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Experimental analysis of process parameters in semi-automatic blow molding of PET bottles: a case study at Universitas Negeri Malang product

Obaja Eden Sentosa Riyanto[1*], Dewi Izzatus Tsamroh[1], Ilham Akbar Wandoyo[1], Den Arsyah Pilar Pancayudha[1], Hikmal Faidillah[1]
[1]Manufacturing Engineering Technology, Universitas Negeri Malang, Malang + 65145, Indonesia
*Corresponding author: obaja.riyanto.fv@um.ac.id

Abstract

This research aims to analyze the effects of key process parameters on product quality and defects in the semi-automatic blow molding of Polyethylene Terephthalate (PET) bottles at Malang State University (UM). The background of this study stems from the increasing demand for high-quality PET packaging and the limited number of direct experimental studies on semi-automatic machines, with a limited number of tests. Most previous studies have emphasized model-based simulation and optimization, while practical studies that observe the relationship between process parameters and defect characteristics remain rare. Unlike simulation-based studies, this work is based on direct field experiments under stable, industry-relevant machine settings to evaluate product quality and production readiness for mass manufacturing. The research method was conducted through direct experiments using 12.5 g PET preforms and a 330 mL capacity two-cavity mold. The main variables tested included preform temperature (70°C and 80°C), blow delay time (0.30–0.50 s), and low-blow duration (0.20–0.50 s). Bottle quality was evaluated based on thickness measurements, dimensions, and visual analysis of defects such as wrinkles, collapses, and wall irregularities. The results showed that a preform temperature of 80 °C and a low-blow duration of 0.50 s produced bottles of the highest quality, characterized by uniform wall thickness, flat bases, and minimal defects. In contrast, low-temperature settings (70 °C) resulted in high viscosity, leading to deformation and wrinkles. This optimal combination of parameters was proven to improve bottle structure homogeneity and reduce dimensional shrinkage to <1%. This study emphasizes the importance of temperature and blow time control in achieving stable, efficient, and mass-oriented PET bottle production, while strengthening the role of universities in experimental manufacturing applied research.

Keywords:
Bottles, PET, blow molding, process optimization, preform temperature, semi-automatic machine

1 Introduction

With the rapid expansion of the food, beverage, pharmaceutical, and consumer goods industries, the global demand for Polyethylene Terephthalate (PET) packaging continues to rise. According to a recent report [1], the market value is projected to reach approximately USD 130 billion by the 2030s, with a compound annual growth rate (CAGR) of 4% and 6%. The global packaging industry relies heavily on PET due to its lightweight nature, transparency, impact resistance, and excellent processability via blow molding. The use of PET packaging has steadily increased, with PET now accounting for approximately 81% of beverage packaging worldwide [2]. Several studies have confirmed that PET plastics have stable mechanical properties and dimensional consistency when processed with proper molding parameters, especially in the packaging industry [3]. Due to its capability to induce polymer biorientation, provide high mechanical strength, and ensure excellent material efficiency, the blow molding process has become the most widely adopted method for manufacturing PET bottles [4]. Therefore, blow molding technology plays a crucial role in meeting the global demand for PET packaging, both in terms of product quality and production cost efficiency. In the context of sustainable manufacturing and Industry 4.0, optimizing the blow molding process has become increasingly important. Manufacturers are under pressure to minimize material waste, reduce energy consumption, and improve product consistency without compromising cost efficiency. Previous research has highlighted that optimizing polymer molding process parameters contributes to waste reduction and energy efficiency while maintaining product quality [5]. PET, being recyclable and widely used, aligns with circular economy principles; hence, enhancing the blow molding process contributes not only to production efficiency but also to environmental sustainability.

The production of PET bottles by blow molding often results in defects due to poorly controlled processing parameters. Among the most common defects are wrinkles, collapse or implosion, and uneven wall thickness, which significantly affect the overall quality and performance of the final product. [6]. For instance, wrinkles may occur when the preform is not heated uniformly or when the pre-blow pressure or blow delay settings are inappropriate. Conversely, collapse can arise when the bottle wall becomes excessively thin or when the blow pressure is insufficient to form the bottle structure fully [7]. Non-uniform wall thickness is also a critical issue, as it can reduce mechanical strength and top-load performance and even lead to structural failure during the bottle's service life [8].

In previous studies, various approaches have been employed, including finite element-based simulations and statistical optimization methods such as the Taguchi method, to predict and analyze the influence of processing parameters on wall thickness distribution and defect formation in PET bottles[9]. For example, the study *"Study on the Effects of Parameters to PET Bottle Thickness in Blowing Process"* utilized a combination of simulation and Taguchi optimization to achieve uniform wall thickness[10]. However, direct observational research focusing on simple, measurable phenomena through trial experiments on semi-automatic blow molding machines with a limited number of tests remains relatively scarce, particularly studies that link these observations to bottle defect characteristics. Most existing research tends to focus on complex simulations or model-based optimizations rather than practical experimental trials conducted under simplified production conditions[11].

