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Stretch Blow Molding Laboratory Using Preform and 3D Printed Mold

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I am an engineering major with a mechanical concentration in the School of Engineering at Oral Roberts University. I will earn a Bachelor of Science in Engineering in May 2026. I have been drawn to science and math for as long as I can remember, and studying engineering has only furthered my desire for it. I am hungry for more and more knowledge so that I can impact the world for good.

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Jonathan Ophus has worked in several facets of the fabrication industry over the last 30 years. He developed several different pieces of equipment and processes for higher yields in the precious metals industry. In the construction industry, he designed equipment and new processes for delivery of 50% stronger concrete to be used in structural applications. He enjoys teaching and working with young people. He currently works with students and faculty at Oral Roberts University's School of Engineering as a machine shop technician.

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Manuel Yanez is a 22-year-old mechanical engineering student at Oral Roberts University. Raised primarily in Tulsa, Oklahoma, and spending a significant portion of his teenage years in Mexico, Manuel gained a unique perspective on the technological and engineering disparities between the two countries. This experience fueled his passion for engineering and design, sparking a deeper curiosity about how innovation can transform communities. His bilingual background and practical experience in construction and FRC Robotics influence his engineering approach, blending creativity with technical expertise.

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Stretch Blow Molding Laboratory Using Preform and 3D Printed Mold

Abstract

This project introduces a stretch blow molding laboratory designed to enhance student understanding of manufacturing processes, material behavior, and simulation techniques. The lab was implemented as part of an undergraduate engineering course, aligning with ABET Student Outcome 1 by integrating theoretical knowledge with hands-on application. Students explored the stretch blow molding process by reverse-engineering a commercial Dr. Pepper bottle, conducting 3D scanning, CAD modeling, and 3D printing to fabricate a mold for experimentation.

The primary educational objective was to provide students with direct experience in designing, analyzing, and evaluating manufacturing processes. Students applied core engineering concepts, such as thermoplastic deformation, wall thickness distribution, and material properties, while comparing experimental results with Ansys Polyflow simulations. Using an Olympus Magna Mike 8500 handheld magnetic thickness gage, students measured the wall thickness profiles of the molded bottles and assessed deviations from the original product, identifying key factors influencing thickness distribution.

This lab was conducted over a structured timeframe with faculty guidance, enabling students to iteratively refine their approach while developing critical engineering skills. The findings from this project contribute to a repeatable laboratory module that can be used in future coursework, providing students with exposure to simulation-driven design, experimental validation, and process optimization.

Assessment of student learning included progress reports, final reports, and direct comparisons between experimental and simulation results, ensuring measurable knowledge gains. By emphasizing engineering analysis, problem-solving, and hands-on experimentation, this project offers a practical, scalable educational framework for integrating advanced manufacturing concepts into the undergraduate curriculum.

Introduction

Engineering education increasingly emphasizes experiential learning to enhance student comprehension of complex manufacturing processes. This study presents the development of an undergraduate laboratory experiment on stretch blow molding, designed to reinforce core engineering principles while providing students with hands-on experience in polymer processing. The experiment integrates theoretical instruction, computational modeling, and physical experimentation, aligning with ABET Student Outcome 1, which focuses on applying engineering principles to solve complex problems [1].

Educational Objectives and Curriculum Integration

The primary objective of this laboratory is to provide students with a comprehensive understanding of stretch blow molding by enabling them to apply fundamental concepts in polymer rheology, thermodynamics, and mold design. Specific learning outcomes include the ability to:

1. Analyze polymer flow and thermal properties to understand material behavior during processing [2].
2. Design and fabricate 3D-printed molds for use in stretch blow molding experiments [3].
3. Evaluate process parameters such as air pressure and temperature to optimize final product quality [4].
4. Utilize computational simulations (e.g., Ansys Polyflow) to model polymer deformation and compare results with experimental findings [5].
5. Diagnose and troubleshoot defects such as thin walls and incomplete inflation [6].

This laboratory is integrated into a senior-level manufacturing processes course, complementing traditional lecture-based learning with practical applications. The experiment spans multiple sessions, including an introduction to theoretical principles, hands-on molding trials, computational simulations, and data analysis.

Assessment and Student Learning Evaluation

To measure student learning, the experiment employs a structured assessment framework:

- Lab report requiring students to document experimental procedures, analyze data, and justify design choices.
- Progress reports where students communicate findings and propose process improvements.

Theoretical Background

Stretch blow molding involves heating a thermoplastic preform and using compressed air to expand it within a mold. Understanding the underlying principles is essential for optimizing the process:

- Polymer Rheology: Viscosity influence material deformation. Excessive viscosity can hinder uniform expansion [7].
- Thermal Behavior: Uniform heating ensures consistent deformation, while improper heating can lead to nonuniform thickness or defects [8].
- Controlled Inflation: Air pressure and blow time must be optimized to prevent thin walls [9].
- Mold Design Considerations: Geometry, cooling channels, and material selection impact product quality. 3D-printed molds provide flexibility but have different thermal properties than metal molds [10].

By combining hands-on experimentation with computational analysis, this laboratory enhances student engagement and bridges the gap between theoretical knowledge and real-world applications. Future iterations of this experiment will incorporate student feedback to further refine learning outcomes and instructional methods.

Experimental Set-Up, Implementation, and Procedure

Bottle Forming Process

The primary objective of this experiment was to determine the optimal temperature and pressure conditions for forming PET plastic bottles. The three main process variables were:

- Preform Temperature: PET exhibits glass transition temperatures between 69°C and 85°C.
- Applied Pressure: Determines bottle expansion characteristics.
- Duration of Heat Exposure: Ensures even heating without degradation.

Heating Method Selection

The experiment evaluated three heating methods:

1. Oven Heating: The machine shop oven, Figure 1, was initially considered, but excessive heating led to uneven temperature distribution, causing bulges and white spots in the molded bottles.

Figure 1. Oven

2. Heat Guns: Rotating multiple heat guns around the preform resulted in surface heating only, leading to inadequate core temperature distribution and excessive heating time.

3. Antifreeze Bath - Final Method: A beaker filled with antifreeze was heated using a hot plate with a magnetic stirrer, Figure 2. This method provided uniform temperature distribution, maintaining the preform within the optimal temperature range.

Figure 2. Antifreeze on heating plate

Temperature and Pressure Optimization

The initial trials focused on finding the correct temperature and pressure conditions. Table 1 summarizes the key findings:

Table 1 The first four trials using the antifreeze heating method

Test	**Temperature (°C)**	**Pressure (psi)**	**Observations**
1	90	100	Small expansion, rapid cooling
2	105	100	Plastic turned white, exceeding glass region
3	100	125	Excess pressure, bottle exploded
4	95-100	110	Ideal expansion, two-liter bottle shape achieved

Figures 3-5 illustrate the results of these trials, showing how excessive pressure led to failure and how optimal conditions yielded a well-formed bottle.

Figure 3. Tests 1 and 2

Figure 4. Test 3

Figure 5. Test 4

To control the expansion, a pressure regulator, Figure 6, was used, and a hose attachment with a clamp, Figure 7, minimized air loss. Temperature measurements were taken using an infrared thermometer, Figure 8.


Figure 6. Pressure regulator


Figure 7. Hose attachment with clamp


Figure 8. Temperature reading

3D Printed Mold Integration

After optimizing temperature and pressure, a 3D-printed mold was introduced to refine bottle shape and consistency. Using the ELEGOO Neptune 4 Max printer, the mold, Figures 9-10, was designed with air escape channels to prevent trapped air from resisting expansion.


Figure 9. Front view of mold half


Figure 10. Isometric view of mold half

The first four trials with the mold, Figure 11, showed:

- Test 1: Best shape and groove formation.
- Tests 2-4: Variations in pressure and temperature led to inconsistent results, including overheated plastic (white discoloration) and air leakage issues.

Further refinements, including enlarging mold vent holes and elevating the base, improved bottle formation. The final process setup, Figure 12, ensured precise and repeatable bottle production.


Figure 11. First four tests with mold


Figure 12. Pressurizing preform - modified adapter

Conclusion and Lessons Learned

The experiment successfully demonstrated fundamental engineering principles related to thermoplastics and fluid dynamics. Students engaged in iterative problem-solving to optimize heating and pressurization techniques. Key takeaways included:

- The importance of even heating in thermoplastic molding.
- The role of pressure regulation in ensuring uniform expansion.
- Practical applications of 3D printing in manufacturing process optimization.

By refining the lab procedure, this experiment enhances engineering education by providing hands-on experience with real-world manufacturing challenges. Future iterations will incorporate additional assessment metrics to quantify student knowledge gains more effectively.

Ansys Polyflow Simulations

The integration of Ansys Polyflow simulations [11] into the lab curriculum provides students with an opportunity to apply theoretical knowledge in computational fluid dynamics to a practical engineering problem. This simulation-based approach helps students visualize material behavior during the blow molding process, reinforcing key concepts in polymer flow and mechanical deformation.

Through the simulation, students analyze the thickness distribution of the final bottle, compare it to both the original soda bottle and experimentally formed bottles, and assess variations in material properties. This process aids in identifying weak spots and inconsistencies, allowing students to refine experimental parameters based on computational predictions. By linking theoretical modeling to hands-on experimentation, students gain a deeper understanding of how simulation tools can enhance manufacturing processes.

The educational objective of incorporating Ansys Polyflow is to strengthen students' abilities in computational analysis, data interpretation, and engineering decision-making. The lab exercises challenge students to validate their experimental findings using simulations, fostering critical thinking and problem-solving skills. Additionally, this approach underscores the importance of simulation-driven design in modern engineering, preparing students for industry applications where digital prototyping is essential for process optimization.

By emphasizing simulation validation and real-world application, this section aligns with the broader learning goals of the course, ensuring students not only engage with computational tools but also understand their role in improving experimental accuracy and product quality.

Student Assessment

The primary objective of the laboratory is to enable students to apply core engineering principles to a real-world manufacturing process. Student learning outcomes are aligned with ABET Student Outcome 1, focusing on the ability to identify, formulate, and solve complex engineering problems. Assessment is multifaceted and includes:

- Final Report and Demonstration: Students submit a comprehensive report—including an abstract, theoretical background, methodology, results, and reflections—demonstrating how they connected course concepts to their experimental design.

- Monthly Progress Reports: Over the semester, students submit three progress reports that document iterative improvements, troubleshooting efforts, and adjustments made during the experiment. These reports require explicit connections between theoretical principles and experimental observations.

- Practical Performance: Faculty directly observe the hands-on laboratory sessions. Students are evaluated on their ability to design 3D printed molds, execute the blow molding process, and accurately measure outcomes using provided instrumentation. This performance component reinforces the integration of theory and practice.

This comprehensive assessment framework ensures that the lab not only enhances technical skills but also fosters critical thinking and problem-solving, thereby supporting broader curricular outcomes.

Student Involvement

Active student engagement is central to the laboratory experience, ensuring that learners are directly involved in every phase of the project:

- Collaborative Design and Fabrication: Students use CAD software to design 3D printed molds, applying theoretical concepts to create practical solutions. Faculty mentors provide targeted feedback during design reviews, ensuring that student designs reflect both innovation and sound engineering principles.

- Experimental Execution: Students conduct the blow molding process by heating PET preforms to the specified temperature range and applying controlled air pressure using standardized equipment. They record real-time data on variables such as temperature and pressure, which informs subsequent adjustments and iterative refinements.

- Data Analysis: After the experiment, students analyze the quality of the molded products by comparing measured dimensions and wall thickness profiles with theoretical predictions. They reflect on discrepancies and propose process improvements.

This structured, hands-on involvement helps students bridge the gap between classroom theory and industrial practice while developing teamwork, communication, and critical analysis skills.

Student Recommendations

Based on feedback from the initial implementation, several recommendations have been proposed to further enhance the educational value of the laboratory:

- Enhanced Pre-Lab Instruction: Introduce a focused session that reviews the core principles of blow molding, emphasizing the importance of maintaining optimal temperature and pressure ranges. This session should clearly outline the scientific rationale behind the process.

- Structured Procedures: Provide students with a concise, step-by-step experimental protocol that highlights key checkpoints for data collection and decision-making. This will help streamline the iterative process and reduce potential frustration during trial-and-error phases.

These recommendations aim to enhance clarity, promote reflective learning, and ensure that the laboratory experience is educationally robust.

Benefits of Reproducing this Project in a Classroom Setting

Integrating the stretch blow molding laboratory into the curriculum offers significant educational and practical benefits:

- Integration of Theory and Practice: The laboratory experience allows students to apply fundamental engineering principles—such as thermodynamics, polymer science, and process control—in a real-world context, thereby solidifying their understanding of complex concepts.

- Development of Essential Engineering Skills: Students gain hands-on experience with modern design tools (e.g., CAD and 3D printing) and experimental techniques. This practical exposure not only enhances technical proficiency but also prepares them for industry challenges.

- Iterative Problem-Solving and Critical Thinking: The experiment is structured around iterative design and troubleshooting, mirroring professional engineering practices. This process fosters resilience, adaptability, and a systematic approach to solving complex problems.

- Enhanced Collaborative Learning: Working in teams and receiving ongoing faculty guidance promotes effective communication, teamwork, and peer learning—skills that are essential for success in engineering careers.

Overall, reproducing this project in a classroom setting not only provides a rich, hands-on learning experience but also bridges the gap between theoretical instruction and practical application, thereby preparing students for future professional success.

Results

The final experimental results demonstrate that the optimized laboratory procedure produces a bottle that closely approximates the profile of the original soda bottle while providing valuable insights into process optimization. Figure 13 presents a comparison of thickness profiles obtained from the first four tests with that of the original bottle. In these experiments, each bottle's thickness was measured along a consistent vertical path using a high-precision Magna Mike 8500 hall effect thickness gauge. The measurements indicate that the flat side of the bottles maintained an average thickness of 0.2 mm across all tests, reflecting a degree of consistency in the overall bottle shape.

Closer analysis of the data reveals variations in the bottom contours of the bottles. In Tests 3 and 4, the appearance of white spots on the bottom—indicative of exceeding the optimal glass temperature—resulted in reduced expansion and consequently thicker regions, as reflected in the lighter blue and green data. By contrast, Tests 1 and 2, while exhibiting more uniform thickness across the bottle's profile, did not achieve the same degree of expansion at the bottom as observed in the original soda bottle. This discrepancy appears to be linked to insufficient material distribution or suboptimal heating during the process.

The results underscore the importance of precise temperature control and material consistency in achieving the desired bottle geometry. The data from the original bottle further illustrate that a thicker bottom is essential for replicating the commercial product's design. For improved accuracy in future iterations, it is suggested that the blow molding process be adjusted to enhance the expansion of the bottle's bottom, potentially by using a thicker preform or modifying the pressure application during the process. These findings not only provide a clear basis for refining the experimental procedure but also offer a tangible learning outcome for students as they analyze and relate the experimental data to the theoretical principles discussed in the course.

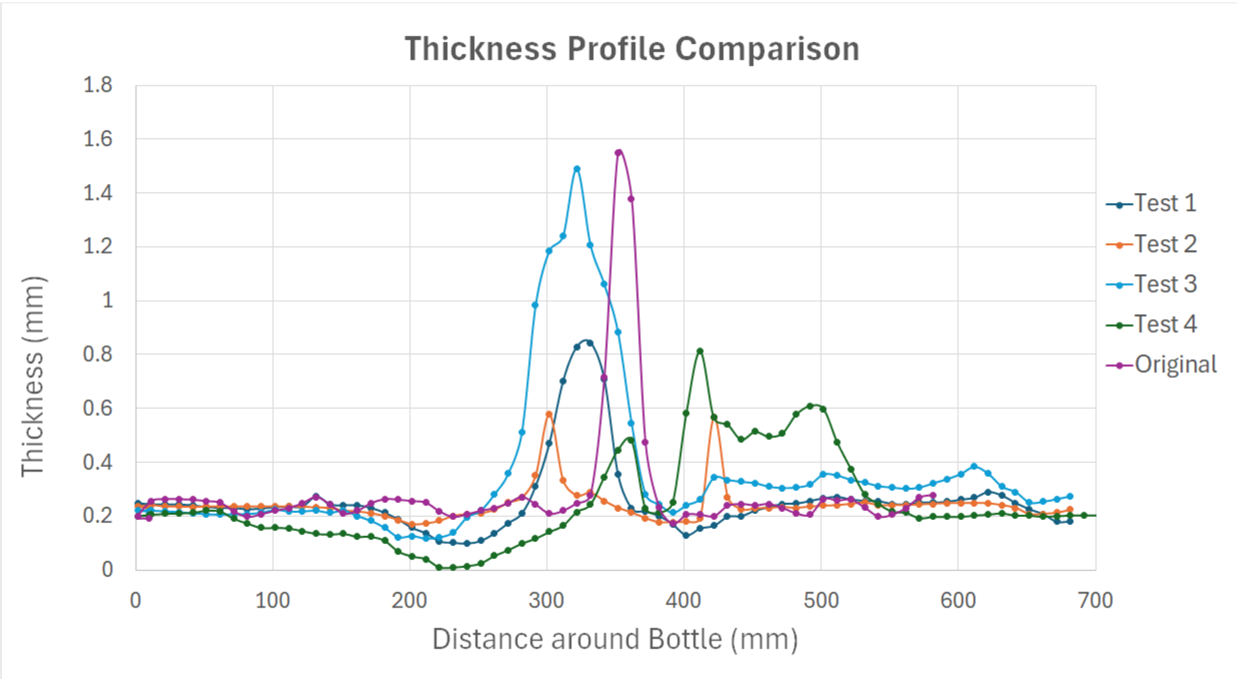

Figure 13. Thickness profiles

Study Design and Faculty Guidance

The blow molding study was specifically designed as a semester-long laboratory experience for senior-level engineering students. The study was structured to provide an immersive learning environment that combined rigorous theoretical instruction with hands-on practical application. At the beginning of the semester, students participated in a dedicated preparatory session where they reviewed key principles such as polymer rheology, heat transfer, and pressure control, ensuring they had the foundational knowledge required for the experiment.

Over the course of the semester, students engaged in iterative experimentation with PET preforms and 3D-printed molds. They conducted a series of tests and each experiment was documented through monthly progress reports, which detailed the modifications made, challenges encountered, and the resulting data from each trial. This iterative process was central to the study, as it allowed students to apply theoretical concepts to real-world challenges and refine their approach based on experimental feedback.

Faculty guidance played a role throughout the study. The instructor provided continuous support through mentoring sessions, during which he offered targeted feedback on design iterations and troubleshooting strategies. Additionally, the faculty member conducted design reviews and one-on-one consultations to ensure that students were effectively connecting their classroom knowledge with the practical aspects of the blow molding process. This structured guidance not only helped maintain the integrity of the experimental process but also ensured that the study directly contributed to the students' ability to identify, formulate, and solve complex engineering problems, in alignment with ABET Student Outcome 1.

Discussion

The findings of this project underscore both the technical feasibility of using 3D-printed molds for blow molding and the significant educational benefits of integrating this process into the engineering curriculum. By standardizing the experimental procedure to use a PET preform heated to 95–100°C under a controlled pressure of 110 psi, students were able to observe firsthand the delicate balance between thermal dynamics, material behavior, and pressure control.

Although the glass temperature exceeded initial expectations by 15–20°C, this outcome provided an important learning opportunity for students to analyze how material composition and environmental conditions affect process parameters. The discrepancies observed in the bottle bottom expansion, largely attributed to challenges in temperature distribution and airflow management, highlighted the critical role of process optimization in manufacturing. These technical challenges were directly linked to theoretical concepts, such as polymer rheology and heat transfer, reinforcing the importance of precise control in achieving desired manufacturing outcomes.

Furthermore, the iterative nature of the project encouraged students to reflect on their experimental design, adjust parameters based on observed data, and propose practical solutions—thereby strengthening their problem-solving and critical-thinking skills.
The project also revealed several areas for further improvement, including ensuring more consistent temperature distribution, addressing material variability in preforms, and designing more robust pressure attachments. Each of these challenges offered valuable insights that were directly connected to the learning outcomes of the course. By understanding these limitations, students were better prepared to engage in future design iterations and to apply theoretical knowledge to real-world manufacturing problems. This alignment of experimental practice with curriculum objectives ensures that the laboratory serves as a comprehensive educational tool, bridging the gap between theory and industrial application.

Conclusion

This project demonstrated that a well-designed laboratory experiment, centered on the use of 3D-printed molds for blow molding, can effectively integrate theoretical concepts with practical application. Students were able to design, fabricate, and test a manufacturing process that not only replicated key aspects of a commercial soda bottle but also provided critical insights into the effects of temperature, pressure, and material properties on product quality. The hands-on experience facilitated a deeper understanding of material science, thermal dynamics, and process engineering, all of which are essential components of modern manufacturing curricula.

By linking the experimental process to educational outcomes, the project not only enhanced technical proficiency but also fostered critical thinking, innovation, and effective problem-solving skills. The successful implementation of this laboratory underscores its potential as a model for future educational endeavors in engineering, providing a dynamic and engaging learning environment that prepares students for the challenges of the manufacturing industry.

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Appendix 1: Lab Manual for Blow Molding Project

Manufacturing Processes
Soda Bottle Blow Molding Lab

Figure 1a) Section View of Preform in Mold

Figure 1b) Section View of Finished Bottle

Part 1: Forming A Bottle from a Preform with an Existing Mold

Introduction

1. The following laboratory experience is developed to provide the student with an introduction to the process of manufacturing plastic bottles from preforms. Students will have the opportunity to heat preforms and use air pressure to blow them into a mold, transforming them into fully formed soda bottles. This hands-on experience will allow students to design, fabricate, analyze, and test the parameters involved in this manufacturing process, enhancing their understanding of material properties and thermal dynamics, see Figure 1 for detailed illustrations of the starting and ending product.

In the blow molding process for soda bottles, understanding the thermal properties of PET (Poly Ethylene Terephthalate) is crucial. PET has a glass transition temperature (T.g) ranging from 69°C to 85°C and a melting temperature (T.m) between 240°C and 270°C. During blow molding, preforms are heated to a temperature above their T.g but below their T.m, specifically in the range of 90°C to 105°C. This temperature range ensures the plastic becomes soft and pliable without melting, allowing it to be stretched and blown into the final bottle shape within a mold. If the temperature is too low, the plastic may not stretch adequately, leading to weak spots. Conversely, if the temperature is too high, the plastic could melt or degrade, compromising the bottle's integrity. Maintaining the correct temperature is essential to ensure the material flows properly and forms a uniform, defect-free bottle, making this process both efficient and effective.

<u>Material List</u>

2. In this lab the following instruments and material is used: thermocouple, C-clamps, wire mesh, 3D printed bottle mold, sharpies, beaker with antifreeze and hot plate, air hose and fittings, 24.7 g PET bottle preforms, IR thermometers, rubber adapter, ring clamps, fume extractor.

Figure 2a) Thermocouple thermometer

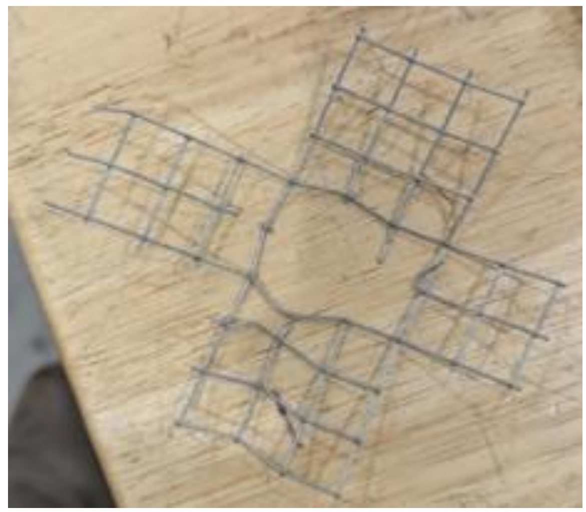


Figure 2b) Wire mesh

Figure 2c) Mold

Figure 2d) Antifreeze and hot plate

Figure 2e) 24.7 g Preform

Figure 2f) IR thermometers.

Figure 2g) Rubber adapter

Figure 2h) Ring clamps

<u>Bottle Forming Procedure</u>

3. Make sure to use safety glasses at all times and other PPE when necessary. Gloves will be used for the person moving the preform between the heating station and the mold. Earplugs or earmuffs are required for all in the vicinity during the actual pressurization of the preform. Take pictures of the equipment in front of you on the table that is being used in the blow molding lab.

Figure 3 Equipment used in laboratory

4. Set up the air system for the laboratory. The air compressor should be set to 125 psi to account for losses in the pipes. You will need a pressure regulator set to 110 psi connected to a flexible air hose (shown in yellow) which will be connected to the rubber adapter (Figure 4). This setup allows for the best control over pressure and airflow. The rubber adapter will be pressed and held in the preform mouth once the preform is heated and ready to be expanded.

Figure 4. Pressure regulator with gauge

5. Pour the antifreeze into a 500 mL beaker to about a centimeter from the top of the beaker. <u>If you overfill the beaker, the antifreeze will spill over when the preform is inserted into the beaker. If you underfill, you won't heat up the entirety of the preform shank.</u>

Figure 5 Filling beaker with antifreeze

6. Adjust the fume extractor if necessary to ensure that any toxic fumes are properly contained.

Figure 6. Ventilation for lab

7. Start to heat up the ethylene glycol (antifreeze) on a hot plate that has magnetic stirring capabilities. Set the temperature setting of the hot plate to a preheat temperature of about 300 degrees Celsius. Set the stir level to around half of the maximum. If you stir too rapidly, the vortex formed may make the antifreeze spill or lose convection contact from the upper portion of the preform shank. If you stir too slowly, you will not distribute the heat uniformly, leading to a non-uniform temperature profile. Insert the probe of the thermocouple into the antifreeze and secure it with the ring clamp.

Figure 7. Thermocouple thermometer probe in antifreeze

8. When the temperature of the antifreeze reaches a temperature between 120 and 125 degrees Celsius, turn the temperature knob down to about 235 degrees Celsius. If your hot plate does not have a digital display, you can measure surface temperature of the plate and use that as reference.

