DESIGN AND THERMAL SIMULATION OF PET BOTTLE AND MOULDING TOOL FOR INJECTION STRETCH BLOW MOULDING

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Abstract - This study presents an analysis of the stages involved in the design of blow moulding tools using the TopSolid system, with a primary focus on the development of a model for a vegetable oil bottle. The initial phase involves the creation of a detailed 3D model of the bottle, essential for ensuring both product functionality and manufacturing efficiency. Following the modelling stage, the paper examines the design process for the blow moulding tools, including material selection, tool geometry, and optimisation of the moulding process. The combined use of TopSolid and SolidWorks software enables precise tool design by considering critical parameters such as temperature regulation, pressure distribution, and material flow during manufacturing. Furthermore, the integration of SolidWorks Simulation tools is highlighted as a means of predicting mould performance and ensuring consistency and high quality in the final product. The study concludes with the presentation of the final mould tool model.

Keywords: Injection stretch blow moulding, Polyethylene terephthalate (PET), Bottle design, Thermal simulation, CAD/CAM, Heat distribution in moulds, ISBM mould tool.

1. Introduction

Injection stretch blow moulding (ISBM) is a principal method for manufacturing hollow PET bottles and other plastic products [1]. The process begins with injection moulding, where structurally amorphous semi-finished products, known as preforms, are created from PET resin granules [2]. The preforms are injected into a specialised mould, with the plastic temperature during injection typically ranging between 280°C and 320°C. After injection, the preform is cooled to approximately 50-60°C to solidify and prepare it for the subsequent stages of the process [3, 4].

Following cooling, the preform is heated in an infrared oven to a temperature of 110-130°C, making it sufficiently flexible for stretching. In the second stage, the preform is placed in a stretching chamber, where an elongation pin extends it in the axial direction [5, 6]. The orientation induced by biaxial stretching is significantly influenced by temperature, with subsequent effects on the mechanical, optical, and barrier properties of the final bottle [7].

The process is governed by both blowing and stretching pressures, which play a pivotal role in defining the final mechanical strength of the bottle. The stretching pressure typically ranges between 1 and 5 MPa, and this axial deformation is combined with radial expansion induced by internal air pressure [8, 9]. The final stage consists of the blow moulding process, during which high-pressure air - ranging from 10 to 50 MPa - is injected into the preform to form the desired product geometry [10, 11]. Precise control of both pressure and air volume is essential to ensure uniform material distribution and achieve high product quality. Following the blow moulding step, the product is cooled to approximately 20–30°C to stabilise its geometry and complete solidification. The kinematics of the blowing process may also serve as a reference for evaluating the accuracy of deformation models [12].

Figure1: Main stages of injection and blow moulding [13]

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Figure 1 shows the main stages of injection and blow moulding [13].

Groot et al. [14] present the relationship between the blow moulding time of a PET bottle at constant inlet pressure. The stages are shown in figure 2. The figure demonstrates that during blow moulding, the polymer form initially expands at the top, while the bottom part stretches, and later the expansion moves towards the bottom of the bottle. This results in achieving an almost constant thickness of approximately 1.5 mm.

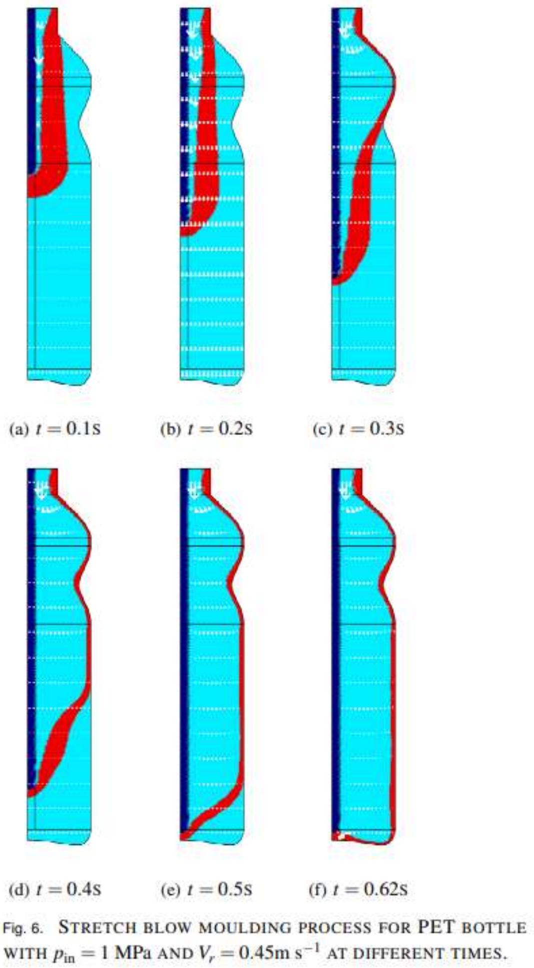


Figure 2: Stretch blow moulding process for PET bottle at different times [14]

2. Preform and Process Parameters

The preform used for manufacturing a vegetable oil bottle via Injection Stretch Blow Moulding (ISBM) is shown in figure 3.

