FABRICATION OF VACUUM FORMING MACHINE

A Final Year Project Report

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Bachelor of Mechanical Engineering

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ABSTRACT

Vacuum forming machines are widely used in the advertising industry for making 3D signage, packaging industry for packing different components such as plastic casing for headphones etc. and orthotics parts in the medical field. The machine is available worldwide but is very expensive.

This thesis aimed to develop a cost-effective Vacuum Forming Machine that can form ABS, HIPS, and acrylic material in a vacuum forming process. The design was achieved through reverse engineering and integration of high vacuum system, smart sensors, and a simple user interface. The machine can form complex 3D parts with high accuracy and consistency. Production of the machine involved outsourcing part and sub-assemblies to various mechanical fabrication shops. The development of this machine strengthens the industry-university linkages and fosters cooperation. This locally developed machine has potential for export and can be repaired in Pakistan, creating jobs and improving the quality of formed parts.

ACKNOWLEDGMENTS

First and foremost, praises to Almighty Allah for granting us the knowledge, persistence and courage to complete this project.

This a great pleasure to express our gratitude to our supervisor, Dr. Mian Ashfaq Ali PhD. and Associate Professor, School of Mechanical and Manufacturing Engineering, National University of Sciences and Technology (NUST), for giving us the opportunity and providing invaluable guidance throughout this project.

We pay co-hearted thanks to Dr. Jawad Aslam and Fazal Badshah for their guidance during the project.

Finally, we are extremely grateful to our parents for their love, prayers, and sacrifices for our education and it was their support that enabled us to finish this project.

ORIGINALITY REPORT

We hereby declare that no portion of the work of this project or report is a work of plagiarism and the workings and findings have been originally produced. The project has been done under the supervision and guidance of Dr. Mian Ashfaq Ali and has not been a support project of any similar work serving towards and similar degree requirements from any institute. Any reference used in the project has been cited and we take responsibility if found otherwise.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABBREVIATIONS

HDPE	High Density Polyethylene
PP	Polypropylene
PC	Polycarbonate
LS	Limit Switch

NOMENCLATURE

d_{min}	Minimum shaft diameter required
E	Modulus of Elasticity of Mild Steel
UTS	Ultimate Tensile Strength of Mild Steel

CHAPTER 1: INTRODUCTION

1.1 Introduction:

Vacuum forming is a cost-effective plastic molding technique that has been used globally for many years. It involves heating a plastic sheet and placing it on a customized mold before applying vacuum, which forces the sheet to adopt the required shape. This technique can produce permanent 3D parts with complex curves accurately and consistently, which cannot be made manually. Vacuum forming machines are widely used in the advertising, packaging, and medical industries.

State-of-the-art vacuum forming machines combine high vacuum systems, smart sensors, adjustable gripping systems, quartz heating systems, and a user-friendly interface. They are designed to be easy to operate by unskilled operators. Although vacuum forming does have some limitations, its economic benefits and versatility make it a critical and simple plastic molding process.

1.2 Problem Statement:

The aim of this project is the design and development of a vacuum forming machine. The vacuum forming process is essential for the creation of 3D parts with complex contours and curves, but the high cost of existing machines limits their accessibility to small businesses in various industries. Therefore, there is a need for a customized vacuum forming machine that is tailored to the requirements of the local market, with limited necessary features and lower costs.

The primary function of the vacuum forming machine is to shape plastic sheets according to customized molds using the vacuum forming process. The machine must be designed to provide high accuracy and consistency in shaping 3D objects, which cannot be achieved through manual methods. Additionally, the machine should incorporate smart sensors, a high vacuum system, a pneumatic or manual gripping system, and a heating system with a sliding guide to provide ease of operation for an unskilled operator. The design and development of a cost-effective and efficient vacuum forming machine will revolutionize various industries and enable small businesses to produce high-quality 3D parts with complex contours and curves.

1.3 Motivation:

Pakistan lacks technical expertise to provide cost-effective customized solutions for expensive international technologies such as vacuum forming machines. Tailoring machines to meet local requirements can reduce costs, but R&D and consultation with industry partners are necessary. Many small businesses are not willing to adopt high-tech solutions due to cost and size limitations. Pakistan can locally manufacture semi-automatic machines such as vacuum forming, wheel balancing, wheel alignment, and hose crimping machines with sensor, actuator, software, and system integration capabilities. Currently, many companies rely on manual fabrication methods, resulting in low production and quality. The local advertising industry requires modern vacuum forming technology, but the high cost limits its accessibility. Indigenous development of these machines can provide a cost-effective solution. The problem is that this machine is expensive, and many companies are unable to afford it.

The impact on local industry includes:

- Utilization of local raw materials
- Creation of employment
- Utilizing current skills or creating new skills
- Impact on local manufacturing or service cluster
- Solution to current local problems

1.4 Scope:

Design and development of a vacuum forming machine that can make desire products form ABS, HIPS, and acrylic material sheet up to a thickness of 2mm.

The machine should be:

- Able to perform vacuum forming process.
- Easy to operate.

CHAPTER 2: LITERATURE REVIEW

Plastic forming processes have become an integral part of modern manufacturing, enabling the production of a wide range of products with varying shapes, sizes, and material properties. However, the choice of manufacturing process depends on factors such as the product's shape, size, material, quantity, and cost. Each process has its advantages and disadvantages, and manufacturers must choose the one that best suits their needs.

2.1 Plastic manufacturing techniques:

Following are different processes that are used in industry to manufacture plastic products.

2.1.1 Injection Molding:

This is the most used process for manufacturing plastic products. It involves melting plastic pellets and injecting molten plastic material into a mold. The mold is then cooled, and the plastic solidifies into the desired shape. Injection molding can be used to produce high volumes of consistent, high-quality parts.

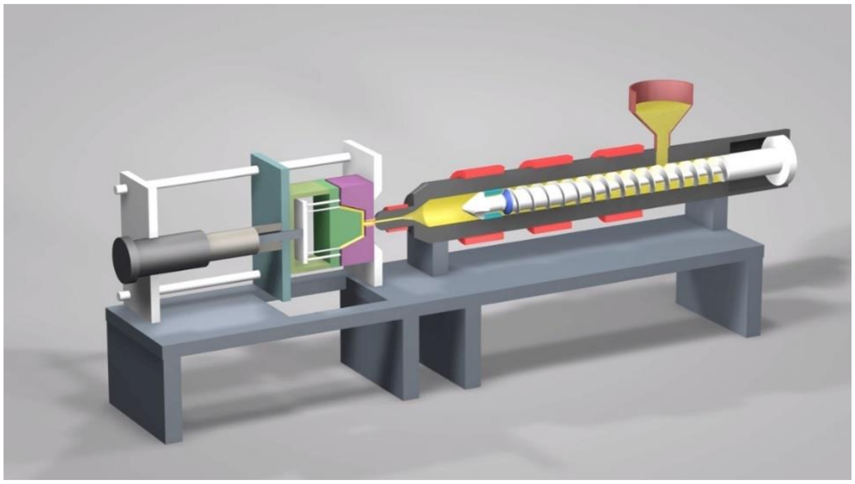


Figure 1. Injection Molding Process

2.1.2 Extrusion:

This process involves melting plastic pellets and pushing the molten material through a die to create a continuous shape, such as a pipe or a sheet. Extrusion is used for products that require consistent cross-sections, such as pipes, tubes, and sheets. The molten plastic material is pushed using a plunger or a rotary screw, hence creating a continuous product with a consistent cross-section.

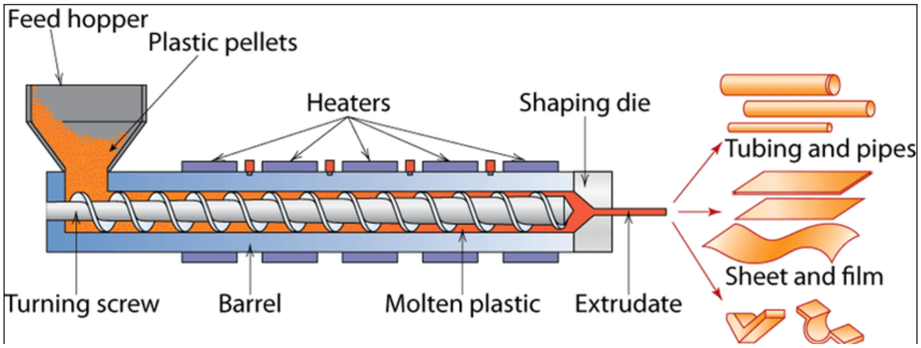


Figure 2. Extrusion Process

2.1.3 Rotational Molding:

This process involves rotating a mold around two perpendicular axes while heating it. Plastic material is then introduced into the mold, where it adheres to the mold's inner surface and cools to form the final product. Rotational molding is used for products with complex shapes and for large, hollow products such as tanks and playground equipment such as hollow tubes.