This research was designed to address that gap by emphasizing practical, mass-production-oriented experimentation within the academic setting of Universitas Negeri Malang. Moreover, the practical experimentation on PET bottle production developed at Universitas Negeri Malang serves as a crucial bridge between academic research outcomes and industrial applications. The produced bottles are part of an institutional initiative that supports sustainable and low-cost product development. This research approach illustrates how academic innovation can be translated into real manufacturing practices through collaboration with local production partners [12]. By directly observing process behavior during production trials, researchers can collect empirical data that validate theoretical assumptions and reveal the influence of key parameters on product quality[13]. Such an approach reinforces the role of universities in applied research while enhancing engineering education through practical case studies that reflect real industrial challenges. Ultimately, this model promotes an integrated framework connecting research, production, and education.

Based on these gaps, the objective of this study is to conduct direct experimental investigations to examine how key process parameters such as particularly preform temperature, blow delay, and micro blow (low blow or high blow) can affect the quality of PET bottles and contribute to the formation of defects such as wrinkles, collapse, and uneven wall thickness when using a semi-automatic blow molding machine. This research aims to provide empirical observational data rather than relying solely on simulations, and to offer recommendations for optimal processing parameters that enable the production of PET bottles with minimal defects under simple production settings. Consequently, the study contributes to the existing body of literature by presenting replicable experimental findings, complementing prior simulation-based studies, and providing validated process parameters applicable to mass-production contexts.

2 Research methodology

The overall research methodology adopted in this study is presented schematically in Fig. 1. This flow chart illustrates the main stages and sequence of the research process.

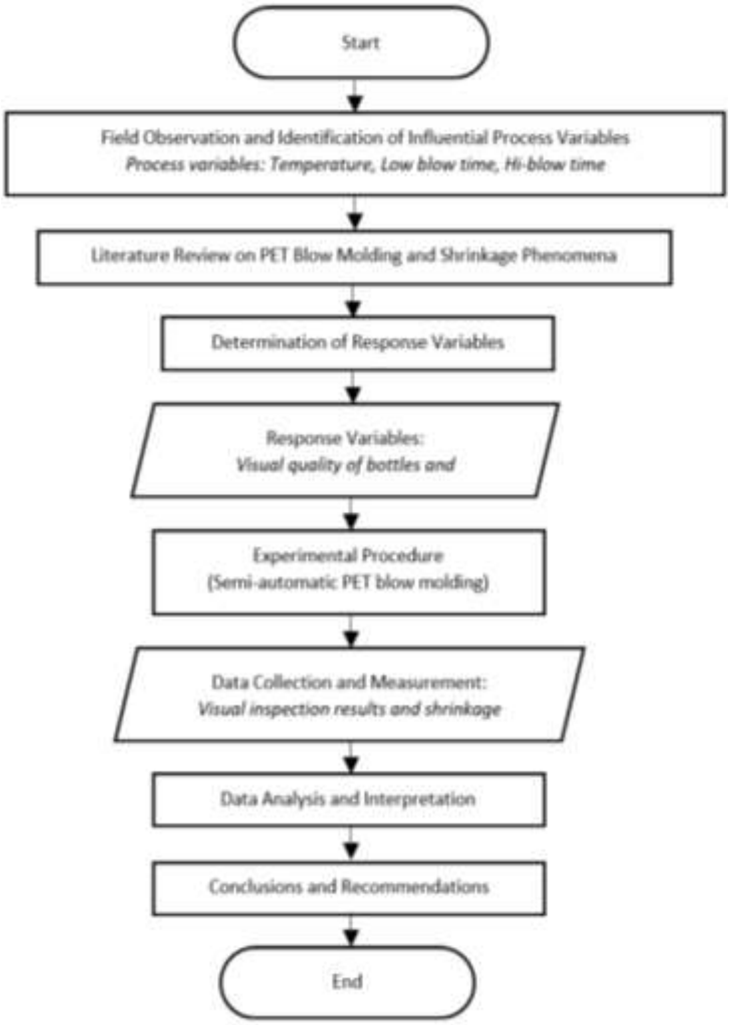


Fig. 1. Research flowchart

Transparent PET preforms weighing 12.5 g were used in this study. A semi-automatic blow molding machine with a two-cavity mold for 330 mL bottles molded the preforms. The mold was specifically designed for the bottled drinking water product of Universitas Negeri Malang (Fig. 2). The machine consisted of a preform heating unit and a bottle-blowing unit, as illustrated in Fig. 3. Field observations were conducted to identify influential process variables in the blow-molding operation. Based on these observations and the literature review, the inspected process parameters were preforming temperature (°C), delay blow time, low-blow time, and high-blow time. These parameters were manually controlled through an integrated pneumatic system during the blowing process. Before molding, the preforms were heated in an oven to the specified temperature and then transferred to the blowing station. The forming process was performed under semi-automatic conditions in a commercial production facility. The response variables evaluated in this study were bottle visual quality and shrinkage behavior. A Visual inspection was conducted to observe surface defects, incomplete mold filling, and deformation irregularities, while shrinkage was assessed by measuring the molded bottles' dimensions with a caliper. The research process is summarized in the flow chart shown in Fig. 1.