It is manufactured from Polyethylene Terephthalate (PET).

Polyethylene terephthalate (PET) is a thermoplastic polyester obtained through the polycondensation of ethylene glycol and terephthalic acid (or its derivatives such as dimethyl terephthalate). Its repeating structural unit can be represented as [-OCH_2CH_2OOC-C_6H_4-CO-]$_n$ - figure 4.

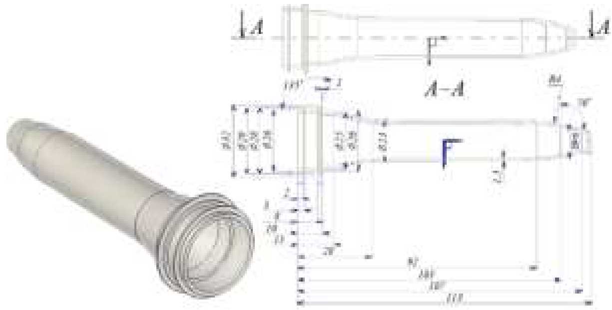


Figure 3: Preform for manufacturing a vegetable oil bottle

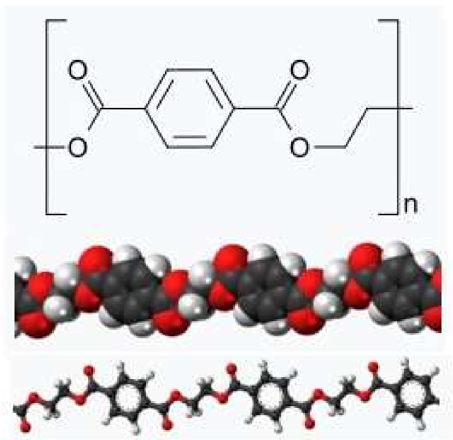


Figure 4: Molecular Structure of Polyethylene Terephthalate [15]

Owing to this chemical structure, PET exhibits an excellent combination of physical, mechanical, and barrier properties, making it highly suitable for packaging applications and technical components.

PET has a density in the range of 1.38 to 1.40 g/cm^3 and demonstrates high tensile strength, typically between 50 and 80 MPa, with a modulus of elasticity ranging from 2600 to 2800 MPa. The elongation at break can reach up to 150%, depending on the degree of molecular orientation. The melting temperature lies between 250÷260°C, while the Vicat softening point is approximately 80–100°C. PET exhibits low permeability to oxygen and moisture, making it particularly effective as a barrier material. Its coefficient of thermal expansion is within the range of 70÷80 ×10^{-6}/°C, and moisture absorption may reach up to 0.5% under saturated conditions.

The combination of high mechanical strength, chemical resistance, processability, and excellent barrier performance establishes PET as a leading material in the production of lightweight and thin-walled containers, particularly via injection stretch blow moulding (ISBM) technologies.

Process parameters include:

- plastic temperature of approximately 295°C during preform injection,
- cooling of the preform to 48–52°C.

First Stage – Stretching:

- preform temperature: 115–118°C,

- air pressure: 1.2 MPa,
- the preform is axially stretched using a rod to improve its orientation and mechanical properties.

Second Stage – Blow Molding:
- preform temperature: 23–27°C,
- air pressure: 8 MPa.

The preform is placed in the mold and inflated to the desired shape using high-pressure air.

Water Cooling:

Purified water at t = 8°–12°C, P = 0.4 MPa, with a flow rate of 2.0 m^3/h. The cooling system is constructed using flexible polyamide hoses and clamping fittings, ensuring quick assembly and disassembly when changing the tool.

3. Bottle Body Design

The vegetable oil bottle is designed using the CAD/CAM system TopSolid (v.6), specifically the "TopSolid' Design" module. The primary tools used for the creation and modification of the model are derived from the solid and surface modelling features available in the Design/Context Bar/Shapes and Surface panels.

