

Mold with Special Cooling and Ventilation System for Preform Design with Reduced Weight Improving Design and Sustainability

Berk ŞAHİN^{1*} , Gamze ARSLAN¹ 

¹Petka Kalıp Sanayi ve Ticaret Anonim Şirketi, Adana, Türkiye

Abstract

In the plastic packaging industry, the concept of sustainable production is gaining increasing importance due to rising environmental regulations and growing challenges in raw material supply. Particularly, the rising procurement and transportation costs of PET raw material in international markets have made energy efficiency and resource conservation improvements a priority in production processes. In line with these developments, this study focuses on the design of an innovative blow mold compatible with lightweight preforms, equipped with specialized ventilation and cooling systems. Within the scope of the study, the preform weight was reduced from 10 grams to 9 grams, and a new model was developed for a 500 cc PET bottle. To enable the lightweight preform to achieve the desired bottle form under lower pressure, extensive improvements were made in the mold design. Specifically, the mold's internal ventilation system was optimized to reduce the required air pressure during the blowing process and to accelerate the cycle time. The number and positioning of the gas evacuation vents were reconfigured based on analytical evaluations. Additionally, to enhance the mold's cooling performance, custom-designed cooling channels were implemented, significantly improving temperature control during production. Structural analyses, temperature distribution, and flow simulations led to a mold design that was optimized both thermally and mechanically. The developed mold model was tested in the production line, where it was observed that the target bottle form was successfully achieved under low pressure and that a notable reduction in cycle time was realized. Moreover, a reduction of approximately 20% in energy consumption was recorded.

The unique aspects of this study include the development of a new bottle model compatible with a lightweight preform, the design of a specialized mold incorporating tailored ventilation and cooling systems for this model, and the enhancement of energy efficiency. The technical achievements obtained contribute not only to product quality and production efficiency but also to the goals of environmental sustainability. Furthermore, the engineering solutions developed through this study are expected to provide a technical foundation for similar R&D and design projects in the future.


Keywords: Blow mold, Grammage optimization, PET preform, Plastic injection mold, Preform mold, Sustainability.

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***Corresponding Author:**
Berk ŞAHİN
berk33834@gmail.com
 0009-0007-3547-1688

Gramajı Düşürülmüş Preform Tasarımı İçin Özel Soğutma ve Havalandırma Sistemine Sahip Kalıp Tasarımının Geliştirilmesi ve Sürdürülebilirlik

Özet

Plastik ambalaj sektöründe sürdürülebilir üretim kavramı, artan çevresel düzenlemeler ve hammadde tedarikindeki zorluklar nedeniyle önem kazanmaktadır. Özellikle uluslararası pazarlarda PET hammaddesinin temin ve taşıma maliyetlerinin artması, üretimde enerji verimliliği ve kaynak tasarrufunu öncelikli hâle getirmiştir. Bu

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bağlamda, bu çalışma, hafifletilmiş preformlarla uyumlu, özel havalandırma ve soğutma sistemlerine sahip yenilikçi bir şişirme kalıbı tasarımını sunmaktadır. Mevcut 10 gramlık preformdan 9 gramlık yeni bir PET şişe modeli geliştirilmiştir. Hafif preformun daha düşük basınç altında istenilen şişe formunu alabilmesi için kalıp tasarımında kapsamlı iyileştirmeler yapılmıştır. Özellikle kalıbın iç havalandırma sistemi, şişirme sürecinde gerekli hava basıncını azaltmak ve çevrim süresini hızlandırmak amacıyla optimize edilmiştir. Gaz tahliye deliklerinin sayısı ve yerleşimi analiz sonuçlarına göre yeniden düzenlenmiştir. Ayrıca, iç soğutma performansını artırmak ve üretim sırasında sıcaklık kontrolünü iyileştirmek için özel soğutma kanalları geliştirilmiştir.

