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Pressure Control System for the Production of Salted Duck Eggs Utilizing Constant and Pulsed Pressure Techniques

Sistem Kontrol Tekanan untuk Produksi Telur Asin Itik dengan Teknik Tekanan Konstan dan *Pulsed*

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Abstract

Duck eggs (Anas javanica) are highly nutritious but prone to spoilage, making preservation methods such as salting necessary. However, traditional egg salting requires a relatively long processing time of approximately 10–14 days, making it less efficient for mass production. Consequently, a technology that can accelerate the salting process while maintaining an acceptable product quality is required. This study proposes an automatic egg salting system based on the principle of osmotic dehydration, employing two pressure modes: constant and pulsed. In the pulsed pressure mode, the salting process consisted of repeated cycles: a 7.5 min pressure phase, followed by a 15 min relaxation phase, whereas in the constant pressure mode, the pressure was maintained continuously throughout the salting process. The resulting products were evaluated for their salt content using the Mohr method, and sensory qualities were assessed through organoleptic tests. The results showed that in the constant-pressure mode, increasing the pressure from 1 to 2 bar over a 2-day processing period increased the salt content from 0.95% to 1.33%. Meanwhile, the pulsed pressure mode accelerated the salting process, achieving a salt content of 1.11% at 1 bar and 1.62% at 2 bars, approaching the results of traditional 10-day salting.

Keywords: osmotic dehydration, pressure control, constant pressure, pulsed pressure, salted eggs.

Abstrak

Telur itik (Anas javanica) merupakan bahan pangan bergizi tinggi namun mudah mengalami kerusakan, sehingga diperlukan metode pengawetan seperti pengasinan. Akan tetapi, proses pengasinan telur secara tradisional membutuhkan waktu relatif lama, yaitu sekitar 10–14 hari sehingga kurang efisien untuk produksi dalam skala besar. Oleh karena itu, diperlukan teknologi yang mampu mempercepat proses pengasinan dengan tetap menghasilkan kualitas produk yang dapat diterima oleh pasar. Penelitian ini mengusulkan alat pengasinan telur otomatis yang memanfaatkan prinsip dehidrasi osmosis dengan dua metode tekanan, yaitu mode tekanan konstan dan mode pulsed pressure. Pada mode pulsed pressure, proses pengasinan dilakukan melalui siklus berulang yang terdiri dari fase tekanan selama 7,5 menit dan fase relaksasi selama 15 menit, sedangkan pada mode tekanan konstan tekanan dipertahankan tetap selama proses pengasinan. Produk yang dihasilkan dievaluasi kadar garamnya menggunakan metode Mohr dan kualitas sensorinya dinilai melalui uji organoleptik. Hasil penelitian menunjukkan bahwa pada mode tekanan konstan, peningkatan tekanan dari 1 bar ke 2 bar selama 2 hari meningkatkan kadar garam dari 0,95% menjadi 1,33%. Sementara itu, mode pulsed pressure memberikan percepatan pengasinan yang lebih signifikan, dengan kadar garam mencapai 1,11% pada tekanan 1 bar dan meningkat hingga 1,62% pada tekanan 2 bar, mendekati hasil pengasinan tradisional selama 10 hari.

Kata Kunci: dehidrasi osmosis, kontrol tekanan, tekanan konstan, tekanan berdenyut, telur asin.

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1 Introduction

Duck eggs (Anas javanica) are a good source of protein; an average egg weighs approximately 65 g and contains 7-10 grams of protein alongside 79-91 kcal of energy [1]. Although eggs are a valuable source of nutrients, they are highly perishable. Egg deterioration is generally caused by the loss of carbon dioxide (CO_2) from within the egg and the entry of microorganisms through the eggshells [2]. To prevent deterioration, eggs are often preserved using several methods, including salting.

Salted eggs have a longer shelf life and enhanced flavors. The use of salt during salting can increase the iodine content of eggs and raise protein and fat levels by 13.6 percent and 13.3 percent, respectively [3]. Salted eggs have high economic value, and demand for them in Indonesia continues to increase [4]. In Indonesia, salting is

commonly performed using traditional methods, such as soaking the eggs in a salt solution or coating them with a mixture of salt and materials like brick powder, scouring ash, and clay [5]. This traditional salting process occurs slowly and requires a relatively long time, taking up to 14 days [6]. The long duration of the salting process can be overcome by osmotic dehydration and pressure-assisted technologies. Recent studies have confirmed that the application of artificial pressure can significantly accelerate the salt mass transfer and shorten the curing time of salted eggs [7], However, no study has compared constant vs. pulsed in an automated system.

Osmotic dehydration using constant pressure has been conducted [8], in which an egg-salting device operates at 4–6 bar and can significantly accelerate the salting process, yielding results similar to the traditional method, although it is still operated manually. Meanwhile, studies using pulsed-pressure osmotic dehydration, commonly known as PPOD (Pulsed Pressure Osmotic Dehydration), have also been conducted, showing that the salting process can be accelerated and that the resulting eggs exhibit characteristics such as hardened yolks, reduced viscosity, decreased water content, and increased oil content in the egg white [9].

Osmotic dehydration is a simultaneous mass transfer process driven by the difference in osmotic pressure between the food material and the surrounding solution [9], [10]. Through a semipermeable membrane, water moves out of the material while solutes diffuse into it. This continuous mass transfer is the main driving force accelerating the salting process and ultimately influencing the quality of the final product [10].

