CONCEPTUAL DESIGN OF CIRCULAR MOULD FOR VERTICAL INJECTION MOULDING MACHINES

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ABSTRACT

Advancement in technological development, materials and techniques are widely acknowledged as the prime catalyst to revolutionize the injection moulding industry in meeting the ever-increasing competitive pressure. Injection moulding machines are used for mass production of plastic products such as combs, utensils, and custom-shaped products in the industry. The current injection moulding machine is rectangular that will limit the amount of product produced per cycle. The purpose of the paper is to introduce a new, innovative approach to the injection moulding machine, which is a circular mould structure. The circular mould will be dissected into stationary and dynamic slices. The mould cavities form when slices are clamped together. The molten plastic will be injected into the mould cavities with the cooling system in place. The plastic hardens and is ejected once the mould plates retract. Temperature needs to be well-maintained in the vertical injection unit that allows plastic flows into each individual mould. In view of further improving on the product yield at the production line, a built-in camera sensor and conveyor belt are utilised to monitor the quality of the products based on a MATLAB code. Hence, quality control on the level of rejection or pass could be determined.
Keywords: Injection moulding machines, plastic product, circular mould, quality control

1. Introduction

Injection moulding is a manufacturing method that enables production of products on mass quantity in view of meeting its market demand. Dominantly, injection moulding machine, as shown in Figure 1, is used for a range of applications where a repeatable manufacturing process is required at a relatively low cost. This includes manufacturing items such as wire spools, packaging, bottle tops, toys, combs, musical instruments, chairs, small tables, storage containers, mechanical parts, automotive parts, and components.
There are many different materials that can be used in an injection moulding machine such as metals, glasses, elastomers. However, it is most typically employed with thermoplastic and thermosetting polymers [11].

Fig. 1. Existing injection moulding machine (Guanxin plastic machinery)

The injection moulding operates by pumping molten materials into a mould, which then hardens and forms the final product. In the economic sense, once the initial costs of the design and the moulds have been covered, the price of manufacturing becomes lower. Thus, the cost of production drops as more parts are produced. In contrast with traditional manufacturing approaches like CNC machining, waste produced by injection moulding is minimal. Thus, the process also allows production of many identical parts, which allows for part reliability and consistency in high-volume production.

The injection moulding machine is a complex machine with lots of components. The injection moulding unit performs different processes which include clamping, injection, cooling, and ejection. The powered clamping unit pushes the mould plates to a close, exerting sufficient force to keep the mould securely closed while the liquid resin material gets injected into the mould cavities. This liquid is then injected into the mould of the product, which has already been pressurised prior to injection. The liquid fills up the mould entirely and is then subjected to cooling, which is done by having water flow through cooling pipes around the mould, extracting the heat from the liquid plastic and solidifying it. The final process is where the mould opens, and the product is ejected out of the mould. The cycle repeats to produce more products. A simplified process flow of these activities is shown in Figure 2 below [12].

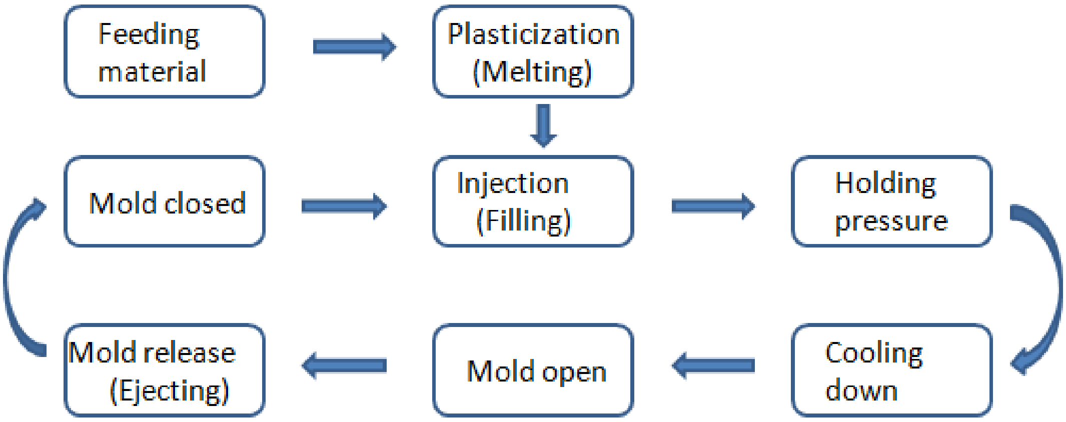


Fig. 2. Process flow of injection moulding machines [12]

Existing injection moulding machines employ rectangular-shaped mould plates with the motion of these plates, while in operation, being linear. The design limits the number of products it can produce. The objective to be explored in this paper is the feasibility of introducing new dimensions into the machine's movements through the utilisation of a circular mould. Success in doing this will enable the machine to operate and produce more products while occupying less floor space.

Current injection moulding machines are efficient in design which able to produce many products. These machines are optimised to operate at peak performance, making them one of the most popular manufacturing methods for plastic products. However, some common downsides of this injection moulding are that most injection moulding machines are designed to be horizontally placed, increasing the footprint of these machines. Vertical injection moulding machines exist but are not fully optimised in certain aspects of their design. These machines usually work on one to two mould plates at a time and have inconsistent cycle times because of its system, which relies on manual removal of the finished product [10].

The main objective of this research paper is to introduce a new, innovative approach to the injection moulding machine, which is of a circular mould structure in nature. It is envisaged that this circular mould can operate at a high efficiency while taking up minimal floor space. The first innovative approach taken was to redesign the mould structure capable of producing more products per cycle, leading to the design of a circular mould structure. Thus, increases its productivity while occupying a relatively smaller area. Second, to maximise efficiency per area, a vertical injection unit is placed above the circular mould. Readjustments in the runner and storage system of the injection unit allowed the molten plastic to have the shortest flow distance to the mould cavity. Cooling and ejection systems tailored-suit and increase the efficiency of the newly created circular mould. Last, an in-built Quality Control system was devised to remove defects at an early stage.

2. Methodology

The conceptual design of the vertical injection moulding machines was designed specifically to reduce the use of floor space and will increase the production rate using the multiple circular mould. Figure 3 shows the computational model of the vertical injection moulding machines with their specification.