Fig. 2. Molding of the PET Product

Fig. 3. Semi-automatic blow molding machine

2.1 Experimental design parameters

The experimental setup consisted of 10 test conditions, including six trials at a preform temperature of 70 °C and four at 80

°C. The primary variables investigated were the blow delay and low-blow parameters, while the high-blow duration was held constant at 2.1 seconds. The pressure applied is constant at 1.5 Bar for the small bottle application. An infrared heating unit was employed to soften the preforms prior to the stretching and blowing stages, as illustrated in Fig. 4. The experimental design followed the principles of an orthogonal array or a simplified Design Of Experiments (DOE) framework, a method widely used in previous studies of Injection Stretch Blow Molding (ISBM) process parameters[14]. Through this parameter variation approach, both individual effects and potential interactions among variables were analyzed to determine their influence on wall thickness distribution and the occurrence of defects such as wrinkles, dents, and non-uniformities in the final PET bottle products. This approach aligns with methodologies previously reported in PET process simulation studies [15].


Fig. 4. Preform infrared heater

2.2 Production procedure

Each PET preform, as shown in Fig. 5, was heated to the designated temperature and then placed in the mold, where it was subjected to axial stretching using a stretch rod. Subsequently, the pre-blow (low blow) stage was initiated, followed by the high-pressure blow in accordance with the predetermined delay sequence.


Fig. 5. PET preform before the blowing process

This series of steps is aimed at optimizing material orientation while minimizing the occurrence of common defects such as wrinkles and collapses, as demonstrated in previous experimental and simulation-based studies that emphasized the influence of pressure sequence and delay duration on bottle quality [16]. After the forming process, each bottle was carefully removed from the mold, labeled with an identification code corresponding to its specific process condition, and stored for subsequent dimensional and visual analyses.

2.3 Evaluation and data analysis

The quality of the bottles was evaluated using two approaches. First, a visual inspection was conducted to detect defects such as wrinkles, collapse, clarity issues, and wall non-uniformity, using a standard rating system. Second, quantitative measurements were carried out, including wall thickness at the shoulder, body, and base areas, overall bottle dimensions, and total weight. The collected data were tested for normality and homogeneity to ensure reliability of the measurement process. Since the data did not meet the assumptions for parametric analysis, the statistical analysis was conducted descriptively to identify trends and consistency across the trials. The combination of visual evaluation and quantitative analysis aligns with the methodological framework commonly adopted in studies on blow molding process optimization and FEM simulation of PET bottles [7]. Blow molding parameters per trial can be seen in Table 1.

Table 1. Blow molding parameters per trial

Trial	Temp (°C)	Delay blow	Micro/Low blow time	Hi-blow time
1	70 °C	0.38 s	0.30 s	2.1 s
2	70 °C	0.38 s	0.30 s	2.1 s
3	70 °C	0.45 s	0.30 s	2.1 s
4	70 °C	0.45 s	0.30 s	2.1 s
5	70 °C	0.30 s	0.20 s	2.1 s
6	70 °C	0.30 s	0.20 s	2.1 s
7	80 °C	0.50 s	0.50 s	2.1 s
8	80 °C	0.50 s	0.50 s	2.1 s
9	80 °C	0.50 s	0.50 s	2.1 s
10	80 °C	0.50 s	0.50 s	2.1 s