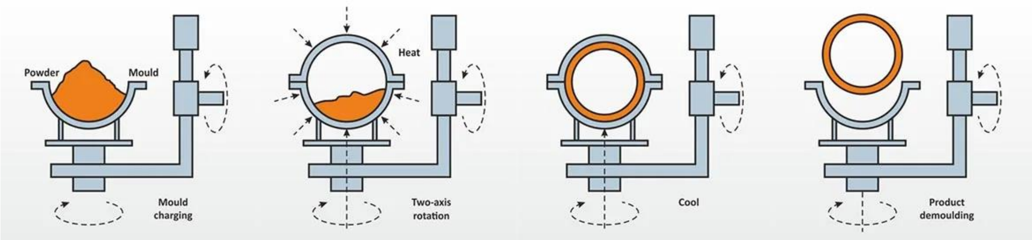


Figure 3. Rotational Molding Process

2.1.4: Blow Molding:

Blow molding is a manufacturing process used to produce hollow plastic parts. In this process, plastic is melted and formed into a hollow tube, which is then inflated to the desired shape using compressed air. The inflated plastic is then cooled and hardened, resulting in a finished product.

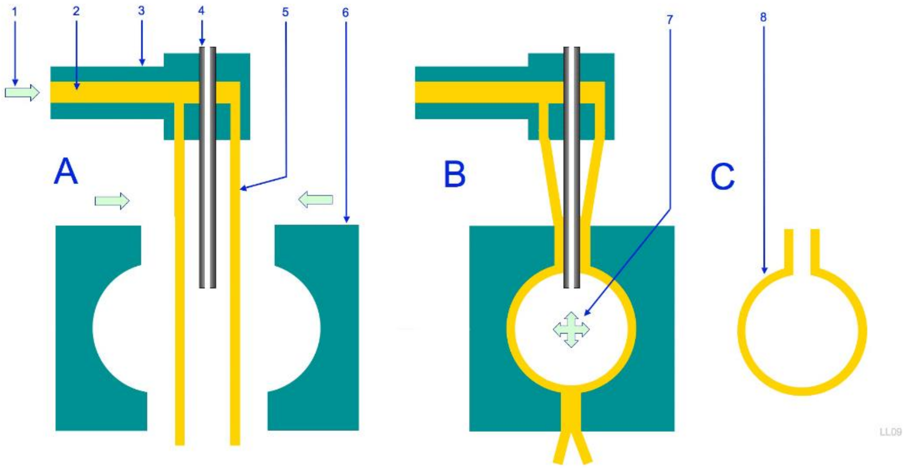


Figure 4. Blow Molding Process

2.1.5: Thermoforming:

Thermoforming is a manufacturing process used to shape plastic sheets into a desired form or shape. In this process, a flat sheet of thermoplastic material is heated to its softening point, and then it is formed over a mold using a vacuum or pressure. The formed plastic is then cooled and trimmed to create the final product.

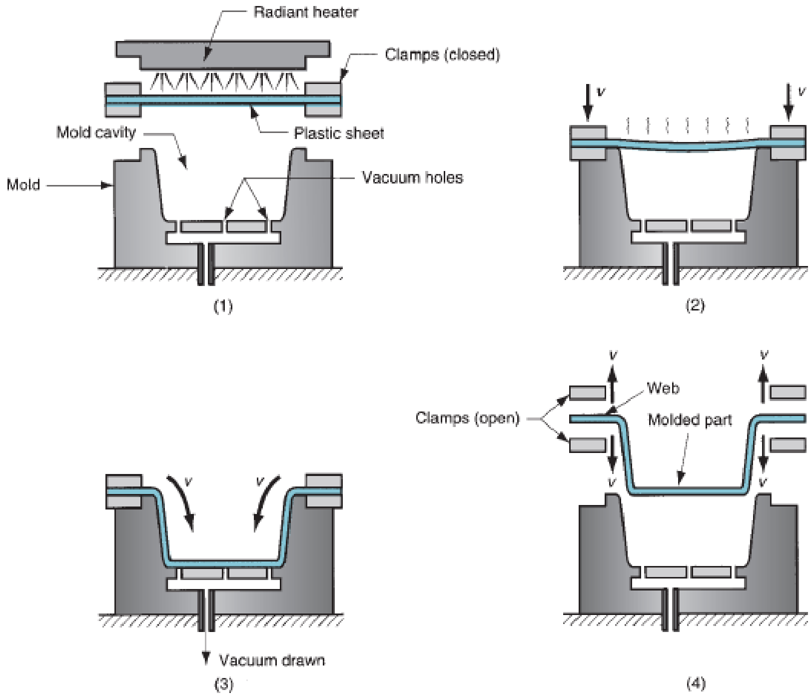


Figure 5. Thermoforming Process

There are two main types of thermoforming: vacuum forming and pressure forming.

Vacuum forming is the simpler and more common method, used to produce large, simple shapes such as trays, covers, and packaging. In this process, the plastic sheet is clamped in a frame and heated to the desired temperature. The mold is then placed below the frame and the plastic sheet is drawn over it through vacuum suction. The vacuum pressure forces the heated plastic to take the shape of the mold, and then it is cooled and trimmed to produce the final product.

Pressure forming, on the other hand, is a more advanced process that can produce more complex shapes and tighter tolerances. In this process, the plastic sheet is heated and then clamped over the mold. Air pressure is applied above the sheet, which forces the sheet to conform to the mold shape. The pressure also helps to create sharper features and tighter tolerances in the final product. After forming, the plastic is cooled and trimmed.

2.2 Why is thermoforming better than other polymer manufacturing methods?

Vacuum thermoforming offers several advantages over other forms of plastic forming, including:

- Lower cost: Vacuum thermoforming is generally less expensive than other molding processes such as injection molding or blow molding. This is because it requires less tooling and machinery, and it is easier to set up for small to medium production runs.
- Low temperature: Vacuum forming process does not require complete melting of the plastic material like that in injection molding, hence requiring less energy and time.
- Quick setup: Vacuum thermoforming requires minimal setup time and can start producing parts immediately. This makes it an ideal process for companies with time-sensitive projects or those that need to rapidly prototype new products.
- Wide range of materials: Vacuum thermoforming can be used with a wide range of thermoplastic materials, including ABS, PVC, PET, polycarbonate, and many others. This allows manufacturers to choose the right material for their specific application, balancing strength, durability, and cost.
- High production speed: Vacuum thermoforming can produce parts at a high rate, making it ideal for large production runs. This is especially true when compared to other plastic forming processes that may require more time-consuming setups or longer cooling times.
- Design flexibility: Vacuum thermoforming allows for a high degree of design flexibility, allowing manufacturers to create complex shapes and geometries that may be difficult or impossible to produce with other molding processes.

Overall, vacuum thermoforming is a cost-effective, versatile, and efficient method for producing plastic parts. Its speed and flexibility make it an ideal choice for a wide range of applications, from packaging and displays to automotive and aerospace components.

2.3 Heating Apparatus:

There are different types of heating elements that can be used to heat the plastic sheets to the optimal temperature to soften them enough for thermoforming. The following are some of the heating methods that can be used in the vacuum forming process.

2.3.1 Infrared Heating:

Infrared heating is a fast and efficient way to heat the plastic sheet before it is formed. In this process, infrared heaters emit electromagnetic radiation, which is absorbed by the plastic sheet and heats it from the inside out. This method of heating is preferred for thin-gauge materials because it does not overheat the surface and cause warping.

2.3.2 Ceramic Heating:

Ceramic heating uses a series of ceramic heating elements to heat the plastic sheet. This method is slower than infrared or quartz tube heating but can provide more even heating across larger sheets. Ceramic heating is preferred for thicker materials that require more heat to soften and mold.

2.3.3 Hot Air Heating:

Hot air heating uses a system of blowers and heaters to circulate hot air around the plastic sheet. This method is slower than infrared or quartz tube heating but can provide more even heating across larger sheets. Hot air heating is preferred for thicker materials that require more heat to soften and mold.

2.3.4 Quartz Heating:

Quartz tube heating uses a series of quartz tubes that emit infrared radiation to heat the plastic sheet. The quartz tubes are arranged in a series of rows and can be adjusted to provide even heating across the entire sheet. This method is preferred for thicker materials that require more heat to soften and mold.

The choice of the heating apparatus depends greatly on the needs of the vacuum forming process. Different factors that affect the choice of heating element are sheet thickness, type of plastic material, precision, and desired process speed. The cost of the heating element also needs to be considered.

2.4 Heater Arrangements:

Different heater arrangements are used in thermoforming process, each having their own advantages and disadvantages. The optimal type of heater arrangement is based on the type of plastic sheet used, its forming area and the desired speed of the process.

Following are the arrangements used in thermoforming process:

- Top-only heating: In this configuration, the heating elements are located above the plastic sheet. This arrangement is used when only one side of the sheet needs to be heated.
- Bottom-only heating: In this configuration, the heating elements are located below the plastic sheet. This arrangement is used when only one side of the sheet needs to be heated.
- Top and bottom heating: In this configuration, the heating elements are located both above and below the plastic sheet. This arrangement is used when both sides of the sheet need to be heated simultaneously.
- Edge heating: In this configuration, the heating elements are located along the edges of the plastic sheet. This arrangement is used to preheat the edges of the sheet before it is formed.
- Contoured heating: In this configuration, the heating elements are arranged to match the contour of the mold. This arrangement is used to ensure even heating and consistent forming across the entire sheet.
- The heating elements can be arranged in such a way that they form multiple heating areas that can be controlled individually to facilitate uniform heating throughout the plastic sheet. However, this arrangement of the heater tends to be expensive and requires greater skill to properly utilize.