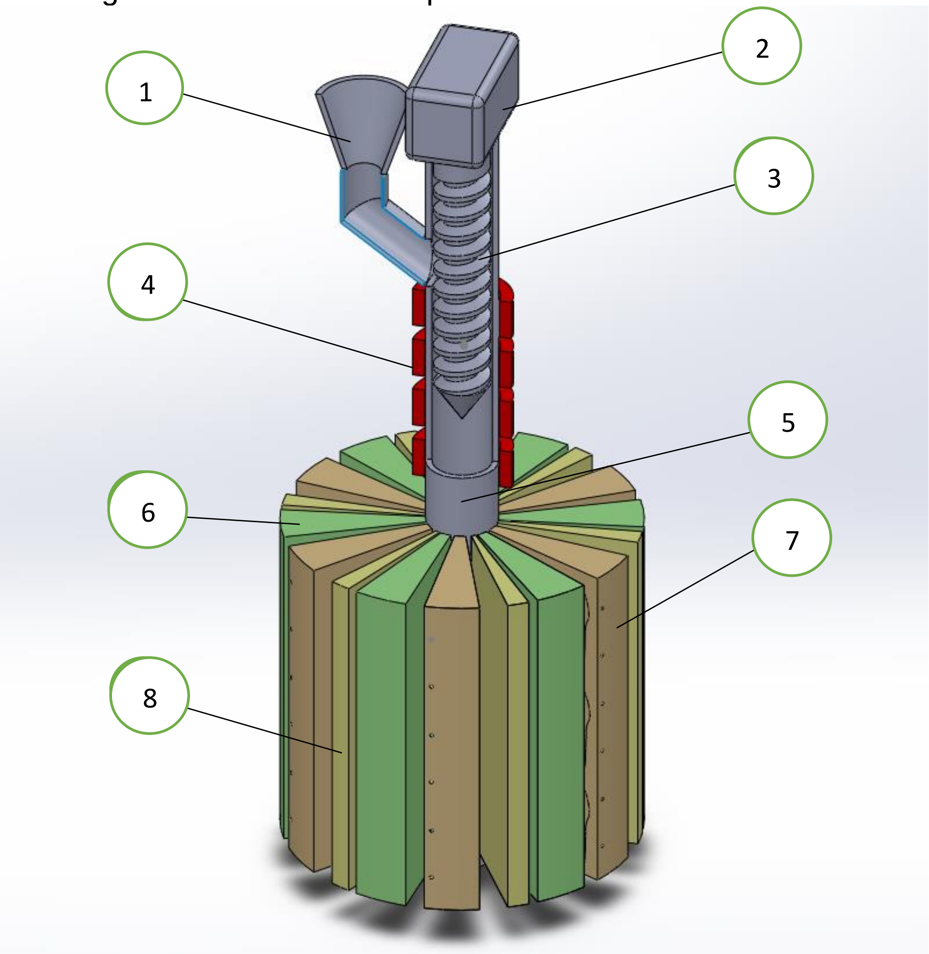


Fig. 3. Assembly design created in SOLIDWORKS

Table 1. Bill of Components

No.	Parts
1	Hopper
2	Motor
3	Screw
4	Heater Band
5	Barrel
6	Dynamic Mould
7	Stationary Mould
8	Clamping Plate

2.1 Design Component Materials

Material selection plays a vital role in determining the manufacturing process, production costs, and machine performance. Understanding the types of materials used for each component makes it easier to run simulations and analyse the machine's performance, especially the mould and clamping plates. An injection moulding machine usually comprises components, namely the base, hopper, barrel, split mould, clamping unit and screw. The smaller components are the nozzle, ejector pins, and heaters. Table 2 shows the functions of each component and the materials they are made of.

Table 2. Material and function of each machine component [9]

No.	Components	Function	Material
1	Base	Holds all the other parts and electronics needed to run the machine.	Stainless steel
2	Hopper	Where raw plastic material is poured before the injection moulding process.	Stainless steel [1]
3	Barrel	Heat the plastic material into a molten state to let plastic flow through the barrel	Nitralloy nitride [2]
4	Screw	Pushes the ingredients of plastic material in a forward direction and provides most of the heat to the thermoforming plastic	EN41B nitriding steel [3], Musco grade
5	Heaters	Regulates the temperature of the system to melt and maintain the temperature of the plastic	• Band heaters and coil/nozzle heaters • Cartridge and strip heater
6	Nozzle	Pushes liquified plastic out of the barrel and into the mould	4140 alloy steel [4]
7	Ejector pin	Pushes the formed part out of the mould	Nitride H13 Pins [5] • Can withstand temperatures up to 200℃
8	Stationary and Dynamic moulds	Type of injection mould, where the plates form the mould cavity	S136H steel [6] • Suitable for all kinds of plastic mould • High wear resistance • Strong rust and acid resistance • Versatile in dry or wet conditions • Lower maintenance
9	Clamping unit	To open and close the injection mould	S136H steel

2.2 Circular Mould Structure

A mould is a hollow metal block into which molten plastic is injected to form a certain fixed shape. Molten plastic flows into a mould through a sprue and fills cavities through runners and gates. Once the cavity is filled, the cooling process solidifies the molten plastic. The mould is then opened, and the solidified product is ejected out of the mould through ejector pins. This is known as a cycle and improving on the cycle time will directly improve the overall efficiency of the system. Implementing a circular mould aims to increase the number of products per cycle.

Figure 4 is an illustration of the design concept. The structure comprises 12 mould pieces and is divided into two parts. First part contains six fixed stationary mould, whilst the remaining six can move freely (Dynamic Mould). The mould cavity is engraved onto one side of all 12 mould pieces. In view of clamping the mould pieces together, 6 clamping plates are introduced. The movement of these pieces is dictated by the track grooves below them, allowing for only radial movement. At the centre of the structure is a heating shaft which is extended from the barrel of the injection unit. This heating shaft contains molten plastic and is connected to the mould pieces through a gate and runner system. The runner and gates as shown in Figure 5 were designed to be placed in locations to ensure minimal travel distance of the molten plastic, ensuring no solidification of the molten plastic occurs prematurely. Air vents were also installed to provide an escape for the air in the cavity and, based on the material chosen, LDPE, the air vents were dimensioned at 0.013mm in order to prevent any leakage of molten plastic.