3 Results and discussion

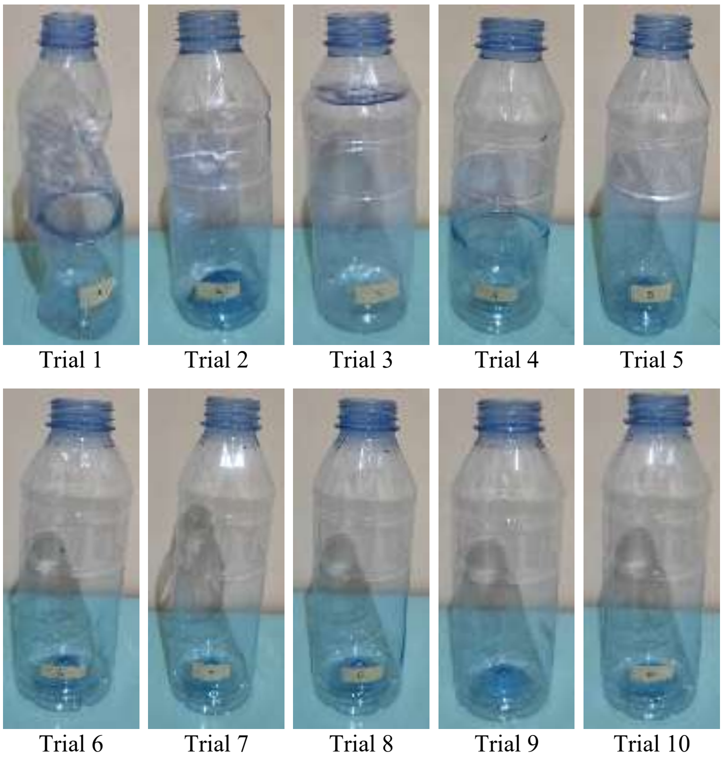
3.1 Visual Inspection of the trial

The experimental analysis showed that preform temperature and low-blow duration were the most critical variables influencing the quality of the produced bottles. At lower temperature settings (Table 2, trials 1–6), the material tended to exhibit high viscosity (insufficient softening), resulting in various form defects. The resulting bottles frequently showed dents, wrinkles, and irregularities at the base or along the sidewalls. This behavior indicates that the preform was not adequately softened, and the short low-blow phase failed to provide sufficient preliminary expansion, leading to the high-blow pressure being applied prematurely. In contrast, increasing the preform temperature combined with a longer low-blow duration (Table 2, Trials 7–10) resulted in substantial improvements. This combination enabled smoother and more uniform material expansion before the high-blow stage. Consequently, Trials 9 and 10 (Table 2) produced bottles with symmetrical shapes, flat bases, and uniform wall thickness, indicating that the optimal process conditions had been achieved.

Visual examination of Bottles 1 through 10 (Fig. 6) illustrates the progressive improvement in quality as process parameters change. The early specimens (Bottles 1 and 2) visually confirmed process failure by exhibiting severe distortion and wrinkling. Although minor improvements were observed in Trials 3 to 6 (Bottles 3 to 6), such as enhanced clarity, visible imperfections, including wall thickness non-uniformity and uneven bases, remained apparent. A marked improvement in visual quality was observed in Bottles 7 and 8, which exhibited more stable and well-defined shapes. Finally, Bottles 9 and 10 represented the ideal product outcomes, characterized by high clarity, perfect symmetry, and overall structural stability. These results clearly validate that the combination of an optimized preform temperature and an extended low-blow duration provides the most effective conditions for producing high-quality PET bottles.

Table 2. Comparison of bottle outcomes in trials 1–10

Trial	Visual & main diagnosis
1	Bottle denting or wrinkling occurs. The preform is insufficiently softened, and the low-blow phase is too short, causing the high-blow air to be applied before the material has adequately expanded.
2	A defect similar to that of Specimen 1 was observed, with more pronounced wrinkles on the bottle body. This condition indicates that the preform was insufficiently softened and the low-blow phase was too brief, causing the high-blow air to enter before the material had adequately expanded.
3	Overall appearance was improved, the bottle base remained uneven, and thinning was observed on the sidewall. This suggests that the material still exhibited high viscosity due to insufficient heating, resulting in unstable material distribution during the blowing stage.
4	Irregularities at the bottle base and slight wrinkling on the shoulder were still observed, indicating that the material maintained relatively high viscosity due to low heating temperature, leading to unstable material distribution during the forming process.
5	The bottle appeared clear; however, certain areas remained thin and slightly wrinkled. This defect occurred because the delay time was too short and the low-blow phase ended prematurely, causing the material to be stretched during the high-blow stage while it was still in a semi-soft state, leading to localized thinning.
6	Similar to Specimen 5, but with noticeable wall thickness non-uniformity. This condition resulted from an excessively short delay time and low-blow duration, causing the material to be stretched during the high-blow phase while it remained in a semi-soft state, leading to localized thinning.
7	The bottle began to form more symmetrically, with a flatter base and a significant reduction in wrinkles. This improvement was achieved through a higher heating temperature and a longer low-blow duration, which allowed for smoother and more uniform pre-expansion before the high-blow stage.
8	The bottle appeared stable with relatively uniform wall thickness, showing only minor irregularities at the shoulder area. This condition resulted from the higher heating temperature and extended low-blow duration, which enabled smoother and more uniform pre-expansion prior to the high-blow phase.
9	The best result was obtained with a clear bottle exhibiting a symmetrical shape, flat base, and uniform wall thickness. This outcome was achieved under higher heating temperature and extended low-blow duration, which allowed for gentle and uniform material expansion before the high-blow stage.
10	The best result was achieved, characterized by a clear bottle with a symmetrical shape, flat base, and uniform wall thickness. This optimal condition resulted from a higher heating temperature and a prolonged low-blow duration, which facilitated smooth and uniform material expansion before the high-blow stage


Trial 1 Trial 2 Trial 3 Trial 4 Trial 5

Trial 6 Trial 7 Trial 8 Trial 9 Trial 10

Fig. 6. Visual outcomes per tria

3.2 Product shrinkage study

To evaluate the dimensional stability of the produced PET bottles, shrinkage was assessed at three critical regions of the bottle geometry, as illustrated in Fig. 7: the bottom, middle, and neck regions. These areas were selected because they represent distinct deformation behaviors during the stretch blow molding process. The bottom section typically experiences complex stress distribution due to the transition from axial to radial stretching, the middle section reflects the overall body expansion and uniformity, while the neck section remains partially constrained and serves as a reference for dimensional comparison. Measuring shrinkage at these three points allows a comprehensive understanding of material distribution and deformation characteristics, providing a quantitative basis for evaluating process precision and product quality.