2.5 Vacuum Pumps:

Pumps play an important role in thermoforming processes, particularly in the vacuum forming stage where the air is evacuated from the mold cavity to create a vacuum that draws the heated plastic sheet onto the mold. The two main types of pumps used in thermoforming processes are:

2.5.1 Rotary vane vacuum pumps:

These pumps use a series of vanes that rotate within a cavity to create a vacuum. As the vanes rotate, they compress the air, creating a vacuum that draws the plastic sheet onto the mold. Rotary vane vacuum pumps are relatively low cost and easy to maintain, making them a popular choice for smaller thermoforming operations.

2.5.2 Positive displacement vacuum pumps:

These pumps use a series of chambers to create a vacuum. As the chambers expand, they draw air into the chamber, creating a vacuum that draws the plastic sheet onto the mold. Positive displacement vacuum pumps are more expensive than rotary vane pumps, but they can create higher levels of vacuum, making them a better choice for larger thermoforming operations or those that require a high level of precision.

The pump used in the vacuum forming process depends upon the suction requirements of the process. The required suction is governed by the forming area of the machine.

Regenerative blowers are also employed in vacuum forming machines to cool down the plastic sheet after it has been formed to speed up the forming process. These blowers use a series of impellers to move air, creating a low-pressure area that draws cool air over the surface of the plastic sheet, helping it to cool and solidify. Draw ratio is a calculation that is used to determine the minimum thickness of the plastic sheet to produce your part. It divides the surface area of the mold by the footprint, or top surface, of the heated sheet. We use this calculated value to help achieve the minimum wall thickness for your ideal part – and with a uniform wall thickness. The deeper or taller the part the heavier the starting gauge of sheet required. Allowing the part or any feature of the part to be narrower than it is tall will thin the sheet at a much quicker rate. A **3:1 ratio** is generally a maximum drawl ratio.

2.6 Areal Drawl Ratio:

Draw ratio is a calculation that is used to determine the minimum thickness of the plastic sheet to produce your part. It divides the surface area of the mold by the footprint, or top surface, of the heated sheet. We use this calculated value to help achieve the minimum wall thickness for your ideal part – and with a uniform wall thickness. The deeper or taller the part the heavier the starting gauge of sheet required. Allowing the part or any feature of the part to be narrower than it is tall will thin the sheet at a much quicker rate. A 3:1 ratio is generally a maximum drawl ratio.

Example: (according to the designed machine):

Assume a part is 18"x 18"x 5" deep. Therefore, the Draw Ratio will be:

Surface Area = 2(18" x 5") + 2(18"x5") + 18" x 18" = 180" + 180" + 324" = 684" (mold)

Footprint = 22" x 22" = 484" (Sheet)

Draw Ratio = 684"/484" = 1.41

If the desired ending wall thickness of the part is 0.04" use the draw ratio as follows to estimate the starting gauge of the sheet:

Draw Ratio x Desired Finished Gauge = Minimum Starting Gauge

1.41 x 0.04" = 0.056 (around 1.5mm) Assuming perfect material distribution.

But in our case the, the sheet is of 2mm, so we will get good wall thickness with uniform material distribution.

2.7 Thin Gauge vs Heavy Gauge thermoforming:

The dimensional difference between the plastic sheets used in thermoforming is the differentiating factor between thin and heavy-gauge thermoforming. Thin-gauge thermoforming equipment is fed using thin sheets from plastic rolls. Heavy-gauge (or thick-gauge) thermoforming is fed using thick plastic sheets.

2.7.1 Thin Gauge Thermoforming:

Thin gauges thermoform packaging uses material less than .090" (2.286mm) thick with the typical material gauges used being between .010" (0.254mm) - .070" (1.778mm). Thin Gauge Thermoforming is a fast, efficient way to produce quantities both large and small in a variety of packaging types. Industries frequently utilizing this method are, but not limited to, medical, food, and retail. Materials commonly used are **HDPE, HIPS, PET, PETG,** and **PVC.**

2.7.2 Heavy Gauge Thermoforming:

Heavy Gauge Plastic Thermoforming pertains to materials that are between .070" (1.778mm) and 0.500" (12.7mm) thick. Heavy gauge plastic thermoforming allows for production of large industrial components that require heavy-duty material. Materials commonly used in Thick Gauge Thermoforming are **ABS, HDPE,** and **PET.**

2.8 Draft angle:

Draft angle is an important factor to consider in thermoforming processes. It refers to the degree of taper or angle that is added to the walls of a mold or tool. A draft angle is necessary to allow the formed part to be released from the mold without damaging or distorting it.

For parts that are formed into a female mold with a texture allow 1 degree of draft plus 1 degree of draft for every thousandth of an inch of texture depth. “With parts formed over a male mold allow 5 degrees of draft as a minimum”. Parts can be molded with little or no draft. However, there is a high probability that the part will not release from the mold or will have severe scuffing from any texture that is on the mold.

A larger draft angle can make it easier to release the formed part from the mold, but it can also affect the final shape and appearance of the part. Conversely, a smaller draft angle may result in parts that are more difficult to release from the mold, leading to damage or distortion of the part.

In general, it is important to carefully consider the draft angle when designing molds for thermoforming processes to ensure that the final product meets the required specifications and is produced efficiently and cost-effectively.

Table 1. Properties of polymer with vs draft angle

Sr. no	**Polymer**	**Female or Outer Draft Angle (degree)**	**Male or Inner Draft Angle (degree)**
1	HDPE	0 to 1.5	1 to 2.5
2	PP	0 to 1.5	1 to 2
3	PC	1.5 to 2.5	3 to 5

CHAPTER 3: METHODOLOGY

This section highlights the design philosophy, the main working components of the machine and their working principle.

3.1 Material Selection

Mild steel, also referred to as low carbon steel, is a popular choice for constructing vacuum forming machines due to several key factors. Firstly, it exhibits excellent strength and durability, enabling it to endure the demanding conditions imposed by these machines, resist deformation, and maintain its structural integrity over extended periods. Additionally, mild steel is cost-effective when compared to other metals like stainless steel or aluminum, making it a suitable option for manufacturing vacuum forming machines, particularly for smaller or medium-scale operations with budget constraints. Moreover, mild steel possesses good machinability, allowing it to be easily shaped, cut, and welded during the fabrication process, facilitating efficient production and assembly of machine components. Its favorable thermal conductivity properties enable the even distribution of heat across the machine's surfaces, ensuring consistent heating of the thermoplastic sheet and contributing to the precision and quality of the formed products. Although not as corrosion-resistant as stainless steel, mild steel can still provide sufficient protection against rust and corrosion when appropriately treated. Lastly, mild steel's wide availability in the market and familiarity among manufacturers streamline the fabrication process, simplify the supply chain, and facilitate maintenance and repair activities.

3.2 Design basics

The design of vacuum forming machine is constrained by the working area of the machine. The design process is started by considering the sheet size of plastic which is available in the market. The size of the sheet is **24x24 inches**. For the sheet to be gripped, between the clamping mechanism, the working area needs to be 2 inches smaller from all sides. Therefore, the cut in blue plate, which is the topmost plate supported by the angle structure is **22x22 inches**. This step ensures that the sheet is given enough room from the 4 sides to be clamped.

3.3 Machine Design

The machine has been designed with the Solidworks software. The picture attached below visualizes the basic machine design.

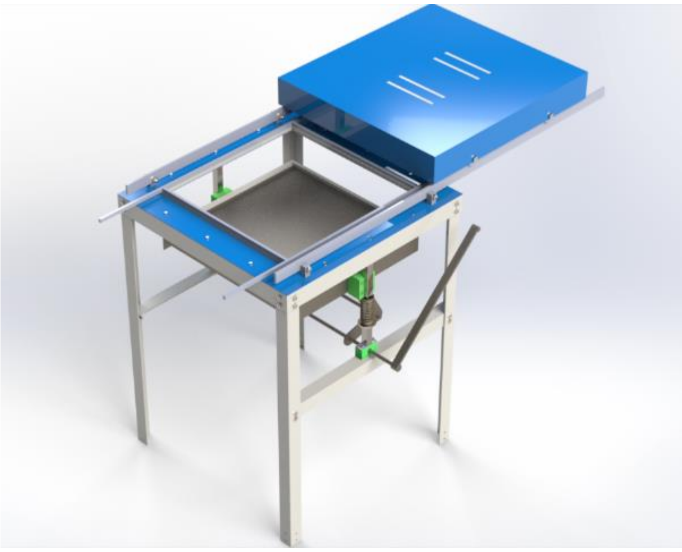


Figure 6. Shows the 3d model of the machine.

3.3.1 Basic components

The basic machine parts are shown below in the exploded view of the assembly:

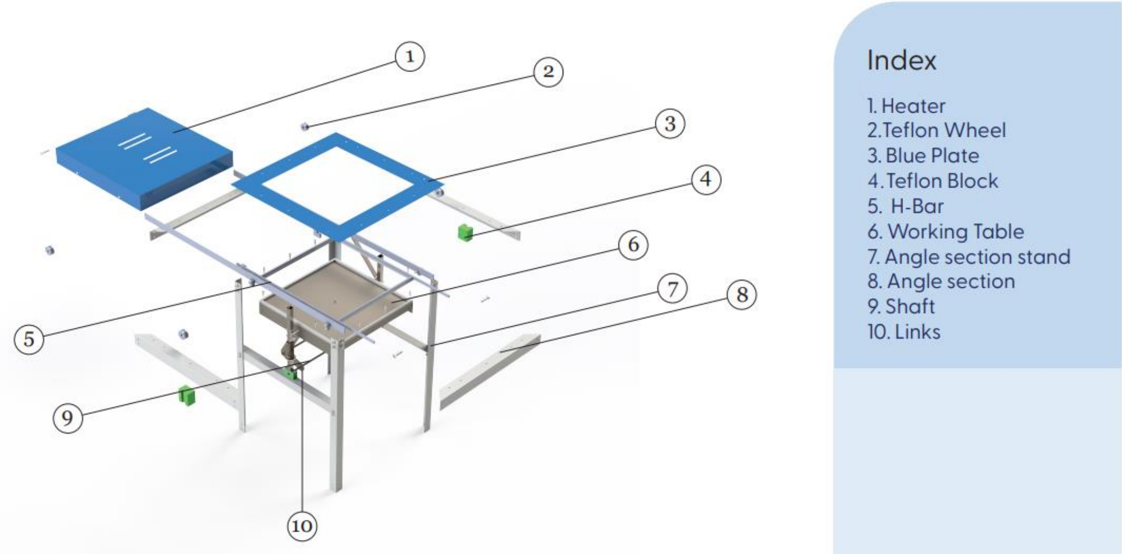


Figure 7. Shows the exploded view of assembly.