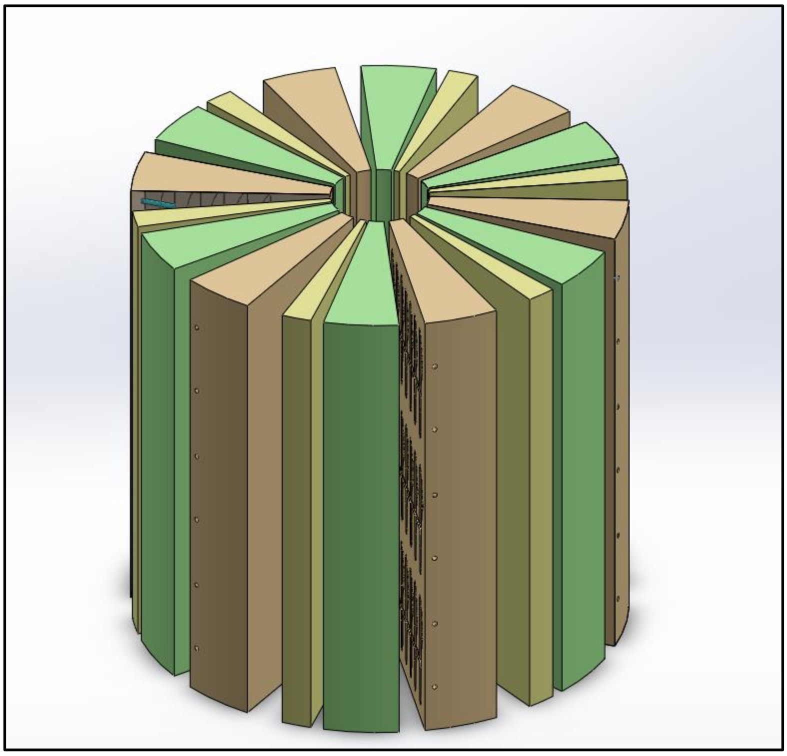


Fig. 4. Circular mould design created in SOLIDWORKS

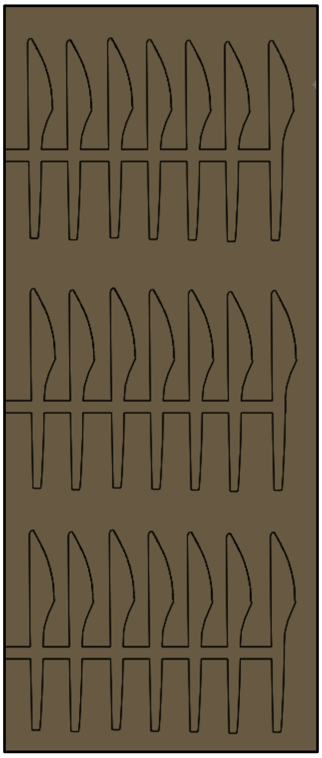


Fig. 5. Mould cross section

Based on the SOLIDWORKS software, a simulation analysis was performed. In the analysis, a plastic knife was selected for the mould cavity. As discussed earlier under the material section, the material chosen for the mould pieces is S136H and this will play an important role when running simulations as its properties dictate the results.

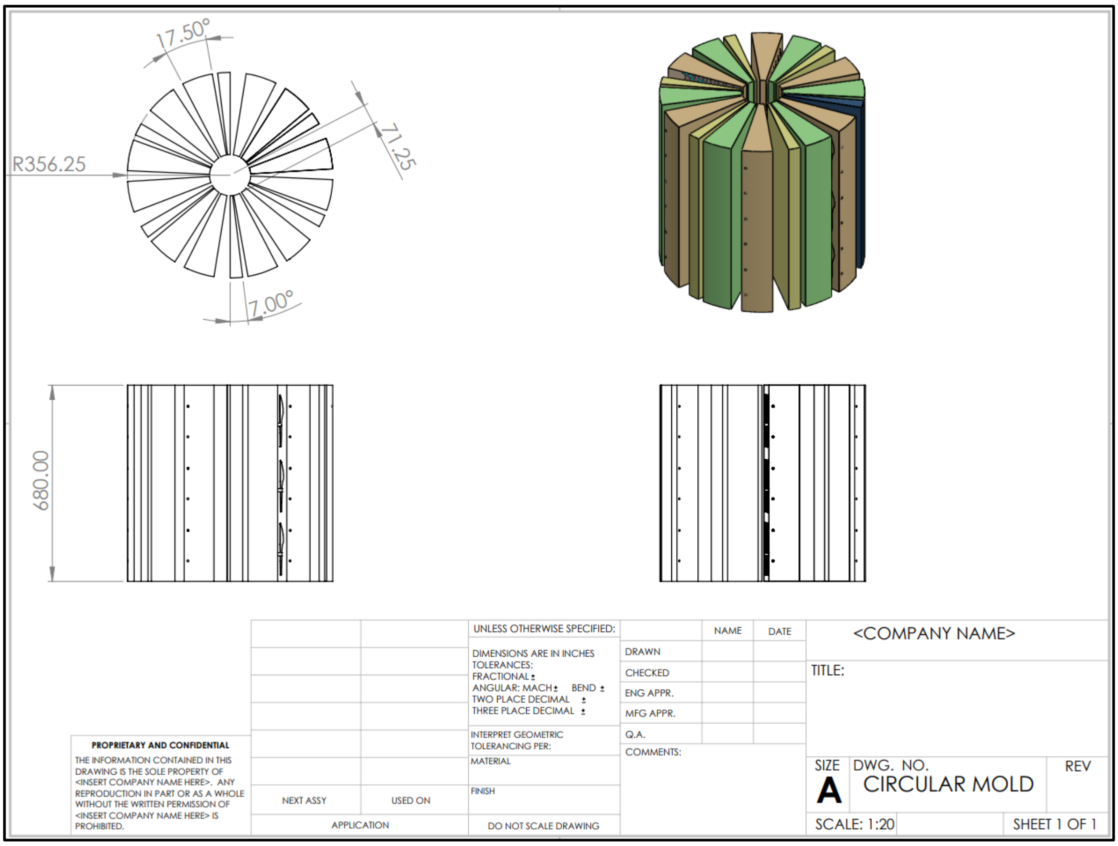


Fig. 6. Drawing file with dimensions of circular mould

2.3 Injection Unit

The injection unit is an important aspect of the design as it is solely responsible for supplying the correct parameters to the mould. Such parameters include the temperature at which the molten plastic enters the mould; the melting consistency of the plastic; the pressure at which the plastic is injected etc. Compactness is a core idea of the machine design and to accommodate for this, a vertical injection unit was utilised to ensure that limited floor space is taken up [7]. By implementing a circular mould structure, this prompted the need to redesign the vertical injection unit to function along with the mould properly. Since the circular mould comprises many different slices, a heating shaft in the middle of the circular structure was allocated for the heating and storage of molten plastic, in order to optimise the flow of molten plastic into the cavities (refer to figure 7). The plastic flows from the heating shaft to the mould through runners. Distance travelled by the molten plastic before reaching the cavity is a crucial design aspect to consider; as if done incorrectly, would lead to solidification of plastic before reaching the cavity. Hence, introducing a heating shaft optimises the flow of molten plastic, leading to a higher consistency in production.