Figure 8. Adapter and preform

9. At this point, you will insert the preform held in the fluid by the wire mesh (Figure 9a). Insert the rubber adapter into the perform, then place the preform into the fluid. The preform should be submerged up to the neck ring of the preform (see Figure 9b) but should not contact the stirring magnet or the bottom of the beaker. This ensures that all the material of the preform shank is heated. It is crucial that the preform only be submerged up to the neck ring. The threads of the preform must stay cool in order to securely attach to the adapter and properly fit in the 3D-printed blow mold stand.

Figure 9. Submerging preform in antifreeze up to neck ring

10. The preform may exceed the glass temperature in less than 2 minutes, so make sure to check the temperature of the preform (not the fluid) using both IR thermometers about every 20 seconds. You need to use the towel to wipe the fluid off the preform before measuring the temperature, or the hotter fluid will interfere with the IR reading. It should take around a minute of submersion to heat up the preform to the target temperature of 98 degrees Celsius. (Possible range of 95 to 105 degrees, but 98 is optimal).


Figure 10. Measuring temperature of preform

11. When the preform has a temperature of between 95 and 105 degrees Celsius (aim for 98) remove the preform from the fluid and quickly transfer it to the mold. Slide the mold halves shut, clamp the bottom and top of the mold, attach the air hose to the adapter, and open the airflow for a duration of about 5 seconds while firmly holding the rubber adapter in the preform. Disconnect the clamps, spread the mold open, and remove the bottle. If the preform didn’t expand and is colored white on any part of the plastic, then it has exceeded the glass temperature range and will not mold properly with the applied pressure.

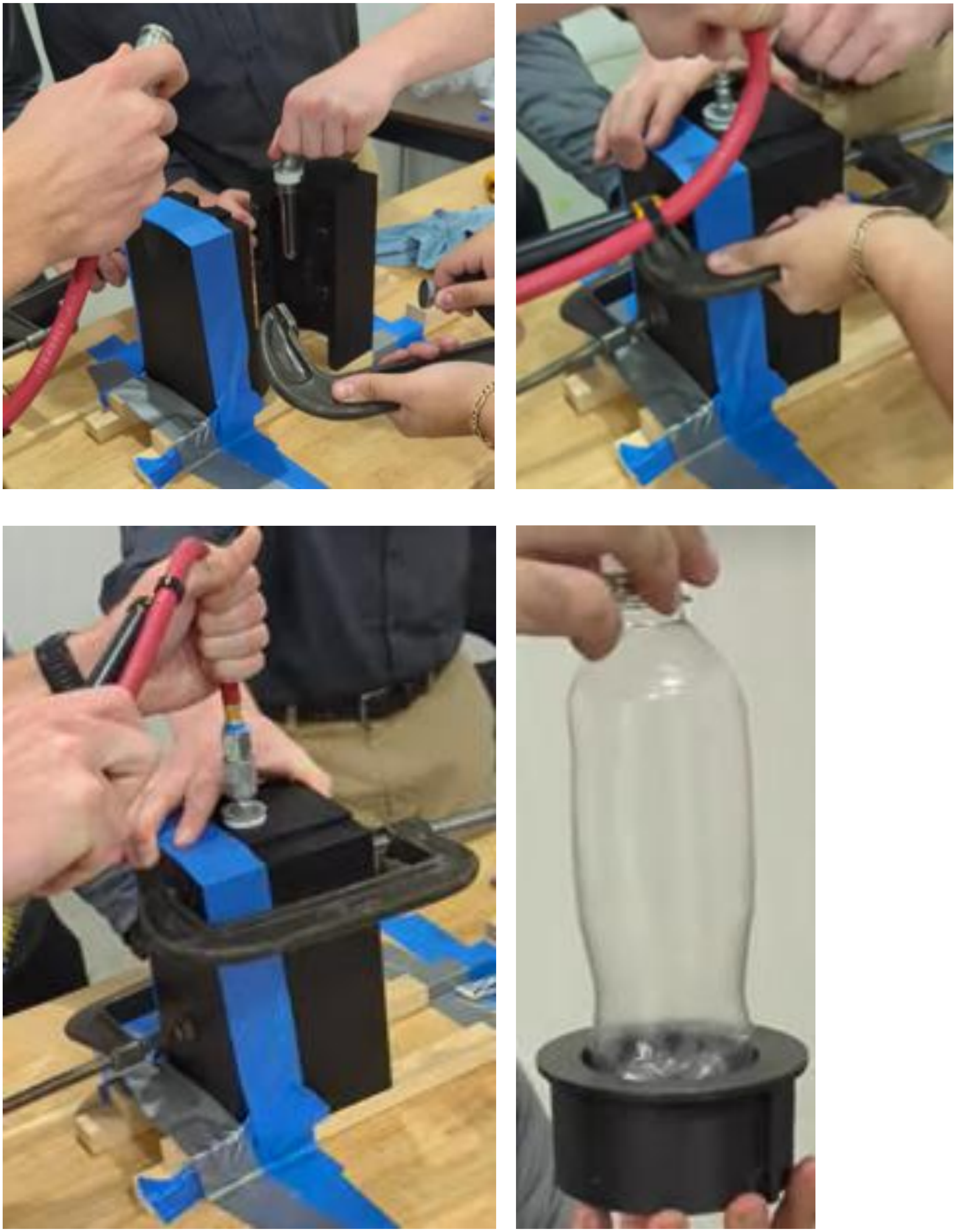


Figure 11. Blow molding process

12. Troubleshooting - If the bottle did not properly expand, there are several possible reasons:

Low Pressure
1. Make sure the adapter does not leak significantly
2. Make sure the air compressor is providing at least 120 psi

Incorrect Preform Temperature Range
1. The preform may have been "too cold" to expand (below the glass temp)
2. The preform may be too hot (starting to change chemical properties). This can be observed by the preform starting to turn white:

Figure 12 Examples of over-heated preforms

Inability to Evacuate Atmospheric Air in Mold
1. Make sure there are adequate holes in the bottom of the mold to permit the air to be displaced by the expanding bottle.

<u>Thickness Profile Measurement Using Magna-Mike Thickness Gage</u>

13. At this step you will measure the thickness profile of your finished bottle and compare it to a standard soda bottle of comparable mass/shape. Take the soda bottle, a Sharpie, and a ruler to the Magna-Mike device next to the computers in the heating area.

Using the sharpie, mark a strip of white paper with marks every 10 mm (1 cm) using the ruler. Use this paper as a flexible ruler to wrap around the bottle to accurately mark every 10 mm. Use the separate "Magna-Mike Lab Tutorial" to measure the thickness at each mark. Take a picture of the marked bottle and Magna-Mike.

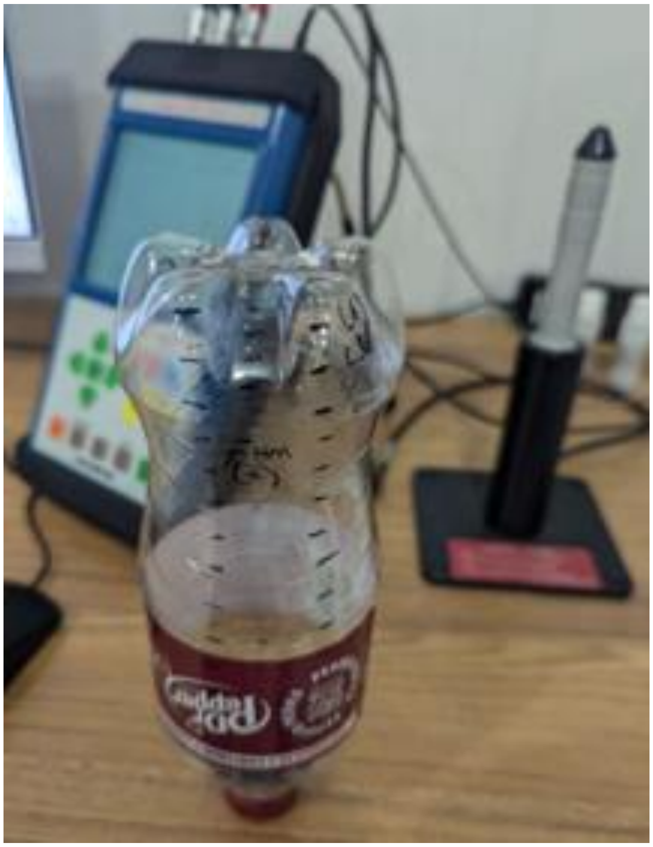


Figure 13. Original soda bottle with marks

14. Repeat step 13 for a standard soda bottle and compare your thickness profiles (show Excel graphs).

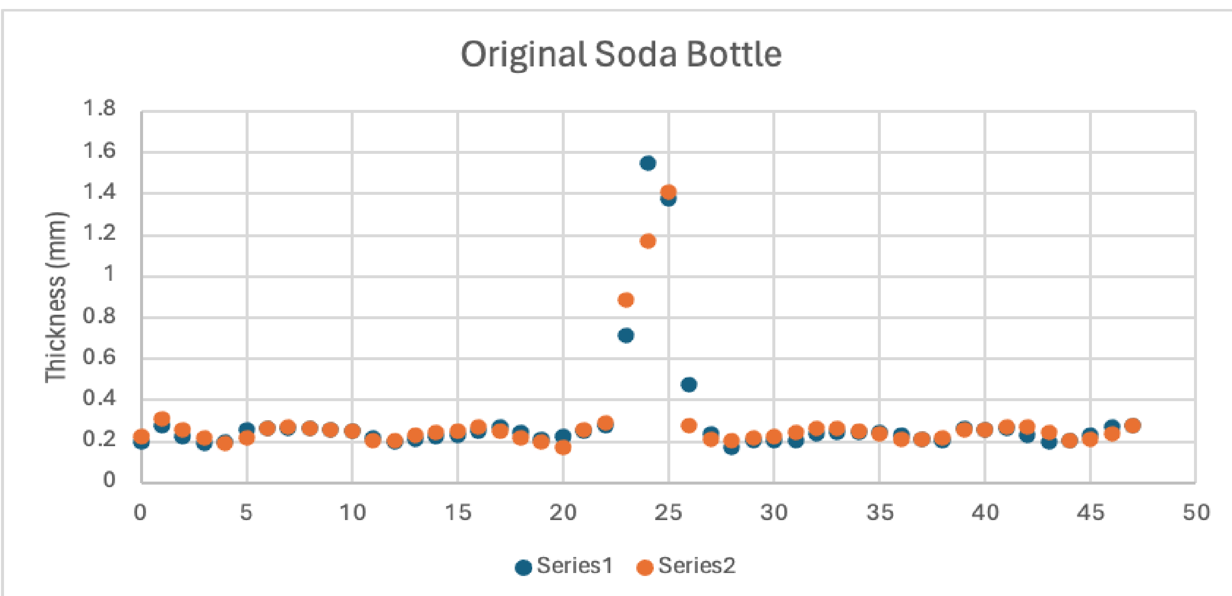


Figure 14a) Original soda bottle measurements

Figure 14 is the original soda bottle thickness measurements. Series 1 and 2 represent two different paths around the bottom of the bottle as shown in Figure 13. Series 1 begins on the lower contour and ends on the higher one, whereas series 2 takes the opposite path, going from the higher contour to the lower one.

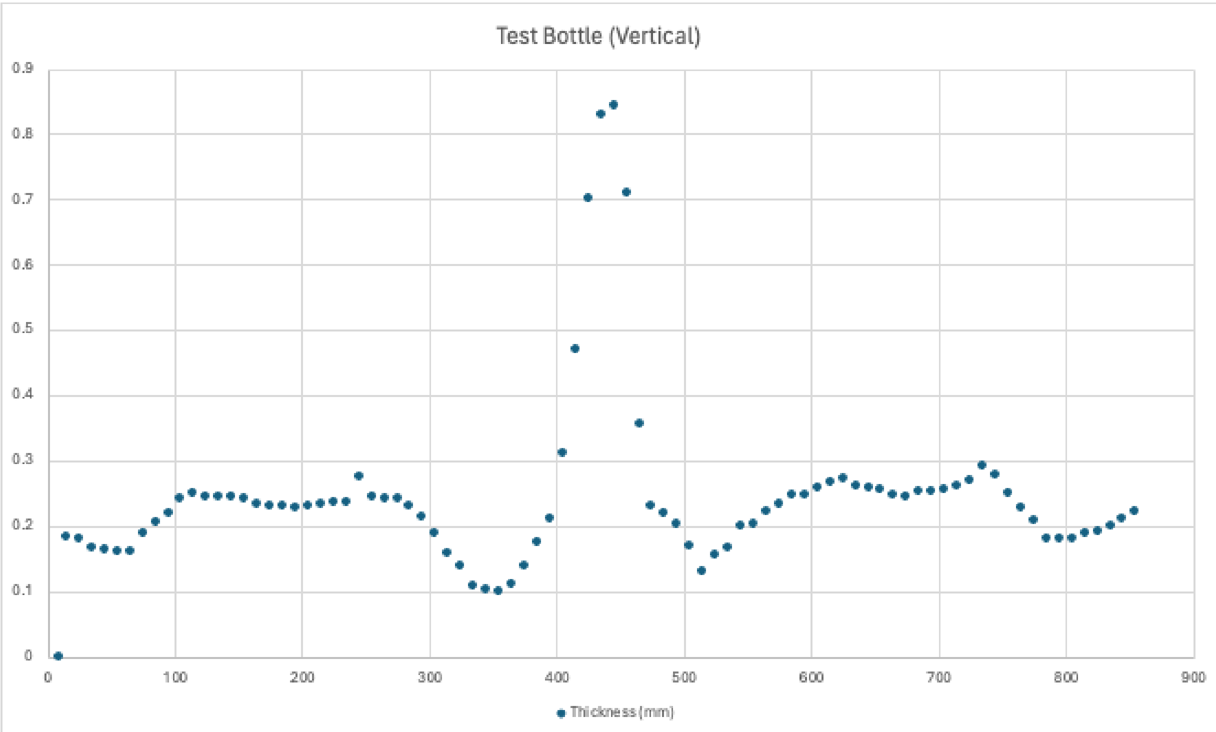


Figure 14b) Test bottle thickness

The scatter plot above in Figure 14b) shows the vertical thickness measurements going around the bottom of the bottle. The vertical axis shows thickness and the horizontal axis is distance around the vertical path of the bottle. The thickness profiles was measured from the vertical path around the bottle.

<u>Part 2: Creating a Customized Mold for the Blow Molding Process</u>

<u>Introduction</u>

This part of the laboratory is intended to aid students in the creation of a new mold from an existing bottle. It walks students through the process of priming their bottle, scanning the bottle into a mesh file, and converting that convex part into a concave mold which can be easily manufactured on a 3D printer.

<u>Priming the Bottle for 3D Scanner</u>

15. Take the bottle you intend to use for the new mold to the spray paint booth in the back of the Machine Shop. Place the soda bottle upside down on the bottle stand. Take a picture.

Figure 15. Soda bottle resting on stand

16. There will be an AESUB permanent 3D scanning spray can in the booth. Turn on the paint booth fan using the switch to the right of the booth and shake the spray can. Place the soda bottle and stand in the paint booth and use the spray can to coat the soda bottle from the bottom of the bottle to the neck. This will take several coats to make the whole bottle as white as possible. Take a picture after the final coat is applied and turn off the fan.

Figure 16. Soda bottle in spray paint booth

Move the soda bottle and stand in a safe place for it to dry which will take about 24 hours. Once dry, the soda bottle is ready to be scanned by the 3D Scanner in the fluid mechanics lab.

Bottle Scanning Procedure

17. Carefully take the painted soda bottle to the laboratory housing the 3D scanner and software, making sure not to smudge the paint. You will vary the positions of the bottle in order to scan a complete 3D scan of the bottle. You may scan approximately six of the eight steps with the bottle on its side, but you will need to scan at least one of the steps with the bottle upright, and one upside down (see Figure 17).

Figures 17. Scanning the bottle in various positions

18. Use the detailed lab manual “Manufacturing Processes –3D Scanning of Hand Casting” to scan and prepare a 3D mesh (.stl file) of the bottle. The object being scanned will be different, but the steps for scanning are the same. As bottle has already been primed, skip to “Calibration of 3D Scanner” if scanner has not recently been calibrated. If another lab team has recently calibrated the scanner, you may skip to “Scanning of Hand Casting.”

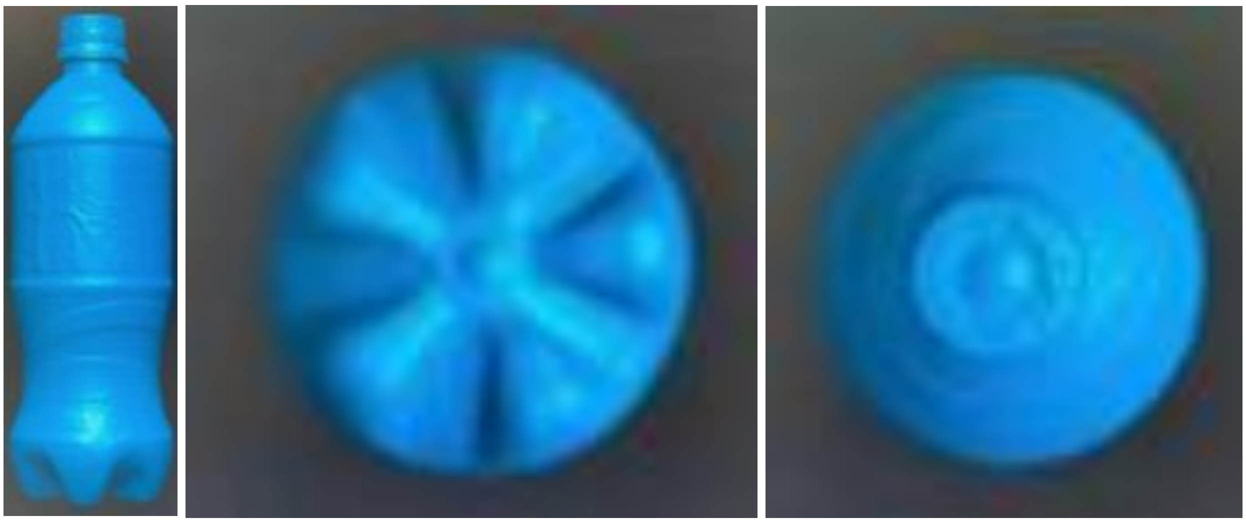


Figure 18. Front, bottom, and top views from 3D scan of original bottle.

Modeling of the Mold in SOLIDWORKS for Printing

19. Begin by obtaining the 3D mesh (.stl file), created using the 3D scanner. This file will initially produce only a complex shell of the bottle which will not be suitable for the following process. To convert the file to a usable form you can first download the free software “MeshLab”. In MeshLab, you can reduce the file size (in terms of triangles creating the object) to somewhere between 50,000 and 100,000 triangles which will make the file easier to work with and should create no noticeable difference in the mesh as it began with extremely high precision. Following this, you can download the free software “FreeCAD”. In FreeCAD you can convert the stl into a solid which can now be imported into SOLIDWORKS.

Open the file in SOLIDWORKS.

Scale bottle by a factor of 1.004 to account for shrinkage in blow molding using scale feature.

Figure 19. 3D scanned bottle as solid body.

20. Extrude a square around the body of the bottle with approximately 1 inch of additional material on the sides and the bottom, with the top reaching approximately half way up the lid of the bottle. Ensure that the box for "Merge result" is unchecked so that the bottle and the mold do not become one body. 

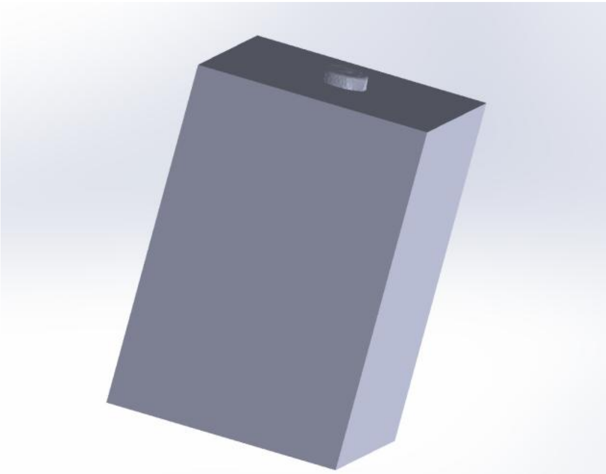


Figure 20. Mold and bottle combined but not merged

21. Use Combine tool to create the bottle shaped cavity inside of mold. Select the extruded square as main body and bottle as body to combine. Ensure that Operation Type is Subtract.

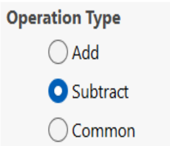


Figure 21. Subtraction for creation of bottle shaped cavity inside mold

22. Extrude an additional disk, approximately 0.3 inches tall, where the cap of the bottle would be so that there will be sufficient material to firmly hold the preform in place.

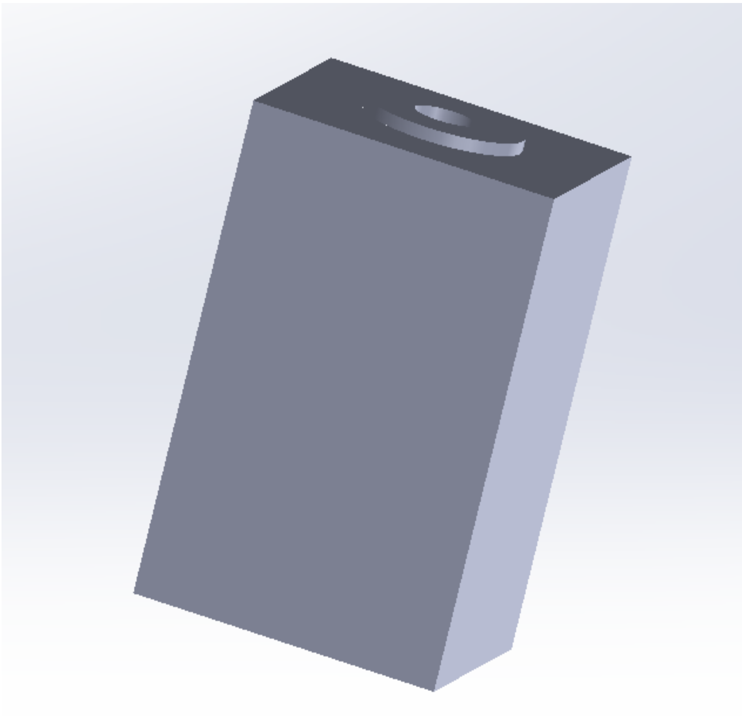


Figure 22. Mold with additional disk

23. Using the center axis of the bottle and a revolved cut, create the gap as seen, which will be used to grip the preform. Specific dimensions will vary but be sure to include a small tolerance.

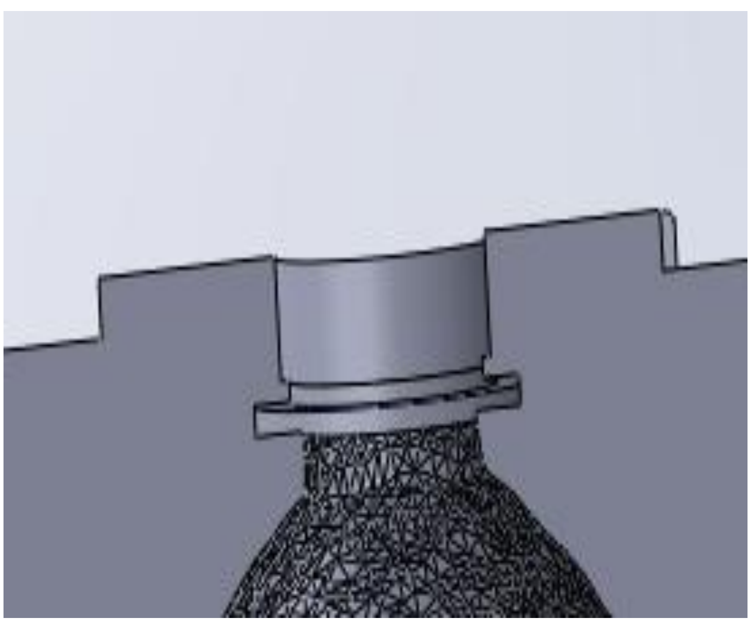


Figure 23. Preform profile cut into mold

24. At the center, on the vertical axis for each side, extrude cut holes for the air to evacuate when blow molding. These holes should start after the neck of the bottle and should be spaced 1 inch apart until approximately 1.5 inches from the bottom of the bottle. Each hole should be 0.1 inches in diameter. Ensure that these holes go through the entirety of the mold.

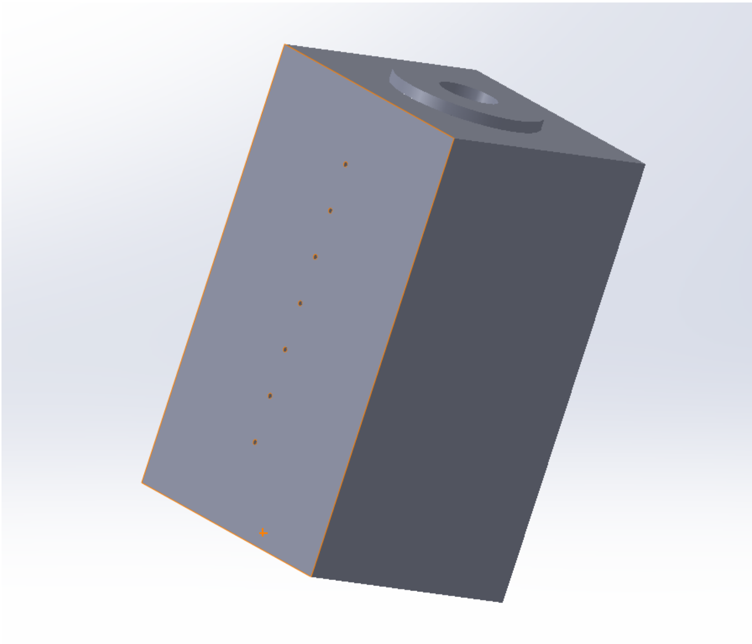


Figure 24. Mold with side air evacuation holes

25. Continue to extrude and cut similar holes on the bottom with a larger diameter of 0.15 inches. The spacing and number of these holes will depend on the geometry of your specific bottle.