The design consists of the following components briefly described below:

- **Machine Frame** consists of angle sections welded together that provide a rigid and firm support to the machine. The angle sizes are **50x50 mm.** For the bearing and sliding mechanism supports two separated angles are bolted to the structure.
- **The heater** for the machine serves the purpose of heating the plastic sheet to make it more moldable. The heater consists of a metal sheet body which carries **silica glass tube heaters.** The heater produces a combined heating load of **7.7 kW.** The heater traversal system consists of 4 Teflon wheels.
- **Sliding Mechanism** for the machine carries the moving table which rests on two springs at the initial position. **Teflon slides** slide onto **SS square tubes.**
- **The linkage mechanism** consists of two sets of links which are welded to a shaft and are pinned at the intersection and to the table. The mechanism is arranged in such a way that the total stroke length is set to **5 inches.**
- **Blue plate** is 6mm thick and is bolted to the frame.

3.4 Design and fabrication of Components

- **Angle Frame**

  The vacuum forming machine's frame is constructed using mild steel angles, strategically arranged to form its sturdy structure. These angles serve as the foundational components, comprising the four legs of the machine's body. At the bottom of the frame, four angles are positioned, each hosting a set of wheels, enabling easy mobility and maneuverability. Similarly, the top portion of the frame is equipped with four angles, serving as anchor points for securing a blue plate that is bolted onto them. This arrangement provides additional stability to the machine's upper section. To ensure a reliable framework, the angles of the body are joined together using electric arc welding. This welding technique creates strong and durable connections, enhancing the overall structural integrity of the machine. Moreover, the frame incorporates specialized angles designed to support the weight of the vacuum pump positioned at the bottom. These additional angles play a crucial role in maintaining stability and distributing the load effectively, ensuring optimal performance of the vacuum pump during the forming process.

Figure 8. Shows the frame on top

Figure 9. Shows the frame in solidworks.

- **Blue Plate**
  The blue plate is mounted onto the top of frame. It is connected to the frame with the help of bolts. The fabrication of the blue plate is done via laser cutting. It supports the weight of heater rails which are mounted onto the blue plate with the help of columns of MS rods connected with the help of threaded fastener. The blue plate is **6 mm thick.**

Figure 10. Shows the blue plate.

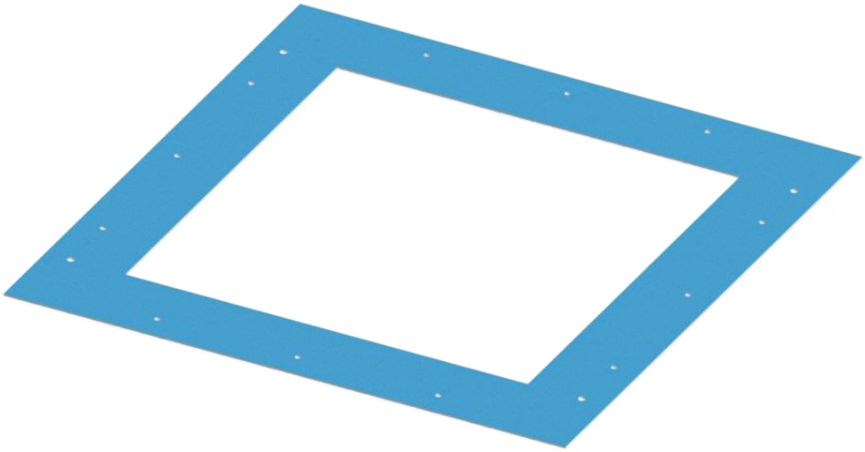


Figure 11. Blue plate in Solidworks

- **H Bar and Clamping**

The H-bar is constructed by welding together strips of mild steel in the shape of an H. This configuration provides strength and rigidity to the H-bar. It is strategically pivoted at the back of the machine frame, allowing it to be securely clamped onto the front of the machine frame. This pivotal arrangement ensures a firm grip on the plastic sheet during the vacuum forming process. By clamping the plastic sheet, the H-bar holds it firmly in place, preventing any unwanted movement or displacement. This stability is crucial for achieving precise and accurate forming of the plastic sheet according to the desired shape and mold. The H-bar in the machine is pivoted at the back using a bolt and spring assembly, as depicted in the figure.

Figure 12. H-bar pivoted at the back

This configuration allows for the flexible clamping mechanism of the H-bar. The inclusion of a spring in the assembly provides the necessary flexibility for the clamping action. The spring allows for slight movements and adjustments, accommodating different thicknesses and variations in the plastic sheet being used for vacuum forming. It ensures that the clamping force is applied uniformly across the sheet, enhancing the overall forming process. The bolt plays a vital role in adjusting the clamping of the H-bar. By tightening the bolt against the spring, the clamping force can be increased or decreased as per the specific requirements of the vacuum forming task at hand. This adjustability allows for precise control over the clamping pressure, ensuring optimal performance and results. The bolt and spring assembly, working together, provide a reliable and versatile clamping mechanism for the H-bar. This mechanism allows for the secure hold of the plastic sheet during the vacuum forming process, ensuring accurate shaping and minimizing any potential for slippage or movement.

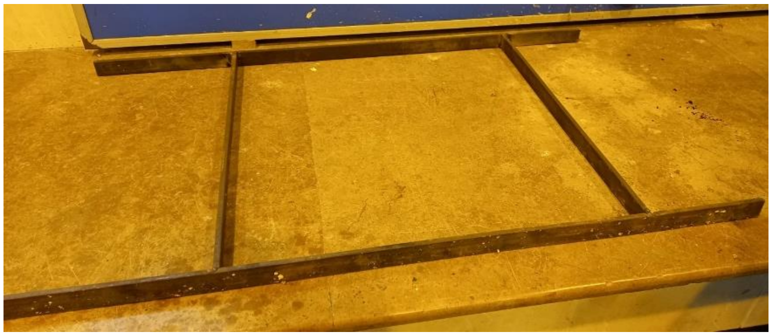


Figure 13. Shows the H bar.

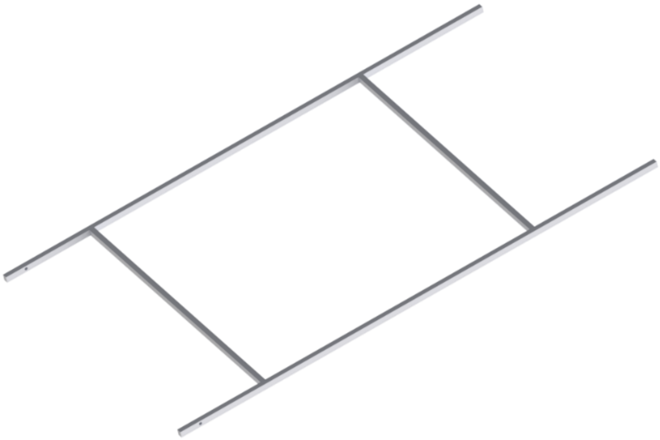


Figure 14. H-bar in Solidworks.

To ensure an airtight seal and prevent the entry of air into the chamber between the moving table and the plastic sheet, the H-bar requires tight clamping against the sheet. For this purpose, a hook is employed due to its ease of availability and flexibility. The hook utilized in the machine features a threaded straight end, which is fastened onto a square-shaped solid rod. This rod is securely bolted in a pin joint assembly with the H-bar. The threaded hook allows for vertical movement, enabling adjustments to the clamping strength applied to the plastic sheet. By tightening the hook, it moves upward, increasing the clamping force exerted on the plastic sheet. Conversely, loosening the hook allows for downward movement, reducing the clamping strength. This adjustability provides the operator with the ability to fine-tune and optimize the clamping pressure according to the specific requirements of the vacuum forming process. The utilization of the hook, in conjunction with the threaded rod and pin joint assembly, facilitates convenient and efficient adjustments to the clamping mechanism. This feature allows for a precise and customizable clamping of the plastic sheet against the EVA material, ensuring a tight seal and optimal forming conditions.

Figure 15. Clamping mechanism (open)

Figure 16. Clamping mechanism (locked)

- **Moving Table**

  The moving table acts as a platform for the mold that is to be vacuum formed. The moving table has a hole in its center to facilitate the formation of vacuum in the chamber between sheet and the table. The table is moved up and down with the help of links that are rotated with the help of a shaft that is powered manually by using the handle.

Figure 17. Shows the moving table.