The various stages of the design process are illustrated in Figures 5-12.

3.1 Creation of the Bottle Body

Initially, a sketch representing the contour of the vegetable oil bottle body is generated and dimensioned in the Absolute Coordinate System (ACS) (see figure 5).

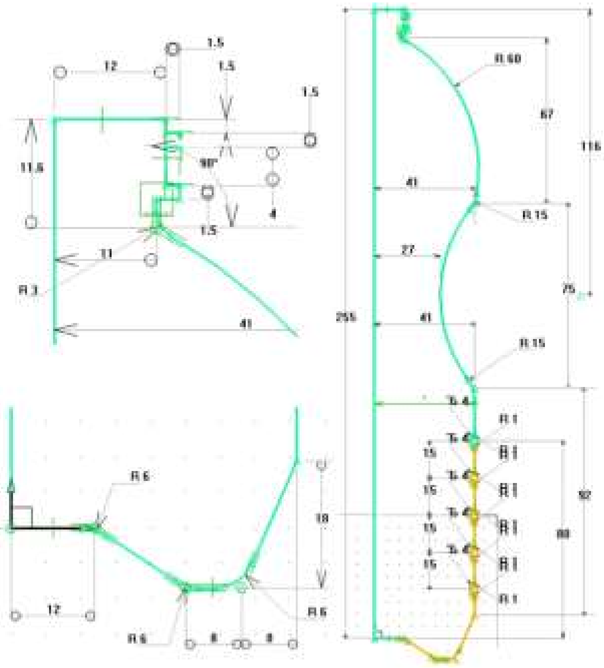


Figure 5: Sketch of bottle body

By rotating the sketch, a solid body model of the bottle is created using the revolved shape operation in the CAD environment - figure 6.

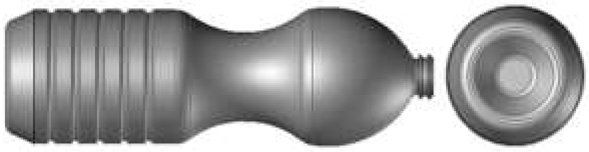


Figure 6: Shape

3.2 Printing of Relief Components on the Bottle

A new coordinate system (CCS 1) is created on the face of the bottle using the function for defining coordinate systems on surfaces (see figure 7). CCS 1 is then duplicated in the direction parallel to the +Z axis with a translation distance of 20 mm.

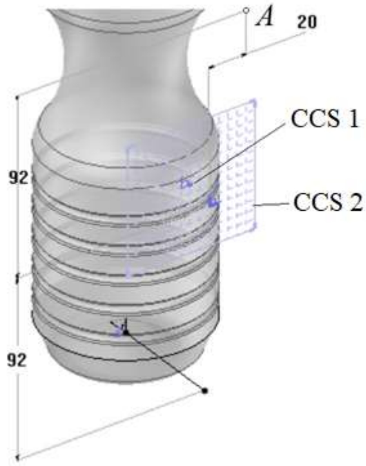


Figure 7: Current coordinate system

The next step involves constructing the profile of the first relief component in CCS 2. This profile is created using a b-spline curve, with the curve starting at point A (see figure 8).

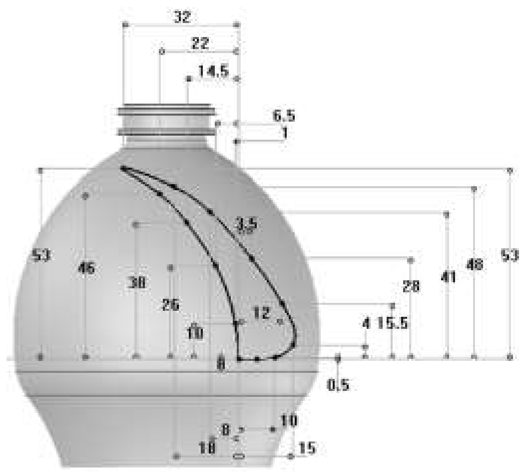


Figure 8: First profile

An identical profile for the second relief component is created in CCS 2, with the curve starting at point 0, 0. This component is formed from two b-spline curves. The two curves are merged into a single curve using the Sew function - figure 9.