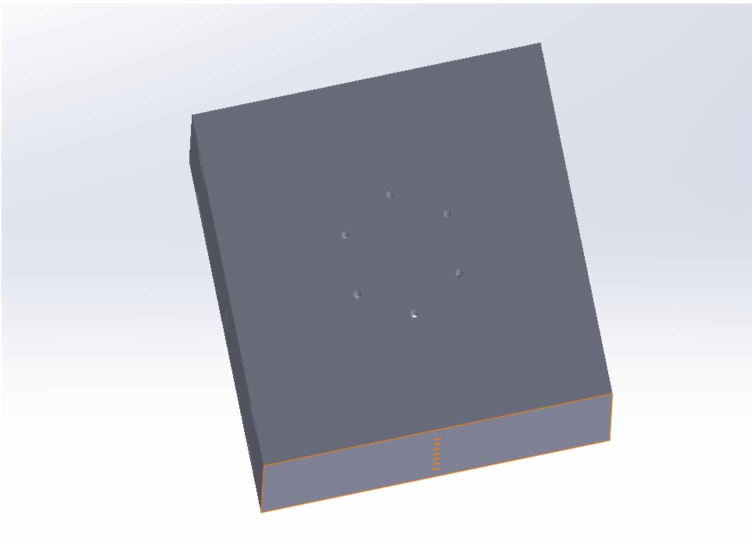


Figure 25. Mold with bottom air evacuation holes

The mold is now technically ready to achieve blow molding but isn’t practically usable as it is a solid object.

26. Save the mold and open a copy. Now, the base will be created. Create a circle on the bottom of the mold that is 0.5 inches wider than the bottle on each side. Continue to extrude and cut the rest of the mold, including the entire upper half, leaving only the disk at the bottom. Extrude down from the top of the disk a 0.2-inch lip that also reaches out 0.2 inches on the perimeter of the circle. Add a rail on both sides of the disk that reaches from the lip to the bottom of the base and is also 0.2 inches thick.

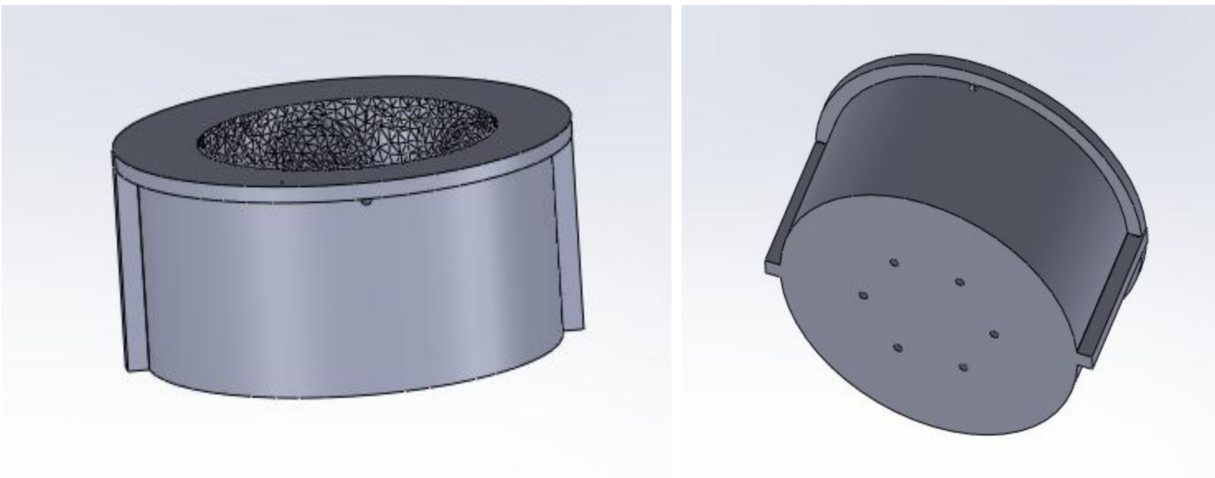


Figure 26. Completed mold base

27. Create the inverse of each of these operations on the original mold, accounting for tolerances. This should leave you with two parts that could fit together to create a complete mold for the bottle. Save this model.

Open a copy of the just edited original mold. Extrude cut one-half of the mold vertically (in the direction that would cut the slots on the side of the base in half). This should leave you with only one-half of the mold. Save this as a new part. Repeat this, but leave the other half of the mold intact. Save this as a new part. It can be helpful to save these parts with names such as 1 and 2 or A and B.

Open one of the halves of the mold and extrude four 0.5 x 0.5-inch squares as seen in Figure 27. Note: it can be beneficial but is not necessary to add a fillet to the top of these squares to help when putting the halves together. As before, spacing may vary depending on your bottle. These will be used to connect and align the two halves of the mold.

The four holes you see could be used to bolt together the mold but are unnecessary in this case. Due to the speed required when handling the heated preform clamping will be much more effective than bolting.

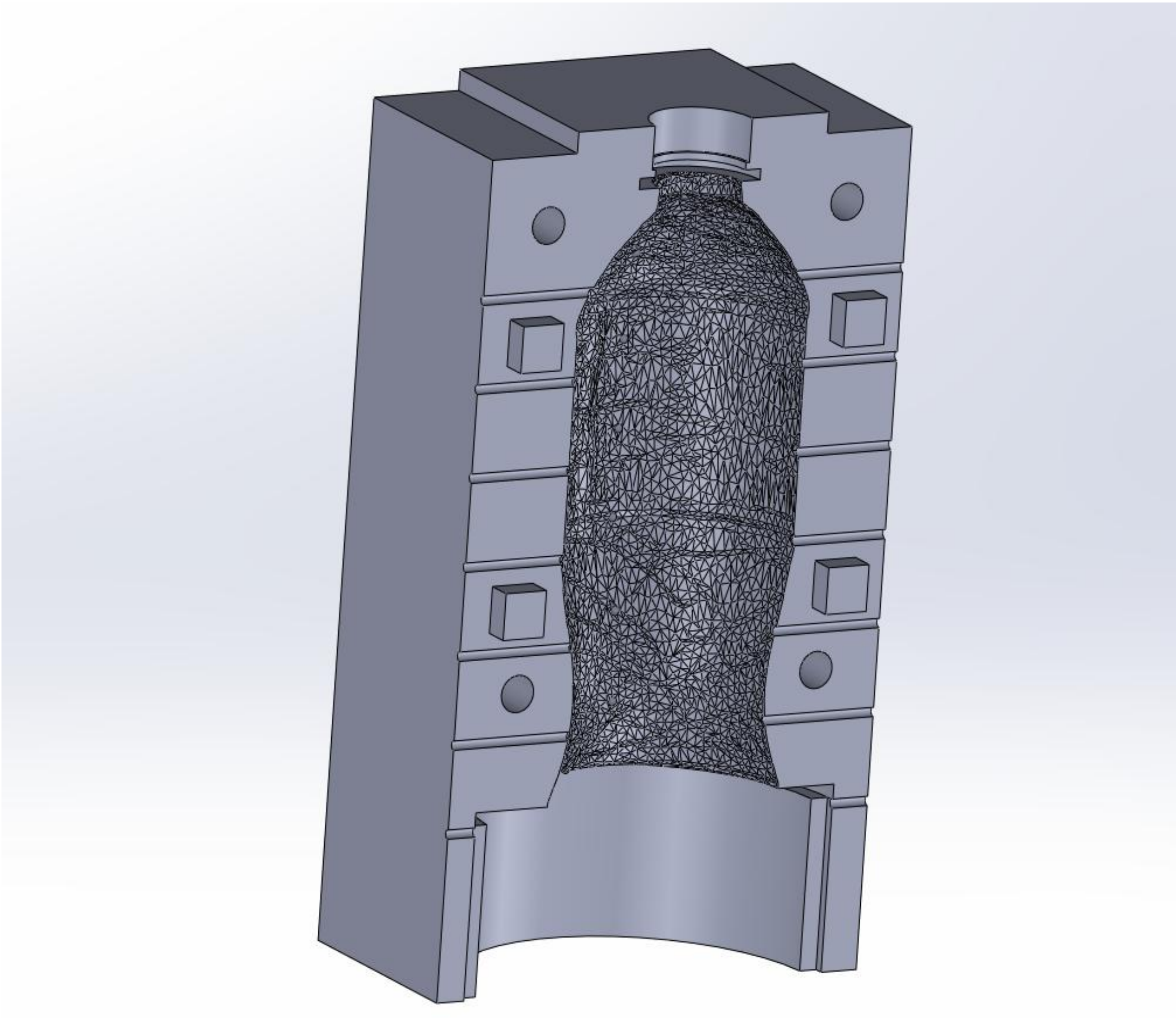


Figure 27. Final male half of mold

Finally, create the extrude cuts of these squares on the other half of the mold, accounting for tolerances. With this, your mold should be completed in three parts and ready for 3D printing and use in blow molding.

Useful Web References

1. Mold Design: Making Blow Mold Design for PET Bottle
   https://www.youtube.com/watch?v=BvfxRV0C1MY
2. How To Design a Bottle Blow Mold in SolidWorks
   https://www.youtube.com/watch?v=bpvSMuPVoGQ
3. Blow Mold Design SolidWorks
   https://www.youtube.com/watch?v=M7QNG1UETVI
4. Blow Mold Design Tutorial
   https://www.youtube.com/watch?v=30MD5teExn8

Appendix 2: Ansys Tutorial for Blow Molding Project

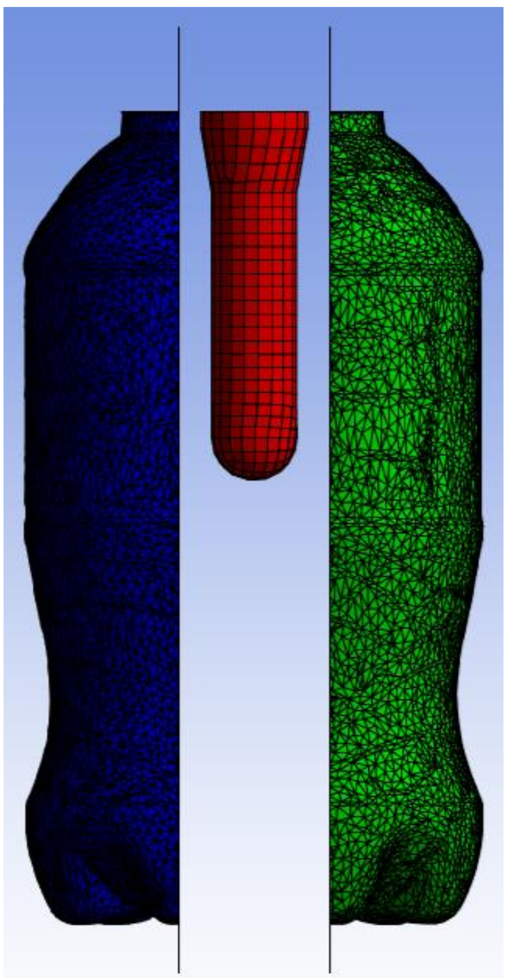
Dr Pepper Bottle Blow Molding

A. Objectives

- Using Ansys Polyflow to Study Blow Molding Process of a Plastic Preform
- Inserting Boundary Conditions
- Running Ansys Polyflow Simulations
- Using Contour Plots and Animations for Visualizations of Blow Molding

B. Problem Description

We will study the blow molding process of a plastic preform. The two mold halves will enclosing the plastic preform. Pressure will be applied to form the preform into a bottle.



C. Launching Ansys Workbench and Selecting Polyflow

1. Start by launching Ansys Workbench 2024 R2. Launch Fluid Flow (Polyflow) that is available under Analysis Systems in Ansys Workbench. Right click on Geometry in Project Schematic and select Import Geometry>>Browse…. Open the file *Assem6.x_t.*

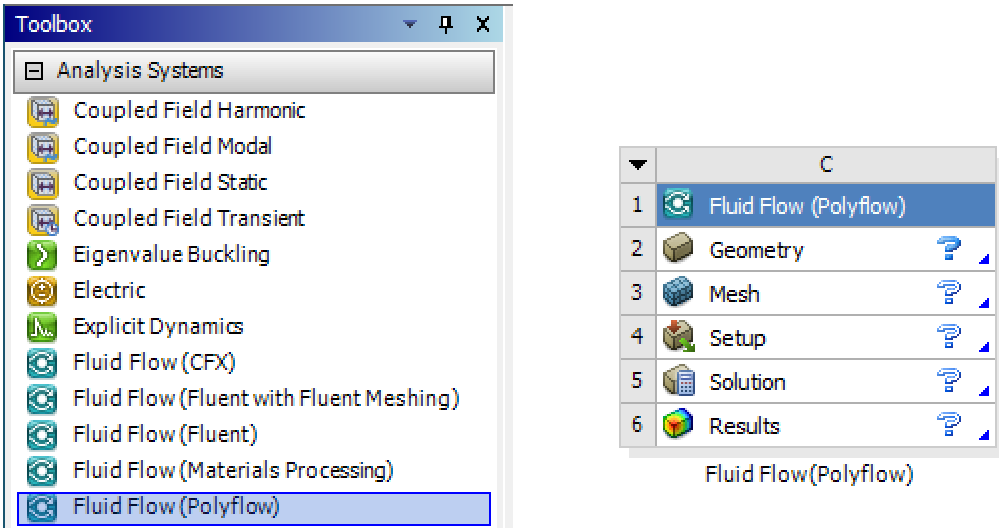


Figure 1.1 Launching Ansys Polyflow

D. Launching Ansys Meshing

2. Double click on Mesh under Project Schematic in Ansys Workbench. Open Geometry under Model (A3) in the Outline. Right-click on the first part, select Rename and name the first part as Preform. Open Graphic Properties in Details of "Mold" and select red Color. Rename the second part as MoldFront and select blue color. Rename the third part as MoldBack and select green color.

   Select Mesh in the Outline. Select the Home tab in the menu and select Tools>>Units>>Metric (m, kg, N, s, V, A). Set the Element Size to 1.e-002 m under Defaults in Details of "Mesh". Right-click on Mesh under Project and Model (A3) in the Meshing window and select Update. Click on the plus sign next to Statistics in Details of "Mesh". The mesh has 11891 Nodes and 21611 Elements.

   Select File>>Export…>>Mesh>>POLYFLOW Input File>>Export from the menu. Save the mesh with the name *DrPepper.poly*. Select File>>Save Project from the menu and save the project with the name *DrPepper.* Close the meshing window. Right click on Mesh in the Project Schematic and select Update.

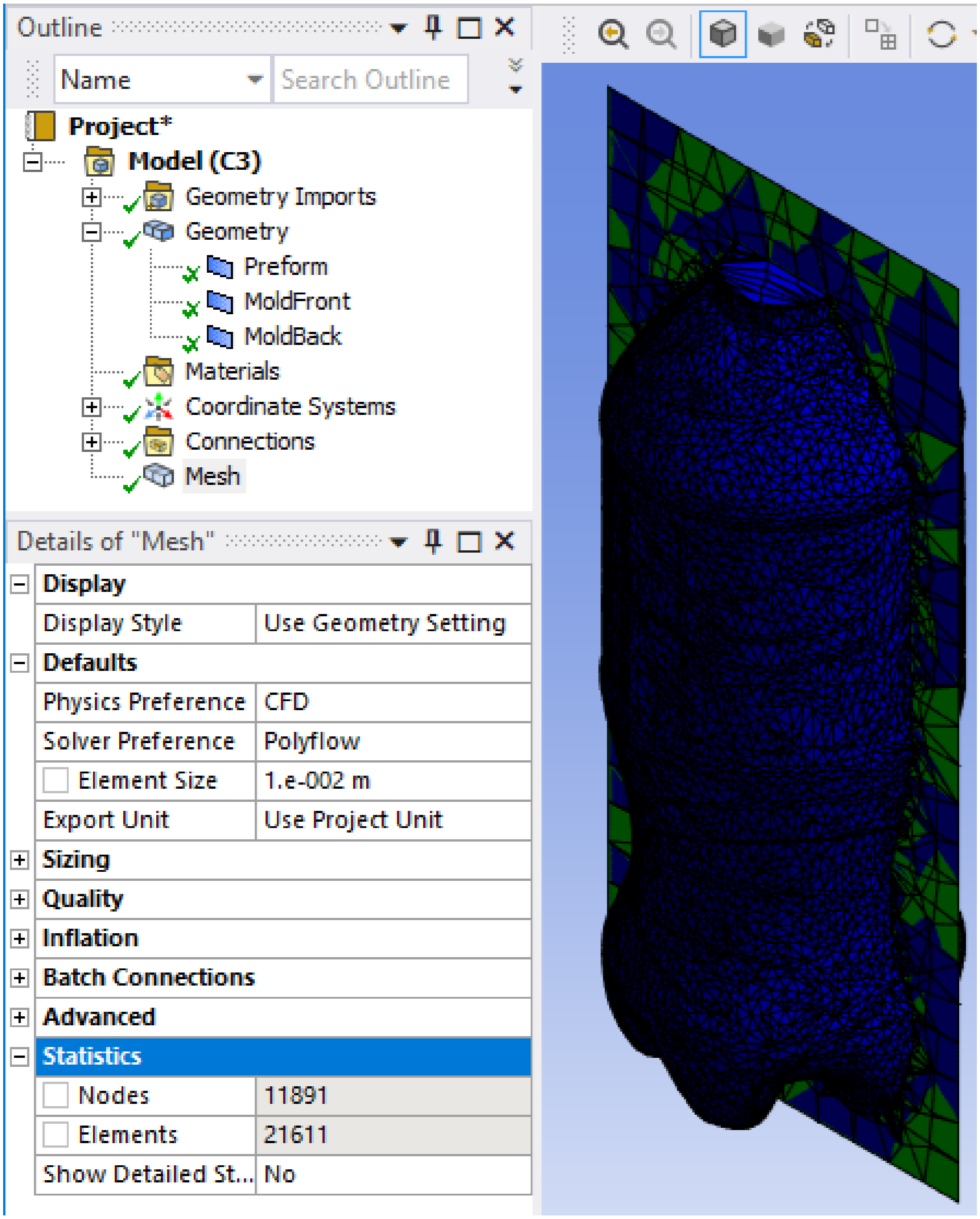


Figure 1.2 Mesh for molds and preform

E. Launching Ansys Polydata

3. Double click on Setup under Project Schematic in Ansys Workbench. Select the Mesh tab at the bottom of the middle Polydata section. Select Grid as Display option. Select the Menus tab at the bottom of the Polydata section. Select Create a new task in the Polydata section. Select F.E.M. task, Time-dependent problem and 2D shell geometry. Select Accept the current setup.