- **Sliding mechanism**

  The vertical motion of the table in the vacuum forming machine is regulated through a slider mechanism. This mechanism incorporates two teflon blocks affixed to the opposing sides of the moving table. These teflon blocks feature grooves on their undersides, enabling them to smoothly slide along stainless steel rods. To control and halt the movement of the moving table at specific positions, a spring is employed. This spring is mounted onto the stainless steel rod using a pin, allowing it to move up and down. When the desired position is reached, the spring acts as a stopper, preventing further vertical motion of the table. This slider mechanism, with the teflon blocks sliding along stainless steel rods and the spring providing controlled stopping positions, ensures precise vertical movement and positioning of the table. It contributes to the accuracy and repeatability of the vacuum forming process, enabling consistent and reliable forming results.

Figure 18. Shows the sliding Mechanism

The stopping mechanism for the mechanism is shown below:

Figure 19. Welded MS plate with the links acts as the stopper.

The rotation of the linkages in the vacuum forming machine is achieved using a shaft. This shaft is mounted onto the machine's frame, utilizing two angles that have teflon blocks affixed to them. These teflon blocks serve as supports for the shaft. The shaft itself is fitted into bearings that are press-fitted into the teflon blocks, ensuring smooth rotation. To facilitate manual rotation of the shaft, a handle is mounted on the right side of the machine. This handle provides a grip for the operator to turn the shaft, initiating the desired movement of the linkages. By manually rotating the shaft using the handle, the vertical motion of the moving table can be controlled. The mechanism, when the table is at the top, is shown below:

Figure 20. Sliding mechanism in its top position.

The linkage mechanism plays a critical role in enabling the vertical movement of the moving table in the vacuum forming machine. This mechanism consists of links that are connected to the body of the moving table through pin joints. Specifically, two links are utilized to facilitate the upward and downward motion of the table. The links are pivotally attached to the moving table, allowing them to rotate around pin joints. This rotation is accomplished with the aid of a shaft. As the shaft is turned or manipulated, it causes the links to pivot, consequently raising or lowering the moving table. By utilizing this linkage mechanism, the vertical movement of the table can be controlled and adjusted as necessary. The number and arrangement of links can vary depending on the specific design of the vacuum forming machine. This mechanism ensures smooth and precise vertical motion, contributing to the accurate positioning of the plastic sheet and enhancing the overall forming process.

- **Teflon Bearing Holder**
  To avoid complexity, ball bearings to be used for the shaft are planted into a teflon holder.

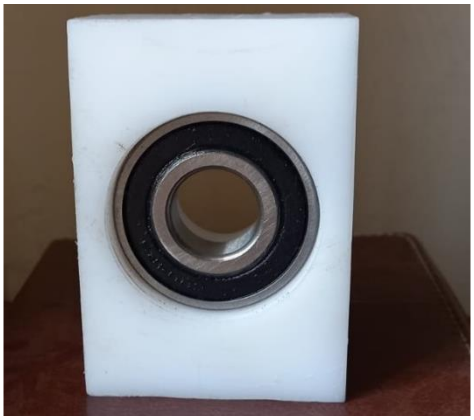


Figure 21. Shows the Teflon block.

- **Heater**
  The heater was fabricated with sheet metal work to make a body which can house the silica heater rods. The heater moves on heater channels which are **60 inches long.**

Figure 22. Shows the outside body of the heater

Figure 23. Shows the ceramic rods of heater on the inside of the body

Figure 24. Shows the copper sheet which is used to connect the ceramic rods with the main power supply

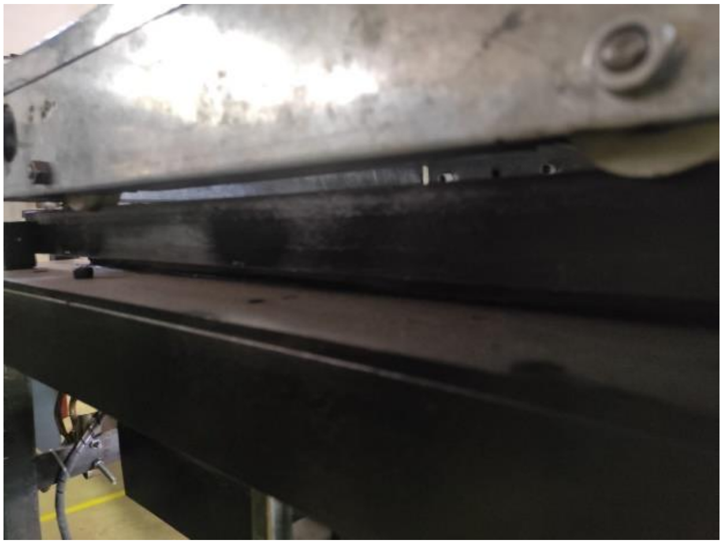


Figure 25. Heater's wheels travelling on the heater rails

- **Vacuum Pump**

The rotary vane pump **(W2V40)** is selected, which has low noise and low vibration design offers a comfortable working environment. Easy to use and maintain with a simple structure. The pictorial view of pump is as:

Figure 26. W2V40 Vacuum pump

The vacuum pump has an air filter to make sure that no particle or object can enter it and damage it. It is shown:

Figure 27. Air Filter of the pump

The vacuum pump is placed at the bottom of the frame:

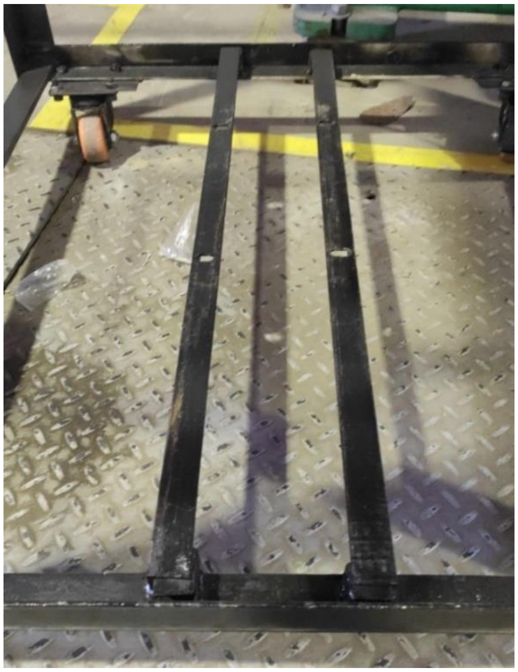


Figure 28. Two angle supports for the pump

The pump is connected to the bottom of the moving table with a pipe:

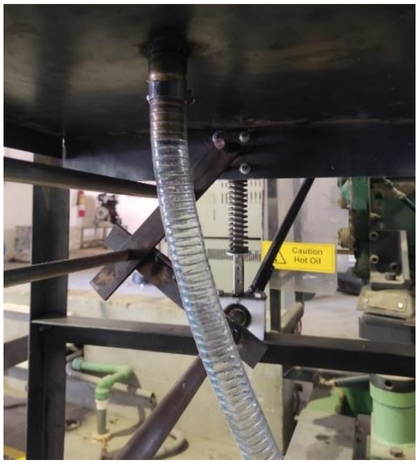


Figure 29. Pipe used to create vacuum

3.4.1 Calculations

The following theoretical design calculations were made:

3.4.1.1 Vacuum Pump calculation

The vacuum pump calculation was done to determine the ultimate vacuum that can be generated inside the pumps casing, so that the air inside the sealed chamber maybe pump from the chamber into the pump to create a vacuum for the plastic sheet to stick onto the mould.

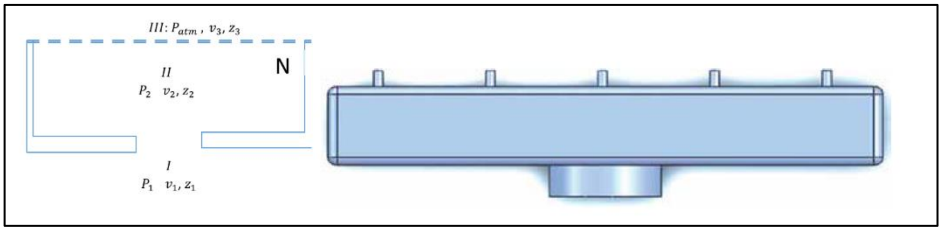


Figure 30. Shows the application of Bernoulli's theorem.

We have:

Table 2. Describes the calculation parameters.