In this study, a salting device for duck eggs was proposed. The device features a pressure control system that uses a feedback closed-loop method with an ON-OFF control mode, utilizing an air compressor equipped with a pressure transmitter and solenoid valve. The device was designed with two main operating modes: static and PPOD. By combining these two modes, users can choose according to their needs and the desired characteristics of salted eggs. These two modes have different working mechanisms and produce different results, but share the same goal of accelerating the traditional salting process. In the static pressure mode, salting is performed by applying a constant high pressure. The PPOD or pulsed pressure mode is applied by combining the pressure and relaxation phases when the pressure is released from the pressure tank. This cycle lasts 7.5 min at high pressure and 15 min at relaxation, and is repeated continuously until the salting duration is complete, using the water compressor actuator, input solenoid valve, and output solenoid valve. The quality assessment of salted eggs in this study was performed using salt content and organoleptic testing. The results of these tests will be used to describe the system's performance and efficiency in producing salted eggs that meet consumer preferences, with a faster salting time. Therefore, this study aims to evaluate the performance of an ON-OFF pressure control system and its effect on the efficiency and quality of salted egg production.

2 Method

The research procedure, illustrated in Figure 1, began with the preparation of raw materials: duck eggs and a salting paste made from red brick powder and salt as the salting medium. The eggs were selected to have a relatively uniform size and shell condition, thereby minimizing variability among samples. Prior to salting, the eggs underwent a pre-treatment stage by immersion in a 10% acetic acid solution for 5 min to open the shell pores and enhance salt diffusion during processing [11]. After pre-treatment, the eggs were divided into several treatment groups (n = 10 eggs per treatment) based on the salting method and pressure level: traditional salting (2 and 10 days), constant pressure osmotic dehydration, and pulsed pressure osmotic dehydration, with pressure variations of 1 and 2 bar for a processing duration of 2 days. For the subsequent quality analyses (salt content and organoleptic tests), one representative egg from each batch was randomly selected as a single measurement sample (n=1) to serve as a preliminary functional evaluation of the pressure control system. The salting process was performed using an automatic pressure-controlled salting system. In the constant-pressure mode, the pressure inside the tank was maintained at a constant setpoint throughout the process. In the pulsed pressure mode, the system operated in cyclic phases consisting of 7.5 min of pressurization followed by 15 min of pressure release, repeated continuously until the total salting duration was reached. These specific time intervals were adopted based on prior literature on pulsed-pressure osmotic dehydration of salted eggs [9], which demonstrated that a cycle of 7.5 min pressurization and 15 min relaxation yields optimal salt absorption and effectively enhances mass transfer. During salting, the pressure control system's performance was evaluated to ensure stable pressure regulation. After completion, the salted eggs were analyzed for salt content using the Mohr method and evaluated organoleptically for aroma, color, taste, and texture. Finally, the results obtained from the different salting methods were analyzed and compared to assess the effect of pressure on salting efficiency and product quality.

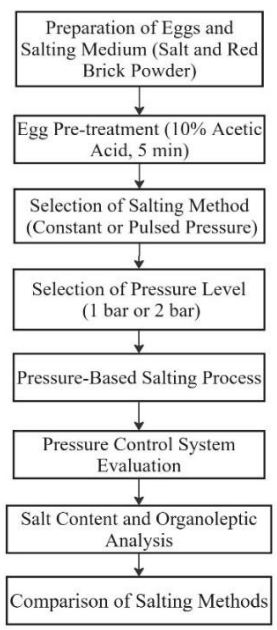


Figure 1. Research methods flowchart

The pressure control system for salted duck egg processing is illustrated in the block diagram in Figure 2, where Figure 2(a) shows the Constant Pressure Mode Block Diagram and Figure 2(b) shows the PPOD (Pulsed Pressure Osmotic Dehydration) Mode. This system uses an Arduino Mega 2560 as the main controller, which reads signals from the pressure transmitter and controls the compressor and solenoid valve. The supporting electrical components include relays or SSRs (electronic switches) to operate the compressor, a power supply as the voltage source, and a driver to activate the solenoid valve. An LCD was included to display the device's pressure and operational status. The system design uses a closed-loop control system with an on/off method. This system is equipped with two main operating modes: constant pressure and pulse pressure. In Constant Pressure Mode, the actuator is an air compressor, and the pressure is maintained at a constant level set by the tank's setpoint. The air compressor continued to run until the pressure reached the setpoint, at which point it turned off. In Constant pressure Mode, the solenoid valve remained off.