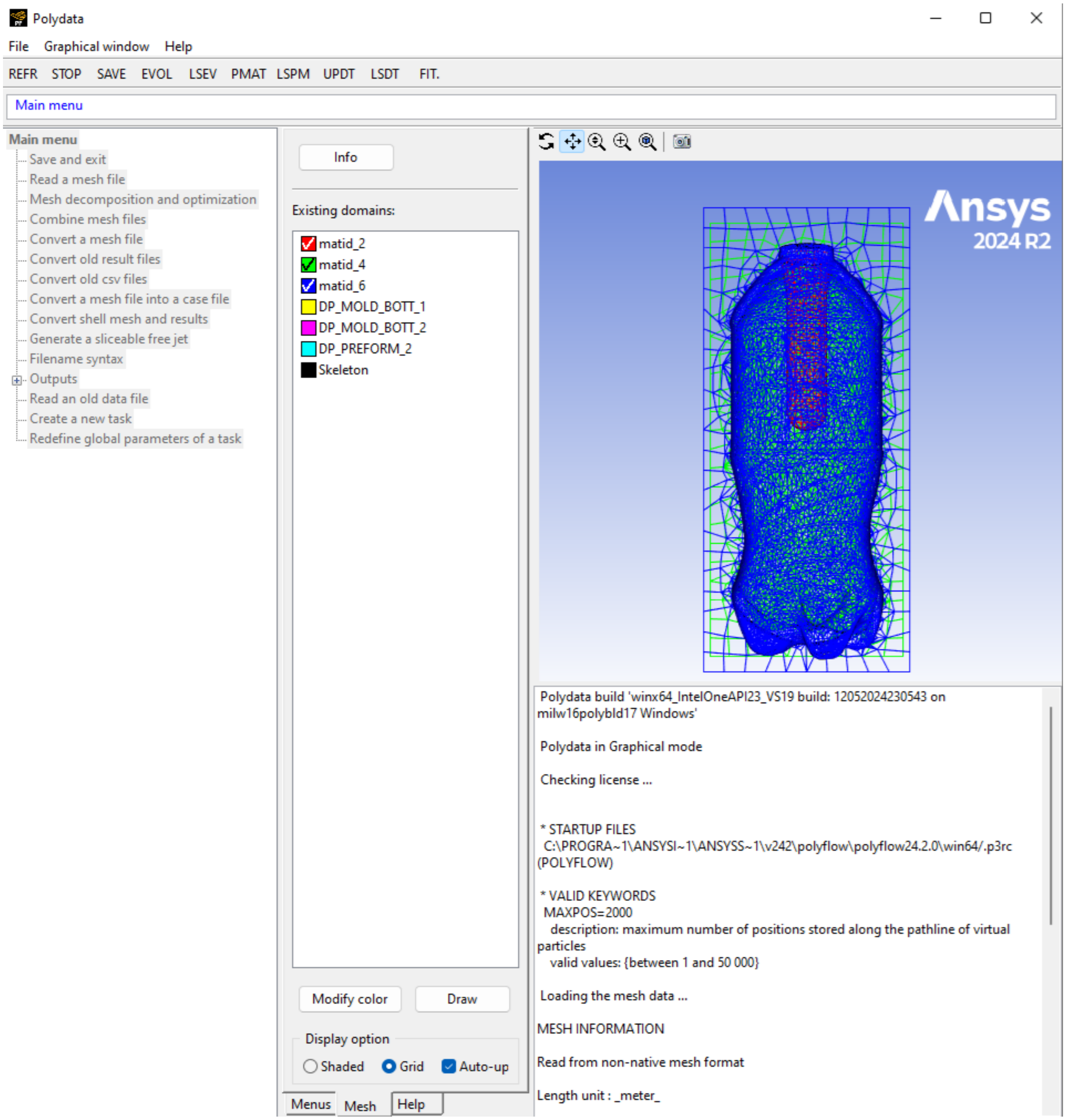


Figure 1.3a) Polydata main menu

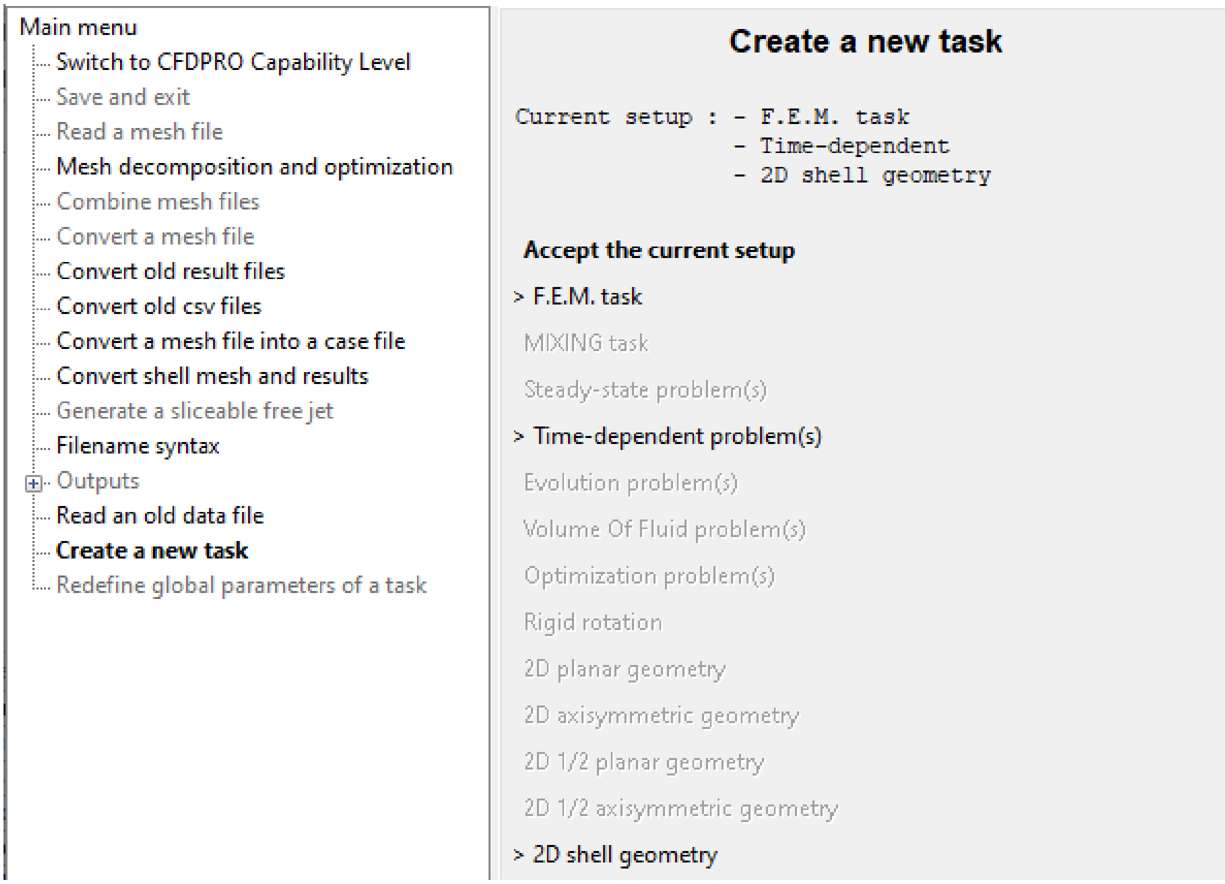


Figure 1.3b) Creating a new task

4. Select Define molds in the F.E.M. Task 1 section and select Create a new mold in the Define molds window.

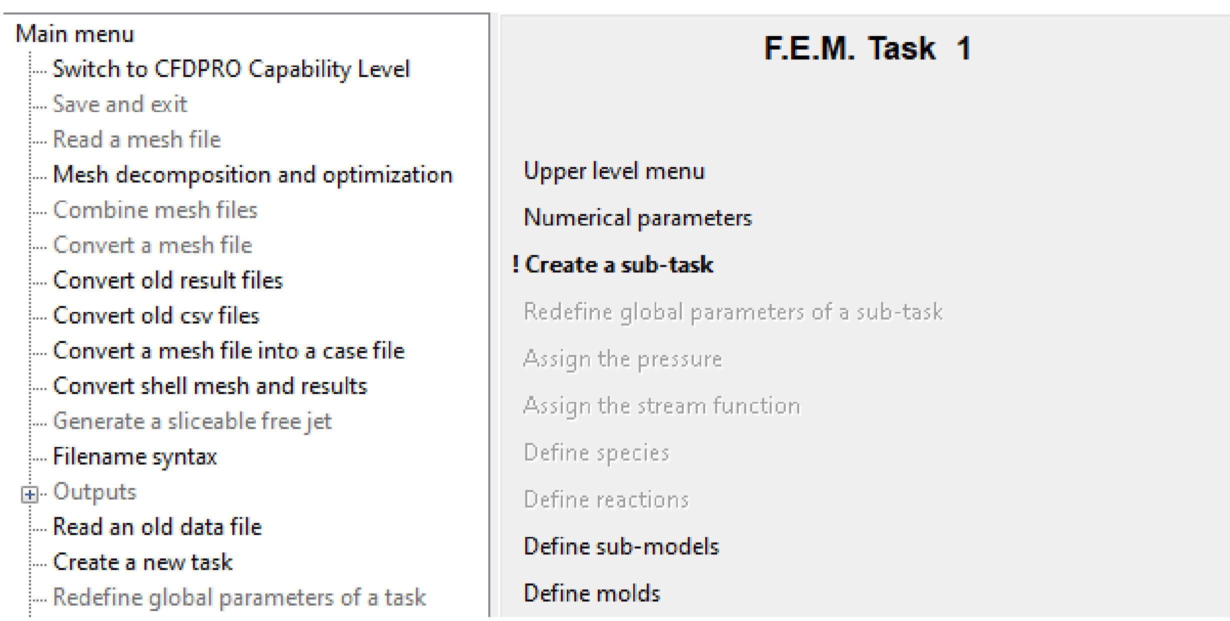


Figure 1.4a) Defining a mold

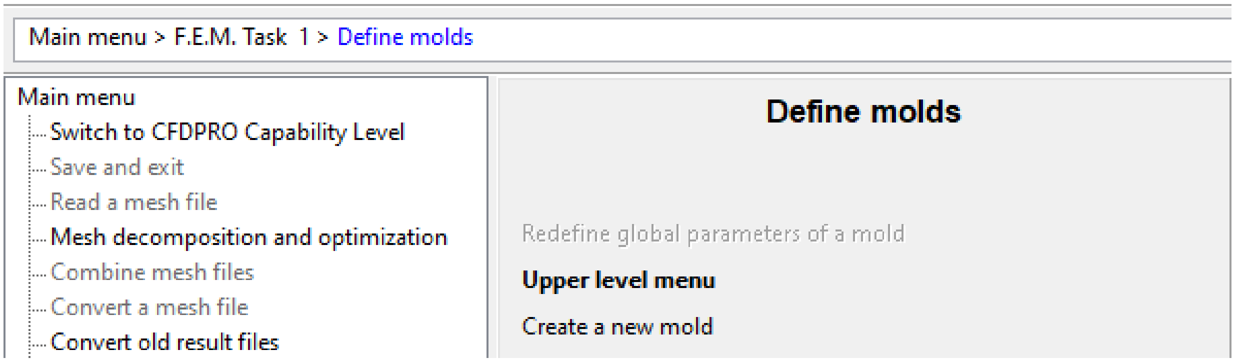


Figure 1.4b) Creating a new mold

5. Select Mold with constant and uniform temperature in the Create a new mold window. Enter the New value: Mold-Front.

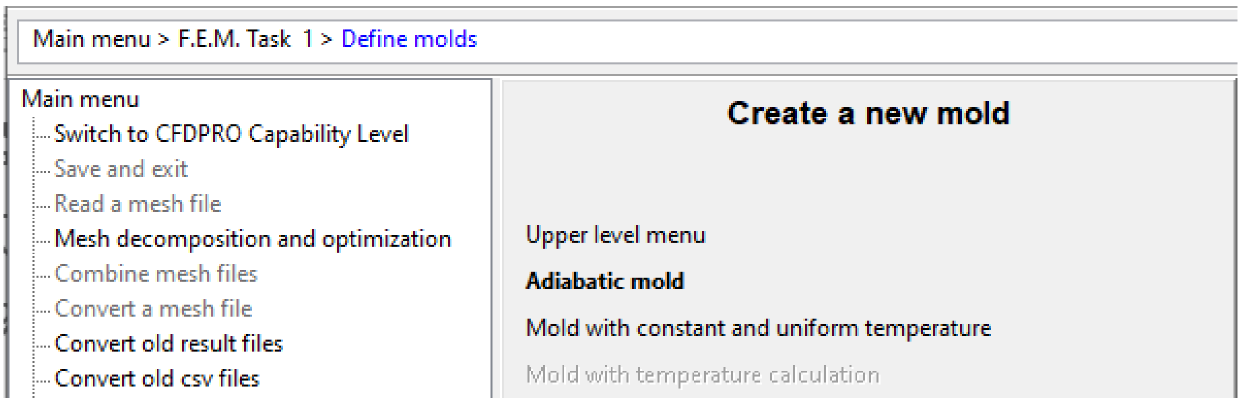


Figure 1.5a) Selection of a mold with constant and uniform temperature

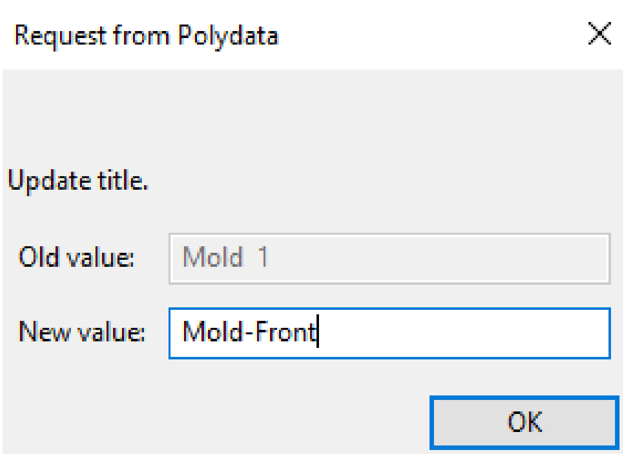


Figure 1.5b) Title for first mold

Select Domain of the mold in the Mold-Front window. Select matid_2 and select Remove in the Domain of the mold window. Select matid_4 and select Remove in the Domain of the mold window. Select Upper-level menu.

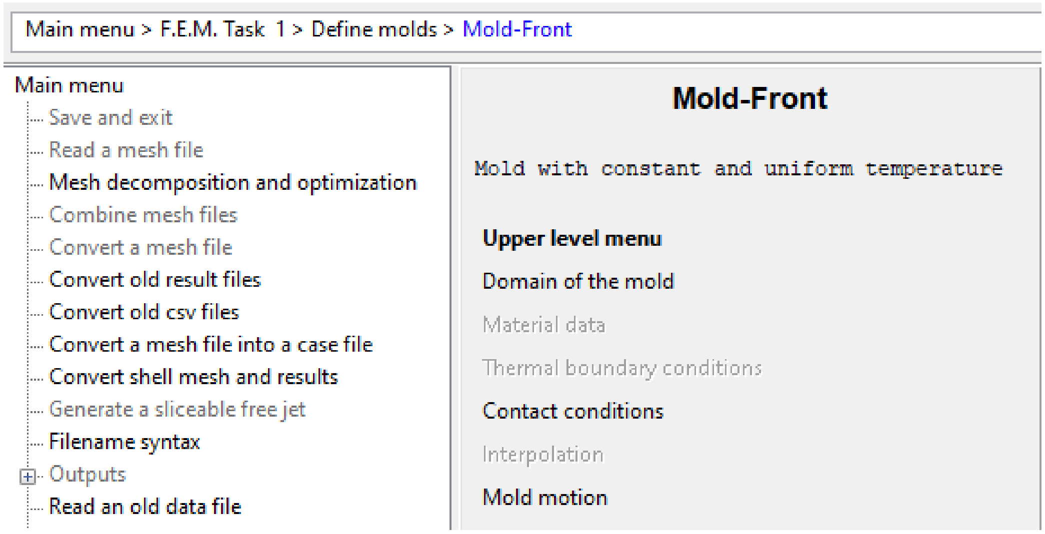


Figure 1.5c) Selecting domain for the mold

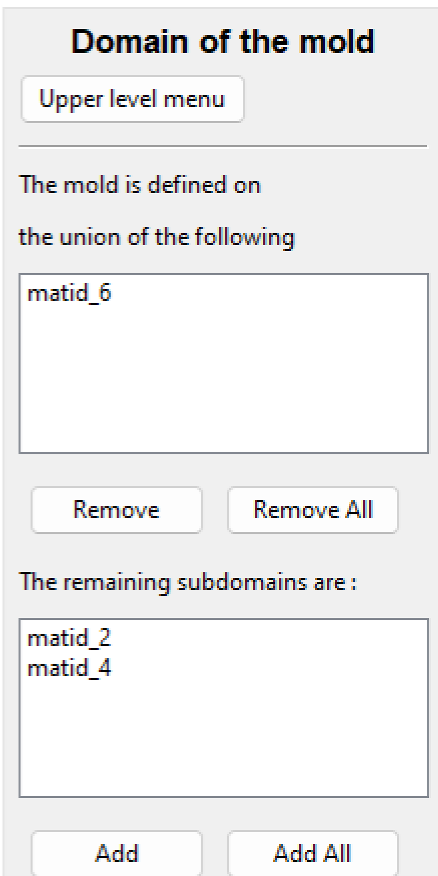


Figure 1.5d) Defining the domain of the mold

Select Contact conditions in the Mold-Front window. Select No contact along matid_6 and select Modify. Select Contact in the Contact condition along matid_6 window. Select Upper-level menu three times.

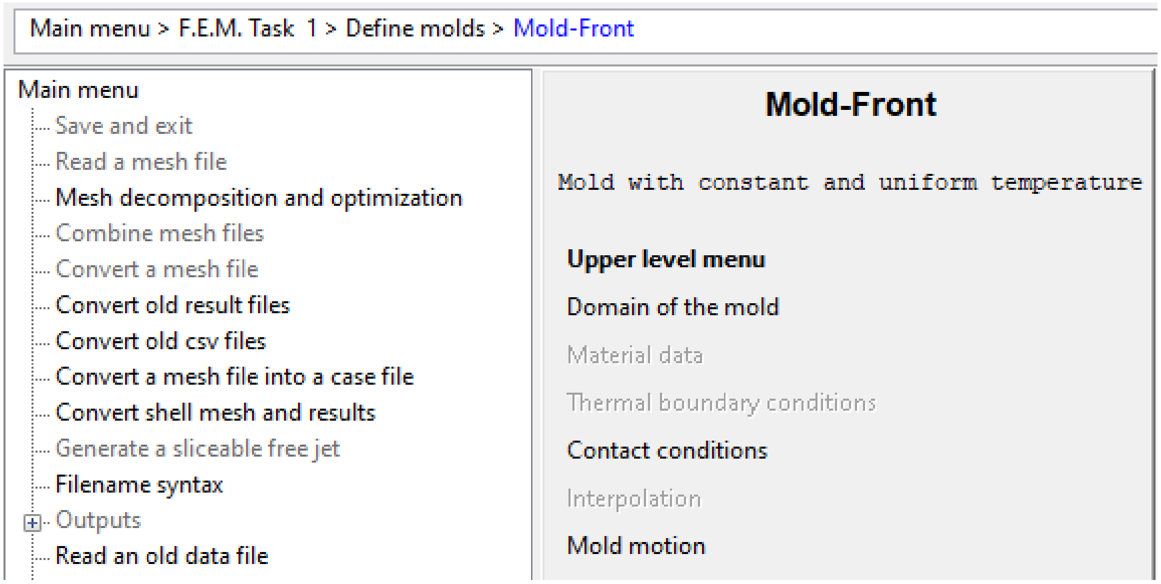


Figure 1.5e) Selection of contact conditions for the mold

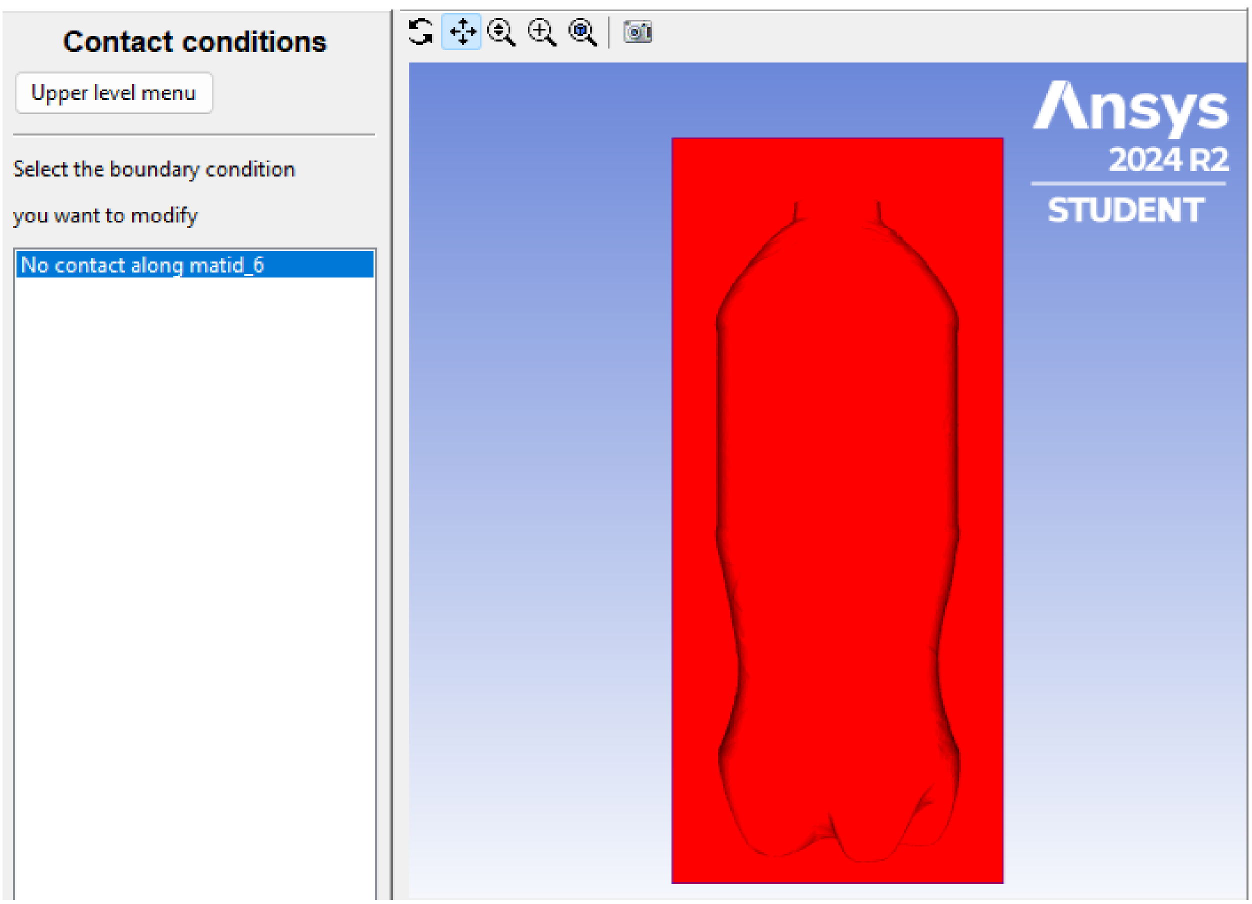


Figure 1.5f) Including contact for the mold surface

Select Create a new mold. Answer No to the question whether you want to copy the data of an existing mold. Select Mold with constant and uniform temperature in the Create a new mold section. Enter the name Mold-Back as New value: and select OK to close the Request from Polydata window.

Select Domain of the mold in the Mold-Back section. Select matid_6 and Remove this selection in the Domain of the Mold. Select matid_2 and Remove this selection in the Domain of the Mold, see Figure 1.5g). Select Upper-Level menu once.

Select Contact conditions in the Mold-Back section. Select No contact along matid_4 and select Modify. Select Contact and select Upper-level menu four times in the Mold motion window to arrive at F.E.M. Task 1.

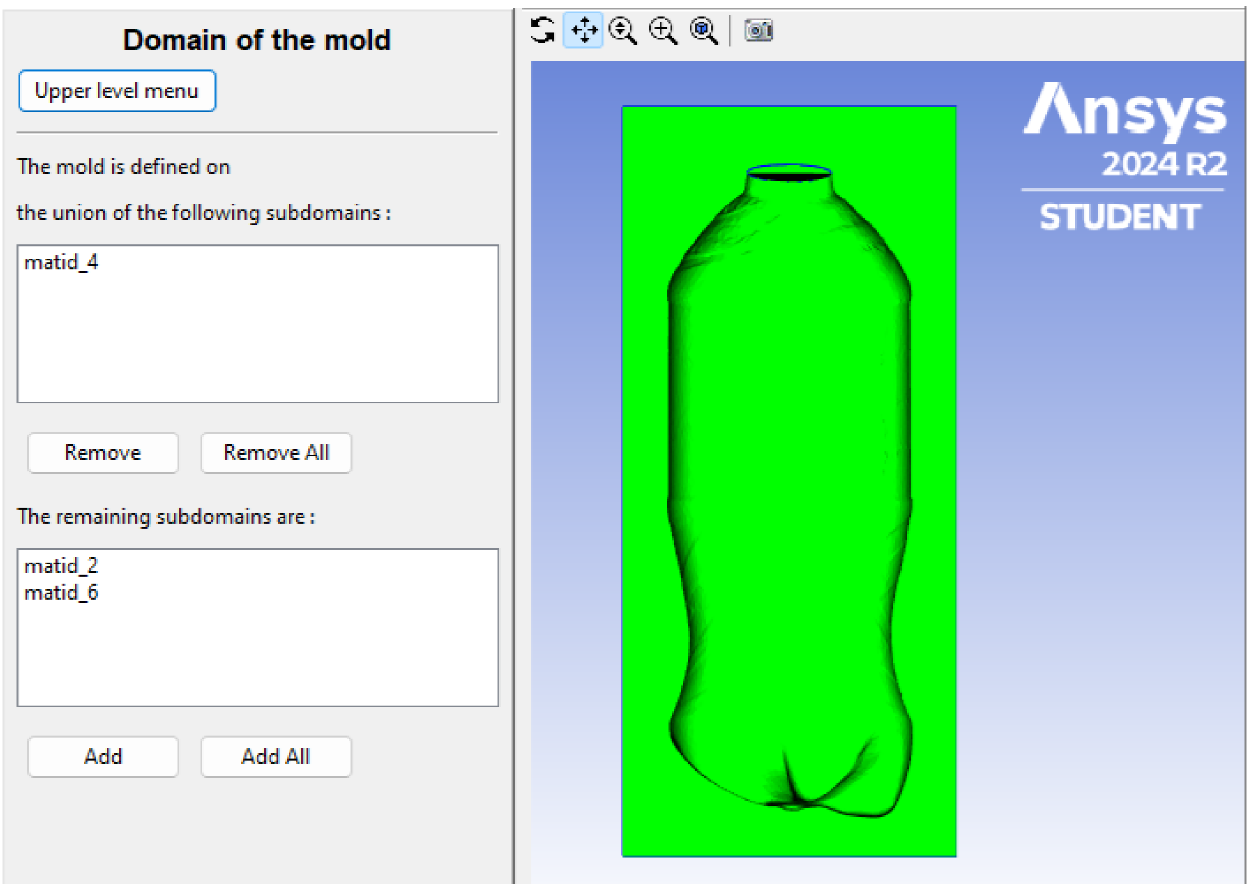


Figure 1.5g) Defining domain of back mold half

6. Select Create a sub-task in the F.E.M. Task 1 window. Select Shell model: Gen. Newtonian isothermal. Enter the New value: Preform in the Request from Polydata window and select OK to close the window.

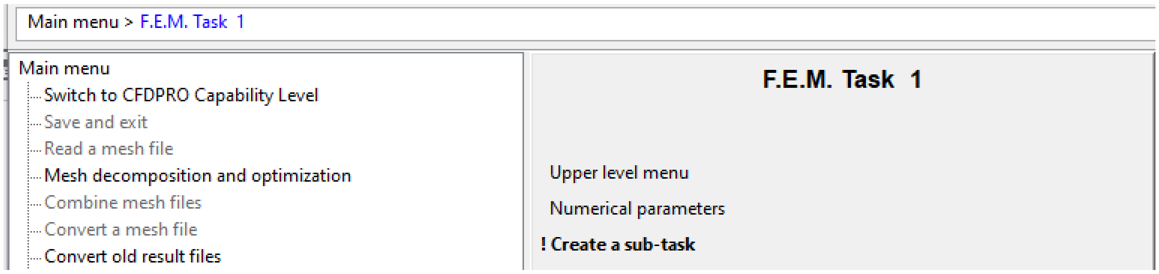


Figure 1.6a) Creating a sub-task

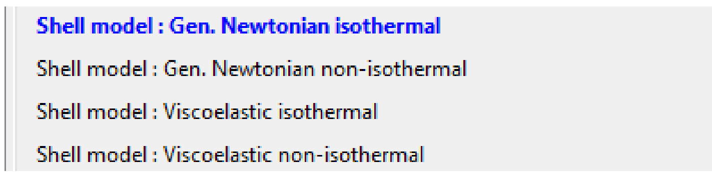


Figure 1.6b) Choosing shell model

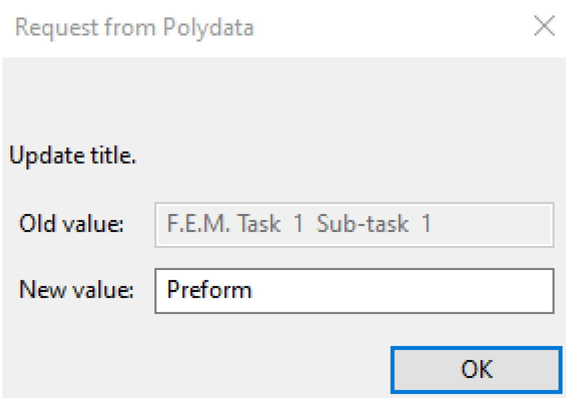


Figure 1.6c) Updating the title for the sub-task

Select Domain of the sub-task. Select matid_4 and Remove in the Domain of the sub-task window. Select matid_6 and Remove in the Domain of the sub-task window. Select Upper-Level Menu.

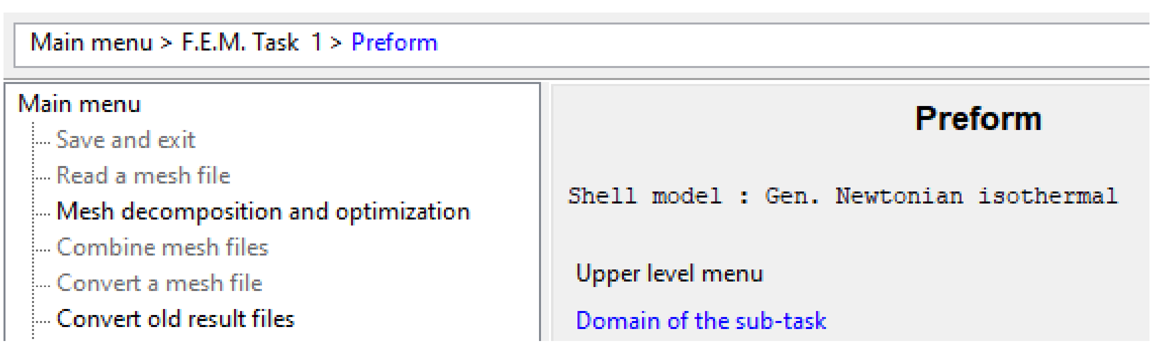


Figure 1.6d) Selecting domain for the sub-task

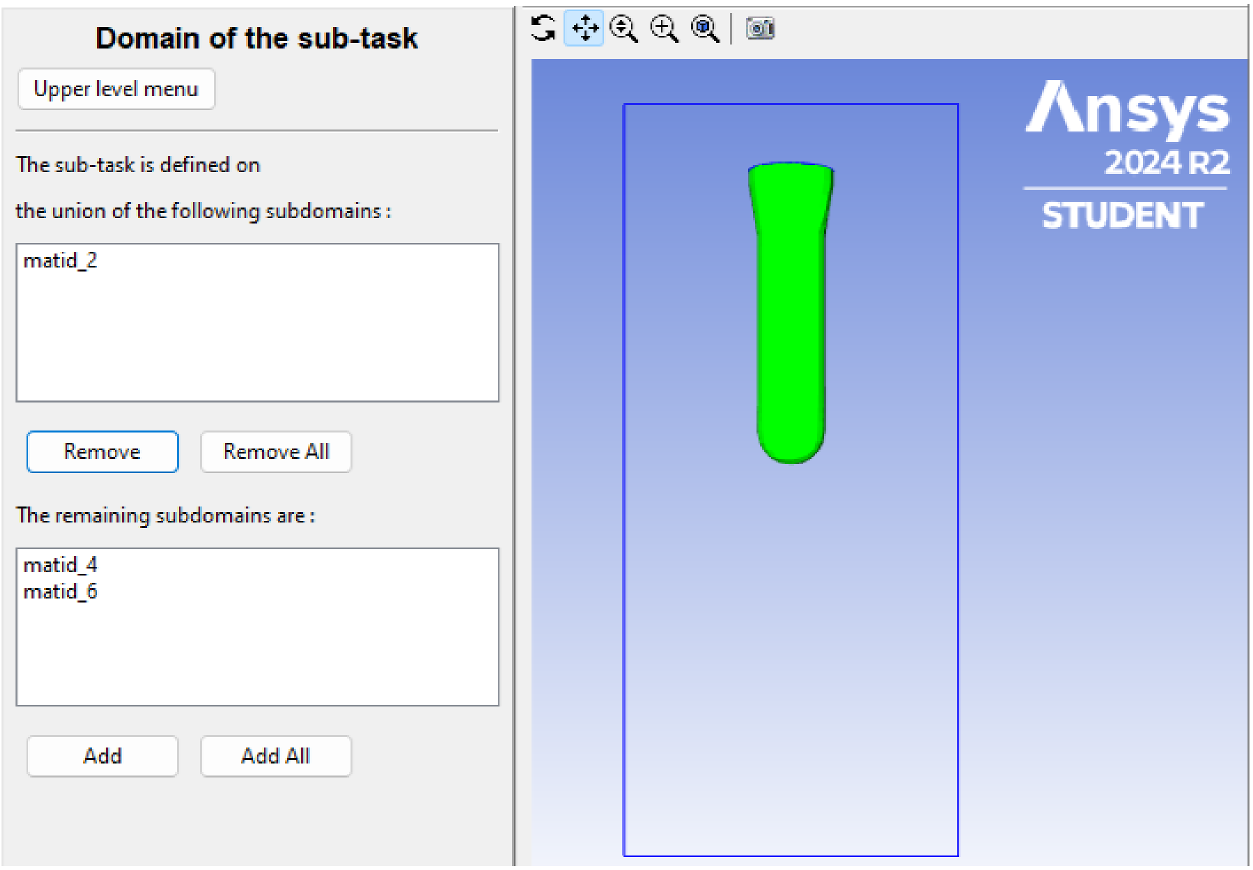


Figure 1.6e) Removing matid_4 and matid_6

Select Flow boundary conditions and select Zero wall velocity (vn=vs=0) along DP_PREFORM_2. Select Upper-Level Menu.