	I region	**II region**	**III region**
Pressure (P)		-	101.325kPa

Velocity (v)	12.55 m/s		
Height (z)	0mm	0mm	28.19mm

We have an inlet diameter of d_1 = 50mm = 0.050m

$$A = \frac{\pi}{4}d^2 = \frac{\pi}{4} * (0.050\text{m})^2 = 0.0019649m^2$$

The volumetric flow rate for vacuum pump is given by:

$$V = 24\frac{m^3}{h} = 0.4\ \frac{m^3}{min}$$

So, now we can find the velocity at point I:

$$V_1 = A_1 * v_1$$

$$v_1 = \frac{V_1}{A_1} = \frac{0.4\, m^3/min}{0.0019649m^2 * 60min/s} = 3.39m/s$$

The area at III:

$$A_3 = 204.53mm^2$$

So, now we can find the value of v_3 using the continuity equation:

$$V = A_3 * v_3$$

$$v_3 = 32.6m/s$$

In regions I and II, applying Bernoulli's equation, we get:

$$\frac{P_1}{\rho g} + \frac{v_1^2}{2g} + z_1 = \frac{P_2}{\rho g} + \frac{v_2^2}{2g} + z_2$$

Since, z_1=z_2, i.e., both are at same height:

$$\frac{P_2}{\rho g} = \frac{P_1}{\rho g} + \frac{v_1^2}{2g} - \frac{v_2^2}{2g}$$

In regions II and III, applying Bernoulli's equation, we get:

$$\frac{P_2}{\rho g}+\frac{v_2^2}{2g}+z_2=\frac{P_{atm}}{\rho}+\frac{v_3^2}{2g}+z_3$$

Plugging in the value of P_2/ρ:

$$\frac{P_1}{\rho g}+\frac{v_1^2}{2g}-\frac{v_2^2}{2g}+\frac{v_2^2}{2g}+z_2=\frac{P_{atm}}{\rho g}+\frac{v_3^2}{2g}+z_3$$

We can simplify the above equation as:

$$\frac{P_1}{\rho g}-\frac{P_{atm}}{\rho g}=\frac{v_3^2}{2g}-\frac{v_1^2}{2g}+z_3$$

$$P_1-P_{atm}=\rho g*(\frac{v_3^2-v_1^2}{2g}+z_3)$$

$$P_1-P_{atm}=\rho g*(\frac{v_3^2-v_1^2+2gz_3}{2g})$$

$$P_1-P_{atm}=\rho*(\frac{v_3^2-v_1^2+2gz_3}{2})$$

Putting the value of $\rho = 1.292$ kg/m3, $z_3 = 28.19$mm and the value of v_1 *and* $v_3$from above:

$$\Delta P=679.606Pa=0.679kPa$$

Note that Vacuum-pump manufacturers gives two specifications: pumping speed and ultimate pressure (also called ultimate vacuum). The ultimate pressure is measured by capping the pump's inlet and finding the equilibrium pressure after operating the pump for many hours. Because it is measured under “ideal” circumstances, it is crucial to remember that a chamber connected to this pump will never reach the quoted ultimate pressure. (“Kurt J. Lesker Company | Basic Pressure Concepts | Enabling Technology ...”) (“Kurt J. Lesker Company | Basic Pressure Concepts | Enabling Technology ...”)

The ultimate pressure of mechanical pumps using a McLeod gauge that cannot measure vapors such as pump oil and water. Consequently, the so-called ultimate (partial) pressure of a rotary vane pump may be quoted very close to perfect vacuum, causing much confusion when the practical ultimate pressure (using a gauge that responds to oil and water vapor) is two decades higher. (“Kurt J. Lesker Company | Pumping Speed | Enabling Technology for a ...”) (“Kurt J. Lesker Company | Pumping Speed | Enabling Technology for a ...”)

3.4.1.2 Heater Wattage calculation

The heater’s wattage depends upon the amount of energy required to heat up the plastic sheet. For a HIPS sheet of 22x22 inches:

Volume of HIPS = 624514.88 mm3

Density of HIPS = 0.00108 g/mm3

So,

Density = Mass/volume

Mass of HIPS = 0.00108*624514.88 = 674.4760 grams

The Thermoforming temperature of HIPS is approximately 160 C, so we can find the heat required to raise the temperature of HIPS from room temperature to 160 C:

$Q = c \times m \times \Delta T$

$Q = 1400$ J/kg-C × 0.6744760 kg × (160-30)

Q = 122754 J = 122.754 KJ

This is the energy required to raise the temperature of a 22*22 inch and 2mm sheet of HIPS from room temperature of 30 C to 160 C, that is the required thermoforming temperature. As we know that the voltage is constant, we can now choose the number of heater elements to be used and change the resistance of the heater’s coil. So, we can now choose the resistance of the heater coil and then find out current, and power of each heating element:

$$P = VI = \frac{V^2}{R} = I^2R$$

Taking number of elements as 7 for uniform heating. As,

$$V = 220V$$

$$Resistance = 60.5\Omega$$

$$P = \frac{V^2}{R} = \frac{220^2}{60.5} = 800W$$

$$Total\ Power = 7 \times 800 = 5600W$$

This is a rough estimation of the heater's required wattage. However, the required level of heating can vary from one type of sheet to the other.

3.4.1.3 Shaft Calculation

According to the design the shaft is restricted at both ends using the bearings. Therefore, the weight of the linkages and the table directly acts onto the shaft. The total weight is divided at two points uniformly.

Theoretically, the minimum shaft diameter required, shear force and bending moments have been calculated below:

Links and stroke parameters

Length of link 1:

$a := 254\ mm = 10\ in$

Length of link 2:

$b := 127\ mm = 5\ in$

Stroke required:

$s := 127\ mm = 5\ in$

$\rho := 7.85\ \frac{gm}{cm^3}$

$x := 22\ in \quad y := 22\ in$

Working area: $A_w := x \cdot y = 484\ in^2$

Table sheet thickness: $t_w := 2\ mm$

Total area: $A_t := A_w + 4 \cdot 2 \cdot x\ in$

Mass of Area: $m_a := A_t \cdot t_w \cdot \rho = 6.685\ kg$

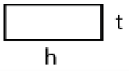
Design Parameters

Weight of working table:

$W := m_a \cdot g$

Allowed mold weight:

$W_m := 40 \cdot 9.8\ N$



Height of link 1 and 2:

$h := 50\ mm$

Thickness of link 1 and 2:

$t := 4.5\ mm$

Material Parameters (ASTM-A36)

$\sigma := 250\ MPa$

$UTS := 400\ MPa$

$E := 200\ GPa$

$k := 140\ GPa$

$\nu := 0.26$

$\rho := 7.85\ \frac{gm}{cm^3} = \left(7.85 \cdot 10^3\right)\ \frac{kg}{m^3}$

Link Bolts min diameter

$d := 2\ mm$

$A_c := \pi \cdot \left(\frac{d}{2}\right)^2 = 3.142\ mm^2$

$W_m := 40 \cdot 9.8\ N$

$V_1 := h \cdot t \cdot a = 0.057\ L$

$V_2 := h \cdot t \cdot b$

$W_1 := \rho \cdot g \cdot V_1 = 4.4\ N$

$W_2 := \rho \cdot g \cdot V_2 = 2.2\ N$

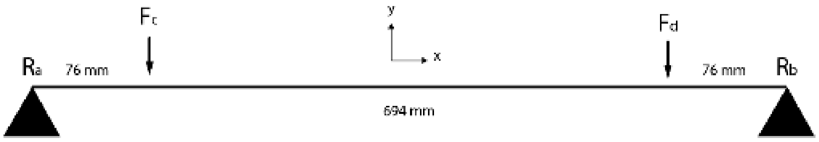
$W_{max} := W + W_m + 2 \cdot W_1 = 466.358\ N$

$\tau_c := \frac{W_{max}}{2 \cdot A_c} = 74.223\ MPa$

$\text{if}\left(1.5 \cdot \tau_c < \sigma, 1, 0\right) = 1$

using d=8 mm

Shaft calculations



$F_c := \frac{W}{2} + \frac{W_m}{2} + W_1 + W_2 = 235.379\ N$

$F_d := F_c$

$\Sigma F_y := 0$

$\Sigma M_a := 0$ ↺

$\Sigma M_b := 0$ ↺

Guess Values

$R_a := 0\ \mathbf{N}$
$R_b := 0\ \mathbf{N}$

Constraints

$$R_a + R_b - F_c - F_d = 0$$

$$-76 \cdot F_c - (694 - 76) \cdot F_d + 694 \cdot R_b = 0$$

Solver

$$\begin{bmatrix} R_a \\ R_b \end{bmatrix} := \mathbf{find}\left(R_a, R_b\right)$$

$$\begin{bmatrix} R_a \\ R_b \end{bmatrix} = \begin{bmatrix} 235.379 \\ 235.379 \end{bmatrix} \mathbf{N}$$

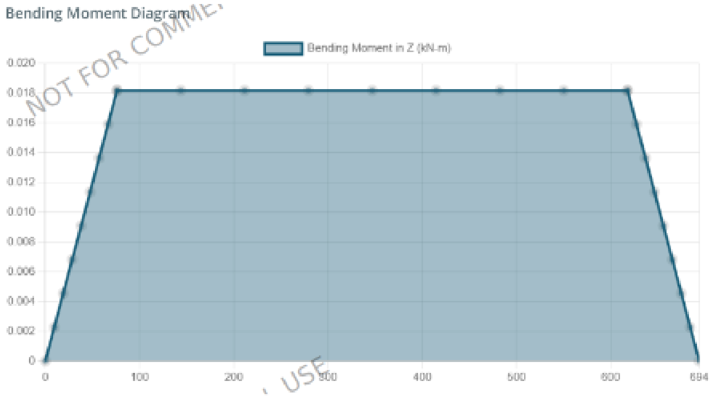
$$M_{max} := F_c \cdot 76\ \mathbf{mm} = 17.889\ \mathbf{J}$$