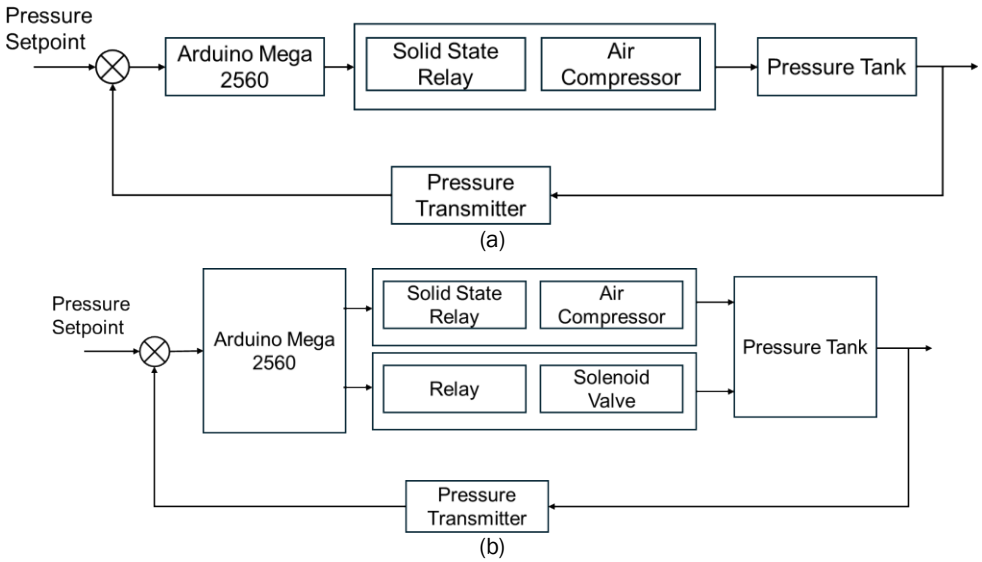


Figure 2. (a) Constant pressure mode, (b) Pulsed pressure mode block diagram

In the PPOD mode, pulsed pressure is used to accelerate osmosis, where the pressure is periodically increased and decreased, with 7.5 min at the setpoint pressure, followed by 15 min of relaxation. In this mode, the air compressor and input solenoid valve are turned on, whereas the output solenoid valve remains off until the pressure reaches the setpoint. Once the setpoint was reached, both the air compressor and the solenoid valve were turned off for the remainder of the 7.5-minute pressurization phase. After this time had elapsed, the solenoid valve was briefly activated for 15 s to release the pressure, then kept closed for the remainder of the 15-minute relaxation phase. This cycle continues until the osmotic dehydration-based salting process is completed.

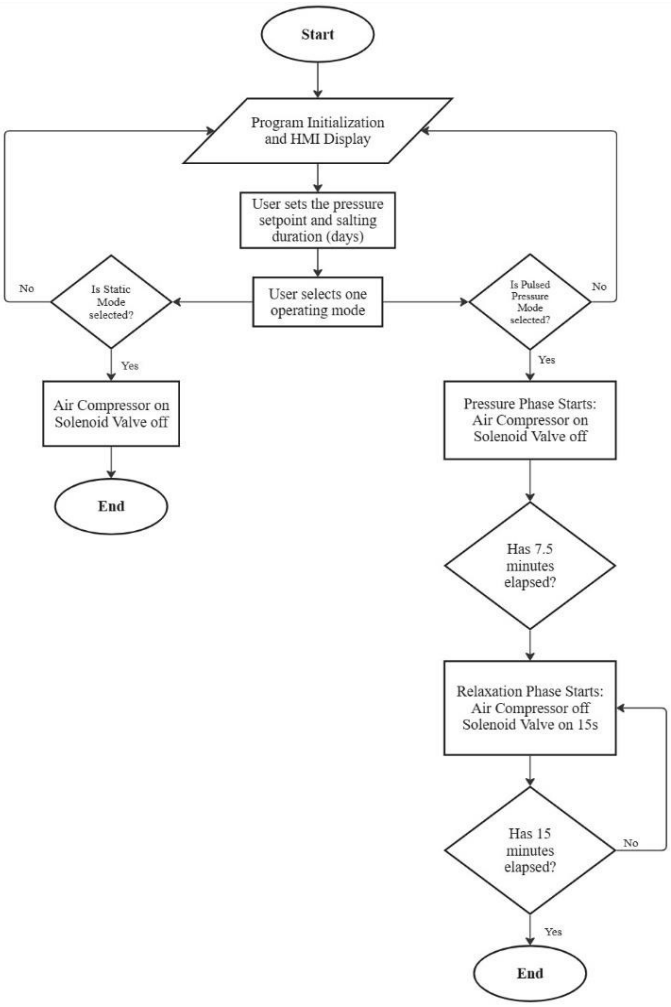


Figure 3. Flowchart program pressure control for the egg salting process

The program flow diagram for pressure control in the egg-salting process is shown in Figure 3. The process begins when the system is initiated. The program was then initialized, and the Human–Machine Interface (HMI) was displayed. After initialization, the user inputs the pressure setpoint and salting duration (in days). Subsequently, the user selects one of the available operating modes. If the user selects Constant Mode, the system turns on the air compressor and keeps the solenoid valve off (closed). The process continues until the operation is completed, at which point the system ends it.

If the user selects the PPOD mode, the system enters the pressure phase. During this phase, the air compressor was turned on, and the solenoid valve was closed to increase and maintain pressure. The system checks whether the pressure phase has reached 7.5 min. If not, the pressure phase continues further. Once the pressure phase reached 7.5 min, the system switched to the relaxation phase. In this phase, the air compressor was turned off, and the solenoid valve was activated for 15 s to relieve the pressure. The system then checks whether the relaxation phase has reached 15 min. If not, the relaxation phase is continued. After the relaxation phase is completed, the system ends the process.