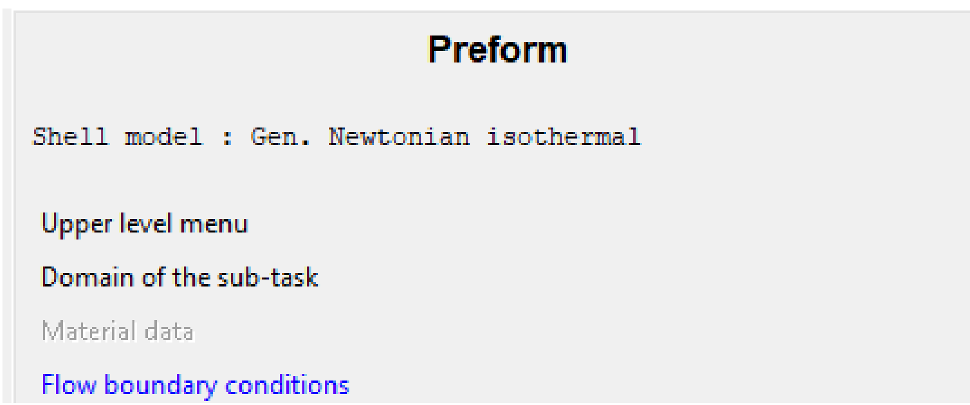


Figure 1.6f) Selecting flow boundary conditions

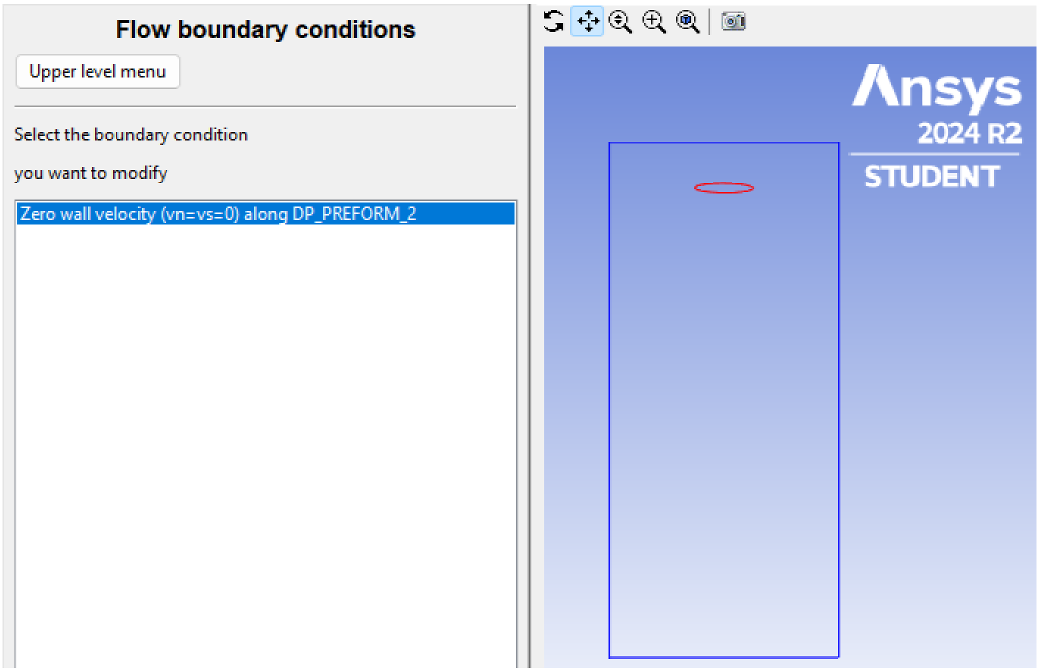


Figure 1.6g) Selecting zero wall velocity

Check the box for Inflation pressure imposed in the Flow boundary conditions window. Select constant in the Flow boundary conditions window. Enter 9e5 Pa as the New value: and click OK. Select Graphical window>>Sizing Darts>>Size up twice.

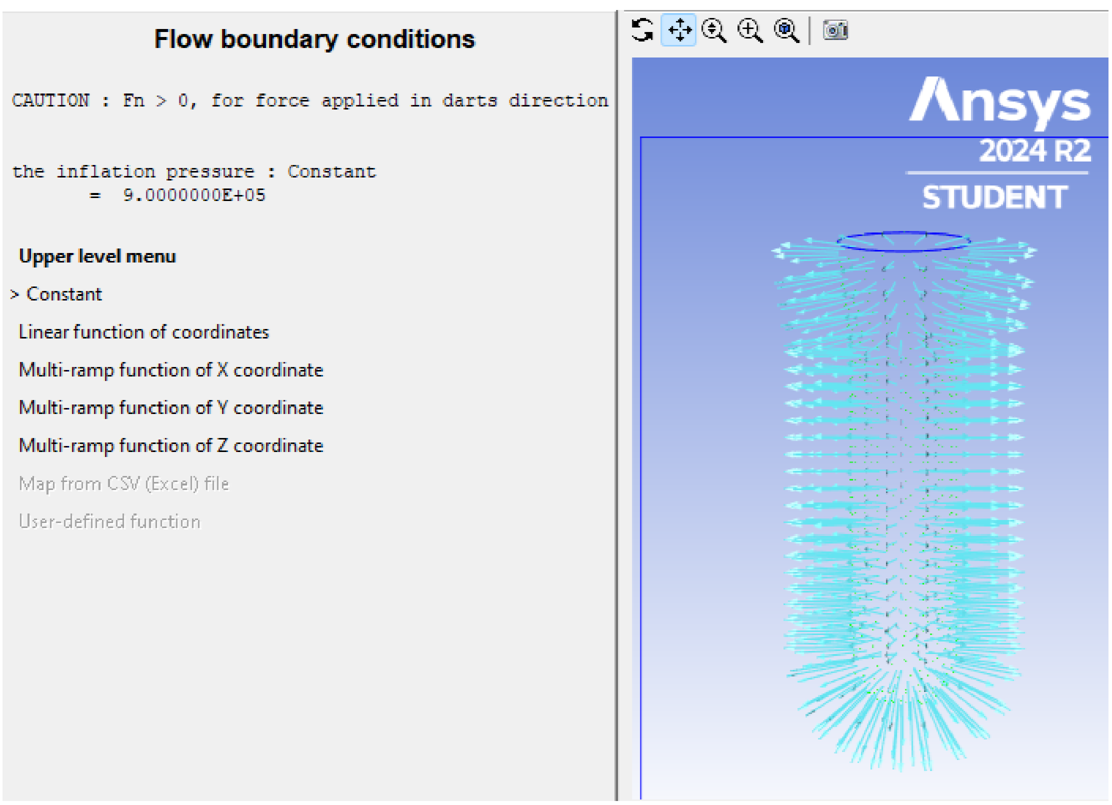


Figure 1.6h) Setting inflation pressure

Select EVOL in the menu and select Upper-level menu in the Flow boundary conditions window. Select f(t) = Ramp function. Select Modify the value of a and enter 0.1 as the New value: and click OK. Enter the values 0, 0.2 and 1 as b, c, and d values. Select Upper-level menu and deselect EVOL in the menu. Select Upper-level menu once again.

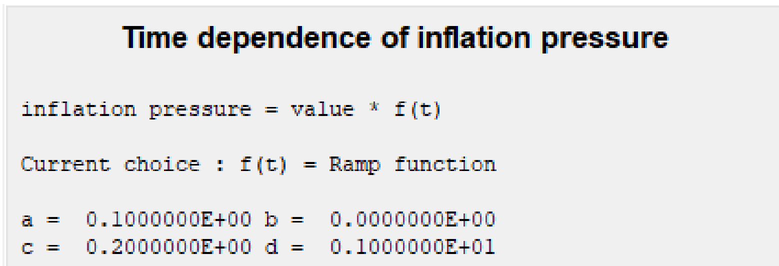


Figure 1.6i) Entered values for a – d

Select Define contacts in the Preform window. Select create a new contact problem and click on Select a contact wall.

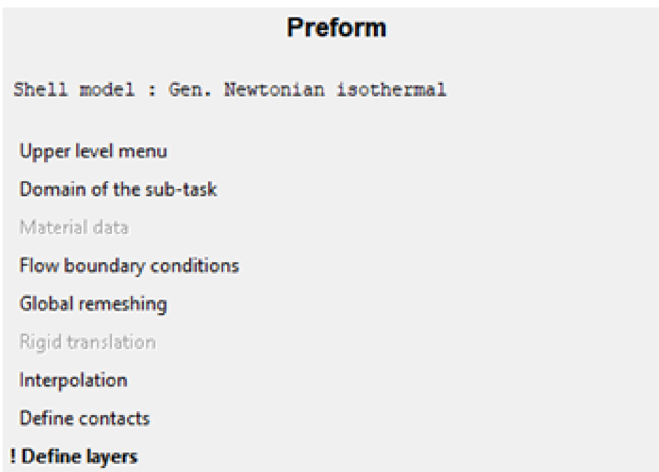


Figure 1.6j) Defining contacts

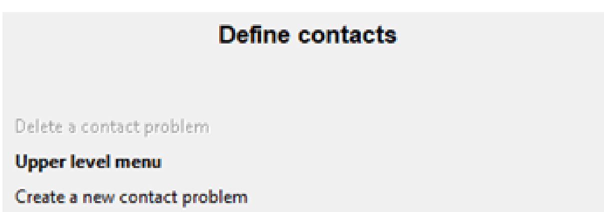


Figure 1.6k) Creating a new contact problem

Figure 1.6l) Selecting a contact wall

Select Mold-Front: Contact along matid_6 and click on Select in the Contact wall selection window. Select Modify penetration accuracy and enter 0.001 as the New value.

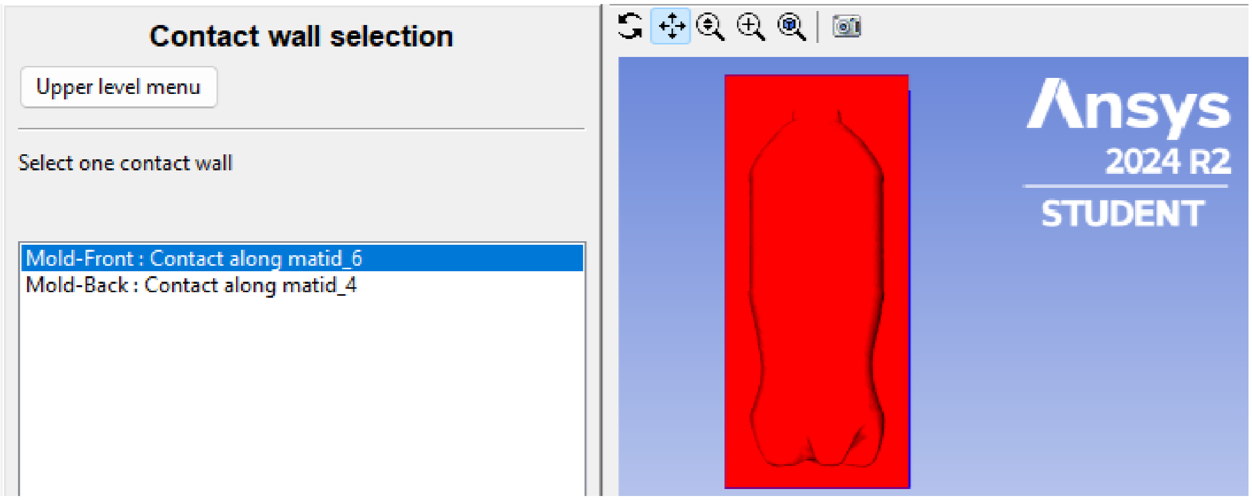


Figure 1.6m) Choosing Mold-Front as contact wall

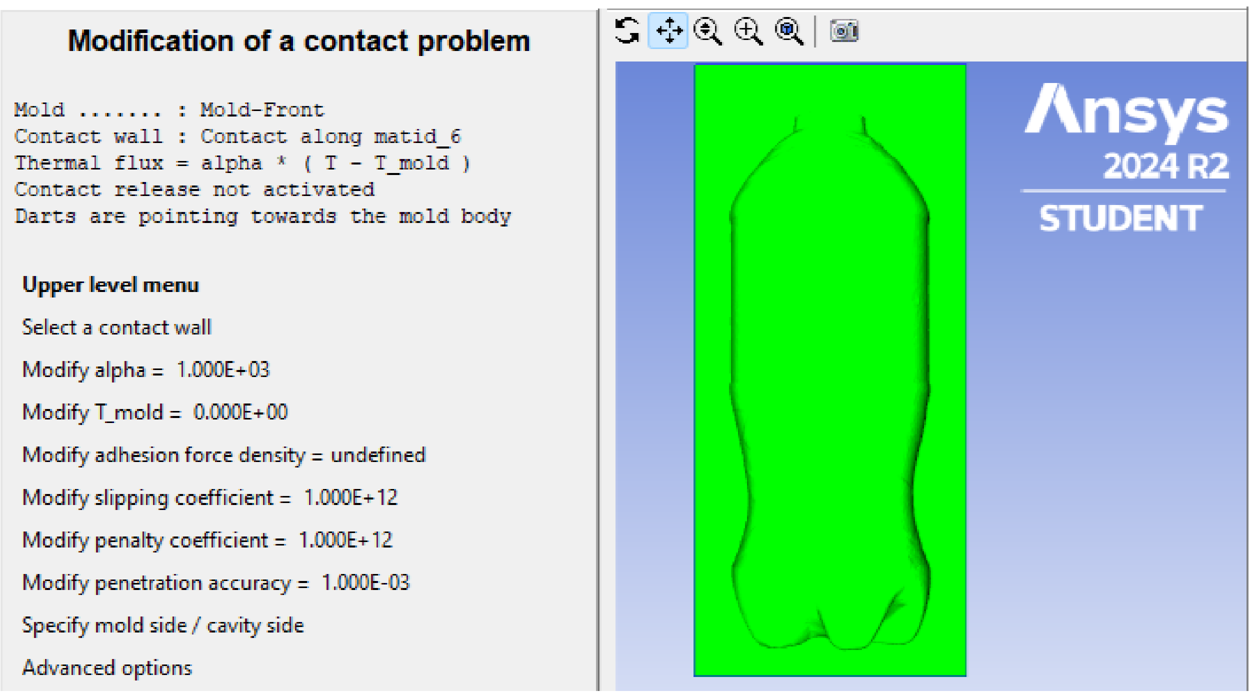


Figure 1.6n) Modified value for penetration accuracy

Select Specify mold side / cavity side in the Modification of a contact problem window. Answer Yes to the question “Are darts pointing towards the mold-body?”. Rotate the view to display the front mold, see Figure 1.6o).

Select Upper-level menu once. Select create a new contact problem and click on Select a contact wall. Select Mold-Back: Contact along matid_4 and click on Select in the Contact wall selection window. Select Modify penetration accuracy and enter 0.001 as the New value. Select Specify mold side / cavity side in the Modification of a contact problem window. Answer Yes to the question “Are darts pointing towards the mold-body?”.

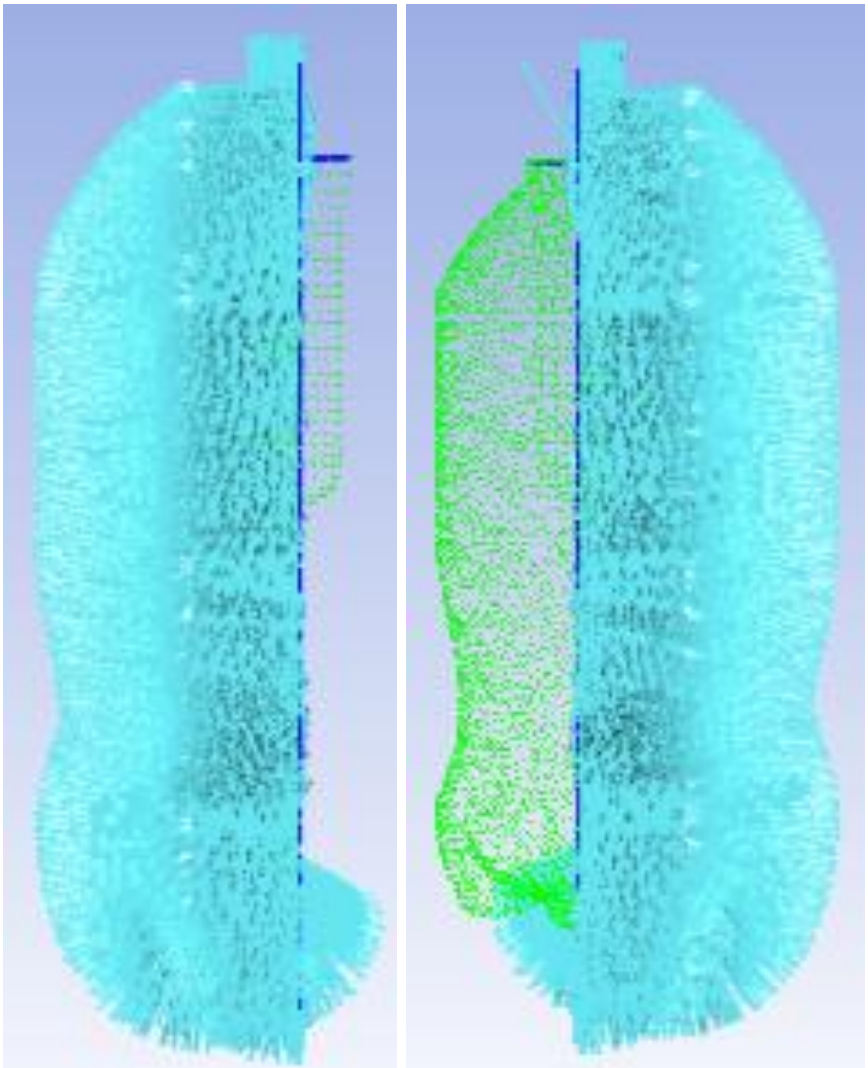


Figure 1.6o) Darts directed into front and back molds

Select Upper-level menu twice. Select OK when you get the following message:

```
The velocity prediction must be disabled
if some contacts are defined.
>> modification automatically done
```

Select Define layers in the Preform window and select Create a new layer in Define layers window. Enter preform as the New value: and click OK.

Select Material data in the preform window and select Shear-rate dependence of viscosity in the Material data window.

Select Constant viscosity in the Shear-rate dependence of viscosity window. Select Modify fac. and enter 6622 Pa·s in the Request from Polydata window. Select Upper-level menu twice.

Select Density in the Materials data window and select Modification of density in the next window. Enter 960 kg/m^3 as New value. Select Upper-level menu.

Select Inertia terms in the Materials data window and select Inertia will be taken into account in the Inertia terms window. Select Upper-level menu twice. Select Initial thickness in the film window and select Constant in the Initial thickness window. Enter 0.003175 m as initial thickness. Select Upper-level menu four times.

7. Select Numerical Parameters in the F.E.M. Task 1 window. Select Modify the transient iterative parameters.

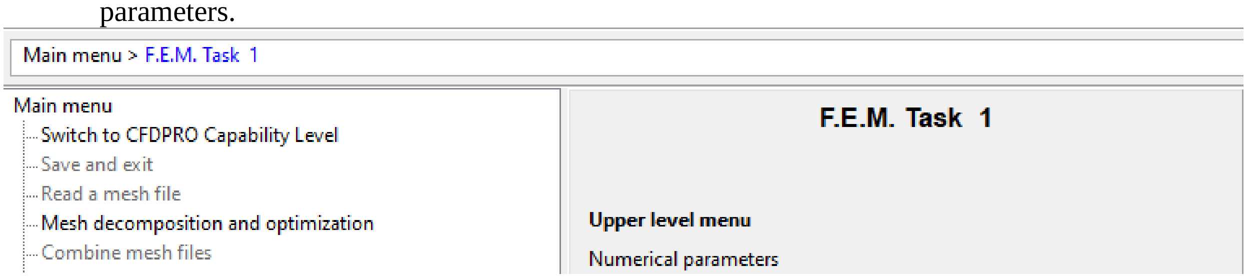


Figure 1.7a) Selecting numerical parameters

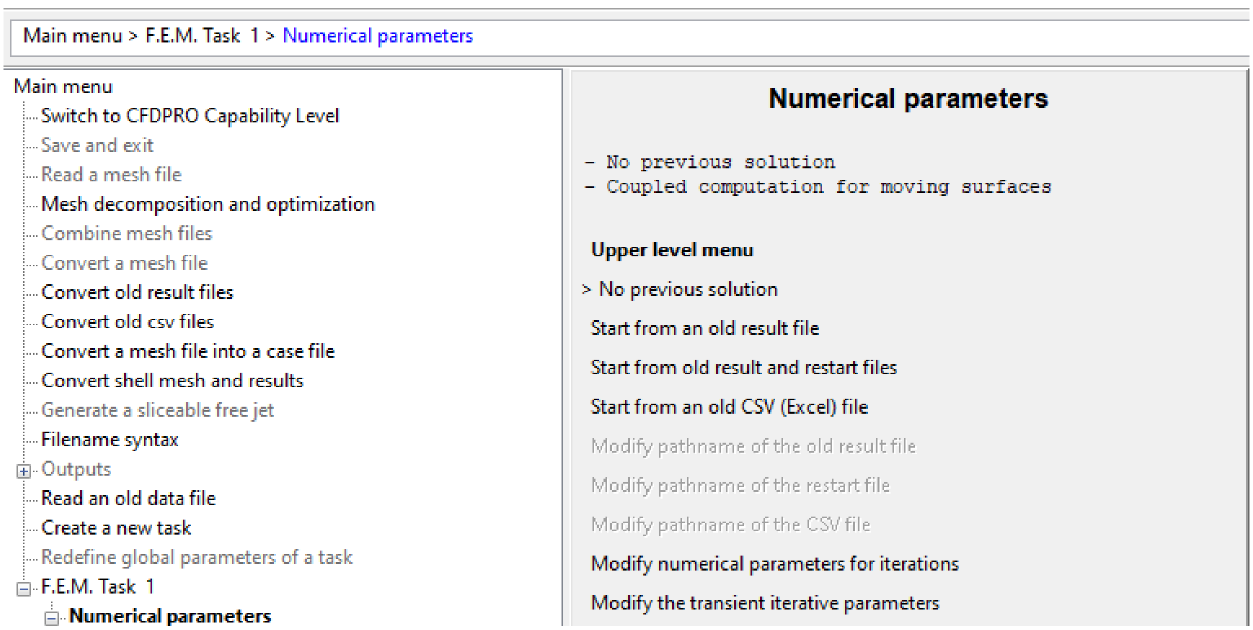


Figure 1.7b) Modifying transient iterative parameters

Select Modify the min value of the time-step and enter 1e-6 as the value. Select Upper-level menu three times.

8. Select Outputs in the Polydata window and select Enable CFD-Post output in the Outputs window (this may already be enabled). Select Set units for CFD-Post, Ansys Mapper or Iges. Make sure the units are metric_MKSA+Kelvin. Select Upper-level menu twice.