Yapısal analizler, sıcaklık dağılımı değerlendirmeleri ve akış simülasyonları gerçekleştirilmiş ve hem termal hem de mekanik olarak optimize edilmiş bir kalıp tasarımı elde edilmiştir. Geliştirilen kalıp modeli üretim hattında test edilmiş ve düşük basınçta hedeflenen şişe formunun başarıyla elde edildiği, ayrıca çevrim süresinde kayda değer bir azalma sağlandığı gözlemlenmiştir. Bununla birlikte, enerji tüketiminde de önemli bir düşüş kaydedilmiştir.

Bu çalışmanın yenilikçi yönleri arasında, hafif preformlara uyumlu yeni bir şişe modelinin geliştirilmesi, özel havalandırma ve soğutma sistemlerinin entegrasyonu ve enerji verimliliğinde sağlanan iyileştirmeler yer almaktadır. Elde edilen teknik kazanımlar yalnızca ürün kalitesi ve üretim verimliliğine değil, aynı zamanda çevresel sürdürülebilirlik hedeflerine de katkı sunmaktadır. Ayrıca, sunulan mühendislik çözümleri, gelecekteki Ar-Ge ve kalıp tasarım projeleri için sağlam bir temel oluşturmaktadır.

Anahtar Kelimeler: Şişirme kalıpları, gramaj optimizasyonu, PET preform, Plastik enjeksiyon kalıbı, Sürdürülebilirlik

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***Sorumlu Yazar:**
Berk ŞAHİN
berk33834@gmail.com
 0009-0007-3547-1688

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1. Introduction

Today, the plastic packaging industry requires high-volume and mass production techniques to meet the demands of the rapidly growing global market. However, this fast-paced production process faces significant challenges in the context of increasing environmental issues and sustainability goals. In particular, difficulties in the global supply of PET (Polyethylene Terephthalate) raw material, rising costs, and fluctuations in supply chains are driving manufacturers to develop more efficient and environmentally friendly production methods. In this context, the concept of sustainable production not only aims to reduce costs but also highlights the necessity of innovative design and process improvements that minimize environmental impacts.

The preforms used in the production of plastic bottles have a direct impact on the quality, shelf life and production efficiency of the end product. While traditionally used preforms with a high weight lead to a high consumption of energy and raw materials during production, preforms with a low weight offer both ecological and economic advantages. However, reducing the weight of preforms can increase the likelihood of technical problems during the bottle molding process. Therefore, comprehensive improvements in mold design are required to ensure that lightweight preforms deliver high-quality results without complications during production.

Various engineering approaches have been developed in plastic blow molding and injection mold design to enhance production efficiency and achieve sustainability. Yılmaz and Kaya (2022) [1] demonstrated that optimizing the cooling channels in injection molds reduced mold cooling time by 20% and achieved 15% savings in energy consumption. Similarly, Demirel and Arslan (2021) [2] reported that increasing and optimizing the number of gas vent holes in blow molds improved product quality and increased production capacity by 10%. Şahin and Kurt (2023) [3] found that mold designs compatible with low-weight PET preforms enhanced energy efficiency by 12% and reduced production time by 18%.

The performance of gas venting in minimizing product deformation and shortening the production cycle was supported by numerical analyses conducted by Öztürk and Demir (2020) [4]. Kılıç and Yıldırım (2019) [5] showed that optimizing the placement of cooling channels improved the internal mold temperature distribution by 25%, thereby enhancing product quality. Arslan and Demirel (2022) [6] noted that reducing the number of mold components simplified the assembly process and improved internal air flow, shortening the production cycle by 15%.

Studies focused on energy savings have also yielded significant developments. Yılmaz and Koç (2021) [7] significantly reduced energy consumption in injection molds through innovative cooling systems. Özcan and Güngör (2020) [8] demonstrated that an enhanced gas venting system improved PET bottle quality and reduced production time. Demir and Çelik (2023) [9] reported that thermal and mechanical optimization in mold design positively influenced mass production performance and increased durability. Finally, Kaya and Şahin (2022) [10] emphasized that material-saving and energy-efficient approaches in sustainable plastic packaging mold designs reduced environmental impacts and lowered costs.