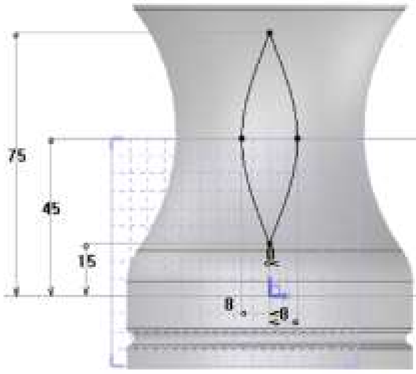


Figure 9: Second profile

The relief curves are then imprinted onto the bottle body. This operation is carried out by selecting the bottle as the shape to modify, and the relief curves are selected for imprinting onto the surface of the bottle. The direction of imprinting is set along the Z axis - figure 10.

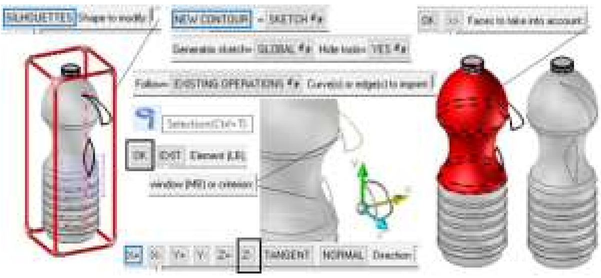


Figure 10: Imprint of profiles

For successful subsequent manipulation, the edges of the imprinted curves are copied and merged using the Sew function.

The cutting of profiles into the bottle body along the relief curves is performed using the cutting by sweeping curve operation in the CAD system. The bottle is selected as the object to trim, and the relief curves are sequentially chosen as trimming profiles. A vector is directed inward towards the bottle with an extrusion length of 1 mm - figure 11.

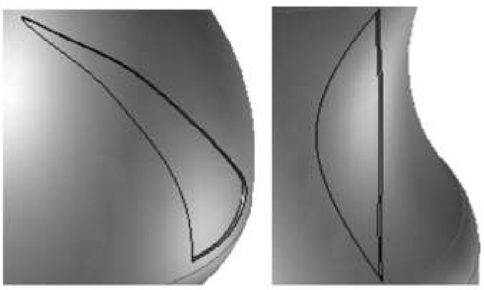
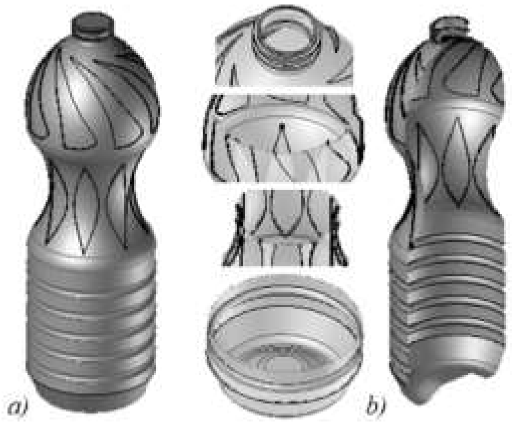


Figure 11: Trim by sweeping curve

The generated cavities are replicated in a polar array, setting the total angle to 360° and the total number of elements to 8, repeating the process for each relief curve – figure 12,a.

A wall thickness of 1 mm is achieved by applying the shell operation, with a global thickness of 1 mm. The bottle body is selected, and the neck of the bottle is designated as the piercing face - figure 12,b.



a) Propagation of profiles, b) Shape to hollow/shell

Figure 12: Finished Form

4. Design of the Tool for Injection Stretch Blow Moulding (ISBM)

The tool is designed using the TopSolid'Mold module. The part model is selected and integrated through the Explore function. A position and material, specifically Polyethylene Terephthalate (PET), are then designated, as illustrated in – figure 13.

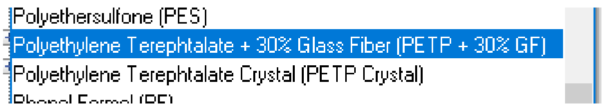


Figure 13: Material PETP

An active coordinate system is established at a point located at the midpoint between the two outermost edge circles of the model. This coordinate system serves as the intersecting surface of the part.

By utilizing the Create Parting Lines function, TopSolid automatically generates all potential parting lines relative to the active coordinate system. The required parting lines are selected without exiting the function, ensuring the contour is fully enclosed. Following this, the Create Parting External Surfaces function is used to generate the external parting surface. The external parting surfaces are selected, and the Flat function is applied to create a flat parting surface along the part's axis, as shown in figure 14.

Next, from the Part and Block menu, the Create Core/Cavity Blocks function is selected. A dialog box appears for the automatic creation of two blocks, during which material shrinkage calculations after injection moulding are also carried out, as depicted in figure 15.