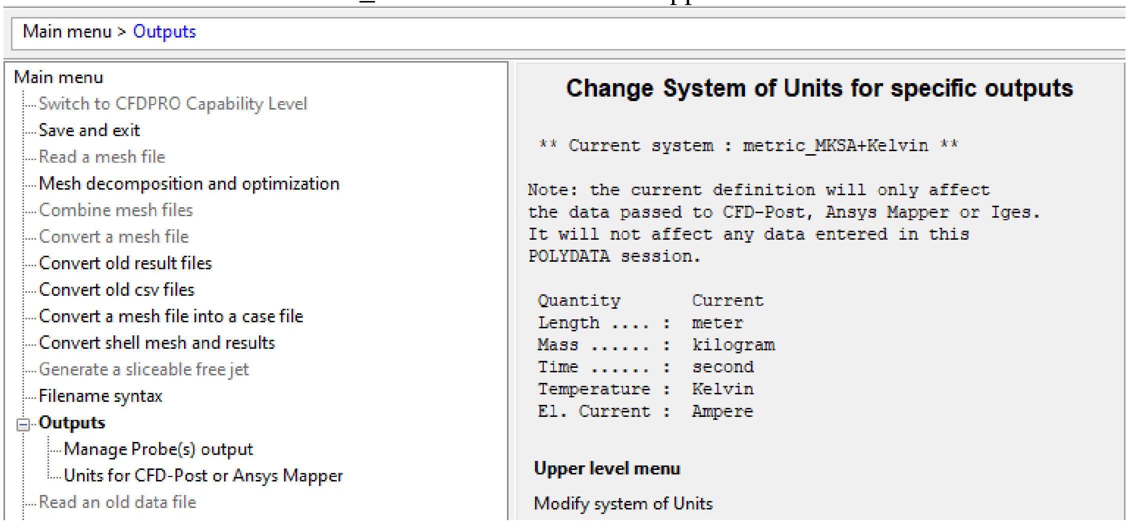


Figure 1.8 Unit system

9. Select Save and exit in the Polydata window. Select Accept in the Field Management window and Continue.

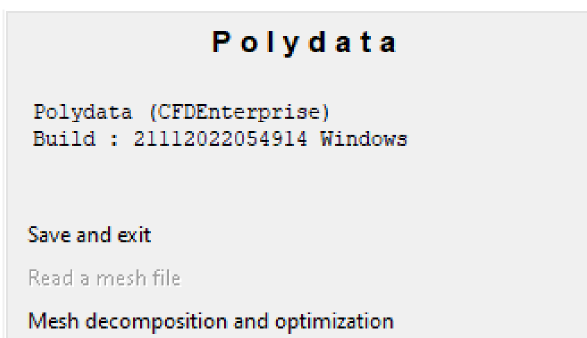


Figure 1.9a) Saving and exiting Polydata

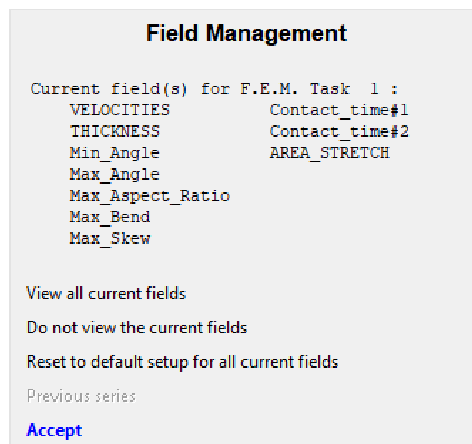


Figure 1.9b) Accepting field management

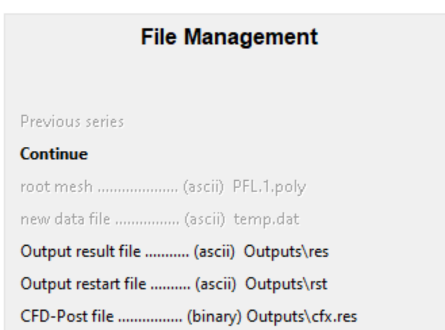


Figure 1.9c) Continuing the field management

10. Right click on Solution in the Project Schematic and select Update. Right click on Solution in the Project Schematic once again and select Listing Viewer…. Check the box for Refresh every and change the value from 10 to 5 seconds. Close the window when computations have finished.

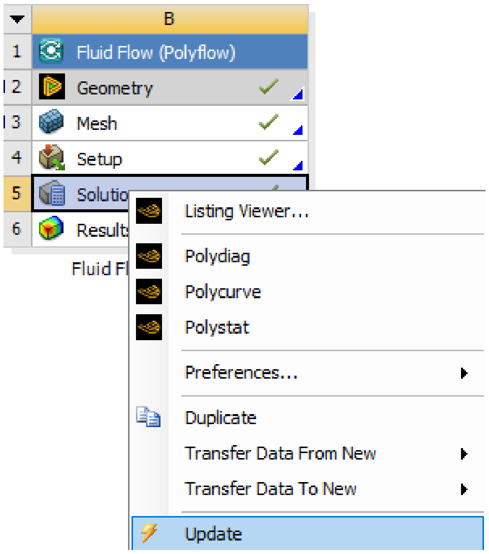


Figure 1.10a) Updating the solution

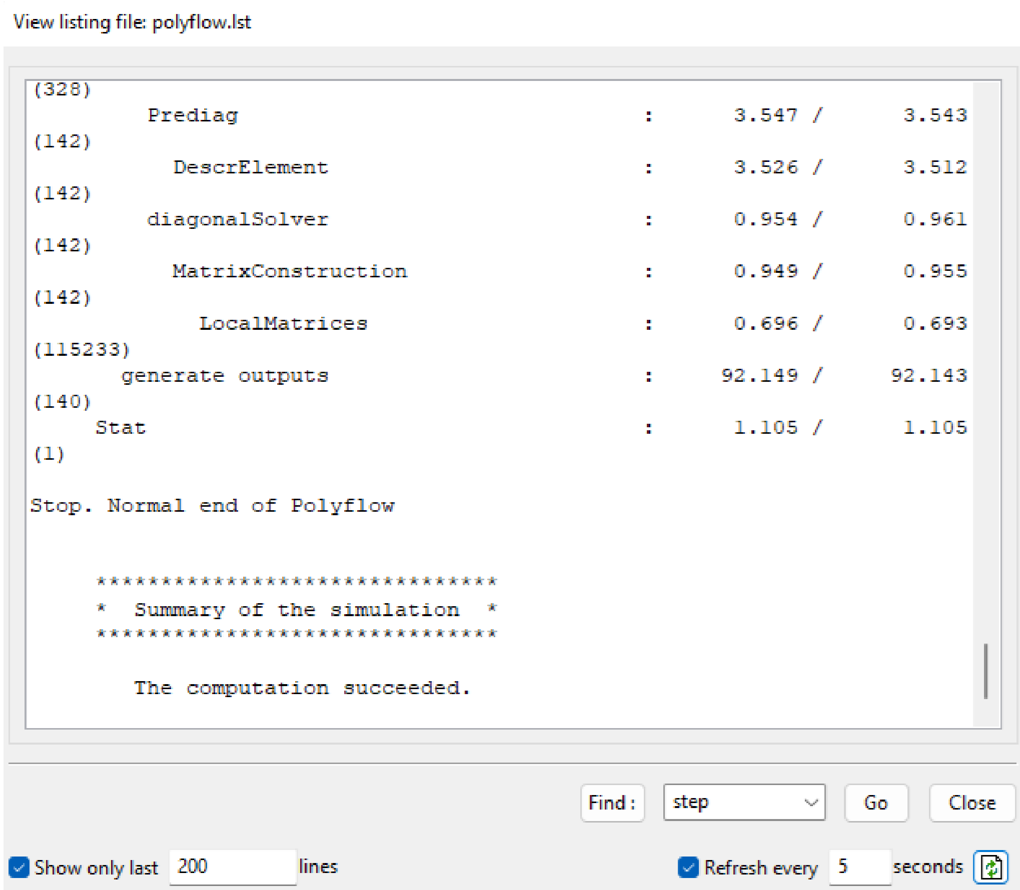
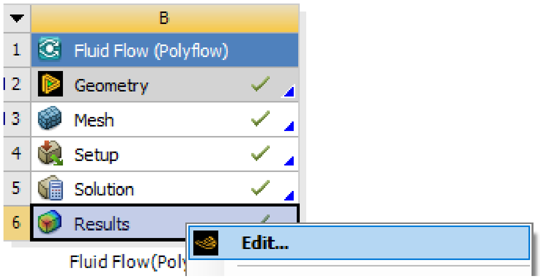


Figure 1.10b) Listing viewer

G. CFD-Post

11. Right click on Results in the Project Schematic and select Edit. Select Insert>>Contour from the menu in CFD-Post and click OK in the Insert Contour window.



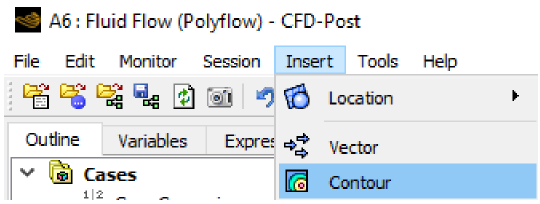


Figure 1.11a) Viewing results Figure 1.11b) Inserting a contour in CFD-Post

12. Select matid_2_surf as Locations in the Geometry Details of Contour 1. Select THICKNESS as Variable. Select Global as Range. Select the Render tab under Details of Contour 1 and uncheck the box for Show Contour lines.

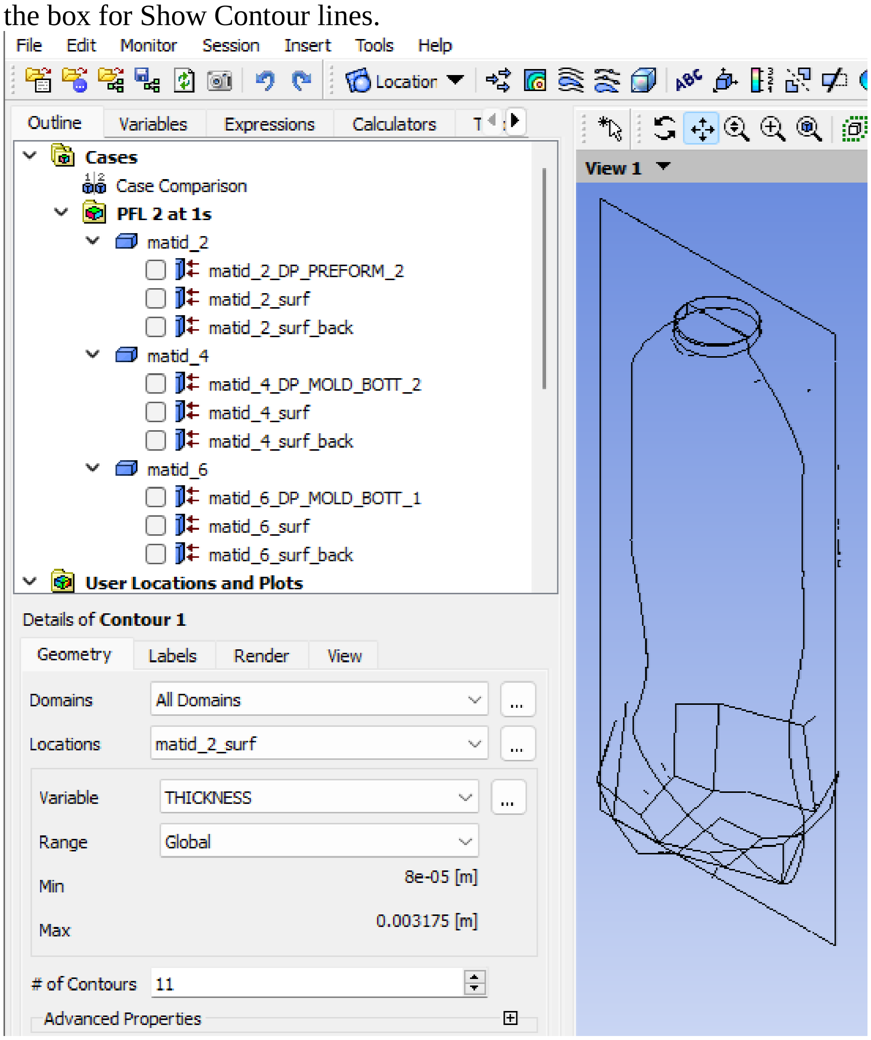


Figure 1.12a) Details of Contour 1

Uncheck the box for Wireframe under User Locations and Plots in the Outline. Click on Apply twice at the bottom left of Details of Contour 1.

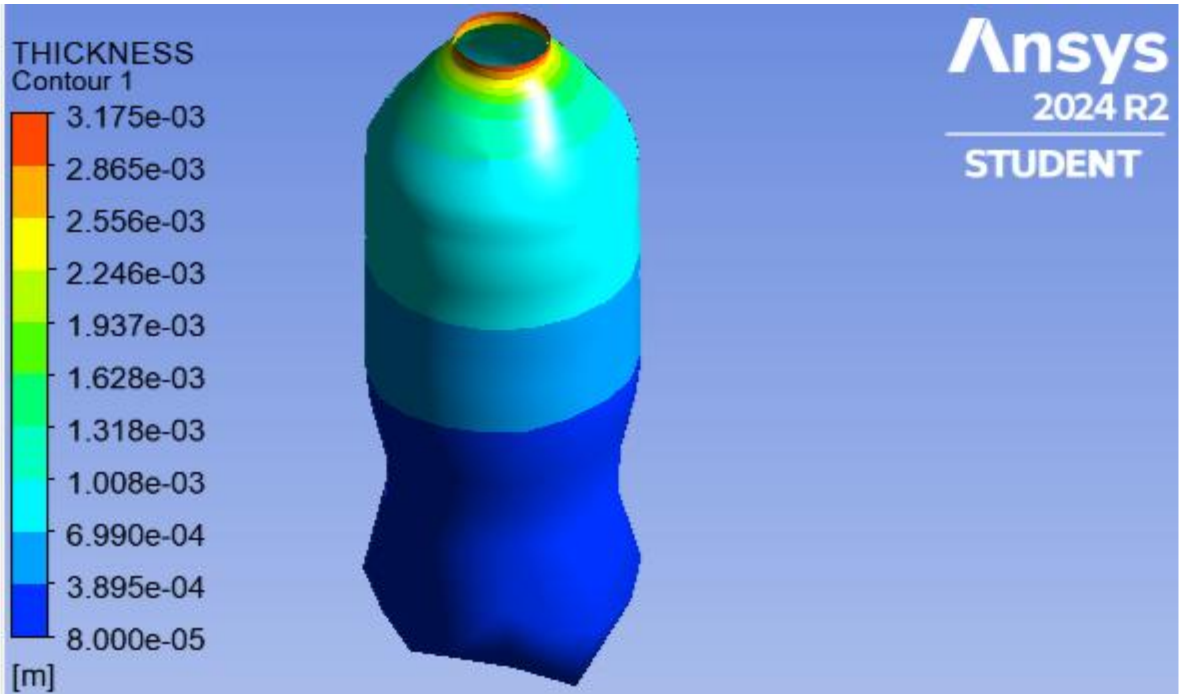


Figure 1.12b) Contours of thickness for blow molded bottle

13. Select the Timestep Selector from the menu. Select Step 1 in the Timestep Selector and click Apply. Repeat this for Steps 15, 20, 25, 30, 35, 40, 45 and 73.

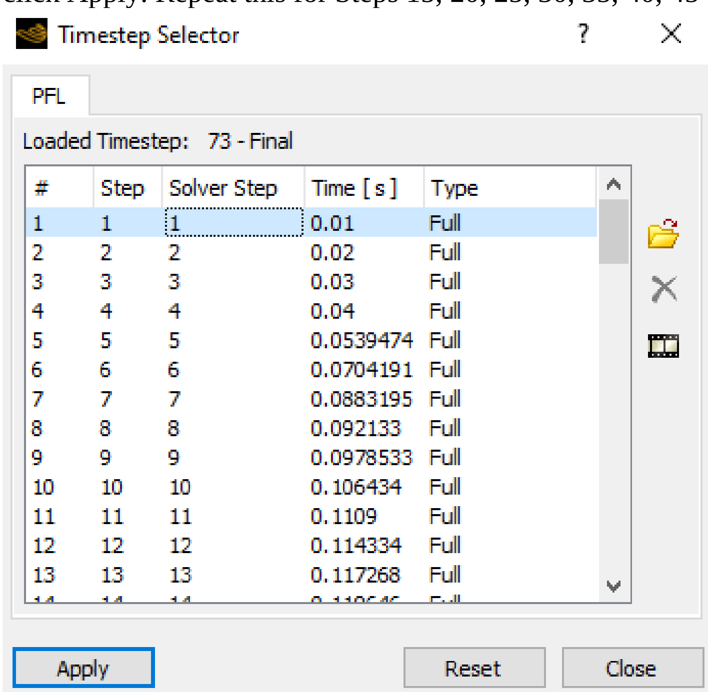


Figure 1.13a) Time selector

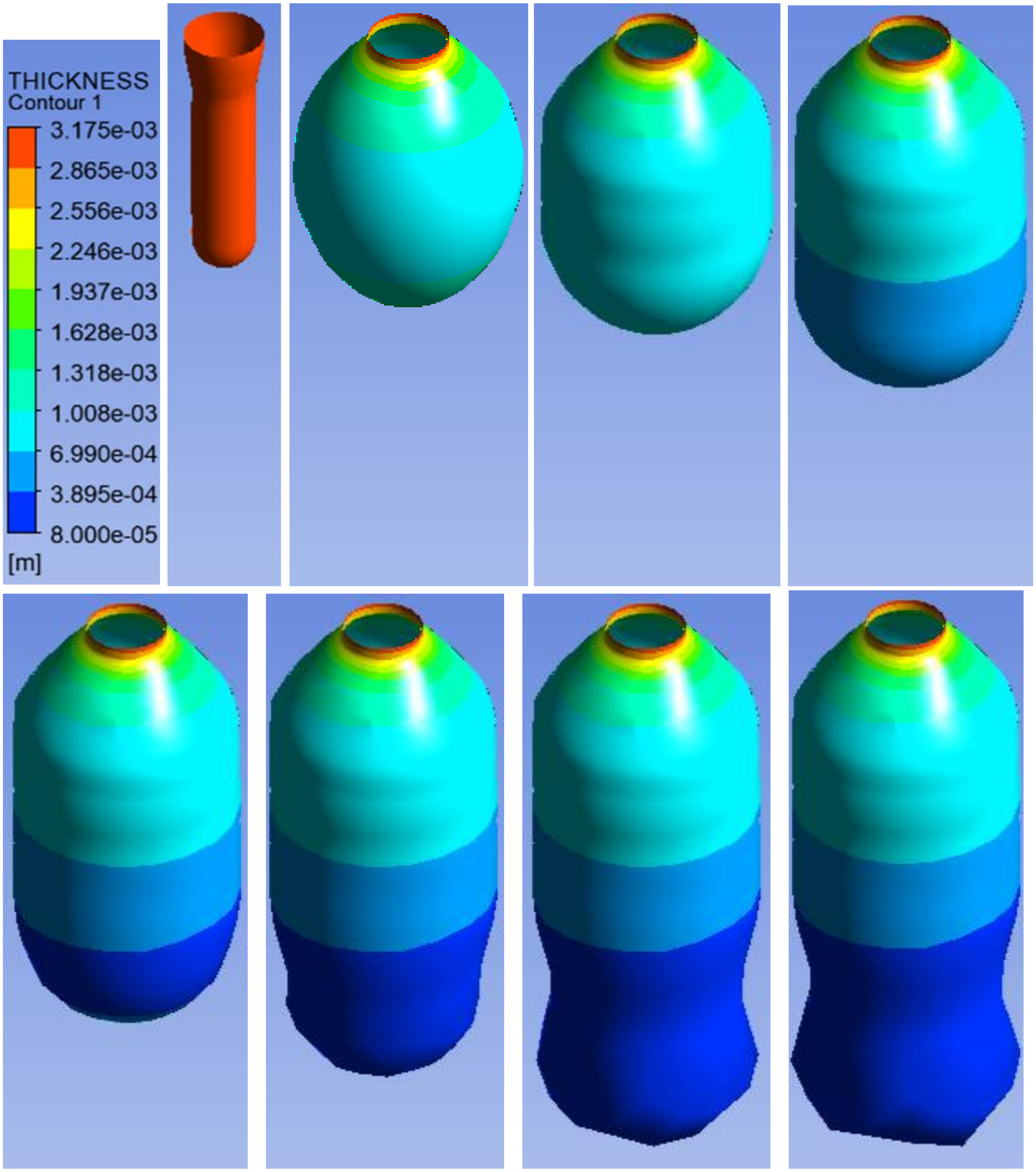


Figure 1.13b) Contours of thickness at steps 1, 15, 20, 25, 30, 35, 40 and 45, t = 0.01 s, 0.12655 s, 0.12796 s, 0.129907 s, 0.131334 s, 0.13243 s, 0.13307 s and 0.133268 s.

14. Select the Animation  from the menu. Select Timestep Animation as Type. Check the box for Save Movie. Browse and save the file with the name *Dr Pepper Bottle Thickness.wmv*. Set Repeat to 1 and click on play. Close the Animation window after completion and Close CFD-Post.

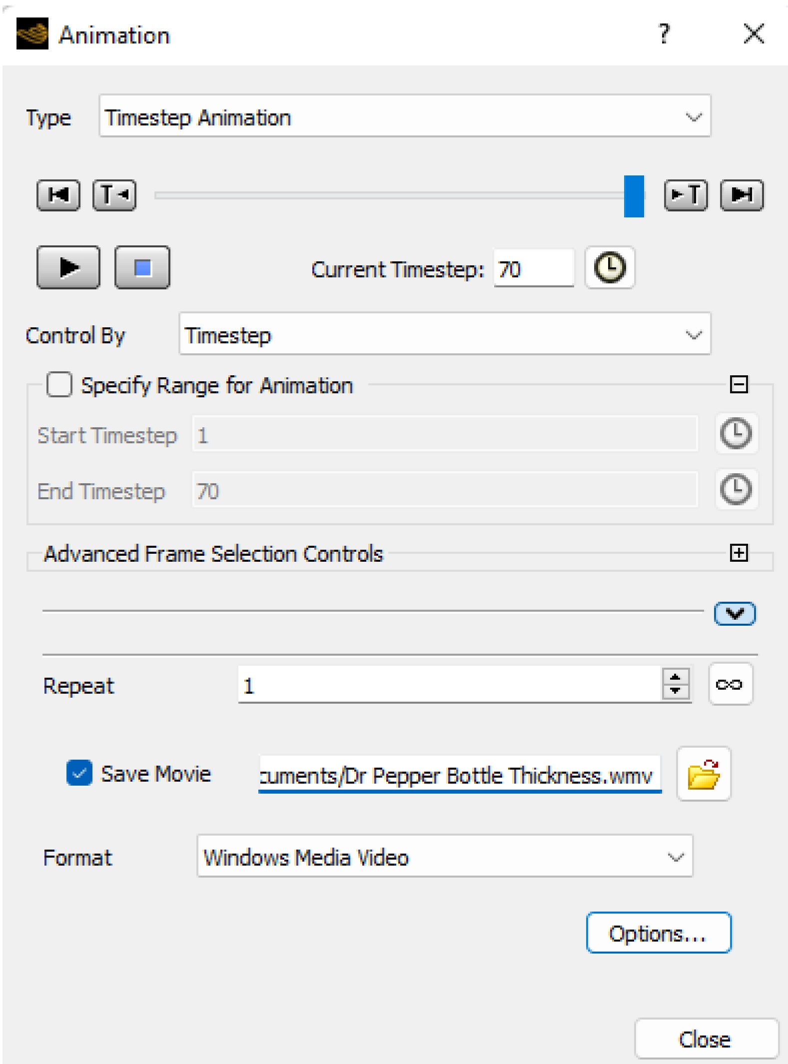


Figure 1.14 Details of animation

H. Refining the Mesh

15. Right click on Setup and select Edit… in the Workbench Project Schematic. Select F.E.M. Task 1 at the bottom of the Polydata window. Select Numerical parameters in the F.E.M. Task 1 window and select Adaptive meshing in the Numerical parameters window. Select Adaptive meshing for contacts in the Adaptive Meshing window. Select Enable all the local criteria in the Global criteria for contact window. Select Switch to 'Global Criteria' mode.

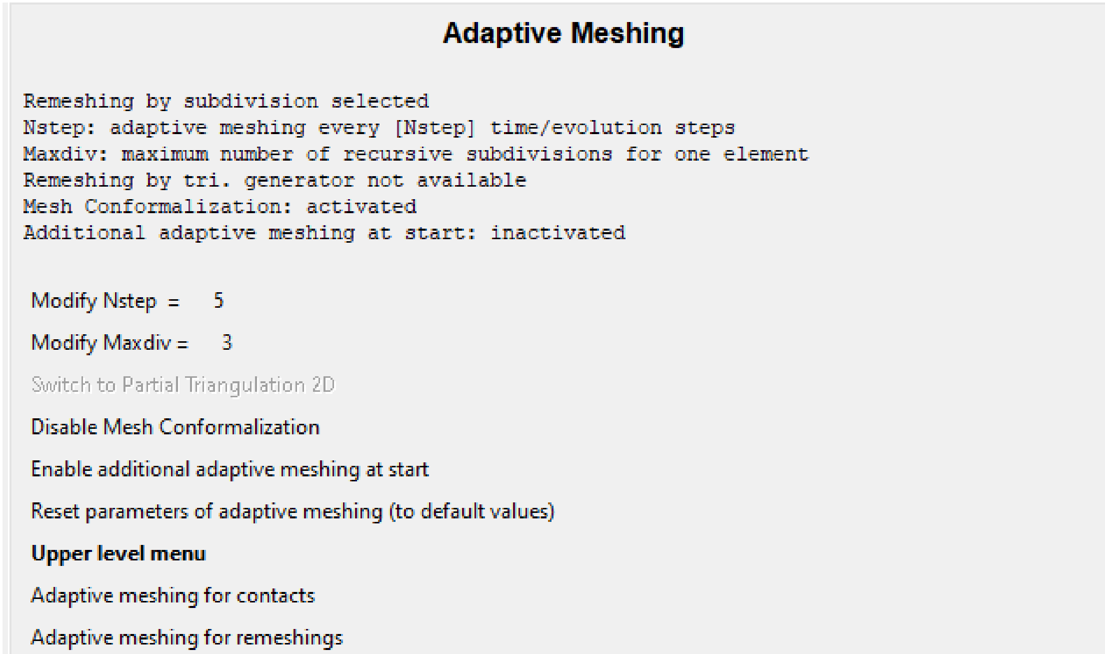


Figure 1.15a) Adaptive meshing

Select Modify size_min and enter 0.0001 as the New value and click OK to close the Request from Polydata window. Set tolerance to 0.00001, size_max to 0.001 and dist_crit to 0.0005. Select Upper level menu.