Since PET is derived from petroleum, increases in oil prices directly affect PET costs, making gram weight optimization economically critical, especially for companies engaged in high-volume production. Moreover, environmental regulations such as the European Green Deal mandate the reduction of carbon footprint in production processes, which necessitates transitioning to mold systems with lower energy consumption and shorter cycle times in PET bottle production. In sustainability reporting, material efficiency and waste reduction are among the key evaluation criteria. During the blowing process, since preforms are expanded at high pressures—around 30 bar—the electricity consumption of air compressors is significantly high. Therefore, designing better-shaped and deformation-resistant preforms that allow the same volume to be achieved at lower pressures contributes to energy savings and enhances production efficiency. Figure 1 shows the blow molding parts.



Figure 1. Blow Mold Parts

These studies demonstrate that optimizing critical factors in mold design—such as cooling, gas venting, number of components, and material usage—not only enhances production efficiency but also makes significant contributions to environmental sustainability goals.

During the design process, the number and angular placement of gas vent holes inside the mold were optimized based on engineering principles to improve ventilation efficiency. Additionally, specially designed cooling channels were implemented to enhance temperature control within the mold. The effects of these improvements on the production process were thoroughly examined, and advancements in energy efficiency, product quality, and production speed were detailed.

The main objective of this article is to develop a new generation PET blow mold that enables higher form quality, can operate with low-weight preforms, ensures high cycle efficiency, and allows high-quality production with lower energy consumption. This goal represents a technical response to the current needs of the PET packaging industry for cost reduction, production efficiency, and environmental sustainability. The project aims to go beyond the limitations of existing mold technologies and present a system that can achieve the same bottle quality with less raw material and lower energy input.

2. Materials and Method

In preform molds, special air channels are required to rapidly evacuate the air inside during the blow molding process; insufficient air venting can lead to incomplete contact between the preform and the mold surface, especially in the base and shoulder areas, resulting in form defects. Additionally, PET preforms need to be cooled to an appropriate temperature before ejection from the mold. However, in conventional molds, inefficient placement of cooling channels extends the cooling time, causing slowdowns on the production line and daily output losses. Furthermore, mold designs are often based on experience and lack simulation support; failure to optimize critical parameters such as material

distribution, flow direction, and heat transfer leads to non-uniform wall thickness and undesirable deformations in the preform. Figure 2 shows the preform and the blow mold.

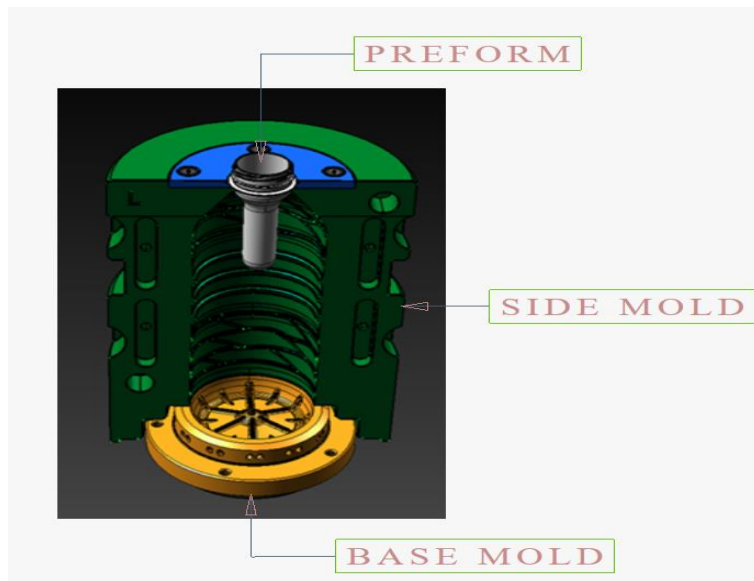


Figure 2. Preform and Blow Mold

In this study, a specially designed blow mold was developed to overcome the production challenges arising from reducing the weight of PET preforms used in plastic bottle manufacturing and to enhance production efficiency. Initially, a new preform weighing 9 grams was selected instead of the existing 10-gram preform. This change not only reduces raw material consumption but also alters the forming conditions during the blow molding process. Therefore, various structural improvements in the mold design became necessary.