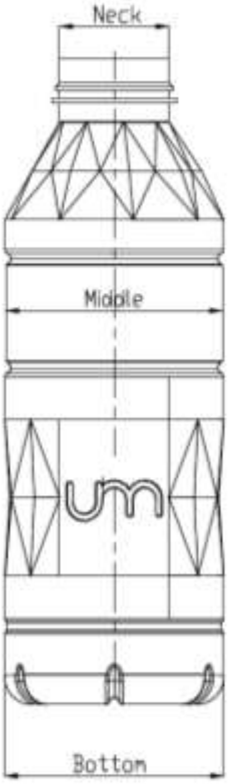


Fig. 7. Shrinkage dimension assessment

Based on the data presented in Table 3, the percentage of shrinkage in the bottle neck area ranged from 0.35% to 3.39%. The highest shrinkage value was recorded for Bottle 1 (3.39%), while the lowest was 0.35% for Bottles 2 and 4. This pattern indicates that the process parameters applied in the early trials tended to result in excessive neck expansion. Such deformation was likely due to uneven preform heating or excessively high low-blow air pressure. After adjustments were made to the heating and pressure parameters, the shrinkage variation became more stable, with an average value approaching 1%. The more consistent results observed in Trials 7 through 10 reflect a stable process condition, suggesting that an optimal balance between thermal deformation and cooling in the neck area had been achieved.

Table 3. Neck shrinkage percentage

No.	Neck design	Neck trial	Shrinkage (%)
1	⌀ 28	⌀28.95	3.39%
2	⌀ 28	⌀28.10	0.35%
3	⌀ 28	⌀28.30	1.07%
4	⌀ 28	⌀28.10	0.35%
5	⌀ 28	⌀28.20	0.71%
6	⌀ 28	⌀28.30	1.07%
7	⌀ 28	⌀28.35	1.25%
8	⌀ 28	⌀28.30	1.07%
9	⌀ 28	⌀28.25	0.89%
10	⌀ 28	⌀28.25	0.89%

Shrinkage measurements in the middle section of the bottles, as shown in Table 4, exhibited a considerably wider range, from 0.55% to 14.24%. The highest shrinkage value was recorded for Bottle 2 (14.24%), indicating substantial dimensional contraction, most likely due to excessively rapid cooling and uneven heat distribution. In contrast, the lowest shrinkage value of 0.55% was observed in Bottles 6, 9, and 10. The process conditions in these trials, which likely involved an optimized combination of preform temperature, delay-blow time, and low-blow duration, produced a more stable distribution of material thickness. The middle section of the bottle proved to be the most sensitive region to variations in air pressure and delay time, as it experiences the greatest degree of stretching and deformation during the blowing process. Additionally, this area retains the most residual stress, which can lead to uneven wall relaxation and post-molding deformation if not properly managed.

Table 4. Middle shrinkage percentage

Trial No.	Middle design	Middle trial	Shrinkage (%)
1	⌀55.4	⌀60.30	10.84%
2	⌀55.4	⌀46.65	14.24%
3	⌀55.4	⌀55.15	1.93%
4	⌀55.4	⌀53.65	1.37%
5	⌀55.4	⌀49.70	8.63%
6	⌀55.4	⌀54.70	0.55%
7	⌀55.4	⌀53.55	1.56%
8	⌀55.4	⌀53.55	1.56%
9	⌀55.4	⌀54.10	0.55%
10	⌀55.4	⌀54.10	0.55%

Data presented in Table 5 show that the percentage of shrinkage at the bottle base ranged from 0.89% to 10.53%. The highest value was recorded for Bottle 1 (10.53%), while the lowest shrinkage of 0.89% was observed in Bottles 9 and 10. The high shrinkage observed in the early trials indicates an imbalance between air pressure and the cooling rate in the mold cavity at the base. By increasing the preform temperature and extending the delay-blow duration, the bottle base expanded more uniformly and experienced more consistent cooling. The results obtained in Trials 7 through 10 demonstrated significantly improved base stability, with no visible defects such as collapse or wrinkling. This finding suggests that the process parameters in the later trials approached the optimal condition. The results summarized across the three tables indicate that the greatest shrinkage occurred in the early trials, whereas the later trials produced bottles with more consistent and uniform dimensions. The middle section of the bottle exhibited the greatest shrinkage compared to the neck and base regions, primarily because it experiences greater stretching and internal pressure during formation.