Figure 14: External parting surface

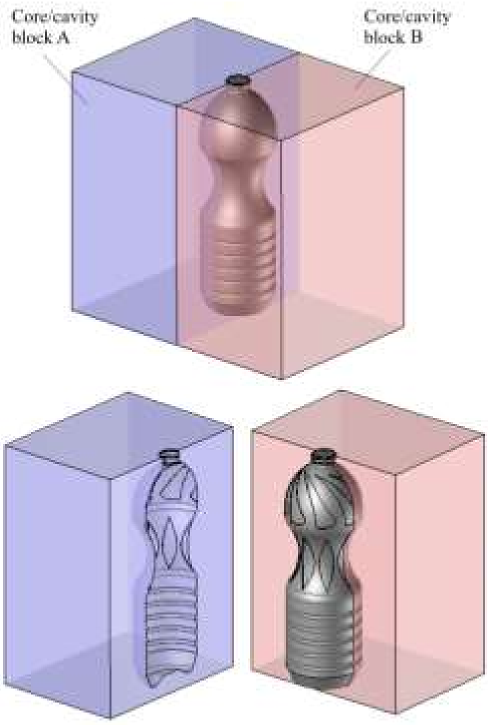


Figure 15. Core/cavity blocks

The 3D contour of the cooling system is designed using the Contour 3D function. Through Circuit Management, the efficiency of the cooling system can be evaluated and visualised. The inlet and outlet of the fluid in the upper plate are implemented using the Extend Pipe Circuit function. Additionally, connecting nipples, pipe plugs, and O-rings are placed at the openings, as shown in figure 16.

After the generation of the blocks and cooling system, a series of technological operations are performed to shape the neck, base of the bottle, and the heating channels.

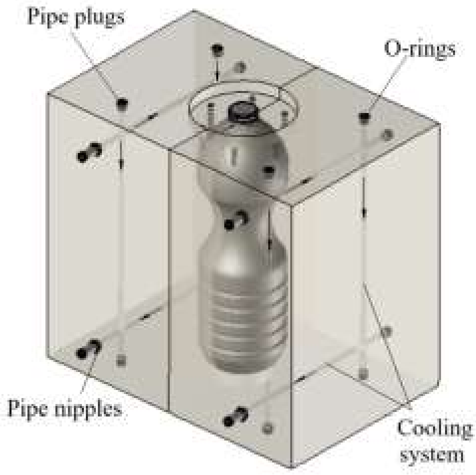


Figure 16: Cooling system

Overall, the model of the tool for the Injection Stretch Blow Moulding (ISBM) process is presented in figure 17.

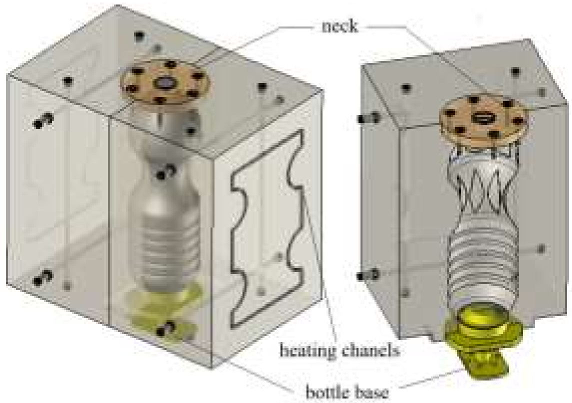


Figure 17. Tool for injection stretch blow moulding (ISBM)

5. Simulation of the Thermal Regime during Injection Stretch Blow Moulding

5.1 Position Regarding the Selection of Materials for ISBM Tooling

The primary materials used for the manufacture of tools for the production of PET bottles through Injection Stretch Blow Moulding (ISBM), must satisfy a specific set of operational, technological, and economic requirements. These include resistance to mechanical and thermal stresses, high corrosion and wear resistance, excellent polishability to achieve smooth and precise surfaces, as well as the ability to maintain high heat resistance and thermal conductivity. These characteristics are critical for producing high-quality PET bottles that conform to industrial standards of safety, functionality, and visual appeal.

The materials are selected according to these requirements and are specifically tailored to the functional demands of various tool components. The mechanical, thermal, and chemical properties of the chosen alloys ensure the reliability and durability of the tools throughout repeated heating and cooling cycles.