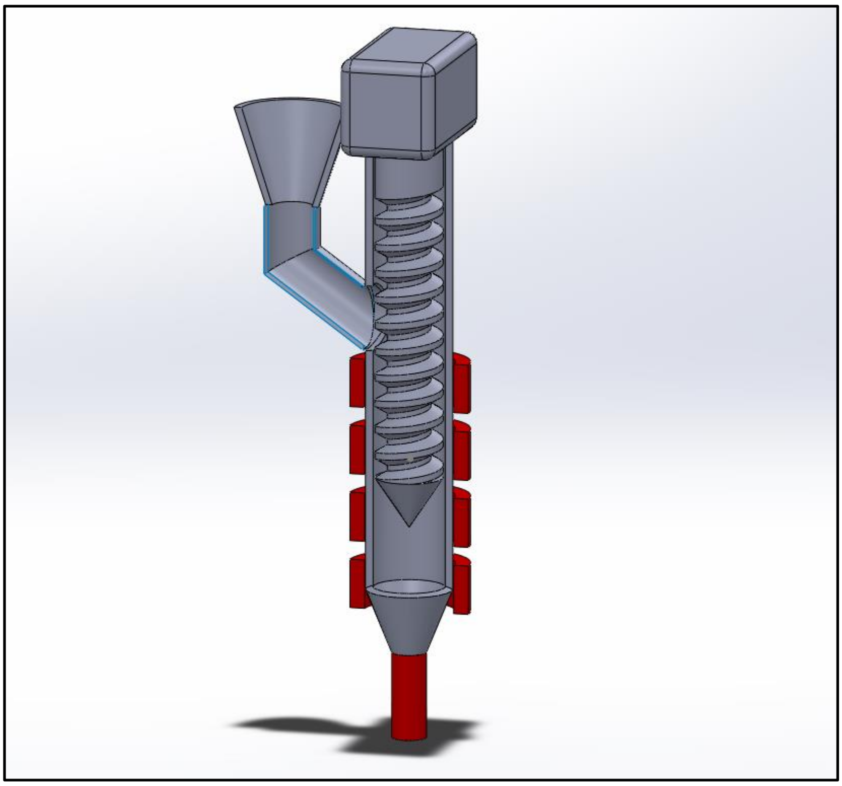


Fig. 7. Vertical injection unit model created in SOLIDWORKS

High repeatability and precision in the screw's movement is achievable through a motor-powered mechanism. Energy consumption only takes place when the machine is in motion, leading to great energy savings, ranging from 30% to 70%. Utilising a vertical injection unit allows for a compact design, as its footprint is considered being half of the horizontal alternative. As previously mentioned, the injection unit plays a vital role in providing sufficient injection pressure, temperature and filling time. Opting for a vertical design enables the machine to utilise gravity to help provide the required pressure, lowering the workload of the motor, which results in a reduced cost of operation. Being primarily responsible for the melting and injecting of the plastic into the mould, the injection unit is able to regulate the various temperatures needed in each section of the barrel. Employing heater bands enables for easy and accurate control of temperature.

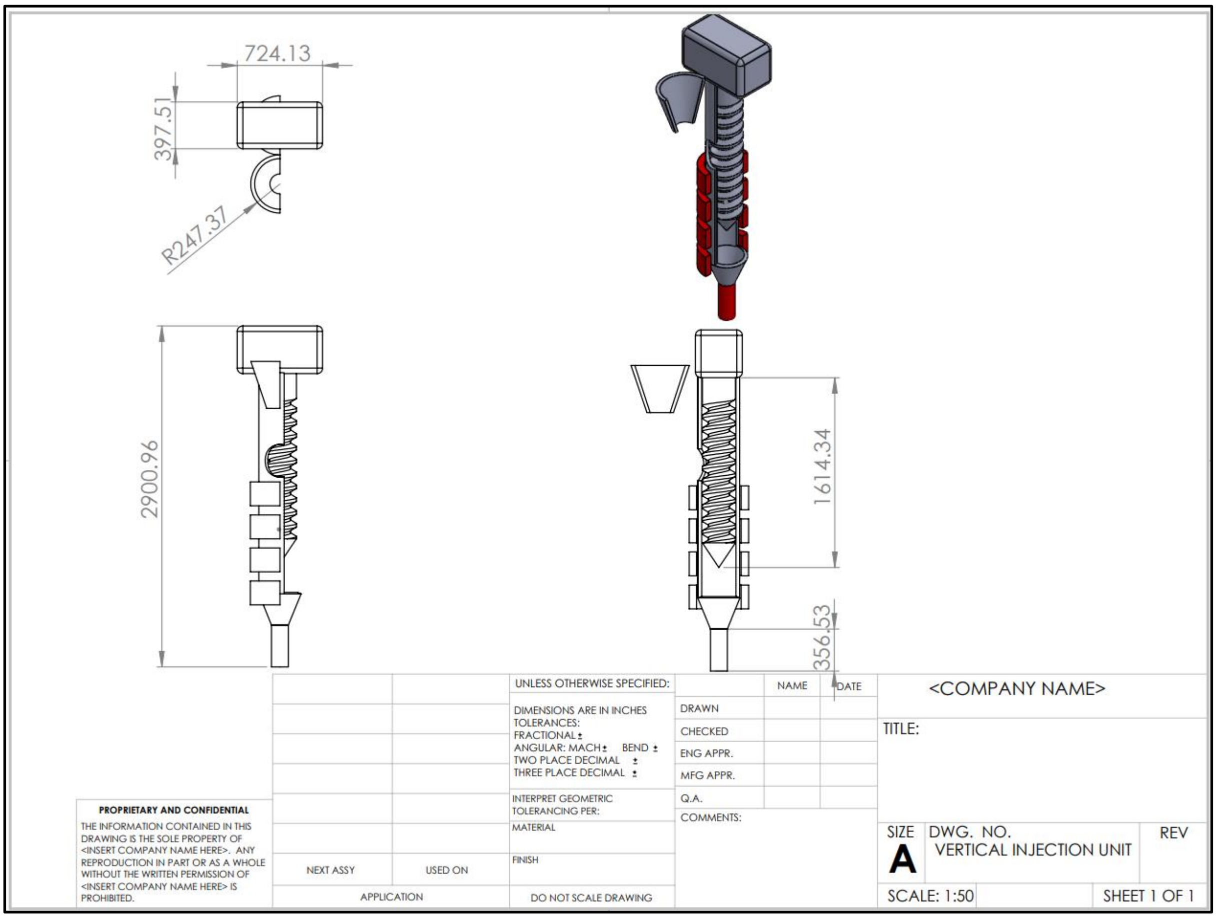


Fig. 8. Drawing file for vertical injection unit created in SOLIDWORKS

2.4 Clamping unit

Clamping force in injection moulding is an important factor because it acts against the separation or swelling force of moulding liquid. To shape the product in the desired manner, the material must pack against the mould walls [8]. The clamping unit in this design operates on a hydraulic system which moves the clamping plates along the track. The hydraulics enable the plates to supply at least the clamping force of 65 Tonne.

