Bedryfsingenieurswese

Development and implementation of a design and manufacture approach for mould performance improvement in the packaging industry.

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DECLARATION

I, the undersigned, hereby declare that the work contained in this thesis is my own original work and has not previously in its entirety or in part been submitted at any university for a degree.

Ek, die ondergetekende verklaar hiermee dat die werk gedoen in hierdie tesis my eie oorspronklike werk is wat nog nie voorheen gedeeltelik of volledig by enige universiteit vir 'n graad aangebied is nie.

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SYNOPSIS

This thesis represents the results of a study for the use of conformal cooling in blow mould design. As a part of this, design case studies and comparative experiments were conducted to determine the difference in performance of blow moulds incorporating conventional cooling and those with conformal cooling. The cooling configurations are compared using simulation to identify the shortcomings of conventional cooling. In addition modern manufacturing methods able to manufacture complex conformal cooling designs, are evaluated. The relevant cooling principles are explained using mould designing handbooks as well as heat flow handbooks. The tie between them is made and the differences explained. The moulding cycles of injection as well as blow moulding process are explained and the applicable simulation software used in these fields is described.

OPSOMMING

Hierdie tesis verteenwoording die resultate van `n studie vir die gebruik van `n verkoelings ontwerp wat die vormholte volg. As `n deel van die studie is verskeie gevallestudies en vergelykende eksperimente gedoen om die verskil in verrigting tussen blaasvorms met konvensionele verkoeling en die met verkoeling wat die giet holte volg. Simulasies is gedoen om die verkoelings metodes te vergelyk en ook om die konvensionele verkoelingsmetode se tekortkominge uit te wys. Moderne vervaardigings metodes, wat veral geskik is vir die vervaardiging van gietvorms met komplekse verkoelingstelsels wat die vormholte volg word ondersoek en bespreek. The relevante verkoelingsbeginsels word bespreek soos verduidelik in gietvormontwerphandboeke en ook hittevloeihandboeke en die skakel tussen hulle word gemaak, die verskille word ook uitgewys. The vormsiklusse van spuit- en blaasvorming word bespreek en die relevante simulasie sagteware word bespreek en vergelyk.

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1. INTRODUCTION

1.1 Problem statement

A prime example of vast possibilities for substantial performance improvement is the plastic conversion in the packaging industry. According to the common practice of for example blow moulding, 60% to 90% of the cycle time is used to cool down the manufactured product. Usually this is achieved through drilling of cooling channels in the mould. Occasionally this operation is very labour intensive, time consuming and costly without achieving the desired effect. Similar conditions and characteristics apply to the injection moulding process too. Ejector pins, parting planes, cores, etc. make it impossible to gain an optimal cooling effect and the methods to improve the cooling such as baffles and bubblers are rather time consuming and expensive.

Cavities are formed, however, differently, and the same type of cooling cannot be used on every mould. There are certain areas of the mould, which need more cooling than others. Those are for example, spots, where the plastic material is particularly concentrated due to the specifics of the moulding process. They become very hot during the operation and are actually the areas, where an adequate cooling must be assured. On the usual type bottles for example those places are normally located at the top and at the bottom of the product. This is why it becomes very important that the layout of the cooling is designed in accordance with the actual conditions of heat generation and formation.

1.2 Objectives

The main objectives of this study are:

- Reduce the cycle time of blow moulded bottles through improved cooling.
- Increase the product quality.
- Ensure that the mould cost stays competitive.

During the span of the research three case studies were completed. Each of the case studies had its own specific objective:

- Case study 1: Learn to use CFD and prove through simulations that conformal cooling is more effective than conventional cooling.
- Case study 2: Design the cooling layout of a complex mould and optimise it with the use of CFD and FEA.
- Case study 3: Redesign an existing conventionally cooled mould and incorporate conformal cooling. Conduct experiments to compare the bottles produced from the respective moulds.

2. OVERVIEW OF PLASTIC CONVERSION

2.1 Blow moulding

The basic process of blow moulding (BM) involves a softened thermoplastic hollow form which is inflated against the surface of a cooled mould. The expanded product solidifies in a hollow product [1]. The surface of the product will have the same surface finish as the mould in which it was manufactured. This surface could be as smooth as a mirror, sand blasted or engraved.