5.1.1 Steel 1.2083 for Blocks and Cores

Steel 1.2083 is well known for its exceptional corrosion and wear resistance properties, making it suitable for tools that must operate in aggressive environments. This steel is primarily used for the production of molds and cores for precise and transparent bottles, where high polishability and minimal surface roughness are critical requirements.

Chemical Composition of 1.2083: C: 0.38-0.45%, Cr: 12.5-14.0%, Ni: 0.3-0.8%, Mo: 0.5-1.0%, Mn: 0.3-0.8%, Si: 0.8-1.2%.

This combination of elements ensures high corrosion resistance, which is crucial for long-term use in environments with high temperatures and humidity, as is typical in the injection molding and stretching processes.

Mechanical Properties: Hardness: 42-48 HRC (hardened), Tensile Strength: ~1100 MPa, Ductility: Excellent, especially in the hardened condition.

Due to its good ductility and high hardness, 1.2083 offers wear resistance even after multiple cycles of use.

5.1.2 Steel 1.2343 for the Bottle Neck

Steel 1.2343 is a high-quality tool steel known for its ability to withstand high temperatures and thermal stresses. It is used in tools that need to maintain stable thermal conditions and handle the heat generated during the molding and cooling of PET material. Steel 1.2343 provides the necessary heat resistance and mechanical properties that are critical for producing precise and stable bottle necks.

Chemical Composition of 1.2343: C: 0.32-0.45%, Cr: 4.5-5.5%, Mo: 1.0-1.5%, V: 0.8-1.1%, Mn: 0.4-0.8%, Si: 0.8-1.0%.

The high content of chromium and molybdenum ensures excellent mechanical properties at elevated temperatures, while preventing rapid thermal wear and extending the service life of the tool.

Mechanical Properties: Hardness: 48-52 HRC (hardened), Tensile Strength: ~1100 MPa, Ductility: Good, suitable for prolonged periods of operation under thermal load.

5.1.3 Beryllium Copper UNS C17000 for the Bottle Base

Beryllium copper UNS C17000 offers exceptional thermal conductivity, which is particularly important for rapid cooling of the mold when forming the bottle bottom. Beryllium alloys are used in tools that must demonstrate high resistance to thermal fatigue while minimizing the risk of cracks or other defects occurring during repeated thermal cycles.

Chemical Composition of Beryllium Copper UNS C17000: Cu: Balance, Be: 1.8-2.0%, Fe: 0.20% max, Ni: 0.40% max, Pb: 0.02% max
Beryllium provides alloys with very high thermal conductivity and mechanical strength, making the material particularly suitable for tool components exposed to high temperatures and wear.

Mechanical Properties: Hardness: 150-200 HV (hardened), Tensile Strength: ~1000-1100 MPa, Thermal Conductivity: ~180-200 W/m·K (very high). These properties make it ideal for tool areas requiring rapid cooling and resistance to thermal fatigue.

The selected materials – steel 1.2083 for blocks and cores, steel 1.2343 for the neck, and beryllium copper UNS C17000 for the bottle base – provide an excellent balance of mechanical properties, heat resistance, thermal conductivity, and corrosion resistance. These materials ensure the durability of the tool, high precision during the molding of bottles, and long service life, which is critical for achieving efficiency and high-quality end products in the ISBM process.

5.2 Thermal Simulation Results and Analysis

To evaluate the thermal efficiency of the injection stretch blow moulding (ISBM) tool, a steady-state thermal analysis was carried out using SolidWorks Simulation. The purpose of this study was to assess the heating and cooling behaviour of the mould, particularly in regions critical for forming the PET bottle—namely the neck, body and bottle base zones.

5.2.1 Simulation Parameters

The simulation model includes embedded cartridge heaters within dedicated heating channels, as well as conformal cooling circuits placed in proximity to the contact surfaces of the cavity. Material properties were assigned according to the selected tool steels and copper alloy: 1.2083 for cores and cavity blocks, 1.2343 for the neck insert, and Beryllium Copper UNS C17000 for the base insert. Boundary conditions involved fixed temperature inputs for heaters (e.g. 110÷130°C) and convective heat transfer for the cooling channels, assuming water at 8–12°C.

5.2.2 Temperature Field Analysis

The results of the thermal simulation indicate a stable and uniform distribution of temperature across the ISBM mould surfaces. In the first scenario—Stretching—the temperature ranges from 115°C to 83°C, with a gradient of 32°C – figure 18.