During the design process, the number of gas vent holes inside the mold was increased, and the diameters and placement angles of these holes were optimized based on engineering calculations and fluid dynamics principles. This improvement aimed to allow the air and gases within the mold to be evacuated more quickly and effectively during the blow molding phase. As a result, the internal air pressure in the mold during the blowing process was reduced, enabling more homogeneous and defect-free bottle formation.

In addition, specially designed cooling channels were developed to improve internal mold temperature control. These channels ensured uniform and effective cooling of the mold surface, minimizing thermal fluctuations during the production process and improving product quality. Thermal simulations were used in the design of the cooling system to determine the optimal flow paths and channel diameters. The benefits achieved through weight optimization are summarized in Figure 3.

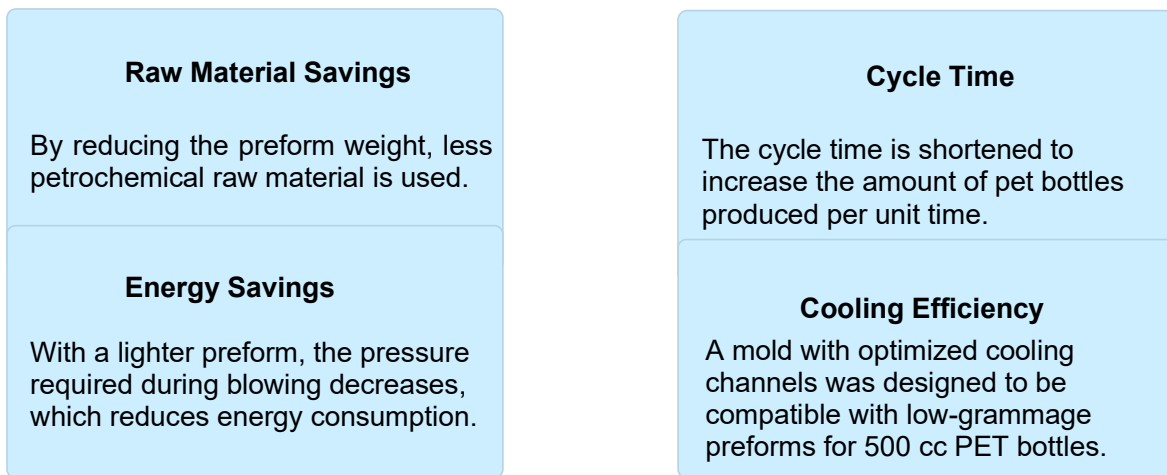


Figure 3. Benefits of Performing Grammage Optimization

Throughout all stages of the design process, the geometric structure of the mold was modeled using three-dimensional CAD (Computer-Aided Design) software, followed by solidworks flow simulations (CFD) and thermal analyses. The analysis input limits for the inflation process were selected as air flow with a pressure of 30 bar. This enabled a detailed examination of gas flows inside the mold, temperature distribution, and mechanical strength. At the end of the design phase, a prototype mold was produced and tested on the production line.

In terms of preform design, the wall thickness of the 9-gram preform is thinner than that of the 10-gram preform. This results in the following during the blowing process:

- Faster heat transfer,
- Higher risk of deformation,
- Lower structural stability.

To prevent these critical risks, mold wall surfaces must be optimized to accommodate the reduced wall thickness of the preform. Geometric reinforcement should be increased particularly in the base, neck, and shoulder regions. Channels that provide thermal bridging and uniform temperature distribution must be designed. Figure 4 shows the preform.



Figure 4. Preform

Recalibration of Blowing Dynamics:

The 10-gram preform, due to its thicker wall, exhibits higher resistance during the blowing process and can withstand higher pressure. In contrast, the 9-gram preform:

- Requires more precise control of blowing pressure.
- Must be blown more rapidly during form shaping; otherwise, sagging may occur.