2.5 Cooling unit

Cooling time in injection moulding is a critical part of the production process. It is the time the molten plastic takes to solidify. An adequate cooling system is required to transfer heat away from the mould and maintain a stable cooling rate, ensuring the highest quality of the final products. Therefore, the uniform design of the cooling water channel has a profound impact on improving the overall cycle. The inlet temperature of the water was controlled at 10°C. The temperature on the surface of the mould cavity would be 45°C. The cooling system for our system will be installed in the stationary mould and it will be parallel to the surface of the cavity. It is evenly spaced to ensure that at least 60% of the projected area of the plastic parts is covered to provide sufficient cooling. The thickness of the cooling pipe was set at 10mm, this is the most appropriate dimensions to achieve the optimum cooling efficiency. In the picture below, the blue pipe represents the inflow of cooling water, whilst the red shows the outflow of the water.

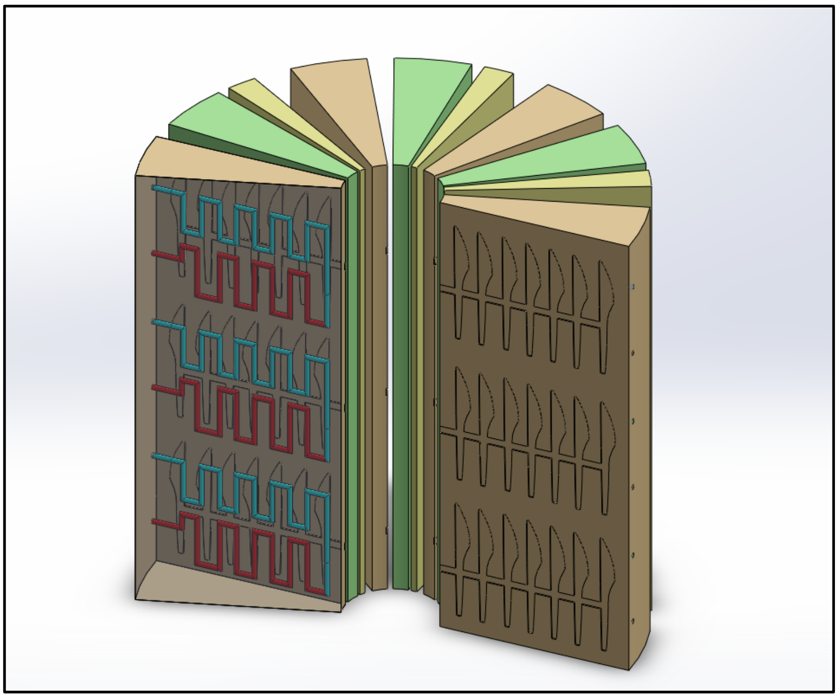


Fig. 9. Cooling system layout in the stationary mould

2.6 Ejection unit

The ejection system is critical because it clears the cavity for the next injection. It may affect the quality of the product, since if not done properly, it might damage the product. An air ejection system will be used in this injection moulding machine system. This system uses a pneumatic release mechanism by using compressed air to eject the plastic parts. The locations of the ejector pins were strategically placed to ensure even displacement of the product from the cavity. During ejection, a small amount of compressed air pushes out the ejector pin to help separate the moulded product from the mould. The air flow is timed to coincide with the ejection cycle, and this air flow opens the valve, allowing the vacuum to be broken and the product to be ejected.

2.7 Quality Control

Implementing a Quality Control (QC) system post-ejection allows for early detection of defects. If the defects could pass through onto the next stages of production, valuable resources will be wasted on them. A few components are needed in order to create a QC system: a camera, MATLAB code and an Arduino board. The camera functions as the ‘eyes’ of the system which captures the image of the ejected products. These images are then compared to the ideal image and if the similarities are smaller than 80%, that specific product will be excluded from the production line. The system can identify the dissimilarities between the MATLAB code. Removal of defects can be carried out manually or by automated systems according to the preference of the manufacturer.