Table 5. Bottom shrinkage percentage

Botol	Bottom design	Bottom trial	Shrinkage (%)
1	⌀56	⌀50.10	10.53%
2	⌀56	⌀50.40	10%
3	⌀56	⌀54.10	3.39%
4	⌀56	⌀54.35	2.94%
5	⌀56	⌀55.30	1.25%
6	⌀56	⌀55.25	1.33%
7	⌀56	⌀55.40	1.07%
8	⌀56	⌀55.30	1.25%
9	⌀56	⌀55.5	0.89%
10	⌀56	⌀55.5	0.89%

These findings confirm that the combination of optimized preform temperature, delay-blow time, and low-blow duration represents the most effective set of parameters for producing PET bottles with good dimensional stability and minimal shrinkage. The experimental findings also demonstrated that the preform heating temperature plays a key role in the success of the bottle-forming process. At 70 °C, the preform remained too rigid, preventing full expansion, whereas at 80 °C, close to the glass transition temperature (Tg) of PET, the material became more plastic and deformable. This behavior is consistent with previous studies emphasizing that temperature regulation is a determining factor in product quality during the blow molding process (Ge-Zhang et al., 2022).

The adjustment of the delay-blow time also significantly affected the final product quality. When the delay time was set to 0.30 s, the high-pressure air was applied too early, resulting in non-uniform formation. At 0.45 s, the outcome remained suboptimal, whereas a delay of 0.50 s allowed the initial expansion to occur in a more controlled manner before high pressure was applied. This pattern aligns with simulation results indicating that wall thickness distribution in blow-molded bottles is strongly influenced by the interaction between time and pressure parameters during the forming process [18]. The role of the low-blow phase in the initial forming stage is also crucial. A low-blow duration of less than 0.30 seconds proved insufficient to achieve uniform material expansion, leading to thinner-walled areas. In contrast, a duration of 0.50 seconds produced a more homogeneous wall thickness distribution. Therefore, the combination of preform heating at 80 °C, a delay-blow time of 0.50 seconds, and a low-blow duration of 0.50 seconds was identified as the most favorable processing range. This finding supports the parameter optimization approach widely applied in experimental blow molding research to achieve consistent product quality. [19].

Fig. 8 shows a comparative evaluation of the shrinkage data. It reveals that the middle section of the bottle consistently experienced the greatest dimensional change among the three regions. This trend can be attributed to the combined effects of biaxial stretching and higher localized internal pressure during the blowing phase, which induce greater molecular orientation and relaxation upon cooling. In contrast, the neck region exhibited the lowest shrinkage values throughout the trials, owing to its thicker wall and limited deformation during the stretch-blow process. The bottom section showed moderate shrinkage, but its early instability in the first two trials, reaching up to 10%, suggests that this area is highly sensitive to the interaction between preform temperature and mold cooling efficiency. As processing conditions were optimized in later trials (Trials 7 to 10), the shrinkage differences between the three regions diminished significantly, indicating improved uniformity in heat transfer and stress relaxation. These results confirm that a balanced combination of thermal and pressure parameters promotes dimensional consistency across the entire bottle profile[20].

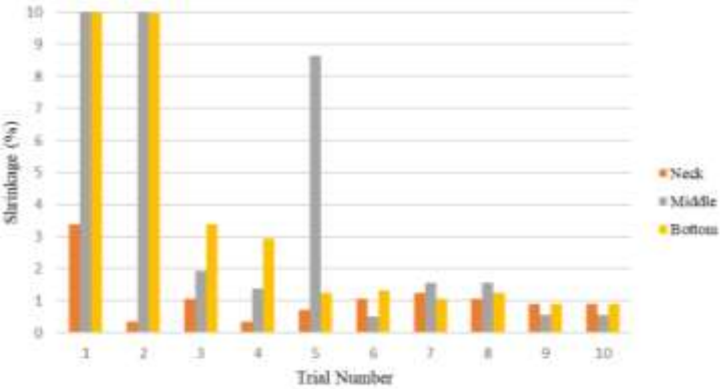


Fig. 8. Comparative table

The concepts of polymer relaxation and molecular orientation in amorphous PET provide additional insight into the observed differences in shrinkage behavior between the neck, middle, and bottom regions. Greater chain orientation and stress accumulation occur in areas with higher biaxial strain during the stretch blow molding process, especially in the middle section. According to Ge-Zhang et al. [21], these oriented molecular chains tend to relax and retract when cooled, resulting in detectable shrinkage after the internal stress is released. Areas with less stretching, like the neck, on the other hand, show less dimensional change because they maintain a more isotropic structure with less internal stress. These results are in line with the thermo-mechanical behavior of PET as reported by Ge-Zhang et al. [21], who highlighted that the interaction of cooling gradients and deformation history largely controls the distribution of shrinkage along the bottle profile. Consequently, a balanced molecular relaxation is reflected in the convergence of shrinkage values in the optimized trials, indicating that the process parameters effectively reduced thermal and stress nonuniformity in the finished product.