3 Results and Discussion

The automatic salted egg processing system developed in this study was designed as an integrated unit combining mechanical, pneumatic, and control subsystems to regulate pressure during the salting process. The system applies controlled air pressure inside a pressure tank using an air compressor, and pressure release is managed through a solenoid valve. A pressure transmitter was employed to continuously monitor the internal tank pressure and provide feedback to the control system, enabling accurate pressure regulation in the selected operating mode. All electrical and control components were housed within a control panel to ensure safe and reliable operation. The overall system configuration, including the conceptual design and assembled prototype, is shown in Figure 4.

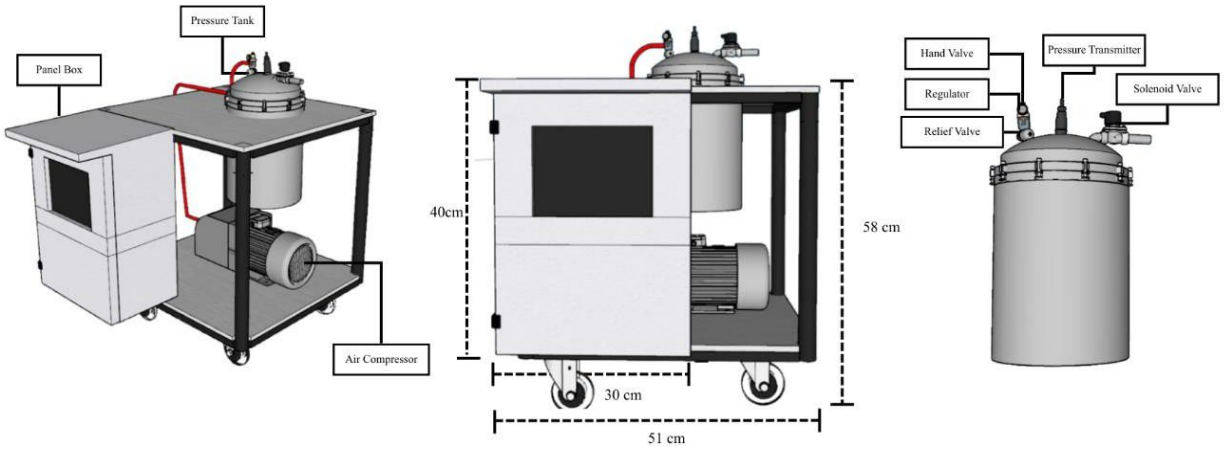


Figure 4. Salted duck egg 3D design

The design shown in Fig. 5 is the proposed device design to facilitate construction. The frame was made of iron. The pressure tank was used to salt eggs and was supplied with pressurized air from an air compressor. It is equipped with a pressure transmitter to measure the tank pressure and a solenoid valve to release excess pressure. The design also includes a panel box that serves as an enclosure for the electrical components.

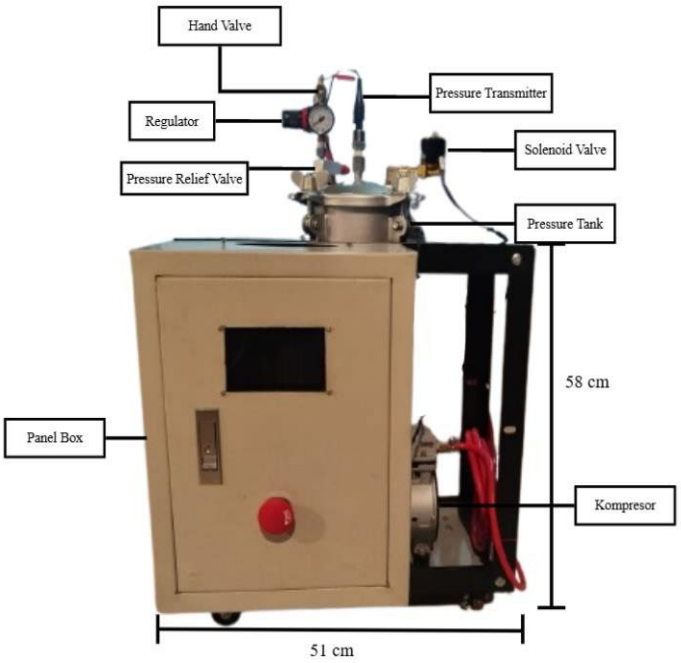


Figure 5. Salted duck egg system

The main components of the apparatus were a pressure tank serving as the immersion chamber for the duck eggs, a compressor supplying the pressure, and a panel box containing various electrical components. After the hardware and electrical assembly were completed, testing was performed.

3.1 Pressure Transmitter Validation

Testing began by comparing the output of the Wisner WPT-83G pressure transmitter, in the form of a voltage signal, with the pressure values obtained from measurements using the Baumer Y913 pressure transmitter validator, expressed in psi. The purpose of this test was to determine the accuracy of the pressure transmitter used.