Considering these factors:

- The pressure profile must be redefined.
- The pressure increase curve throughout the blowing process should be smoother and more controlled.
- The heat profile should be revised to suit the 9-gram preform.

Figure 5 shows the blowing process.

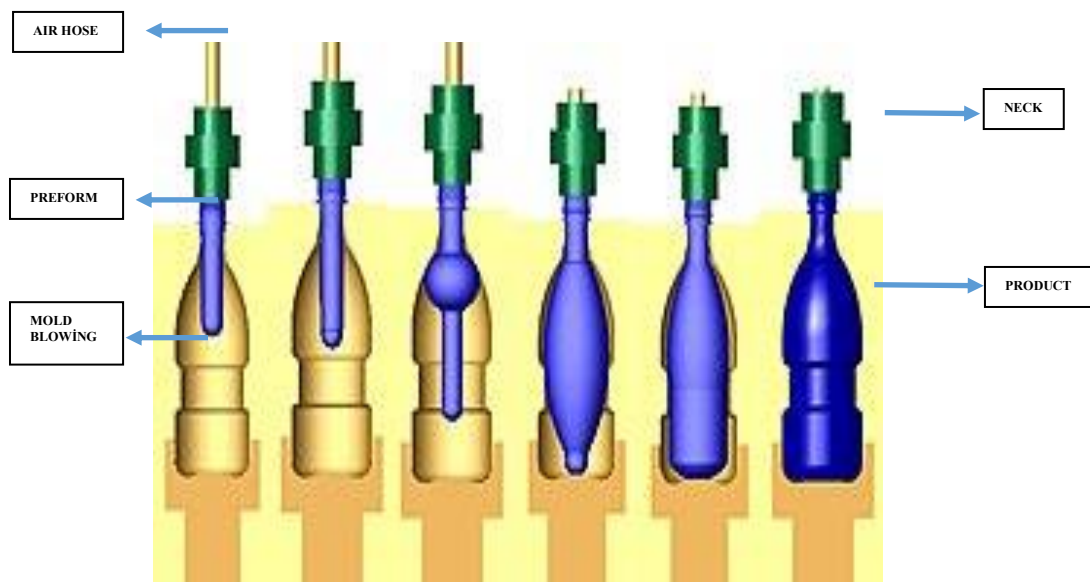


Figure 5. Blowing Process

Blow Molding Process Parameters and Energy Savings:

In the PET blow molding process, the highest amount of energy is consumed during the blowing stage, which uses high-pressure air. Compressed air production accounts for approximately 60–70% of the total energy consumption. Optimizing air pressure has a direct impact on energy efficiency and operating costs. While conventional preforms require 30 Bar of air pressure during the blowing stage, 22 Bar is sufficient to blow a reduced-weight preform. With the decrease in pressure, compressors consume less power. This has provided energy savings. This savings has been seen in energy consumption meters.

Figure 6 illustrates the improvement in thermal control achieved through specially designed cooling channels and vent holes.

