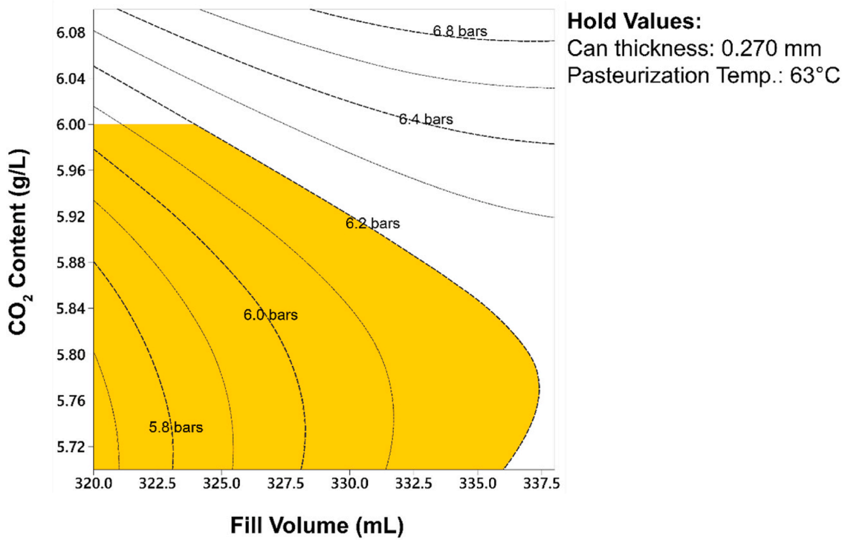

Fig. 2. Optimal zone for fill volume to minimize can bulging during pasteurization, and maximize foam stability and minimize permanent haze of pasteurized beer, for 330 mL canned beer with CO_2 content of ≤6.00 g/L, at a can thickness of 0.270 mm and pasteurization temperature of 63 °C.

or pasteurization temperature of 59–65 °C (Table 7; Scenario 3). Adhering to these recommended specifications and conditions ensures permanent haze, and foam stability meet industrial standards, aligning with the optimization criteria of low permanent haze and high foam stability.

4. Conclusions

An empirical mathematical model was developed to elucidate the effects of can thickness (0.245–0.270 mm), fill volume (320–338 mL), CO_2 content (5.70–6.10 g/L), and pasteurization temperature (59.0–66.0 °C) on the internal pressure inside pasteurized canned beer. The model (R^2 = 0.90) revealed that all independent parameters significantly influenced internal pressure (p < 0.05). The simplified model (R^2 = 0.90) was then validated for practical use, aiming to reduce the occurrence of can bulging, thus minimizing product and packaging loss. The results obtained in the study also indicated that product and process parameters had significant effects on the color, foam stability, and haze of pasteurized beer. To optimize the pasteurization process, a composite desirability analysis suggested that lower fill volume, CO_2 content, and pasteurization temperature and/or higher can thickness, could lower internal pressure during the heating process, minimize haze issues, and improve foam stability of canned beer. For the current setting (0.270 nm can thickness and a pasteurization temperature of 63 °C), canned beer should ideally contain ≤6.00 g/L CO_2 and have a fill volume of ≤336 mL to prevent can bulging during in-package pasteurization while maintaining beer quality. It is important to note that the research focused on 330 mL canned beer and tunnel pasteurization with process errors. The study did not consider pasteurization time as an independent factor, even though it does influence internal pressure inside the canned beer during the heating process. Further research is needed to adapt these findings to other product sizes and pasteurization conditions in an industrial context.

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Data availability statement

Data included in article/supplementary material/referenced in article.

CRediT authorship contribution statement

Ruthaikamol Thongon: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Siriyupa Netramai:** Conceptualization, Data curation, Formal analysis, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Thitisilp Kijchavengkul:** Conceptualization, Data curation, Formal analysis, Methodology, Resources, Software, Validation, Writing – review & editing. **Gong Yaijam:** Data curation, Resources, Supervision, Writing – review & editing. **Rojrit Debhakam:** Conceptualization, Resources, Writing – review & editing.

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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Appendix A. Supplementary data

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