Building on these thermo-mechanical findings, the experimental findings also imply that, while maintaining a constant high blow pressure during the forming stage, the ideal set of process parameters for mass production consists of a controlled preform heating temperature and optimized delay blow and low blow durations. It was discovered that this arrangement ensured efficient production while achieving the best possible bottle rigidity and consistent wall thickness. Because it ensures consistent product quality and dimensional stability over time, this setup is considered ideal for large-scale manufacturing. Further observations showed that this combination improves the overall homogeneity of the bottle wall structure by effectively reducing common defects such as wrinkles and collapses. These findings are consistent with previous studies that emphasize the importance of maintaining stable heating and blowing pressure conditions in semi-automatic stretch blow molding processes for achieving high-quality and consistent plastic bottle production [22].

3.3 Confirmation test

To validate the results, more than 100 PET bottles were produced using the chosen parameters: a preform temperature of 80°C, a delay blow time of 0.50 seconds, and a low-blow time of 0.50 seconds as part of a confirmation test to verify the consistency and dependability of the optimized process parameters. The goal of the test was to confirm whether the optimized parameters could sustain consistent product quality over a prolonged production run. The findings showed a high degree of repeatability, with every bottle having a flat base, symmetrical shape, uniform wall thickness, and clear transparency. Throughout the trials, no notable changes or flaws, such as thinning, collapse, or wrinkles, were observed. This consistency demonstrates that the selected process parameters provide reliable, repeatable results appropriate for semi-automatic blow molding operations in achieve optimal single-cycle performance. Therefore, the confirmation test supports the application of the experimental results in small- to medium-scale industrial production and reaffirms their validity.

4 Conclusions

This study shows that the preform temperature setting plays a critical role in the success of the PET bottle stretch blow molding process. Heating the preform to 80°C produces significantly better results than 70°C, as this temperature exceeds the glass transition temperature (Tg) of PET, enabling sufficient elasticity for effective biaxial molecular orientation. This optimization is reflected in two primary quality indicators: more uniform wall thickness distribution and a significant reduction in product defects. Precise temperature control during the heating stage is therefore essential for regulating plastic deformation and improving the geometric and mechanical quality of PET bottles. In addition to temperature, blowing time also strongly influences product quality. A 0.50-second delay blow combined with a 0.50-second low blow enables controlled expansion and promotes balanced molecular orientation and crystallization. The delay period allows PET molecules to adjust to axial stretching by the stretch rod before high pressure is applied, resulting in more uniform material distribution. These findings have practical implications for semi-automatic machines used in laboratory-scale and small-to-medium production. The combination of an 80°C preform temperature and 0.50-second blowing time can serve as an operational reference to improve product consistency, reduce waste, and enhance production efficiency.

References

[1] F. Market, I. Global, and C. Pvt, “Global PET Packaging Market to Reach USD 130 . 4 Billion by 2033 , Driven by Sustainability and E-commerce Growth | FMI,” 2024.

[2] P. Benyathiar, P. Kumar, G. Carpenter, J. Brace, and D. K. Mishra, “Polyethylene Terephthalate (PET) Bottle-to-Bottle Recycling for the Beverage Industry: A Review,” *Polymers (Basel).*, vol. 14, no. 12, 2022, doi: 10.3390/polym14122366.

[3] Muslimin, H. M. Ridlwan, D. Luqyana, B. Pambudi, and A. M. Muhamad, “Design Analysis of Mold Cavity and Core on Compression Molding of Composite Material,” *J. Polimesin*, vol. 21, no. 2, pp. 241–242, 2023, doi: 10.30811/jpl.v21i2.3311.

[4] Y. M. Luo, L. Chevalier, T. T. Nguyen, and H. Attar, “Identification of polymer behavior from nonequibiaxial elongation test with temperature and strain rate conditions close to blow molding process,” *Polym. Eng. Sci.*, vol. 63, no. 10, pp. 3268–3287, 2023, doi: 10.1002/pen.26442.

[5] R. A. Ismoyo, M. Hartono, and A. Murdani, “Optimizing Injection Molding Parameters to Minimize and Prediction Potential for Flashing Defects,” *J. Polimesin*, vol. 22, no. 2, pp. 227–233, 2024, doi: 10.30811/jpl.v22i2.4576.

[6] M. Grzelak, M. Szostak, P. Rzepka, and A. Kloziński, “Comparison of post-consumer recycling PET bottles from flakes and regranulate,” *Polimery/Polymers*, vol. 70, no. 7–8, pp. 510–519, 2025, doi: 10.14314/polimery.2025.7.9.