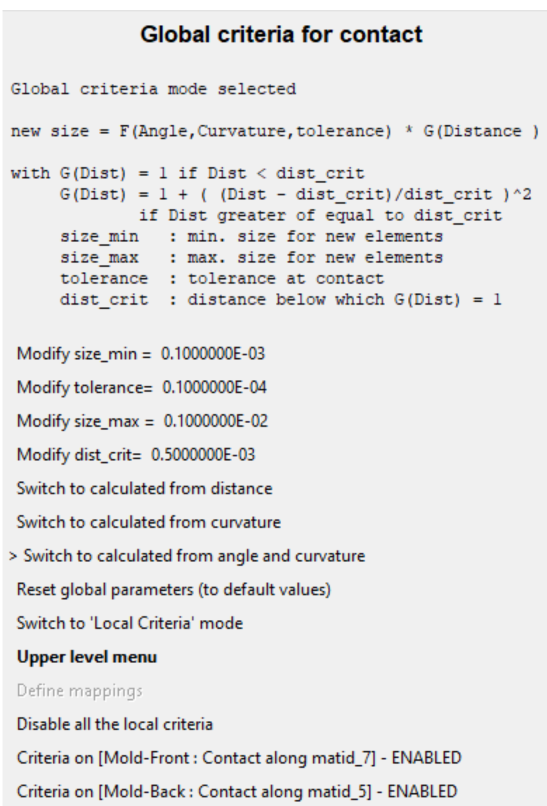


Figure 1.15b) Global criteria for contact

Select Modify Nstep in the Adaptive Meshing window, set New value: to 4 and click OK to close the window. Select Modify Maxdiv and set the value to 3. Select Upper-level menu three times. Select Save and exit, select Next Series and Accept in the Field Management window and select Continue in the Field Management window. Right click on Solution in the Workbench Project Schematic and select Update. Right click on solution and select Listing Viewer…. Check the box for Refresh every and set the time to 5 seconds.

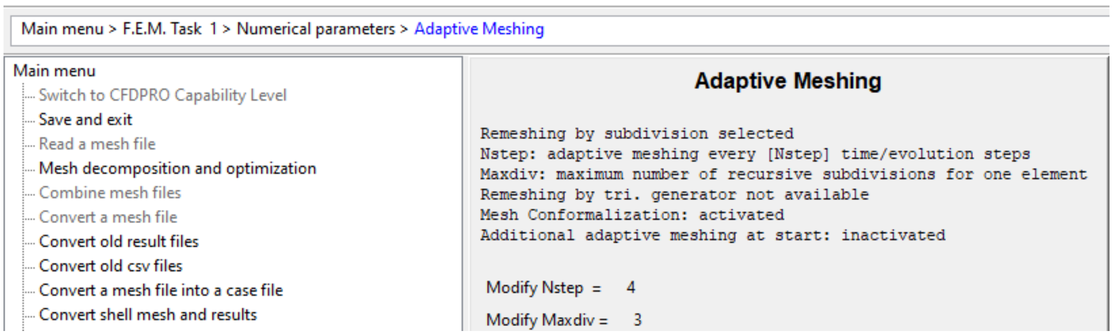


Figure 1.15c) Updated values for adaptive meshing

16. Right click on Results in the Workbench Project Schematic and select Edit…. Double click on Contour 1 under User Locations and Plots in the Outline.

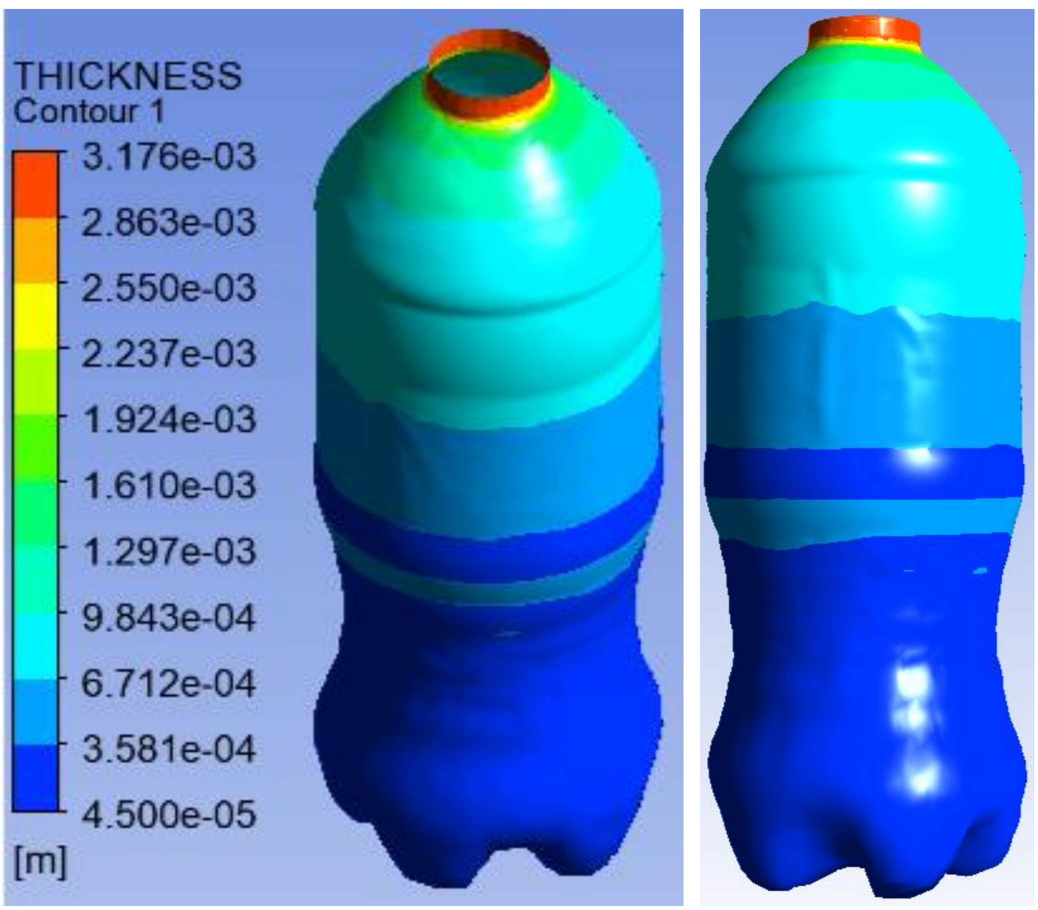


Figure 1.16b) Refined mesh thickness contour plots from isometric and side views

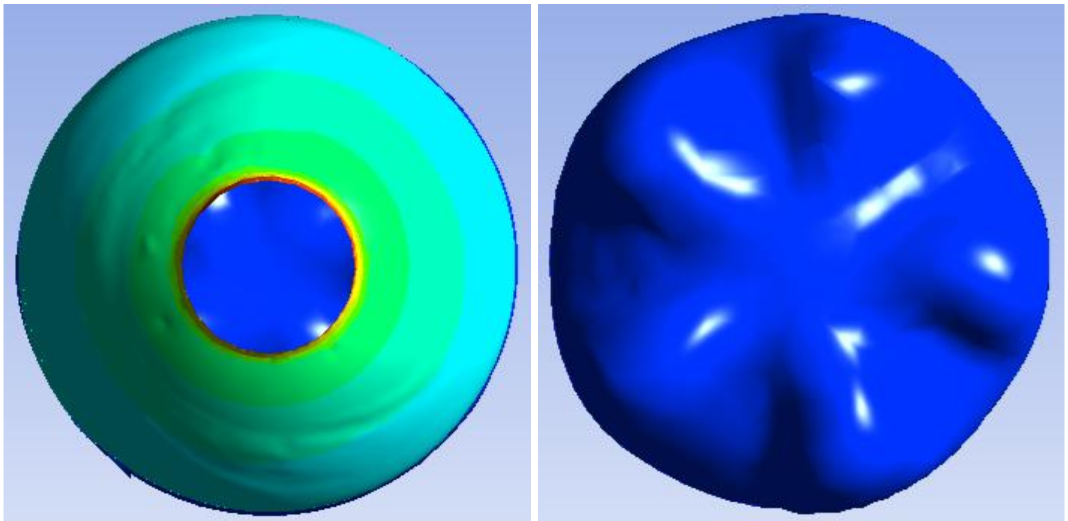


Figure 1.16b) Refined mesh thickness contour plots from top and bottom views

17. Select the Animation  from the menu. Select Timestep Animation as Type. Check the box for Save Movie. Browse and save the file with the name *Dr Pepper Thickness Refined Mesh.wmv*. Set Repeat to 1 and click on play. Close the Animation window after completion of the movie.

    Select Insert>>Clip Plane from the menu. Accept the Name Clip Plane 1 and click OK to close the Insert Clip Plane window. Select XY Plane as Method and set the X value in [m] to 1.3405 in Details of Clip Plane 1. Select Apply, right click in the graphics window and select Clip Scene>>Clip Plane 1.

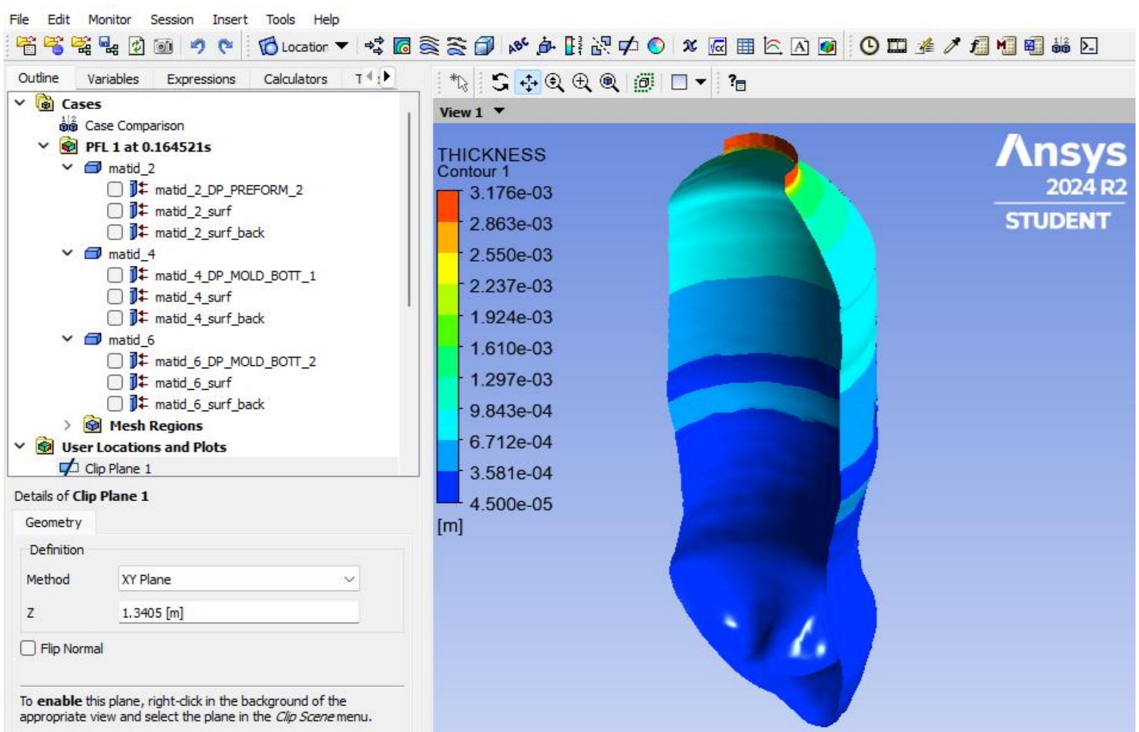


Figure 1.17 Inserted clip plane

18. Select Insert>>Location>>Iso Clip from the menu. Accept the Name Iso Clip 1 and click OK to close the Insert Iso Clip window. Select matid_2_surf from the drop-down menu next to Locations. Right click in the rectangular area under Visibility parameters and select New. Select THICKNESS as Variable under Visibility Parameters Properties and Visible where >= 0 [m]. Select the Render tab under Details of Iso Clip 1. Check the box to Show Mesh Lines and click on Apply.

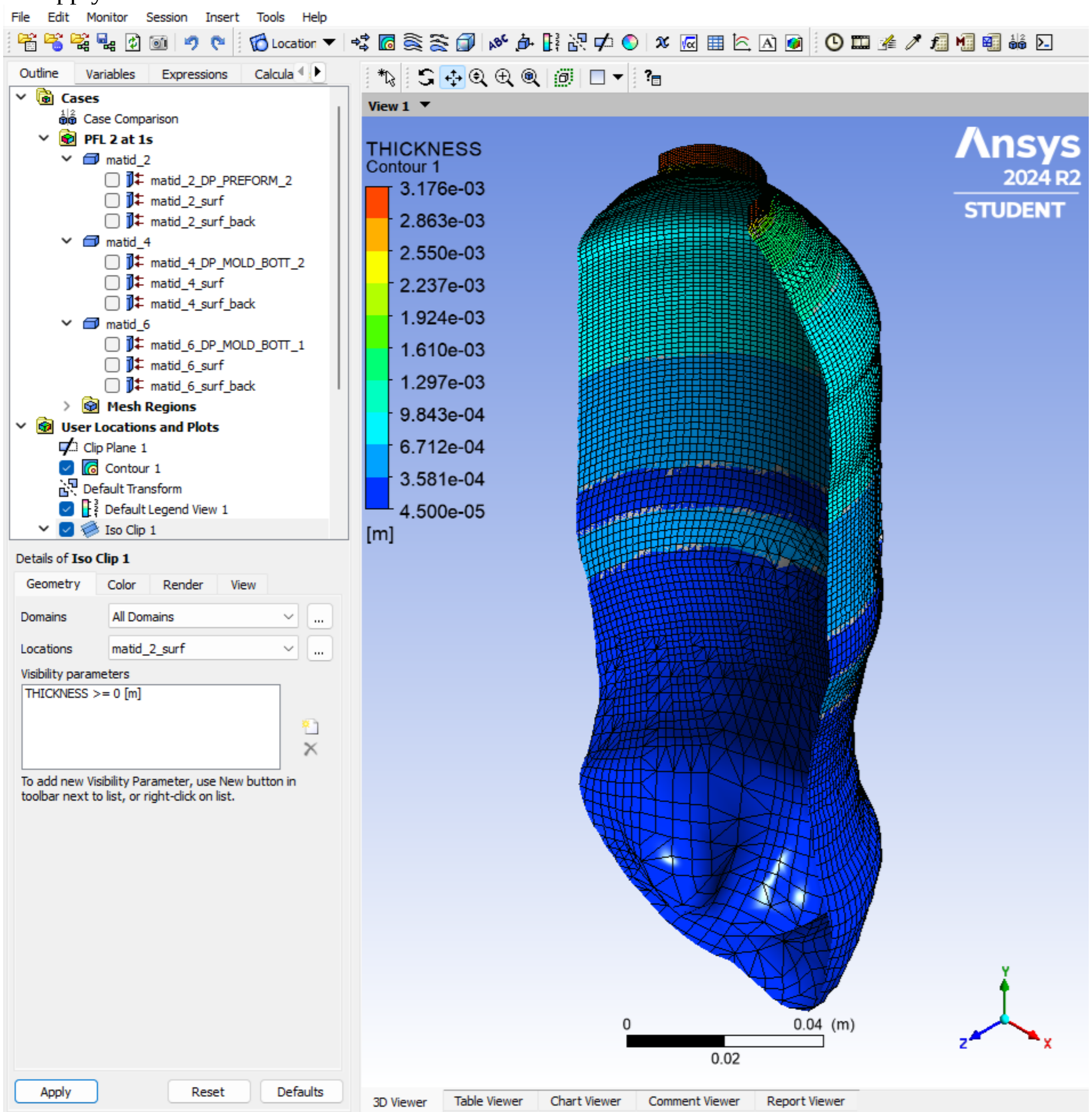


Figure 1.18 Inserted clip plane

Select Insert>>Location>>Plane from the menu. Accept the Name Plane 1 and click OK to close the Insert Plane window. Select matid_2 from the drop-down menu next to Domains. Select XY Plane as Method and set Z to 1.3405 [m] under Definition. Set Plane Type as Slice and Type as None under Plane Bounds. Select the Render tab under Details of Plane 1. Uncheck the box for Show Mesh Lines and click on Apply.

19. Select Insert>>Location>>Point Cloud from the menu. Accept the Name Point Cloud 1 and click OK. Select matid_2 as Domains and select From Locations as Method under the Geometry tab. Select Plane 1 as Locations under Details of Point Cloud 1. Set # of Points to 1000 and set Sampling to Equally Spaced. Select the Color tab and set the color to black. Select the Symbol tab and choose Ball as symbol and set the Symbol Size to 0.15. Select Apply.

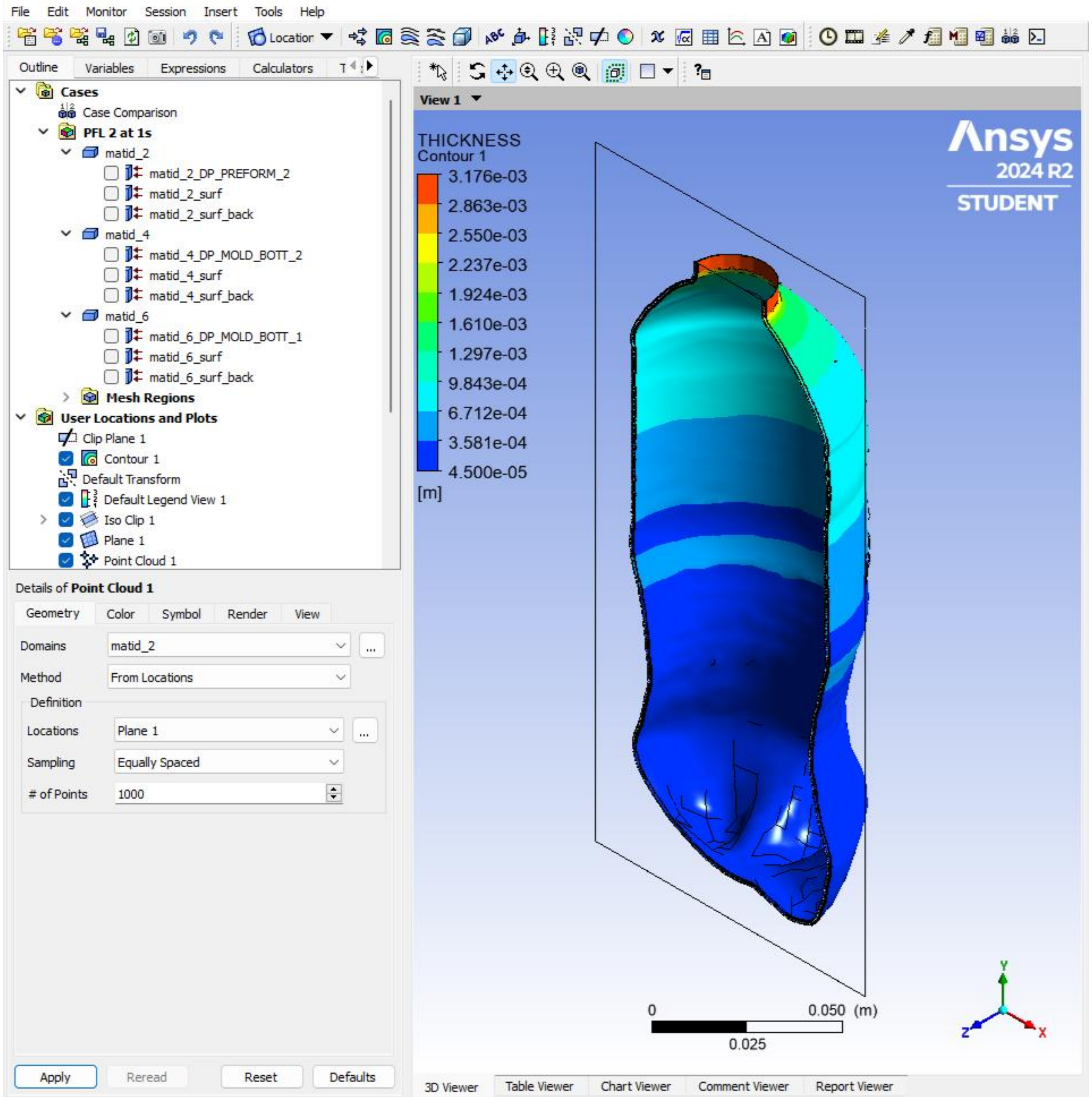


Figure 1.19a) Inserted point cloud

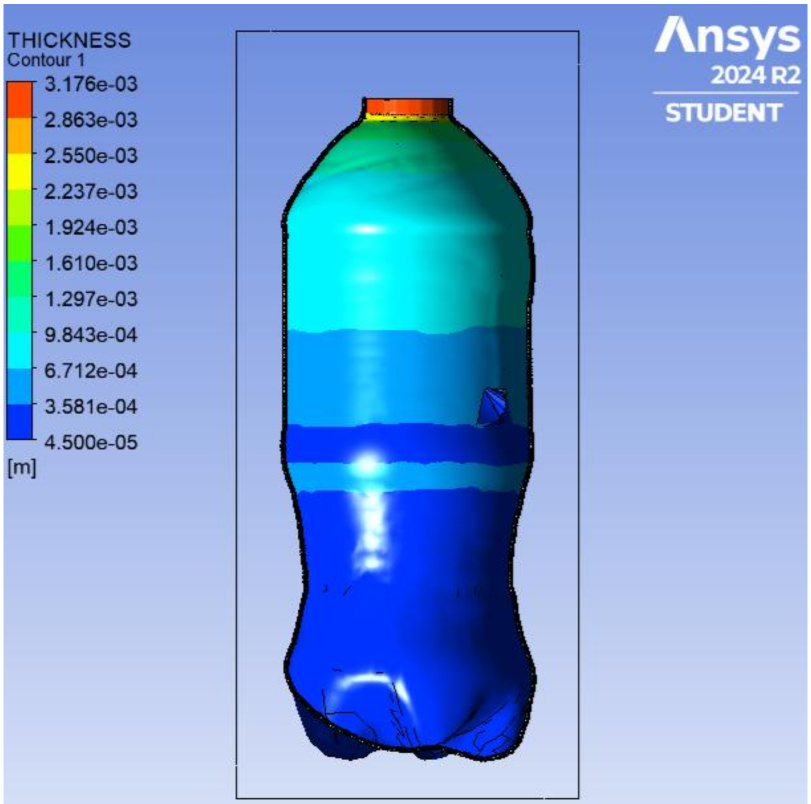


Figure 1.19b) Point cloud in XY plane

20. Select File>>Export>>Export… from the menu. Select Point Cloud 1 as Locations and THICKNESS as variable. Check the boxes for Line and Face Connectivity and Node Numbers. Enter *DrPepperthickness* as Name Aliases. Click on Save to save the file with name *export.csv*.

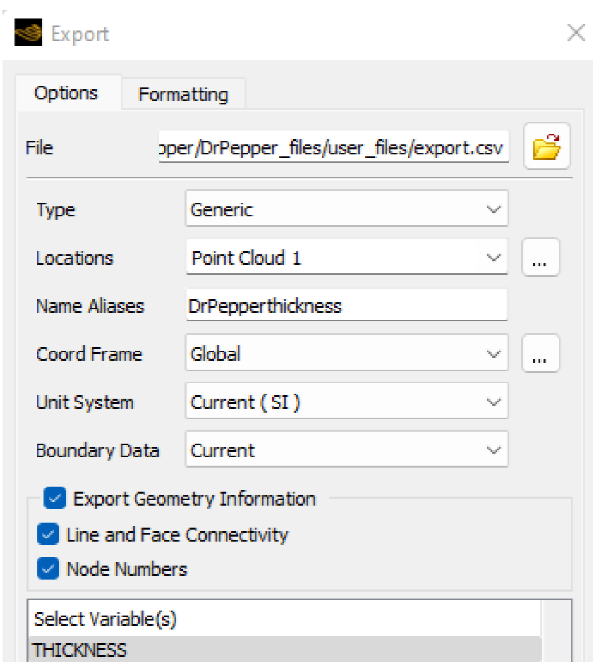


Figure 1.20 Exporting point cloud

21. Open the file *export.csv* in Excel. Save the file as an Excel Workbook with the name *DrPepperthickness.* Delete the first five rows. Select column C and select Sort Smallest to Largest above Editing under the Home tab. Select Expand the selection in the Sort Warning window and select Sort.
Enter *x* [mm] in cell E1 and enter =(B2-0.5*(B953+B954))*1000 in cell E2. Drag this cell down the E column.

Enter *y* [mm] in cell F1 and enter =(C2-C2)*1000 in cell F2. Drag this cell down the F column.

Enter *h* [mm] in cell G1 and enter =D2*1000 in cell G2. Drag this cell down the whole G column, see Figure 1.21a).

Select columns E and F, *x* [mm] and *y* [mm], and select Insert>>Scatter>>Scatter from the menu in Excel. Insert Axis Titles labeled *x* [m] on the horizontal axis and *y* [m] on the vertical axis, see Figure 1.21b).

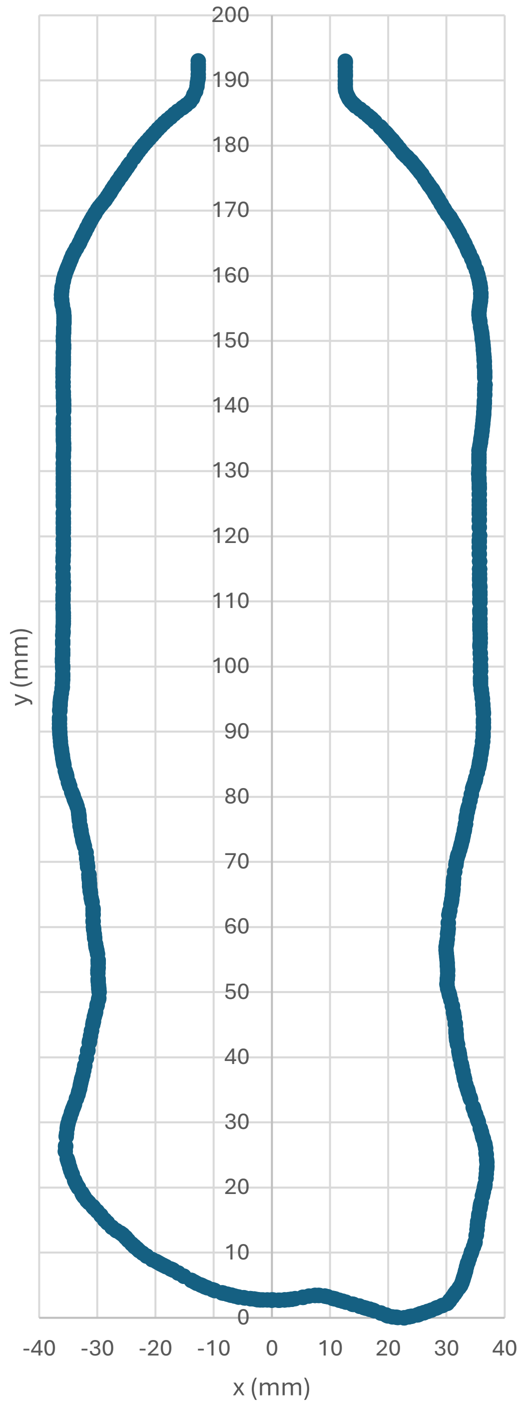
Control select columns E and G, *x* [mm] and *h* [mm], and select Insert>>Scatter>>Scatter from the menu in Excel. Insert Axis Titles labeled *x* [m] on the horizontal axis and *h* [m] on the vertical axis, see Figure 1.21c).