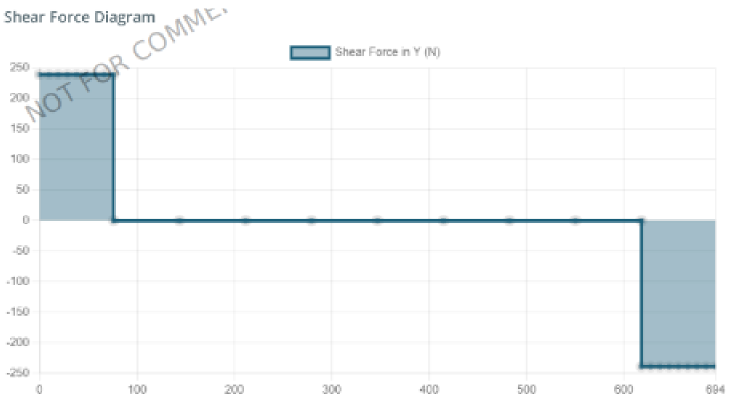
$$d_s := 8\ \mathbf{mm}$$

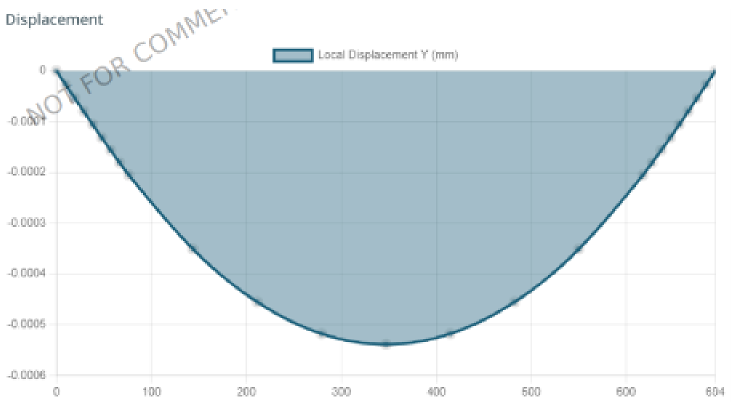
$$d_{min} := \sqrt[3]{\frac{32 \cdot 1.5 \cdot M_{max}}{\pi \cdot \sigma}} = 10.302\ \mathbf{mm}$$

$$\sigma_{in} := \frac{32 \cdot M_{max}}{\pi \cdot {d_s}^3} = 355.886\ \mathbf{MPa}$$

$$\mathbf{if}\left(\sigma_{in} > \sigma, 0, 1\right) = 0$$







So, min d must be greater than 11

Diameter of shaft = 12 mm=0.472 inch

3.4.1.4 Linkages Calculation

The links are engineered to enable a 5-inch stroke. Initially, the links are positioned at an angle of approximately 75 degrees, ensuring that the moving table is positioned 10 inches above the bottom. In the final position, the angle between the links becomes zero degrees, thereby raising the moving table to a height of 15 inches, thus achieving a 5-inch stroke.

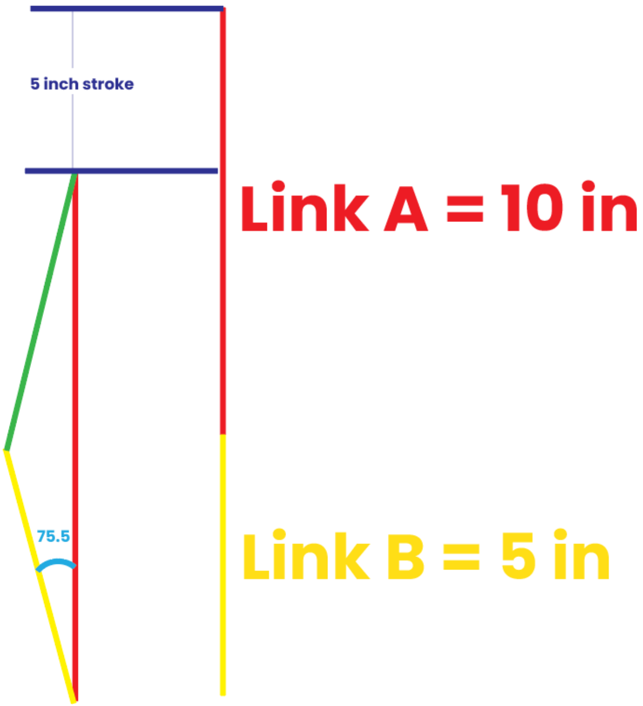


Figure 31. Linkage System

3.5 Fabrication processes

The major processes used in the fabrication are:

- Welding, cutting, and grinding of MS angle sections
- Bending of MS sheet
- Turning of MS shaft
- Milling of Teflon pieces

The final fabricated machine picture is attached below:

Figure 32. Vacuum Forming Machine

3.6 Specifications

The technical specifications of different parts of the machine are given below. These parts include machine structure, vacuum pump, and electrical distribution box (DB box).

3.6.1 Machine Structure

The machine is designed and fabricated to make plastic molds using different plastic sheets as per requirements. The principal used to make these molds is Vacuum forming. The Machine CAD and pictorial view is as follows:

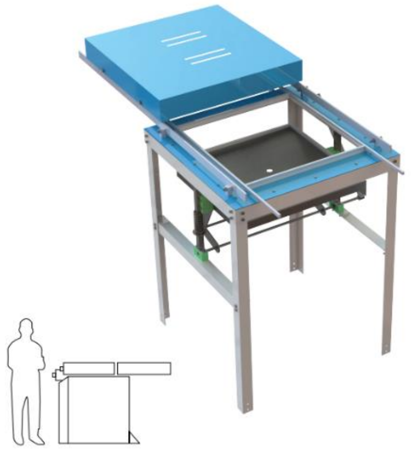


Figure 33. Render (CAD) image of machine

And its technical specifications are as follows:

Table 3 Technical specifications of the machine

Technical Specifications	
Forming area (mm/inches)	558.8 x 558.8 mm / 22 x 22 in
Sheet Size (mm / inches)	609.6 x 609.6 mm /24 x 24 in
Max Material Thickness	Sheer: 6 mm /0.25
Stroke length	127 mm / 5 in
Machine Width	779.78 mm / 30.7 in
Machine Height	1189 mm / 46.8 in
Power consumption	8.0 kW / (Heater = 7 kW)
Weight	95 kg / 209.5 lb
Power requirements	220-240 V / 50 Hz (Single phase)
Material	ASTM A36 / As per requirement

3.6.2 Vacuum pump

The specifications of the pump are:

Table 4. Pump Specifications

Pumping Speed	400ℓ/min	
Ultimate Pressure	Gas Ballast Open	5X10^{-3} Torr (6.7 Pa)
	Gas Ballast Closed	≤1X10^{-3} Torr (1.3X10^{-1} Pa)
Power Input	Standard	220VAC 1Φ 50/60Hz
	Option I	220VAC/380VAC 3Φ 50/60Hz
	Option II	Customer’s Request (Voltage, Frequency)
Full load Power	0.4kW (0.5 HP)	
Motor Power	750W(1hp)	
Motor Speed	1,700 rpm	
Inlet	Standard	NW25
	Option I	+ Hose Nipple: Φ12, Φ16, Φ26 OD for NW25
	Option II	+ PT Nipple :1/4″, 3/8″, 1/2″, 3/4″, 1″ for NW25
	Option III	User Requested Type
Weight	34.8kg	
Oil Capacity	1,500cc (1.5ℓ)	
Ambient Operation Temp.	7~40°C / 45~104°F	
Overall Dimension(mm)	170x484x287 (unit: mm)	

3.6.3 Electric wiring and circuit

The electric wiring is done to operate two main components:

1. Vacuum forming pump (Single phase 1kW)
2. Electric Heater (Single phase 7 kW)

The heater is ON/OFF by limit switch which also operated on AC (220 V). The circuit diagram and components picture attached accordingly is as:

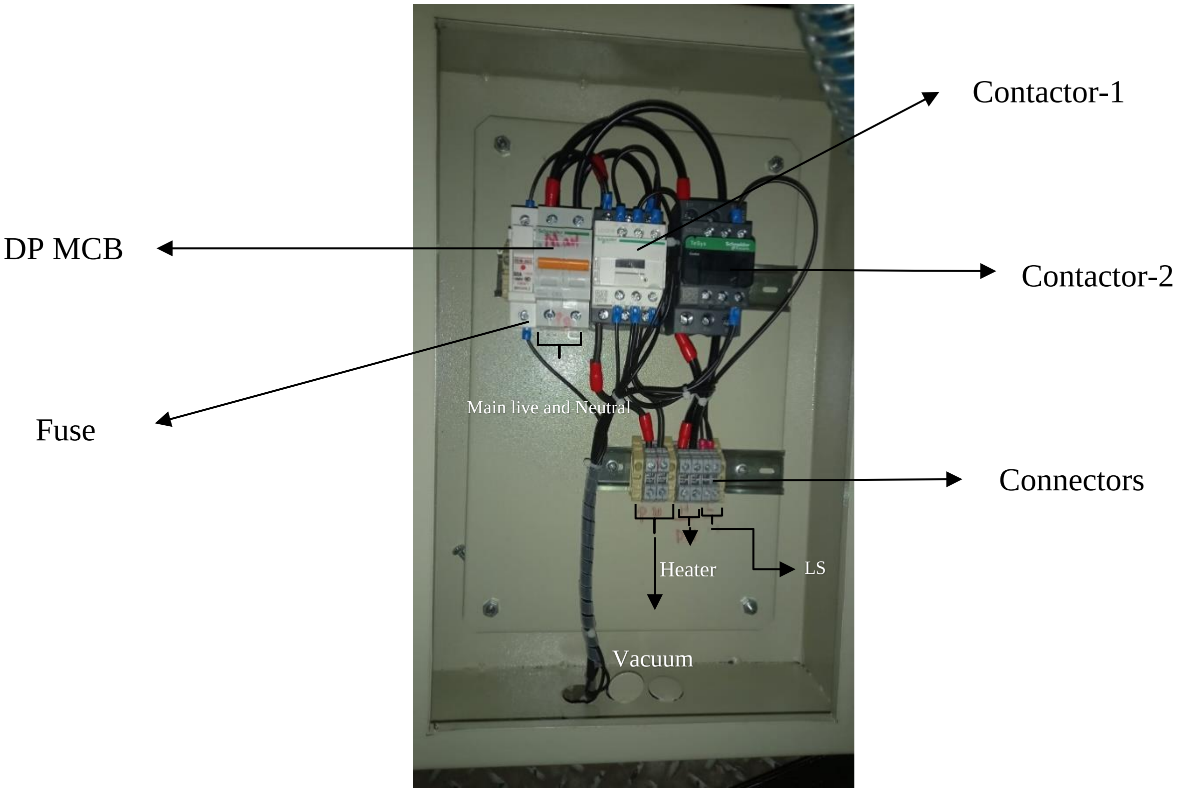


Figure 34. Components of a DB box

Here LS means limit switch which is shown below:

Figure 35. Limit switch

The electric system of vacuum pump is controlled by switches at the front of the machine:

Figure 36. Buttons used to control the working of vacuum pump

In the figure, there are three buttons: red, green, emergency stop button. The green button is to start the pump, red is used to stop the pump while the emergency stop button opens all the electric circuits and stops the working of machine.

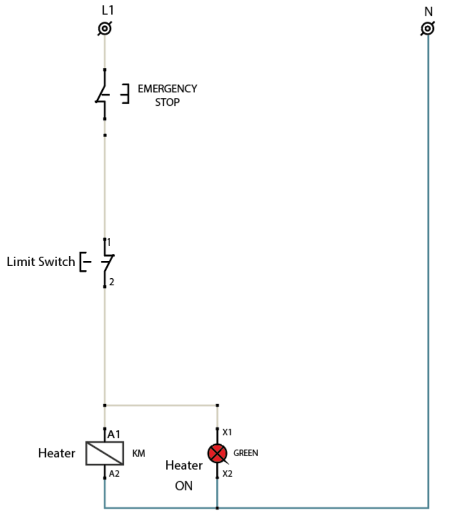


Figure 38. Heater ON/OFF Circuit diagram

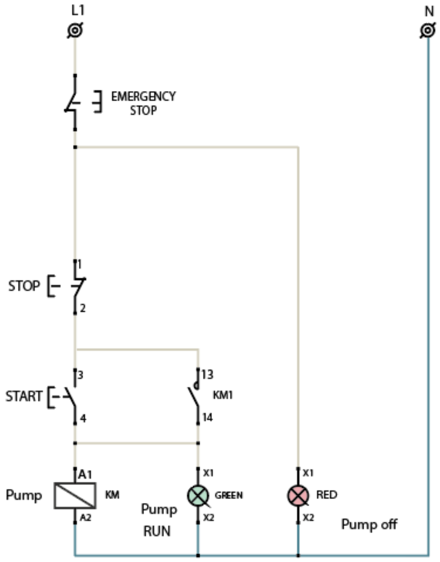


Figure 37. Pump ON/OFF circuit Diagram

3.7 Working Procedure:

The working procedure is briefly described below:

- The machine is powered ON and the control box becomes operational.
- Pump testing is tested by switching it ON through the control box.
- The heater is moved onto the blue plate. A limit switch turns ON when the heater strikes it, and the heater is turned off.
- After checking operation, a plastic sheet of **24x24 inches** is placed onto the white EVA material which is used in sealing the sheet.
- Wood fiber mold is placed onto the table.
- The H bar is locked while the sheet gets clamped between the EVA and the H bar.
- The heater is moved onto the sheet which becomes operational only when impacted with the limit switch.
- The sheet gets heated up. The sag on the sheet is checked to get an idea about the level of heating.
- The heater is pushed back and gets turned off.
- The lever mechanism lifts the table, and a vacuum is generated in the now sealed chamber.
- The pump is operated through the button on the control box.
- Once the sheet gets imprinted onto the mold, the pump is switched OFF.
- The H bar is disengaged, and the mold is removed from the sheet.
- The table is lowered.
- The machine operation is finished.

It is to be noted that thermoforming is a high-deformation rate process in which polymeric material is deformed by heating to a temperature above its glass transition. The main source of concern is uneven heating, which directly relates to thinning of parts. This leads to a decrease in the mechanical properties of formed parts. In the current thermoforming process, the optimization of the final part thickness is done by trial and error, by changing the design of the component, polymer material and processing conditions such as heating temperature, mold temperature, applied pressure and plug design.

CHAPTER 4: RESULTS AND DISCUSSION

In the project, mild steel is used to create the framework or the body of the machine because it is strong, durable, resistant to corrosion and relatively inexpensive. It also has good ductility and can be easily welded, making it a versatile material for constructing frames of different shapes and sizes. Compared to other types of steel, mild steel has a lower carbon content, which makes it more malleable and easier to shape. It also has a high tensile strength, which means it can withstand a lot of stress without breaking or deforming. Furthermore, Teflon was used in the sliders because of its excellent non-stick properties due to its very low coefficient of friction. It is also highly resistant to heat, with a melting point of around 327°C. Additionally, Teflon is highly durable and long-lasting, with a low coefficient of thermal expansion and excellent electrical insulation properties.

Figure 39. Shows the wooden mold.

The vacuum forming machine available in DME was utilized to replicate a side skirt of the electric vehicle used in NUST, which is supplied by YES Electromotive Company. The wooden mold utilized in the production process was created with the aid of wood machining, while ABS plastic sheets were used. The entire procedure was completed in under 60 seconds. Currently, YES Electromotive employs fiberglass to manufacture their side skirts, which requires a significant amount of machining time.

Figure 40. The side skirt formed using ABS.

The finalized product requires machines to cut out the part from the whole sheet. This part will now be sent to YES Electromotive as an alternative to their fiber glass skirt.

The product manufactured in our FYP is a completely working vacuum forming machine. The H bar of the machine rests on the sealant which is made up of EVA plastic (Ethylene-vinyl acetate) commonly used in household water wipers. This sealant is an alternative to the silicone sealant which is expensive and imported from China. At the back of H bar, there is a spring assembly that holds the bar and provides support just like counterweights. The locking mechanism of H bar is same as the older machine which is done by use of hooks. In the moving table mechanism, 2 sets of 2 links of different lengths are used. Welding provides strength to the ends of the linkage system while there

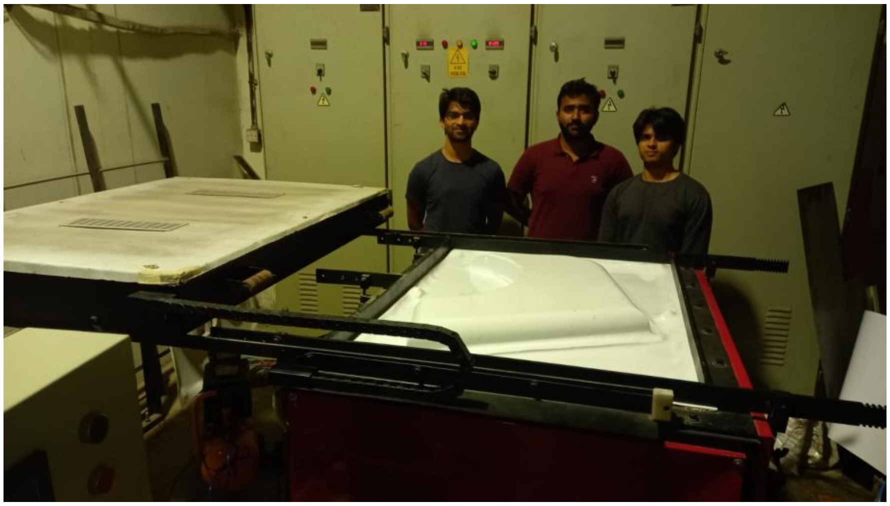


Figure 41. The Side skirt being formed in the machine.

are two rotating joints in which Teflon washers are present. They help in reduction of friction and help moving the table with ease. To add the finishing flourish, a coat of black spray paint was applied, giving the machine a pleasing appearance. At the bottom of the machine, the vacuum pump rests on two mild steel angles which are welded with the frame.

CHAPTER 5: CONCLUSION AND RECOMMENDATION

Throughout the project, there were many problems and hurdles that the team faced. Some of the recommendations about manufacturing a vacuum forming machine are:

- Make sure to check the availability of raw materials in the local market before designing the machine. For example, the dimensions of the mild steel angles available in the market can be different than the one designed in the software. So, if the market is checked beforehand, it can save a lot of time.
- Manufacturing processes should be done in an order. For example, in this case, holes should be made before welding any joints.
- For the manufacturing of bearing pillows, mild steel can also be used instead of Teflon.
- There must be high accuracy in the manufacturing of heater's body as metal sheet working is delicate.
- Handling of heater rods should be with care as they can break on impact.

This machine can create multiple products of different types at the same time, reducing idle time. Also, the linkage system has lower friction so moving the table is not a problem in this scenario. To ensure mobility, the machine has 2 sets of wheels. This machine is a better and enhanced version of the already available one in DME, NUST.

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