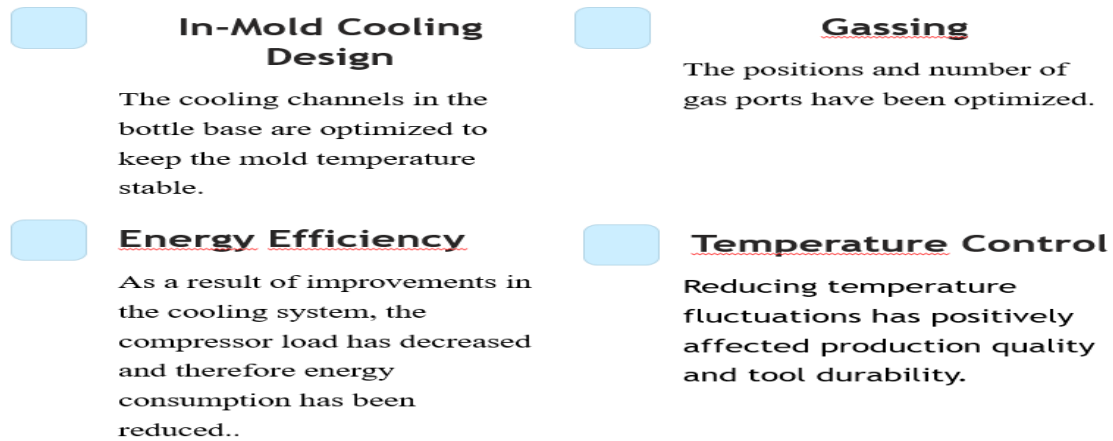


Figure 6. Improving Thermal Control with Custom Cooling Channels and Gas Venting Holes

Figure 7 shows the base mold details.

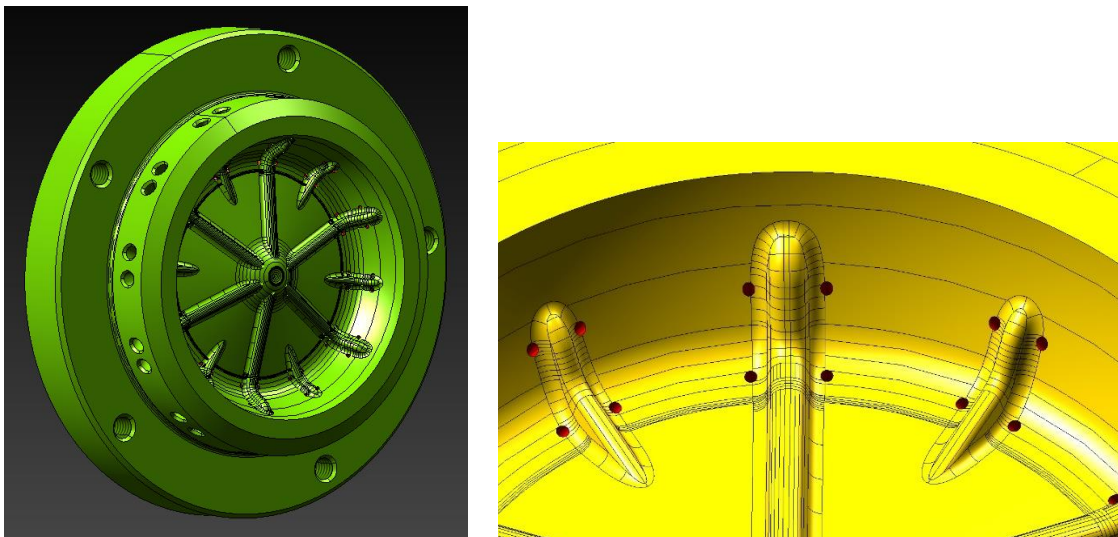


Figure 7. Base mold details

In production tests, the effects of the new mold on the blowing process were evaluated; especially the cycle time, product quality (geometric form and deformation rates) and energy consumption were measured. The obtained data were compared with the previous molds and the effectiveness of the design and the increase in efficiency were analyzed. These methods have provided innovative solutions in terms of engineering and have also created an important infrastructure for achieving sustainable production goals.

3. Results & Discussion

As a result of the design improvements, increasing the number of gas vent holes inside the mold and optimizing their angles significantly accelerated the air evacuation during the blowing process. CFD simulations and field tests showed that the air evacuation time was reduced by an average of 25%. This

allowed the blowing process to start earlier and enabled the PET bottle to spread more uniformly against the mold surface.

With the redesign of the cooling channels, temperature irregularities on the mold surface were minimized, noticeably reducing deformation and shape defects that could occur during blowing. Thermal simulation results and actual production data confirmed that mold temperature control was optimized and production quality improved.

Production tests using the prototype mold showed a 15% reduction in blow molding cycle time, which in turn increased production capacity proportionally. This improvement allowed for more efficient use of the production line and higher output per unit time. Additionally, an approximate 25% reduction in energy consumption provided cost advantages while contributing to environmental sustainability goals.