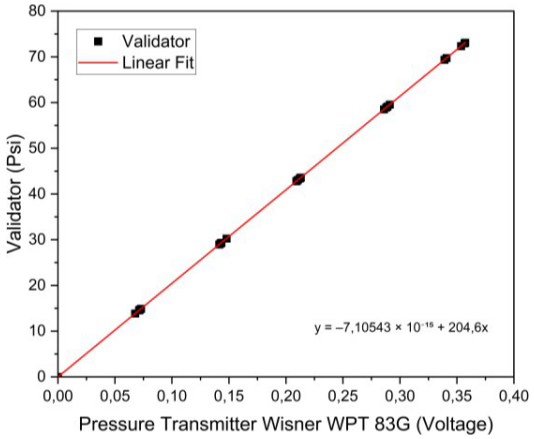


Figure 6. Pressure transmitter validation results

The minimum and maximum pressure limits tested on the Wisner WPT-83G Pressure Transmitter were 0.00 to 5.04 bar. The span, which is the difference between the maximum and minimum measurable pressure values, was 5.04 bars. The sensitivity was 0.4974 V/bar. In addition, the difference between the readings of the Wisner WPT-83G Pressure Transmitter and the Baumer Y913 Pressure Transmitter resulted in an error of 0.99%. Based on these values, the measurement accuracy was determined to be 99%.

3.2 Pressure Control System Mode Test

This test also aimed to evaluate the control system's performance in maintaining pressure stability in both constant and pulsed pressure modes, and to ensure that the control process operated automatically and responded appropriately to pressure changes within the tank.

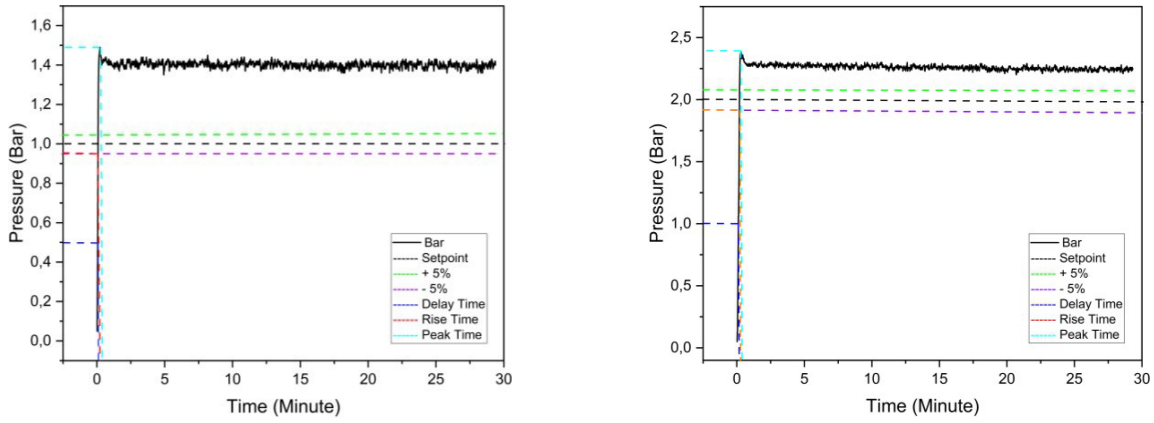
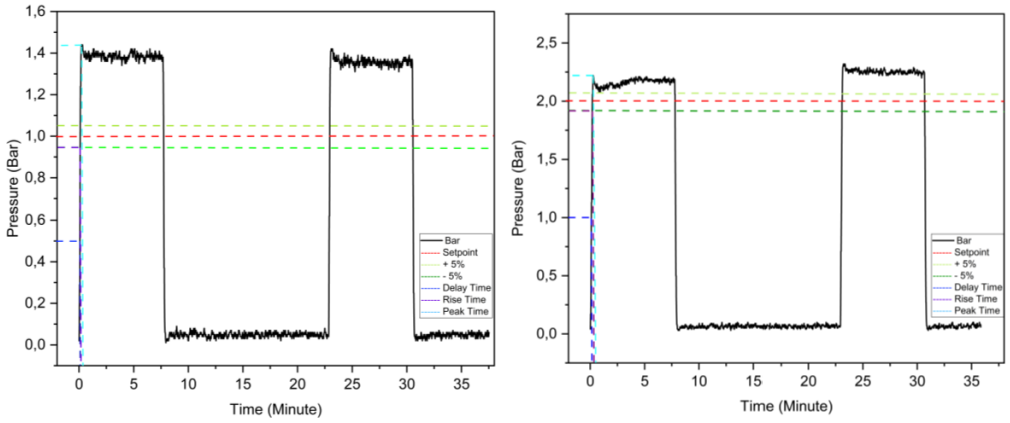


Figure 7. Constant pressure mode pressure test at (a) 1 Bar, (b) 2 Bar

Based on the analysis of Fig. 7(a), in the constant pressure control system test at 1 bar, the maximum pressure achieved by the system was 1.49 bar, resulting in a maximum overshoot (M_p) of 0.49 bar, or 49 percent above the setpoint. The delay time (t_d) was recorded at 4 s, and the rise time (t_r) was 5 s. The peak time was 16 s. Because the control system operates in an ON-OFF mode, the pressure does not remain within the ±5 percent tolerance of the setpoint. Therefore, the settling time (t_s) and steady-state error (e_{ss}) could not be determined.