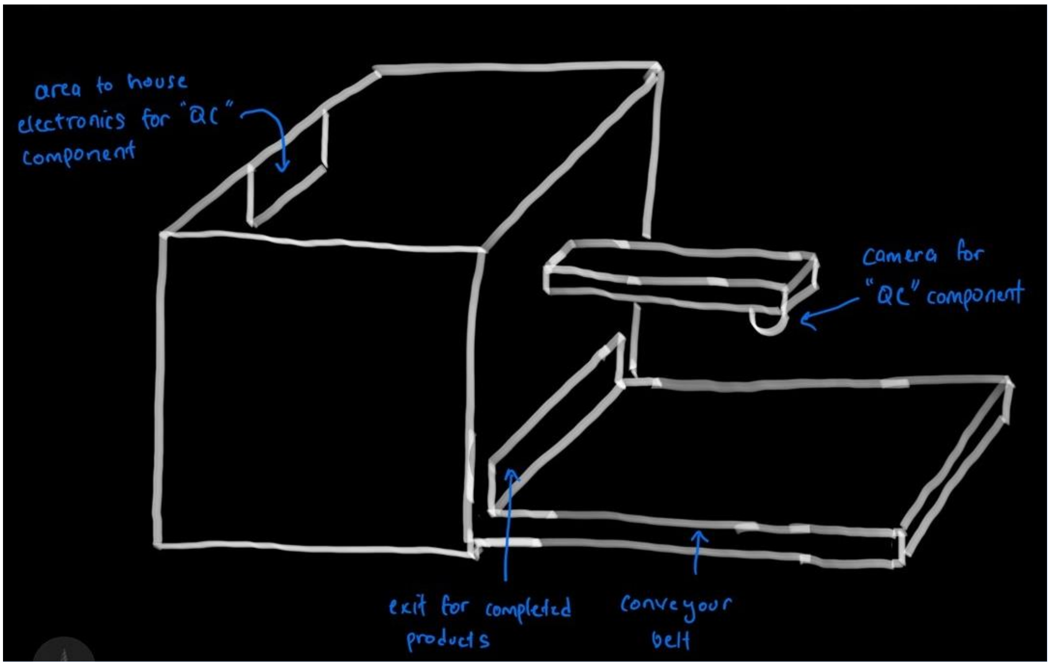


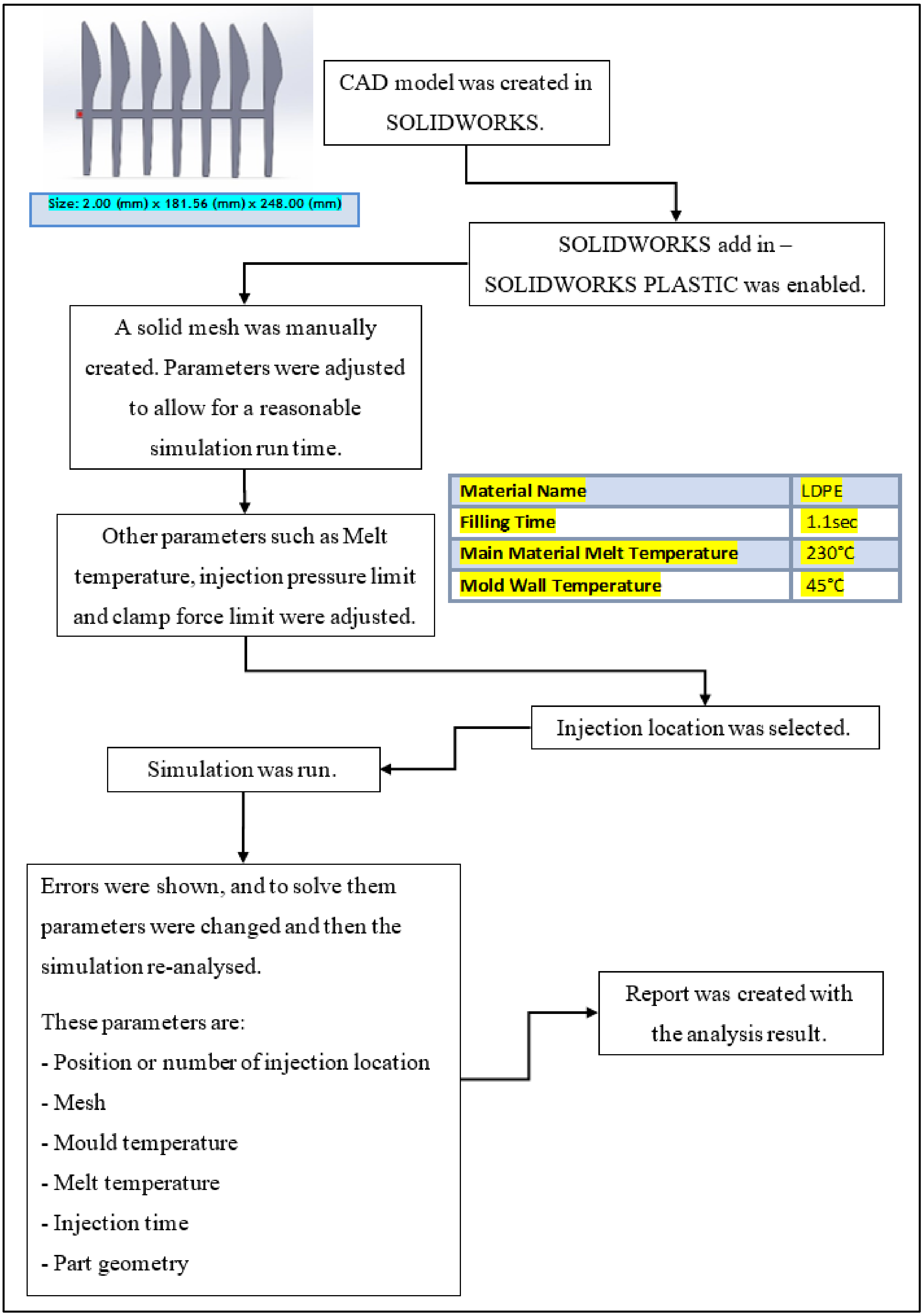
Fig. 10. Sketch of the QC system at the base of the product

2.8 SOLIDWORKS Simulation Procedures

To successfully run simulations on the design, a suitable plastic was required. Low-Density Polyethylene (LDPE) was decided to be the injected plastic material, as it is one of the most used plastics in injection moulding works. Utilising LDPE in the simulations would provide a good sign of how the machine would perform in industrial settings. LDPE majorly revolves around manufacturing containers, dispensing bottles, wash bottles, tubing, plastic bags for computer components, and various moulded laboratory equipment.

Table 3. Properties of Low-Density Polyethylene (LDPE)

No.	Properties	Value	Units
1	Density	0.91 – 0.94	g/cm3
2	Melting Point	105 - 115	°C
3	Maintaining Melt Temperature	180 - 280	°C
4	Mould Cavity Temperature	20 - 70	°C
5	Injection Pressure	150	MPa
6	Pack Pressure	75	MPa
7	Shrinkage	2.0 - 4.0	%



Material Name	LDPE
Filling Time	1.1sec
Main Material Melt Temperature	230°C
Mold Wall Temperature	45°C

Fig. 11. Procedures of SOLIDWORKS Simulation

2.9 Fabrication Process

The prototype comprises 3 major components which are the injection unit, the circular mould and the conveyor belt. Below are the processes involved in creating said prototype, including all of its components included in the conceptual design.

- To produce a cost-effective prototype, the team used the university's resources, such as a 3D printer and the workshop materials.
- Each of the individual components was fabricated separately to ease the assembly process. Portability of the prototype was prioritised because of the distance between the university (Shah Alam, Selangor, Malaysia) and the site of competition.
- All of the 3D printed components were made using Polylactic Acid (PLA).
- The mould pieces and clamping plates were placed on guide tracks which dictate the motion in which they move. The guide tracks were made on a piece of wood and to cut the tracks out, a drill press with a 10mm drill bit was used.
- The base support of the machine represents a cube structure, and the component was created out of wood. It was made to be dismantled easily and reassembled for the ease of transportation.
- Below the support of the mould structure, a conveyor belt is housed. The conveyor belt is operating on a rolling mechanism which is created by using a PVC pipe, a rubber mat, and an electric motor to rotate the conveyor belt.
- The design comprises a QC (Quality Control) component. The camera was installed on a plastic Perspex piece which is attached on top of the conveyor belt mechanism via two aluminium machined pillars. The camera of the QC component is placed on said plastic Perspex to ensure enough height for the camera to capture a full frame picture of the product on the conveyor belt.

Fig. 12. Multiple pictures of the Completed Prototype

3. SOLIDWORKS Simulations Results and Discussion

Each mould comprises three layers, but each layer is independent of one another. Therefore, running a simulation for each individual row is redundant because it would yield identical results. Hence, the simulation was run with a single layer of the mould, and the following section displays the results.