Table 1 shows a comparison of the old and new models and the post-project goals. The old and new blow molding methods were compared and the profit rates were determined.

Table 1. Comparisons and Targets

Area of Benefit	Current Situation	Post-Project Target	Gain/Explanation
Grammage	10 g	9g	%10 raw material saving
Blowing Pressure	30 bar	22 bar	%25 energy saving
Products/hour	25000	32000	%28 production increase
Cooling Performance	Conventional, unbalancing	Simulation-assisted	Homogeneous temperature
Mold Life	Standart	+%50 cycle increase	Longer-lasting and more reliable production
Form Quality	Maintained with manuel balancing	Guaranteed by pre-simulation	Homogeneous bottle wall thickness, less scrap
Energy Consumption	High (compressor-based)	%18-22 lower	Compressor load and electricity consumption decrease
Carbon Footrint	High	Low (Green Deal compliant)	Annual reduction of thousands of kg of CO ₂ emissions
R&D Competency	Fragmented and based on classical methods	Simulation-assisted integrated approach	Permanent development in engineering infrastructure
Technical Documentation	Limited	CAD moldels, analysis reports, validation	Corporate knowledge accumulation increases

From a product geometry perspective, significant improvements have been recorded in the surface smoothness and dimensional accuracy of the bottles thanks to the optimized gas evacuation

system. These improvements, in addition to enhancing product quality, have increased customer satisfaction and reduced post-production quality control costs.

In light of all these findings, it has been observed that the engineering approach in mold design yields positive results not only in terms of technical performance but also in economic and environmental impacts. The integration of the design into existing production processes stands out as an effective and feasible solution for achieving sustainable production goals.

4. Conclusion

1. Optimized Mold Cooling System:

- A customized cooling layout tailored to reduced-grammage (e.g., ~9g) PET preforms enhanced heat dissipation.
- This directly contributed to shortening the cooling phase within each cycle, reducing overall cycle time.

2. Accelerated Gas Evacuation:

- Redesigned ventilation channels and an increased number of degassing vents improved internal mold air discharge.
- As a result, mold cavity filling and preform expansion occurred more uniformly and rapidly.

3. Reduced Cycle Time:

- Through improved cooling and gas evacuation, the blow molding cycle time was significantly reduced, increasing line throughput.

4. Increased Production Efficiency:

- The system enabled higher output without compromising quality, leading to a measurable rise in daily production capacity.

5. Lower Energy Consumption per Unit:

- Faster cycles and efficient thermal control reduced energy usage per bottle, contributing to both cost savings and environmental compliance.

6. Improved Preform Compatibility:

- The design is optimized for low-weight preforms, ensuring structural support during blowing despite thinner wall sections.

7. Enhanced Bottle Quality:

- Deformations and shrinkage in bottle geometry were minimized, yielding consistent dimensional accuracy and improved aesthetic quality.

8. Reduced Product Rejection Rate:

- Fewer shape defects and visual imperfections resulted in a lower scrap rate, improving first-pass yield.

9. Lower Quality Control and Rework Costs:

- More uniform output reduced the need for post-production inspection, sorting, or corrective actions.

10. *Improved Customer Satisfaction:*

- High-quality, dimensionally stable bottles increased customer trust in the product and brand.

11. *Sustainability Contributions:*

- The new design aligns with environmental goals by minimizing material waste, energy use, and overall process emissions.

12. *Cost-Effective Production:*

- The mold enables savings across multiple domains: material, energy, labor, and downtime — making it economically beneficial.

13. *Support for Lightweighting Strategy:*

- The project supports the industry trend toward lighter packaging while maintaining performance standards.

14. *Long-Term Design Adaptability:*

- The modular and scalable design allows future integration of digital monitoring, predictive maintenance, or real-time thermal feedback systems.

15. *Transferability and Industrial Applicability:*

- This engineering solution can be used as a template for upgrading existing blow molding systems across similar production environments.

16. *Contribution to Engineering Knowledge:*

- The study serves as a comprehensive design reference for future mold developments focusing on energy efficiency and performance optimization.

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