Meanwhile, in the constant pressure control system test at 2 bar, as shown in Fig. 7(b), the maximum recorded pressure was 2.39 bar, resulting in a maximum overshoot (M_p) of 0.39 bar, which was 18.5 percent above the setpoint. Although the absolute overshoot values in both settings are quite similar (0.49 bar at the 1-bar setpoint and 0.39 bar at the 2-bar setpoint), the relative percentage overshoot is much higher at 1 bar (49%) than at 2 bar (18.5%). This occurs because the compressor's minimum air delivery rate and the system's mechanical delay are relatively fixed, a common characteristic of on-off pneumatic valve systems [12]. Thus, a similar amount of absolute excess pressure translates into a smaller percentage at a higher setpoint. Furthermore, this initial high-pressure spike (overshoot), particularly when it reached nearly 2.4 bar in the 2-bar setting, exerted excessive mechanical stress on the eggshells, resulting in cracking in some samples. The delay time (t_d) was 8 s to reach 50 percent of the setpoint (1 bar), whereas the rise time (t_r) was 12 s, which is the duration for the system to rise from 10 percent of the setpoint (0.2 bar) to 90 percent of the setpoint (1.8 bar). These t_d and t_r values indicate a rapid initial response. The peak time (t_p) was set to 20 s.



(a) (b)

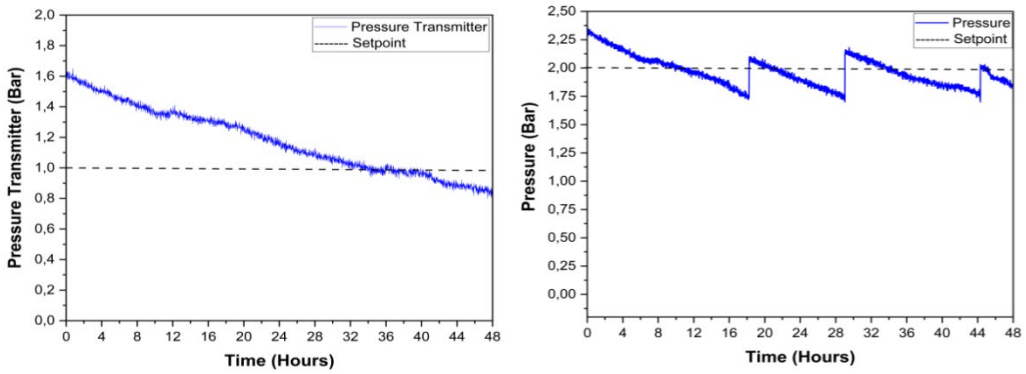
Figure 8. Pulsed pressure mode test at (a) 1 Bar, (b) 2 Bar

Based on Fig 8(a), the system reached a maximum pressure of 1.44 bar, resulting in a maximum overshoot of 0.44 bar, or approximately 44 percent. The delay time (t_d) was 4 s, and the rise time (t_r) was 6 s. The pressure reached its first peak at 13 s. Because the pulsed pressure system operates in a repeated cycle (increase–hold–decrease), the pressure never enters or remains within the ±5 percent tolerance range of the setpoint for a sufficient duration. Consequently, the settling time (t_s) and steady-state error (e_{ss}) could not be determined.

Based on the graph in Fig. 8(b), the system reached a maximum pressure of 2.32 bar, resulting in a maximum overshoot of 0.32 bar. The delay time (t_d) was 7 s, indicating the time required for the system to reach 50% of the setpoint value, 1 bar. The rise time (t_r) was 11 s. The pressure reached its first peak at 16 s, identified as the peak time (t_p), with a value of approximately 2.22 bar.

3.3 Pressure Control System Test Mode After 2 Days

Upon successful testing and verification of the control system's functionality, the next step was to initiate the salting of duck eggs.



(a) (b)

Figure 9. Constant pressure mode graph after two days (a) 1 Bar (b) 2 Bar

The salting control system was tested consistently at 1 bar. Figure 9 shows the detailed salting process carried out over two days at a constant pressure of 1 bar. In this 48-hour graph, the initial pressure of 1.7 bar gradually decreased. During the observed pressure decline, although the pressure decreased below the setpoint at approximately the 42nd hour, the compressor did not reactivate. This was due to the pressure remaining within the deadband range, which had a lower threshold of 0.7 bar. To clarify the system's operational parameters, the controller's deadband was consistently configured to be exactly 0.3 bar below the target setpoint across all treatments (i.e., 0.7 bar for the 1 bar setpoint and 1.7 bar for the 2 bar setpoint) to prevent excessive compressor short-cycling. The graph analysis indicates that in constant mode, the system effectively maintained pressure within the designated setpoint range.

The stable characteristics of the on-off control mechanism were evident during the continuous salting control system test conducted at 2 bar, as shown in the pressure graph over 48 hours in constant mode with a 2-bar setpoint. The system successfully maintained the pressure within the designated setpoint range throughout the salting process. Notably, when the pressure reaches the lower deadband limit of 1.7 bar, the compressor automatically activates for 1 second to restore the pressure to the set point.