[7] V. T. Hoang *et al.*, “Study on the effects of parameters to PET bottle thickness in blowing process,” *Univ. Danang - J. Sci. Technol.*, no. December, pp. 74–78, 2023, doi: 10.31130/ud-jst.2023.413e.

[8] T. Muringayil Joseph *et al.*, “Polyethylene terephthalate (PET) recycling: A review,” *Case Stud. Chem. Environ. Eng.*, vol. 9, no. February, 2024, doi: 10.1016/j.cscee.2024.100673.

[9] T. Wuryandari, T. Widiharih, and S. D. Anggraini, “Metode Taguchi Untuk Optimalisasi Produk Pada Rancangan Faktorial,” *Media Stat.*, vol. 2, no. 2, pp. 81–92, 2012, doi: 10.14710/medstat.2.2.81-92.

[10] V. T. Hoang *et al.*, “Study on the effects of parameters to PET bottle thickness in blowing process,” *Univ. Danang - J. Sci. Technol.*, pp. 74–78, 2023, doi: 10.31130/ud-jst.2023.413e.

[11] P. Wawrzyniak, W. Karaszewski, and A. Różański, “Effect of rPET Content and Preform Heating/Cooling Conditions in the Stretch Blow Molding Process on Microcavitation and Solid-State Post-Condensation of vPET-rPET Blend: Part I—Research Methodology and Results,” *Materials (Basel).*, vol. 17, no. 21, 2024, doi: 10.3390/ma17215233.

[12] N. Evans, A. Miklosik, and J. T. Du, “University-industry collaboration as a driver of digital transformation: Types, benefits and enablers,” *Heliyon*, vol. 9, no. 10, p. e21017, 2023, doi: 10.1016/j.heliyon.2023.e21017.

[13] F. Teng, G. Menary, S. Yan, J. Nixon, and J. B. Stevens, “A Hybrid Artificial Neural Network Approach for Modeling the Behavior of Polyethylene Terephthalate (PET) Under Conditions Applicable to Stretch Blow Molding,” *Polymers (Basel).*, vol. 17, no. 8, 2025, doi: 10.3390/polym17081067.

[14] B. Demirel, F. Akkurt, I. A. Uysal, and E. Senyigit, “Determination of The Best Injection Stretch Blow Molding Process Parameters in Polyethylene Terephthalate Bottle Service Performance,” *Gazi Univ. J. Sci.*, vol. 35, no. 4, pp. 1297–1316, 2022, doi: 10.35378/gujs.704371.

[15] S. Bagherzadeh, F. R. Biglari, and K. Nikbin, “Parameter study of stretch-blow moulding process of polyethylene terephthalate bottles using finite element simulation,” *Proc. Inst. Mech. Eng. Part B J. Eng. Manuf.*, vol. 224, no. 8, pp. 1217–1227, 2010, doi: 10.1243/09544054JEM1853.

[16] A. Lontos and A. Gregoriou, “The effect of the deformation rate on the wall thickness of 1.5LT PET bottle during ISBM (Injection Stretch Blow Molding) process,” *Procedia CIRP*, vol. 81, no. March, pp. 1307–1312, 2019, doi: 10.1016/j.procir.2019.04.018.

[17] S. Ge-Zhang, X. Chen, H. Zhu, Y. Song, Y. Ding, and J. Cui, “Computer Simulation of Polyethylene Terephthalate Carbonated Beverage Bottle Bottom Structure Based on Manual–Automatic Double-Adjustment Optimization,” *Polymers (Basel).*, vol. 14, no. 14, 2022, doi: 10.3390/polym14142845.

[18] S. Ge-Zhang *et al.*, “Advances in Polyethylene Terephthalate Beverage Bottle Optimization: A Mini Review,” *Polymers (Basel).*, vol. 14, no. 16, pp. 1–14, 2022, doi: 10.3390/polym14163364.

[19] E. A. Berihun and T. M. Bogale, “Parameter Optimization of PET Plastic Preform Bottles in Injection Molding Process Using Grey-Based Taguchi Method,” *Adv. Mater. Sci. Eng.*, vol. 2022, 2022, doi: 10.1155/2022/4416602.

[20] Y. M. Luo, T. T. Nguyen, H. Attar, L. Chevalier, and F. Lesueur, “A new biaxial apparatus for tensile tests on Poly Ethylene Terephthalate optimized specimen at stretch blow molding conditions,” *Polym. Test.*, vol. 113, p. 107676, Sep. 2022, doi: 10.1016/J.POLYMERTESTING.2022.107676.

[21] S. Ge-Zhang, M. Song, Z. Huang, M. Li, and L. Mu, “Comparison and Optimization: Research on the Structure of the PET Bottle Bottom Based on the Finite Element Method,” 2022. doi: 10.3390/polym14153174.

[22] P. C. Hsieh, “Intelligent Temperature Control of a Stretch Blow Molding Machine Using Deep Reinforcement Learning,” *Processes*, vol. 11, no. 7, 2023, doi: 10.3390/pr11071872.