Table 3. Results generated by the SOLIDWORKS simulation

No.	Description	Results
1	Cycle Time	8.45s
2	Filling Time	1.36s
3	Cooling Time	4.72s
4	Mould Open Time	2.37s
5	Average Clamping Force	65.23 Tonne
6	Required injection pressure	67.6224 MPa

3.1 Cycle time

Cycle time is the total time required to complete all the stages of the injection moulding cycle and it is directly associated with the efficiency of the product. Cycle time comprises fill time, cooling time and mould open time. Thus, to improve on the cycle time, each of these factors needs to be improved on. A lower cycle time would yield a higher production rate, and vice versa. The cycle time computed from the SOLIDWORKS simulation was 8.45 seconds and based on the proposed design of the circular mould, it would produce 126 knives per cycle, yielding 53,676 knives per hour. Although the cycle time for this design is not the fastest in the market, it certainly makes up for it with the amount it can produce per cycle.

3.2 Fill Time

This is the time required to fill the mould completely with the polymer. The figure below illustrates the time it takes for the molten plastic to flow into the mould pieces. The time taken to fill the mould completely is 1.36s, which falls within an acceptable range, and this is showed by the red colour, whilst the blue shows the beginning of the fill. There is a gradual change in colour as the mould fills from left to right.
By looking at the top and bottom outlines of the knives, the molten plastic does not fill the mould completely. This is because of the enormous size of the triangles in the mesh (The mesh determines the level of simulation detail through the triangle sizes. The smaller the triangle, the more detailed and longer the simulation takes to run, and vice versa). Time being a crucial aspect in injection moulding processes, it is paramount that the mould cavity is filled in the shortest amount of time possible.

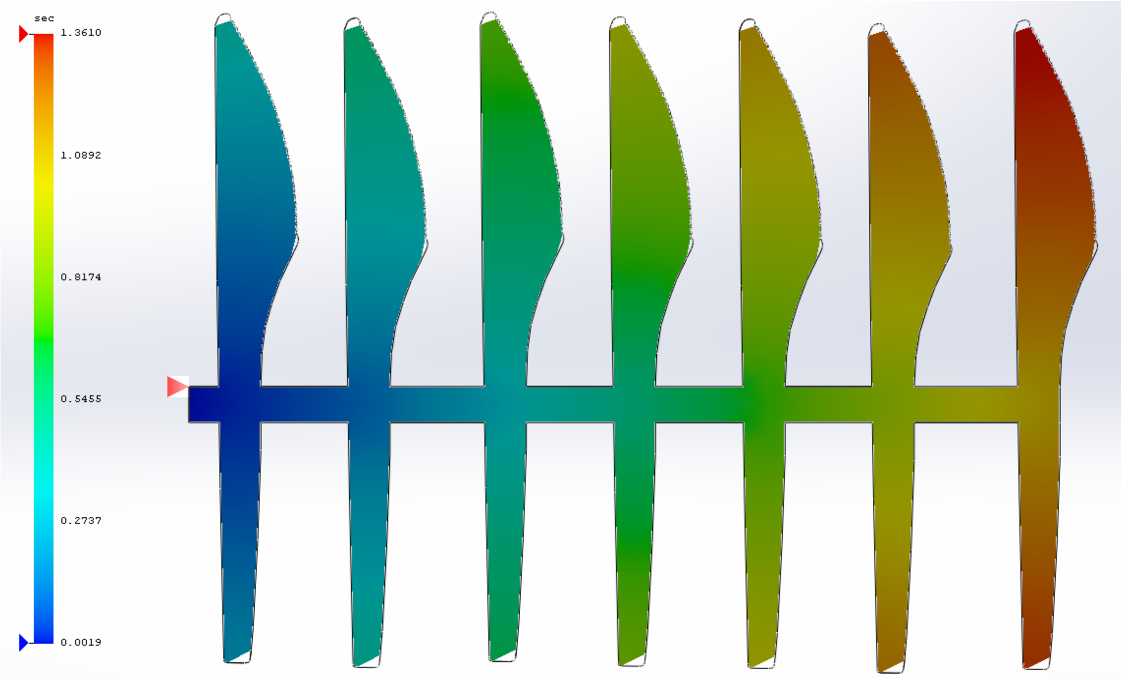


Fig. 13. Fill time results obintiained from the SOLIDWORKS simulation

3.3 Temperature at End of Fill

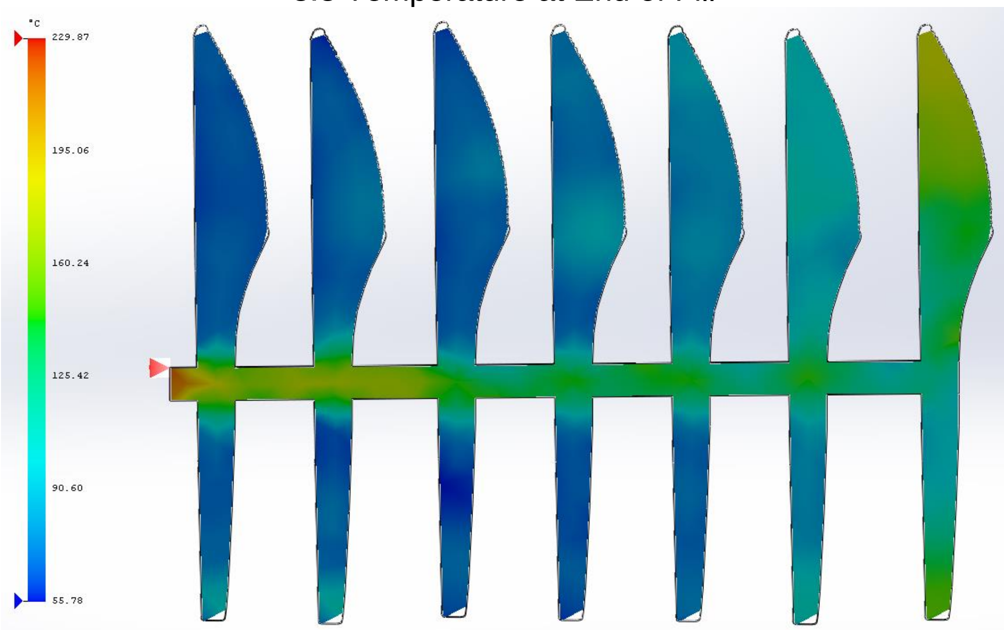


Fig. 14. Temperature at the end of fill obintiained from the SOLIDWORKS simulation

The figure above shows the temperature of the molten plastic at the end of the fill. As can be seen, the lowest temperature of the molten plastic is 55.78°C, whilst the highest temperature is 229.87°C. The highest temperature mostly occurs within the runner, connecting all the plastic knives together. As for the temperature of the knives, the first knife is the coolest, with each successive knife temperature increasing gradually, up to the last knife.