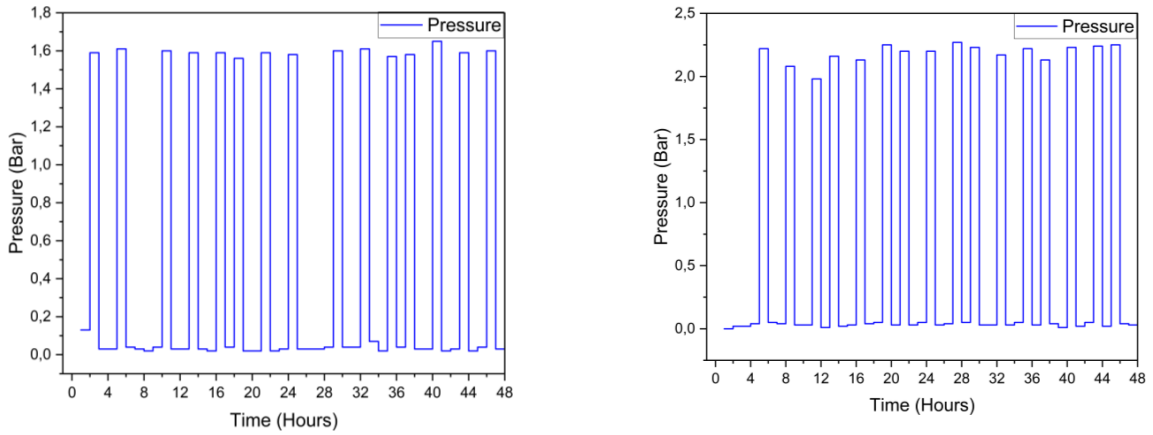


Figure 10. Pulsed Pressure Mode after two days at (a) 1 Bar, (b) 2 Bar

The pulsed salting control system test at 1 bar is shown in Fig. 10 (a), which shows the salting control process in pulsed pressure mode with a 1 bar setpoint over 48 h. A repeating pressure cycle is clearly observed throughout the salting duration, a main characteristic of the pulsed pressure mode. A total of 128 cycles were performed during the process. The graph shows that the pressure rises rapidly at the beginning of each cycle, then drops back to approximately 0 bar after 7.5 min during the 15 min relaxation phase.

The graph in Fig. 10(b) shows the pulsed salting control system test at 2 bar, indicating the salting process in pulsed pressure mode with a 2-bar setpoint over 48 h. The graph indicates that the control system operates stably and consistently, with pressure rising to 2.2–2.3 bar during the pressurization phase and dropping to approximately 0 bar during the relaxation phase. A total of 128 cycles occurred during the process.

3.4 Salted Egg Result

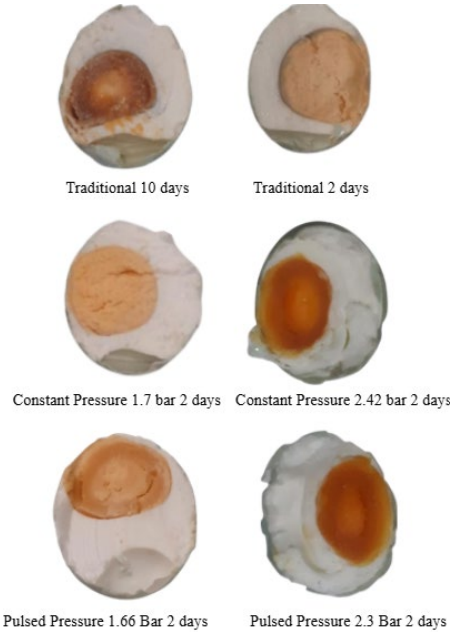


Figure 11. Salted egg results after the steaming process

The results of salted eggs after steaming using the traditional, constant, and pulsed pressure methods are shown in Figure 11. Salted eggs processed for 10 days using the traditional method showed a darker yolk color and a more granular texture, whereas those processed for 2 days did not. The salting process using pressure-controlled equipment, in both constant and pulsed modes, for 2 days, also resulted in different characteristics. In constant mode with a setpoint of 1 bar, the egg yolk appeared slightly more intense than that obtained using the traditional 2-day method. This effect became more pronounced at a constant setpoint of 2 bar, where the yolk color shifted toward reddish-yellow and the texture became more granular, indicating that pressure accelerated the penetration of salt into the egg. In pulsed pressure mode, visual changes were even more noticeable at both 1 and 2 bar. At 1 bar, the yolk appeared yellow with a slight reddish tint, whereas at 2 bar,

the yolk color shifted further toward reddish yellow. Furthermore, at 2 bar, the yolk texture became noticeably firmer and more granular due to the rapid salt penetration. While the overall external shape of the eggs remained unchanged during the pressurized process, the 2-bar treatments compromised their physical integrity, with the initial pressure overshoot causing shell cracking in the observed sample.

3.5 Salt Content

Salt content is one of the quality parameters established by SNI 01-4277-1996, which states that salted eggs must have a minimum salt content of 2.0% w/w to meet the quality standards for salted-food products. Salt content analysis was performed using the Mohr method. The results of the salt content testing are shown in Figure 12.

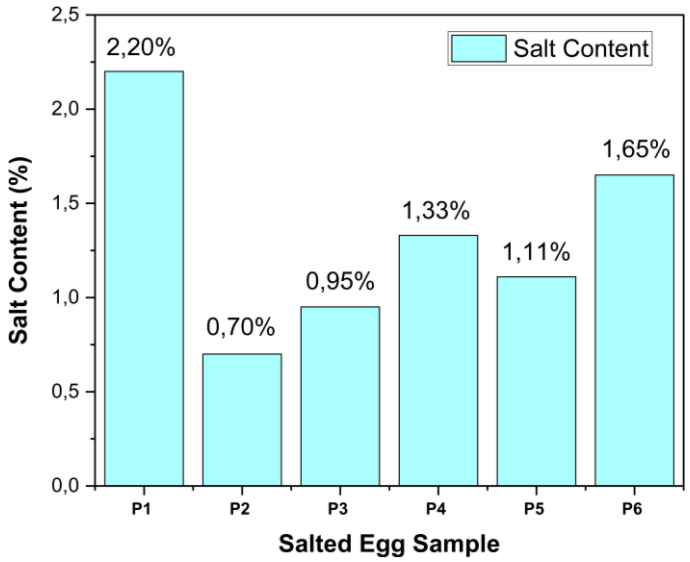


Figure 12. Salt content

Information of Fig. 12:

P1 = Traditional, 10 days
P2 = Traditional, 2 days
P3 = Constant Pressure 1 bar, 2 days
P4 = Constant Pressure 2 bar, 2 days
P5 = Pulsed Pressure 1 bar, 2 days
P6 = Pulsed Pressure 2 bar, 2 days

As this study focuses primarily on the engineering performance of the pressure control system, the salt content values presented in Figure 12 represent a single measurement (n=1) taken from a representative sample of each treatment batch. Therefore, standard deviation is not provided, and the data indicate observational trends rather than statistical significance. Salt content analysis showed that P1 (traditional salting for 10 days) had the highest salt content at 2.20%, while the lowest (0.70%) was observed in P2 (traditional salting for 2 days). Constant-pressure salting for 2 days yielded a higher salt content than the traditional 2-day method. At 1.7 bar (P3), the salt content reached 0.95%, increasing to 1.33% at 2.42 bar (P4), indicating that a higher pressure accelerates osmotic mass transfer. Based on the observed trends, pulsed pressure appeared to facilitate greater salt uptake than constant pressure under these preliminary test conditions. The pulsed pressure at 1.66 bar (P5) yielded 1 salt content of 1.11 %, demonstrating that cyclic pressurization improves salt diffusion. The highest performance was achieved at a pulsed pressure of 2.3 bar (P6), with a salt content of 1.62%, approaching that of the 10-day traditional method despite a processing time of only 2 days. Compared to Rohmat et al. [8], which required 4-6 bar, our system achieves comparable acceleration at only 2 bar, representing a potential 50-67% reduction in operating pressure

3.6 Organoleptic Result

The sampled eggs were then subjected to an organoleptic test to evaluate the characteristics of salted eggs using human sensory perception. This test assessed the taste, color, aroma, and graininess of the salted eggs produced by the device and subsequently steamed. Ten panelists participated in the evaluation.

Table 1. Organoleptic parameters

Variable	Assessment score			
	1	2	3	4
Smell	Abnormal aroma	Less aromatic	Normal aroma	Distinct salted egg aroma
Color	Slightly yellow	Yellow	Yellowish red	Reddish yellow
Taste	Not salty	Slightly salty	Salty	Very Salty
Texture	Not grainy	Slightly grainy	Grainy	Very Grainy

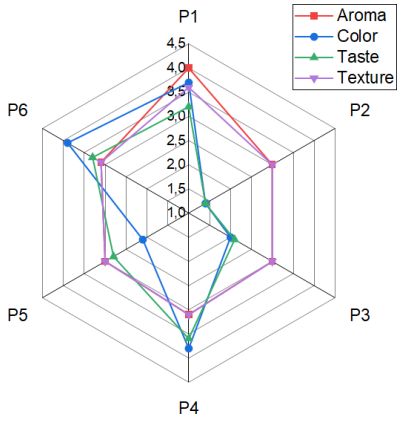


Figure 13. Organoleptic result

The organoleptic test results in Figure 13 indicate variations across all four parameters (aroma, color, taste, and texture) among the six salted egg samples. Since this study serves as an initial functional validation of the control system, statistical significance tests were not performed. Therefore, the sensory data represent observational trends rather than absolute statistical differences. In terms of aroma, sample P1 (traditional 10-day method) was the most distinct, whereas samples P2–P6 exhibited relatively similar profiles. The color parameters displayed the most complex differences, influenced by salting duration and pressure variations in both constant and pulsed methods. For texture, samples P1, P2, and P5 showed clear differences compared with several other samples, whereas some samples, such as P1, were similar to P4 or P6. In terms of taste, samples P1, P2, and P4 differed significantly from many other samples, whereas the pulsed method (P5 and P6) produced taste intensities that closely resembled those of the traditional 10-day sample. Overall, salting duration and applied pressure were the primary factors affecting the variation in the organoleptic quality of salted eggs.

4 Conclusion

The designed pressure control system operated stably and maintained the setpoint pressure in both constant and pulsed pressure modes. The constant mode at 1 bar produced salted eggs with appeared visually uniform salt distribution, whereas the constant mode at 2 bar resulted in higher salt content but less appeared uniformity, and one egg cracked. The pulsed pressure mode proved more effective, with 1 bar sufficient to accelerate osmosis without causing cracks. The 2-bar pressure was optimal, producing salted eggs that were richer in flavor, firmer, and more uniform, with quality close to that of the traditional 10-day method but achieved in only 2 days, though one egg cracked due to dynamic pressure. Overall, the pulsed pressure method significantly accelerated processing time compared to traditional methods. While traditional 10-day salting still yields the highest organoleptic scores, the pulsed mode at 2 bar offers the optimal balance between rapid production (2 days) and acceptable product quality, though control system tuning is required to minimize pressure overshoots that cause egg cracking.

Acknowledgement

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