Copy column F to column H. Select columns G and H, *h* [mm] and *y* [mm], and select Insert>>Scatter>>Scatter from the menu in Excel. Insert Axis Titles labeled *h* [m] on the horizontal axis and *y* [m] on the vertical axis, see Figure 1.21d).

Use Mathematica or Matlab to plot 3D scatter plot of *h* versus *x* and *y* as shown in Figure 1.21e).

	A	B	C	D	E	F	G	H
1	Node Number	*X* [m]	*Y* [m]	*THICKNESS* [m]	*x* [mm]	*y* [mm]	*h* [mm]	*y* [mm]
2	194	0.7412	0.8222	5.2378E-05	22.7173	0.0000	0.0524	0.0000
3	191	0.7412	0.8222	5.2378E-05	22.7173	0.0005	0.0524	0.0005
4	190	0.7401	0.8223	5.3451E-05	21.6066	0.0462	0.0535	0.0462
5	187	0.7399	0.8223	5.3763E-05	21.3290	0.0793	0.0538	0.0793
6	196	0.7420	0.8224	5.1970E-05	23.4810	0.1385	0.0520	0.1385
7	186	0.7392	0.8224	5.4399E-05	20.7041	0.1509	0.0544	0.1509
8	195	0.7422	0.8224	5.1922E-05	23.7173	0.1799	0.0519	0.1799
9	200	0.7426	0.8225	5.1694E-05	24.0366	0.2384	0.0517	0.2384
10	182	0.7384	0.8225	5.5753E-05	19.9136	0.3118	0.0558	0.3118
11	181	0.7382	0.8226	5.6466E-05	19.6849	0.3882	0.0565	0.3882
12	180	0.7381	0.8226	5.6496E-05	19.6085	0.4131	0.0565	0.4131
13	202	0.7435	0.8227	5.1192E-05	24.9572	0.4410	0.0512	0.4410
14	201	0.7437	0.8227	5.0979E-05	25.1795	0.5063	0.0510	0.5063
15	207	0.7441	0.8228	5.0749E-05	25.5490	0.6179	0.0507	0.6179

Figures 1.21a) Bottle data



Figures 1.21b) Bottle *x*, *y* coordinates

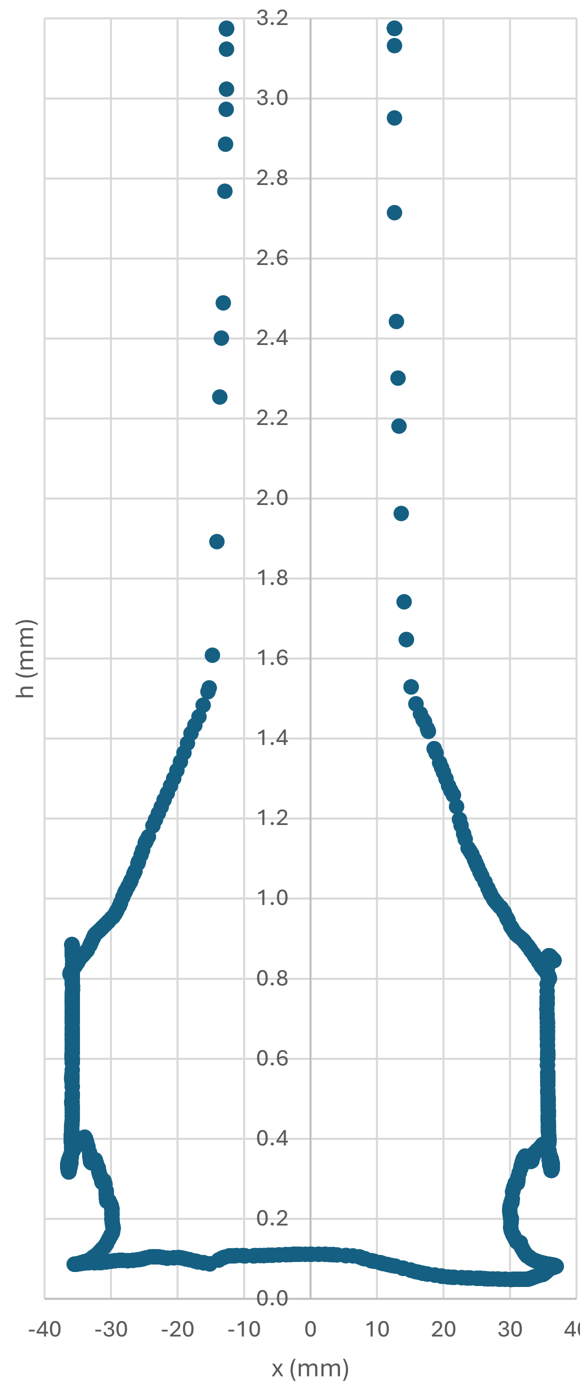
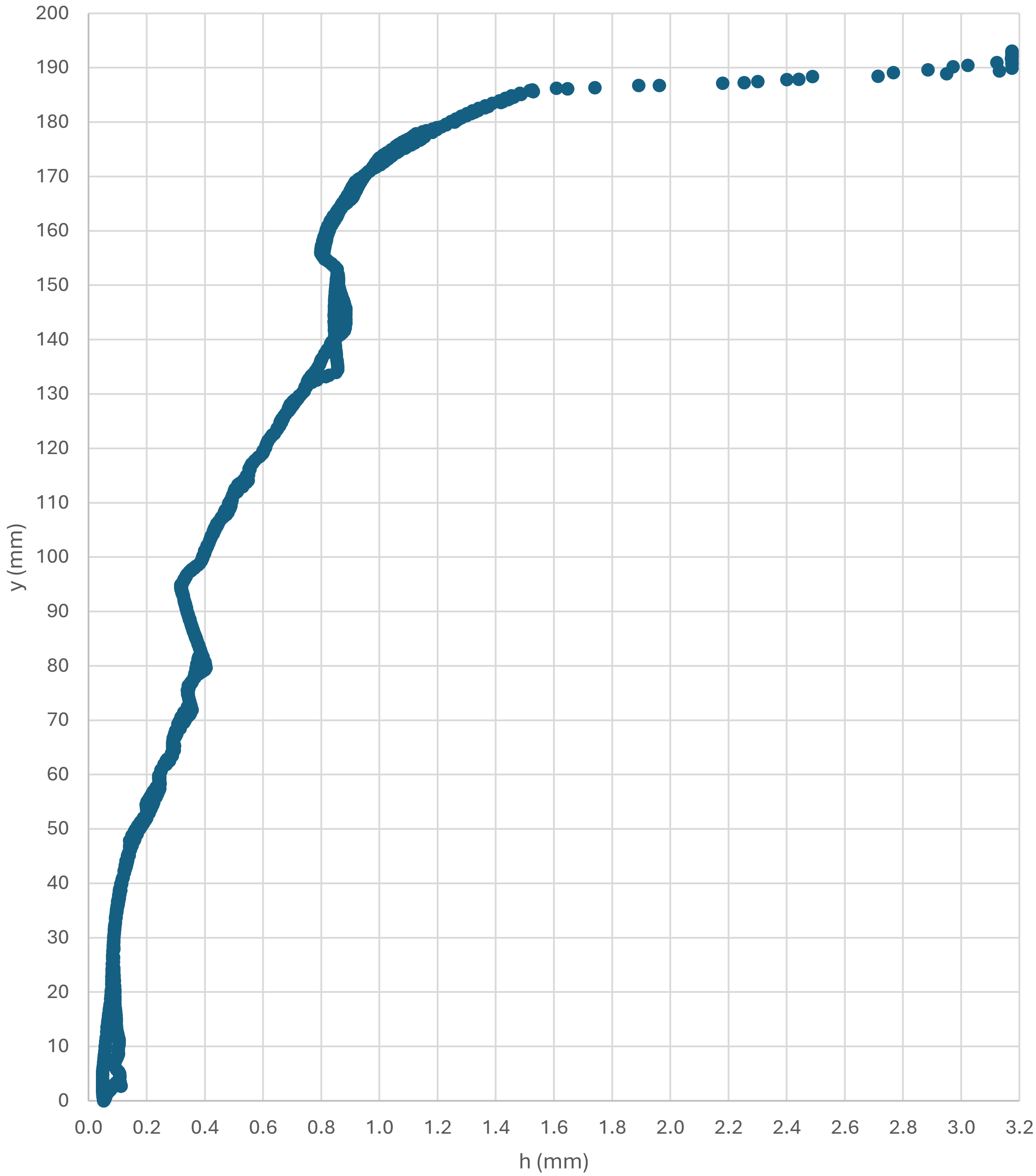
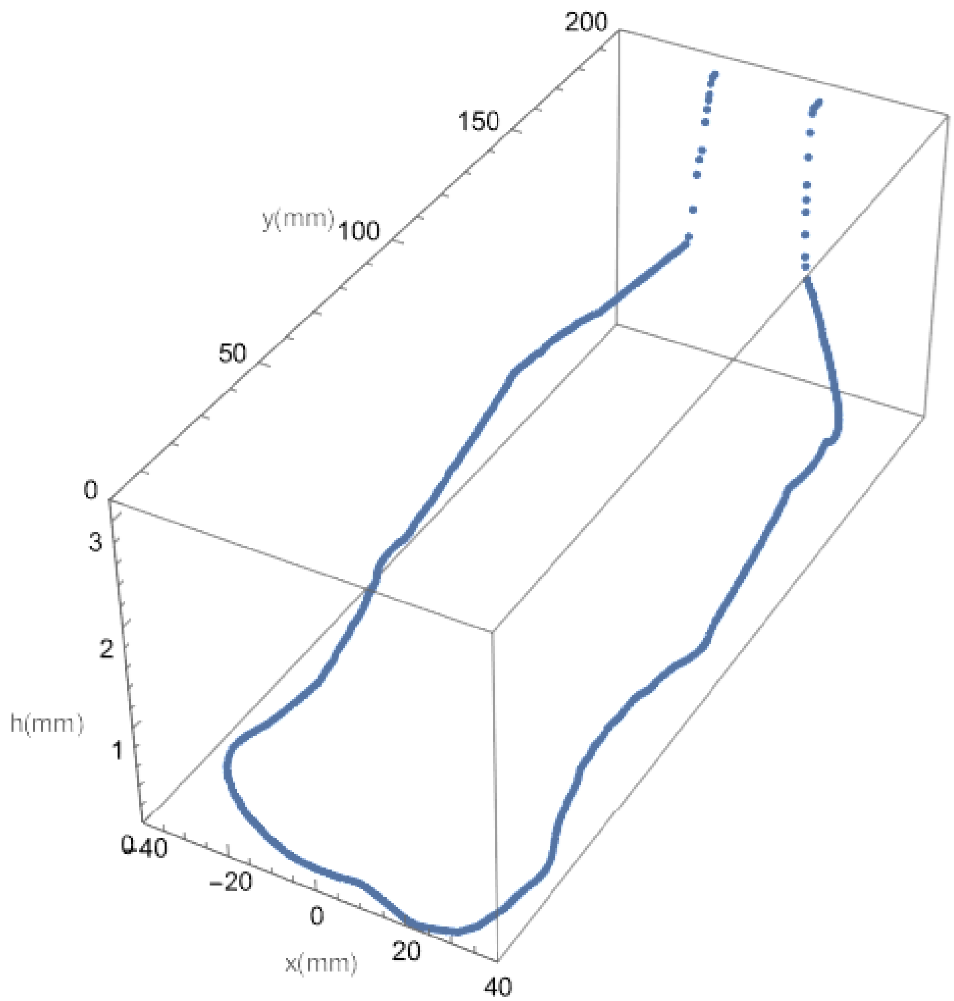


Figure 1.21c) Wall thickness *h* versus *x* coordinate



Figures 1.21d) Wall thickness *h* versus *y* coordinate



Figures 1.21e) Bottle *x, y* coordinates and wall thickness *h* distribution.

Copy columns E – G from the Excel document and paste the values in another Excel Sheet1 in the same document. Select the A column with *x* [mm] data in the new sheet and Sort from Smallest to Largest. Select Expand the selection in the Sort Warning window and select Sort.

Copy all three columns (*x*, *y*, and *h*) with data corresponding to negative *x* values in the A column and include the row of data for *x* [mm] = 0.0007 following the negative *x* values. This corresponds to 460 rows with data. Paste these three columns of copied data into another new Sheet2 in the same document. Select the B column with *y* [mm] data in Sheet2 and Sort from Largest to Smallest. Select Expand the selection in the Sort Warning window and select Sort. Enter *L* [mm] in cell D1 in Sheet2 of the same Excel document and enter 0 in cell D2.

Enter =D2+SQRT((A3-A2)^2+(B3-B2)^2) in cell D3. Drag cell D3 down the whole column D.

Go back to Sheet1 in the same document, copy rows with data from x [mm] 0.1738 to 12.1918. Move to Sheet2 and paste the copied data from Sheet1 at the end of Sheet2. Drag the D column of data all the way to the end of data.

Go back to Sheet1 in the same document, copy all the remaining rows with data from *x* [mm] 12.6043 to 36.9493. Create a new Sheet3 in the same document and paste the copied data from Sheet1 to Sheet3. Select the B column with *y* [mm] data in Sheet3 and Sort from Largest to Smallest. Select Expand the selection in the Sort Warning window and select Sort.

Copy all the rows with data in Sheet 3 from *y* [mm] 192.9770 to 2.5982. Create a new Sheet4 and paste the data in Sheet 4. Select the B column with *y* [mm] data in Sheet4 and Sort from Smallest to Largest. Select Expand the selection in the Sort Warning window and select Sort.

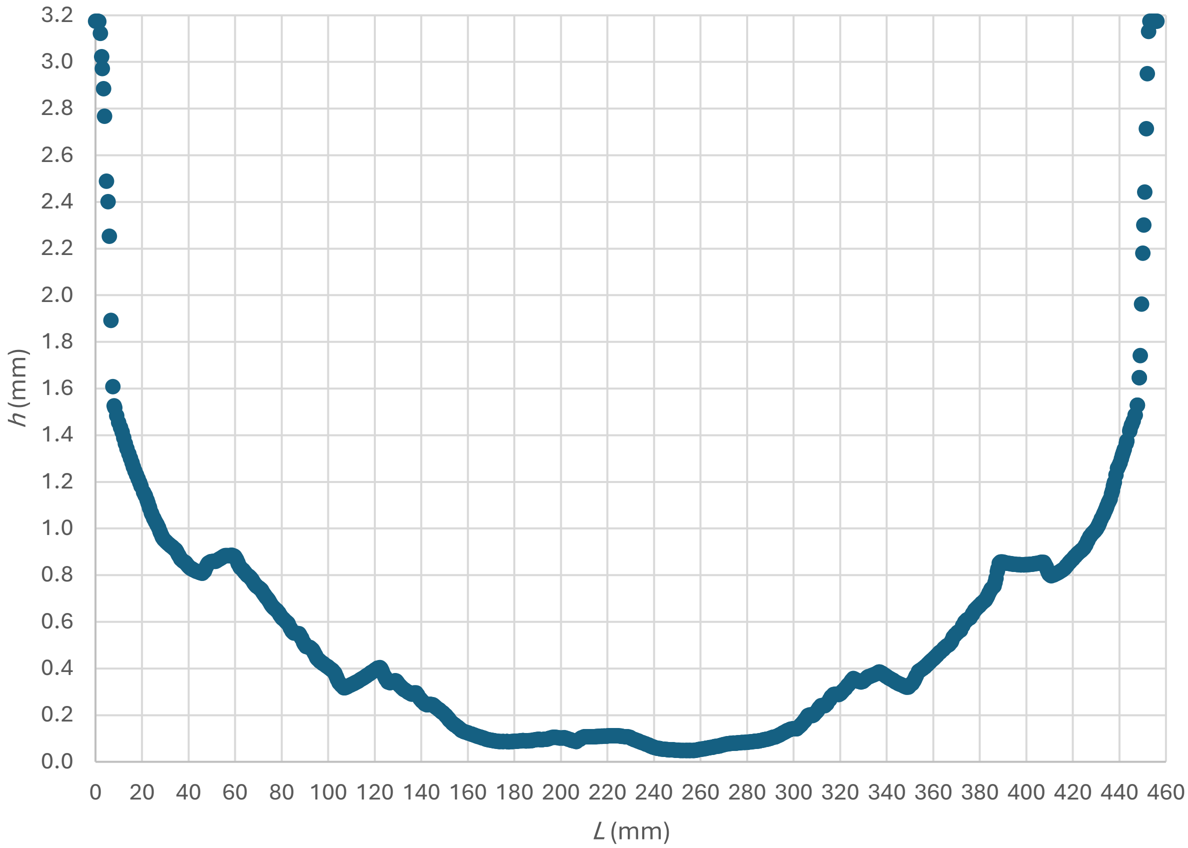
Go back to Sheet3 and delete the data that you copied to Sheet4. Select Shift Cells Up when deleting the selected data. Select column A with the remaining *x* data in Sheet3 and Sort from Smallest to Largest. Select Expand the selection in the Sort Warning window and select Sort. Copy the sorted data rows and paste these at the end of Sheet2. Drag the D column of data all the way to the end of data.

Go back to Sheet4 and copy the data. Paste the copied data at the end of Sheet2. Drag the D column of data all the way to the end of data in Sheet2. Copy column C to column E in Sheet2.

Select columns D and E in Sheet2, *L* [mm] and *h* [mm], and select Insert>>Scatter>>Scatter from the menu in Excel. Insert Axis Titles labeled *x* [m] on the horizontal axis and *h* [m] on the vertical axis, see Figure 1.21c).

	A	B	C	D	E
1	*x* [mm]	*y* [mm]	*h* [mm]	*L* [mm]	*h* [mm]
2	-12.6401	193.0279	3.1749	0.0000	3.1749
3	-12.6396	192.4688	3.1748	0.5591	3.1748
4	-12.6407	192.0878	3.1748	0.9401	3.1748
5	-12.6399	191.6561	3.1729	1.3719	3.1729
6	-12.6407	190.9450	3.1229	2.0829	3.1229
7	-12.6636	190.4280	3.0229	2.6005	3.0229
8	-12.6955	190.1633	2.9723	2.8670	2.9723
9	-12.7971	189.6275	2.8856	3.4124	2.8856
10	-12.8809	189.0886	2.7673	3.9577	2.7673
11	-13.1076	188.3572	2.4888	4.7235	2.4888
12	-13.4034	187.8017	2.4010	5.3529	2.4010
13	-13.6539	187.2417	2.2536	5.9663	2.2536
14	-14.0801	186.7108	1.8918	6.6472	1.8918
15	-14.7469	186.2260	1.6083	7.4715	1.6083
16	-15.2466	185.9053	1.5263	8.0653	1.5263
17	-15.4216	185.7869	1.5172	8.2766	1.5172
18	-16.1535	185.2865	1.4830	9.1632	1.4830
19	-16.7920	184.8289	1.4545	9.9487	1.4545
20	-17.3903	184.3775	1.4329	10.6982	1.4329
21	-17.9630	183.9209	1.4129	11.4307	1.4129
22	-18.5192	183.4590	1.3881	12.1536	1.3881
23	-19.0605	182.9916	1.3639	12.8689	1.3639
24	-19.5865	182.5189	1.3415	13.5760	1.3415
25	-20.0973	182.0428	1.3200	14.2743	1.3200

Figures 1.21f) Data with bottle coordinates *x*, *y*, thickness *h* and length *L* along the bottle.



Figures 1.21g) Bottle thickness *h* versus length *L* along and around the bottle cross section measured from bottleneck with negative *x* value to bottleneck with positive *x* value, see Figure 1.21b).

Select Functions Calculator  from the menu in CFD-Post. Select area as Function in the Function Calculator and choose matid_2_surf as Location. Check the box for Clear previous results on calculate. Click on Calculate. Results show the Area on matid_2_surf as 0.0437115 [m^2].

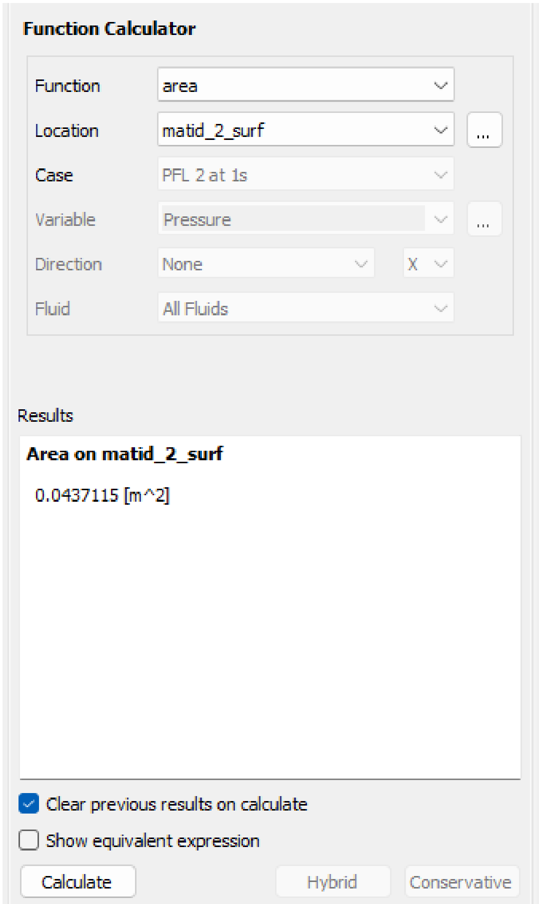


Figure 1.21h) Calculated bottle surface area

I. Theory

22. The Aerial Draw Ratio *ADR* is the overall stretching of the preform. The *ADR* > 1 is determined from the Surface Area of the Formed Bottle *SAFB* divided by the original Surface Area of the Preform *SAP* that was used to form the bottle.

$$ADR = SAFB / SAP \tag{1}$$

The maximum values of *ADR* for different plastics are shown in Table 30.1. We see from this table that the plastic Polystyrene *PS* has the highest max *ADR* of all plastics listed.

Plastic	**Maximum *ADR***
ABS	5.5
Acrylic	3.4
HDPE	6.5
LDPE	6.0
PP	7.5
Polystyrene PS	8.0
PVC	4.3

Table 32.1 Maximum aerial draw ratio for different plastics

The Average Thickness Reduction *ATR* is

$$ATR = 1 / ADR \quad (2)$$

Another draw ratio is the Linear Draw Ratio *LDR*. This ratio compares the length of the symmetry line on the preform before and after blow molding.

$$LDR = LFB / LBF \quad (3)$$

where *LFB* is the line length on formed bottle and *LBF* is the line length before forming.

J. References

1. Bordival M., Schmidt F., Le Maoult Y. and Velay V., "Simulation of the Two Stages Stretch-Blow Molding Process: Infrared Heating and Blowing Modeling", NUMIFORM 2007 – 9th International Conference on Numerical Methods in Industrial Forming Processes, Porto, Portugal, June 2007.
2. Daver F. and Demirel B., "A Simulation Study of the Effect of Preform Cooling Time in Injection Stretch Blow Molding", Journal of Materials Processing Technology, 212, 2400-2405, 2012.
3. Gupta S, Uday V., Raghuwanshi A.S., Chowkshey S., Das S.N., and Suresh S, "Simulation of Blow Molding Using Ansys Polyflow", APCBEE Procedia 5, 468-473, 2013.
4. Hassan Y.R., Farahaty M.A., Ibrahim S.I. and Nassar M.A, "Design and Producing Blowing Mold Using Additive Manufacturing", International Design Journal Vol. 9: Iss. 4, Article 6, 2019.
5. Kadam A.V., Patel S. and Vajir A., "Simulation of Blow Molding of Polyethylene Bottle Using Ansys Polyflow", International Research Journal of Engineering and Technology (IRJET), Vol. 6: Iss. 4, April, 2019.
6. Lontos A. and Gregoriou A., "A Numerical Investigation of the Effect of Preform Length for the Fabrication of 1.5 Lt PET Bottle Through the Injection Stretch Blow Molding Process", MATEC Web of Conferences 188, 01021, 2018.
7. Lontos A. and Gregoriou A., "The Effect of Deformation Rate on the Wall Thickness of 1.5 LT PET bottle during ISBM (Injection Stretch Blow Molding) Process", Procedia CIRP 81, 1307-1312, 2019.
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Appendix 3: Table with Project Cost for Blow Molding Project

Vendor	**Quantity**	**Item Description**	**Item # or Model #**	**Price**
Amazon	1	Thermocouple	68022_2P	$29.99
Harbor Freight	2	C-clamps	SKU: 37850	$6.99
Amazon	1	Wire Gauze	WGCC66	$19.28
Amazon	2	3D printing rolls	3D PLA-1KG1.75-BLK	$25.99
Amazon	2	Sharpies	00071641301016	$2.49
Walmart	1	Gallon of Antifreeze Concentrate	AF2100	$9.98
Amazon	1	Hot Plate with Magnetic Stirrer	B0CP21XCJM	$58.99
Amazon	1	500 mL Beaker	B006VYXZ88	$8.99
Harbor Freight	1	Air Hose	60356, 54147, 6194	$7.99
eBay	1	PET Preforms	TRTV2046	$33.39
Harbor Freight	2	IR Thermometers	63985, 64310, 64626	$22.99
Amazon	1	Rubber Adapter	40051	$13
Amazon	1	Ring Clamp set	B08N14D1VB	$12.99
Amazon	1	Fume Extractor	B0D1TSZQKK	$251.99
			Total	**$564**