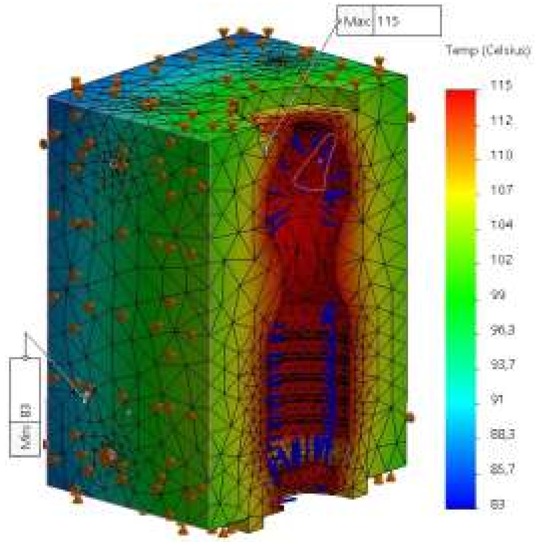


Figure 18: Temperature Field - Stretching

This relatively small temperature difference suggests that heat is evenly distributed throughout the mould, which is crucial for the consistent and uniform heating of the PET preform.

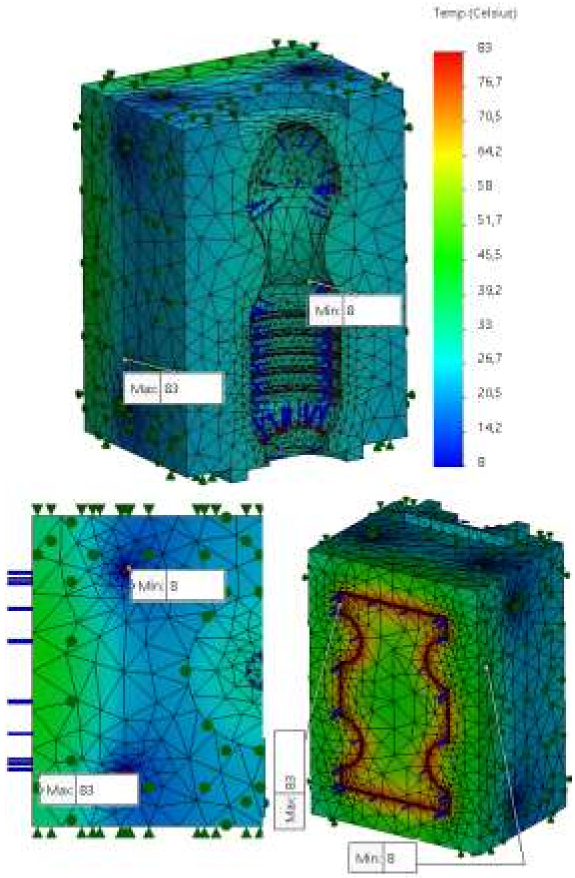


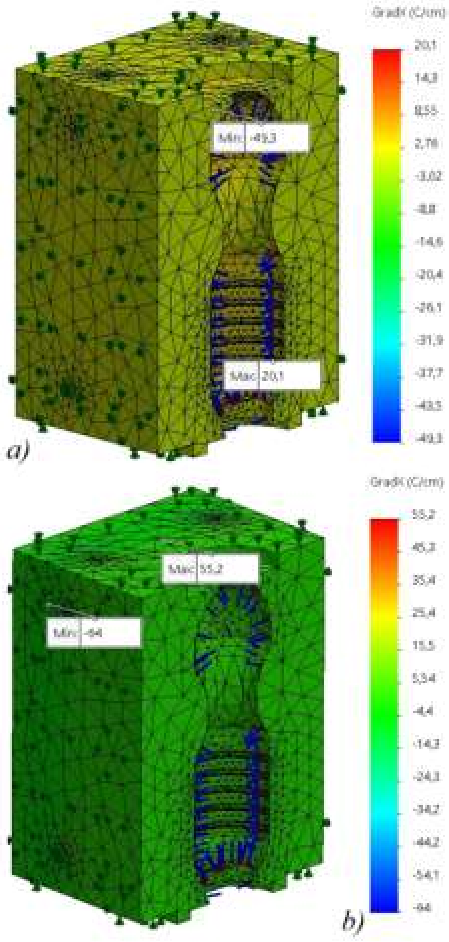
Figure 19: Temperature Field - Blow Molding

This uniformity is crucial for maintaining the quality and consistency of the preforms during the production process. In the second case, Blow Molding – figure 19, the temperature range is from 83°C to 8°C, with a temperature gradient of 75°C. Although the gradient is wider compared to the first case, it still falls within acceptable limits for the ISBM process.