3.4 Cooling Time

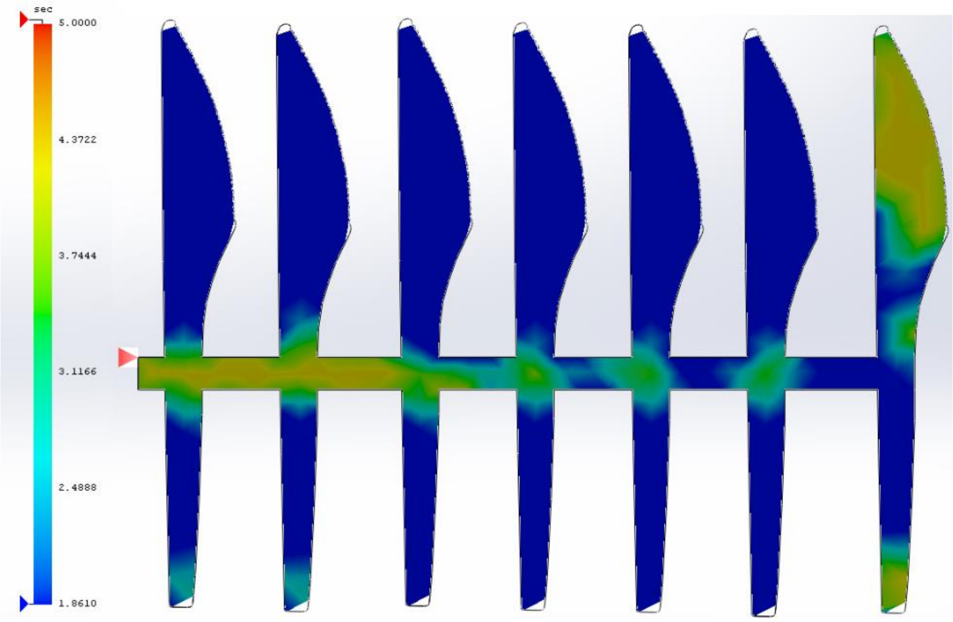


Fig. 15. Cooling time results obintiained from the SOLIDWORKS simulation

The cooling time is the stage of the injection moulding cycle when there is no more pressure applying to the polymer. It is seen that the cooling time is relatively low throughout the mould cavity, with the exceptions being the runner and last knife, because of the flow of molten plastic into the cavity. As shown, most of the molten liquid has a small cooling time (shown in blue). However, there are certain portions of the mould that have a slightly higher cooling time, up to a maximum of 5 seconds. Therefore, the total cooling time for the molten liquid is 5 seconds.

3.5 Maintenance

Maintenance plays a vital role in a machine's design and some of the design aspects made to accommodate for this is by making the stationary and dynamic moulds easily removable. This means that once the faulty components are removed, the machine can still function with shorter interruptions, resulting in a lower downtime. Another design factor is the mechanism in which the QC camera is attached to the base of the machine. With it being detachable, it allows for easy replacement of the camera in the event of failure.

3.6 Limitations

After a series of simulations, the one consistent limitation discovered was the relatively high cycle time. The one obvious limitation faced by the design is its incapability to produce large objects, such as chairs. It is possible to increase the overall size of the mould to allow for large objects. However, doing this will eliminate its advantage of having a smaller footprint.

3.7 Tooling Cost

Estimating the cost of manufacturing is a difficult task, hence a rough approximation can be made from the price of current existing moulding machines. The price ranges from RM22,222 - RM314,946 based on the complexity and size of the design. To manufacture the machine, the material cost is important. Listed below are the costs of each component’s material.

Table 5. Material costing

No.	Material	Cost/kg
1	S136H steel	RM8.88
2	Stainless steel	RM6.67
3	4140 alloy steel	RM6.98
4	EN41B nitriding steel	RM5.02
5	Nitride H13	RM9.43
6	Nitralloy nitride	RM16.74

3.8 Comparison between current industrial design versus proposed design

Table 6. Comparison table

<table>
<tr><th></th><th>Current Industrial Machines</th><th>Proposed Design</th></tr>
<tr><td>Cycle Time</td><td>2s- 120s</td><td>8.45s</td></tr>
<tr><td rowspan="2">Floor Space Utilised</td><td>Horizontal Injection Unit ~125.7sqft (model HXH260 from HX-HIGHSUN)</td><td rowspan="2">~15.5sqft</td></tr>
<tr><td>Vertical Injection Unit ~27sqft (model JY-450ST from Dongguan Jieyang Machinery Co., Ltd.)</td></tr>
<tr><td>Products per Cycle</td><td>24 pieces (model HXH260 from HX-HIGHSUN)</td><td>126 pieces (6x21)</td></tr>
</table>

The table above shows the differences between current industrial machines versus the proposed design in terms of cycle time, floor space utilised, and products per cycle. The cycle time computed through SOLIDWORKS simulation reads 8.45s, suggesting the proposed design is workable. With one of the primary objectives being the reduction of floor space used by the machine, the proposed design meets this requirement by occupying a less space from both of the current standards of vertical and horizontal injection moulding machines. Finally, to compare the number of products per cycle, the results show that the proposed design can produce 126 knives compared to the HXH260 model, which can produce 24 knives per cycle.

4. Conclusion

In conclusion, the whole new conceptual design of Circular Mould for the Vertical Injection Moulding machine brings up a one-of-the-kind circular mould shape. With that, the machine can produce 126 knives per cycle, yielding 53,676 knives per hour. Along with the vertical injection unit, the footprint of the whole machine is relatively smaller compared to the current injection moulding machine found in the market. With a smaller surface area in the factory, this new concept can produce more and reduce the cost of production.

To support the conceptual idea, the complete simulations were done by using SOLIDWORKS. With the report generated by SOLIDWORKS, the filling time temperature at the end of fill and cooling time was obintiained. The time taken to fill up the moulds was 1.36s, the lowest temperature of the molten plastic in the mould was 55.78°C whilst the highest was 229.87°C, and the total cooling time was found to be 4.72 seconds. The addition of all these time factors yielded the cycle time of 8.45 seconds. With that being said, the simulations indicated of how the design would operate in an industrial setting.

There is room for improvement in the current design. First, for the simulation, a much more detailed analysis could be performed by utilising a finer mesh. This will take a considerably longer time to run but will yield more accurate results. Next, various parameters, such as shrinkage and warpage, could be analysed to provide a better grasp on the quality of the product produced. Last, building the actual machine and testing it will produce results from the real-world application of this idea.

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