The temperature difference may indicate more intense cooling towards the end of the cycle, which is common depending on the material and cooling time. Nonetheless, it is essential to monitor for any localised thermal stresses that could lead to defects in the final product.

5.2.3 Temperature Gradient Analysis

In the first case, Stretching – figure 20,a, the temperature range is from –49.3°C to +20.1°C, resulting in a temperature gradient of 69.4°C.

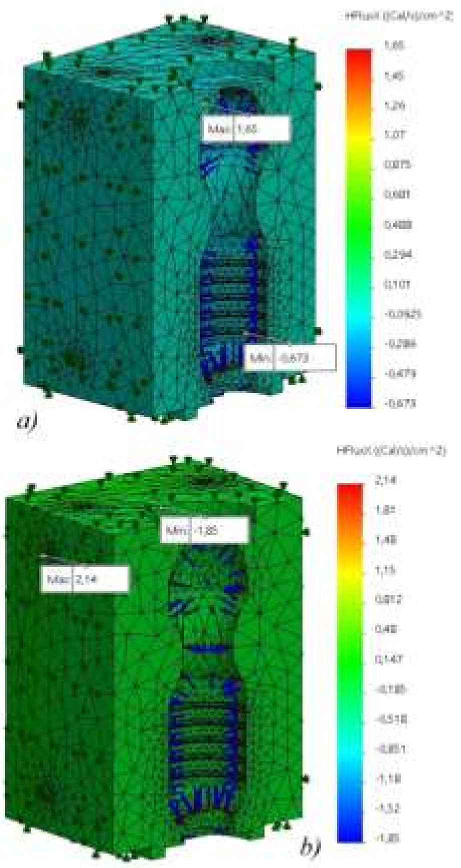


a) Stretching, b) Blow Molding
Figure 20. Temperature Gradient

Despite this relatively low gradient, it suggests that the heat distribution is well-optimised, with minimal temperature variations across the tool. This is ideal for stable heating, ensuring that the preform expands uniformly without inducing significant thermal stresses. In the second case, Blow Molding, the temperature range spans from –64°C to +55.2°C, leading to a gradient of 119.2°C – figure 20,b. Although this gradient is higher, it still remains within acceptable limits for the ISBM process. The temperature variation may be attributed to localised areas of intense cooling or heating, but with proper system balancing, these gradients should not cause significant defects.

5.2.4 Heat Flux Analysis

The thermal simulation also revealed a narrow and stable distribution of heat flux across the ISBM mould's functional surfaces. During Stretching (Figure 21,a), the heat flux ranges from −1.82 to +2.14 W/m^2 in the central areas of the cavity and core blocks. In the Blow Moulding phase (Figure 21,b), it ranges from −0.673 to +1.65 W/m^2 in peripheral regions, such as the neck and base inserts.



a) Stretching, b) Blow Molding
Figure 21. Heat Flux

These values are relatively low compared to typical heating or cooling zones, suggesting that the mould is in a steady-state thermal condition. Heat input from embedded cartridge heaters is effectively balanced by heat dissipation through conduction and cooling channels. Positive heat flux values correspond to zones of thermal input, particularly near heating channels, while negative heat flux values are associated with areas of active cooling or heat loss, typically through the tool structure or designated cooling circuits. The narrow gradient of heat flux suggests effective thermal management, which is vital for maintaining consistent preform heating and ensuring the optical clarity and dimensional stability of PET bottles.

6. Conclusions

A complete geometric and numerical model of a PET bottle has been successfully developed, enabling accurate simulation of the reheating and stretch-blow moulding stages.

The temperature field across the preform wall reveals a complex yet consistent distribution, underscoring the precision and effectiveness of the heating phase in preparing the preform for subsequent deformation.

Thermal flux analysis confirms the efficiency and balance of the heating system, with no localised thermal anomalies detected—demonstrating uniform energy distribution throughout the tool.

Simulation results validate the strong coupling between thermal and mechanical phenomena by confirming that pre-blow temperature distribution significantly influences wall thickness evolution.

The implemented simulation model proves to be a reliable tool for predicting and controlling the ISBM process, offering substantial potential for process optimisation, quality assurance, and defect prevention in industrial PET container manufacturing.

A comprehensive digital model of the PET bottle was developed, enabling precise simulation of the reheating and ISBM phases. Thermal analysis confirmed uniform temperature distribution and efficient heat management—both critical for achieving high-quality bottle formation.

Acknowledgements

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