Blow moulding has three derivatives, known as Extrusion Blow Moulding (EBM), Stretch Blow Moulding (SBM) and Injection Blow Moulding (IBM) [1].

The modern blow moulding machines are very sophisticated and almost all parts of the cycle time are well controlled. It is safe to claim that these machines are efficient and that all the other parameters, except for the cooling cycle time, can be optimised by the operator. The cooling cycle easily constitutes 60%-90% of the total cycle time thus improvements here would yield the greatest returns.

2.1.1 Extrusion blow moulding

A typical extrusion blow moulding machine consists out of the following components:

- Extruder
- Crosshead with single or multiple parison
- Clamping arrangement

<u>Creating the parison</u>

The plastic is homogenously melted in the plasticator screw and then passed through the extruder head and die unit. The extruder head and die unit form the melt into a tube called the parison [1]. A section view of such a plasticator with two extruder heads is shown in Figure 1. The plastic pallets are fed from the left to the right and are melted with a combination of shearing and heating. The screw is tapered from left to right, this ensures that the plastic is compressed and the trapped air removed.

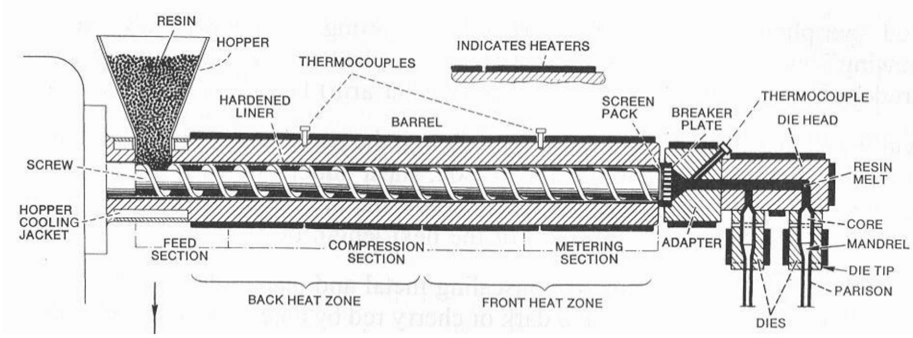


Figure 1: Section view of plasticator and extruder heads [1].

The clamping arrangement is shown in Figure 2. The air injection pin (or blow pin) is used to force high pressure air into the parison during the inflation cycle.

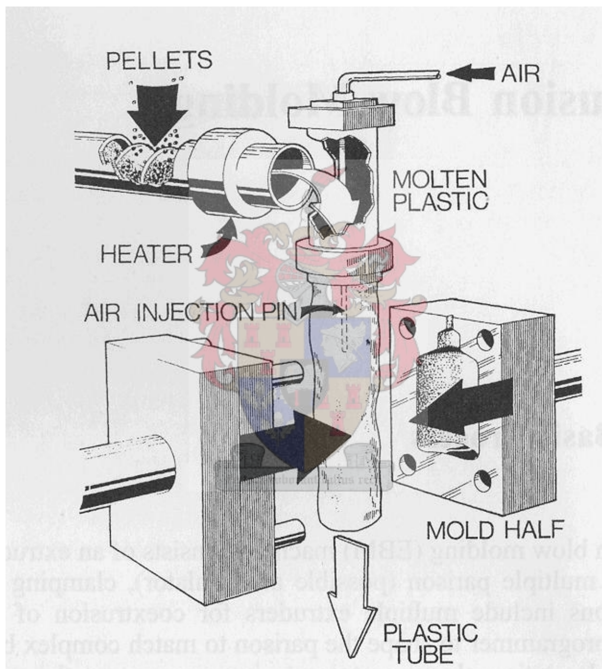


Figure 2: Mould movement illustrated [1].

<u>Forming the product</u>

There are different ways of introducing the inflation air into the bottle. It depends what type of machine is being used. On rotary machines (Figure 3) needles, which pierce the parison, inflate the product.

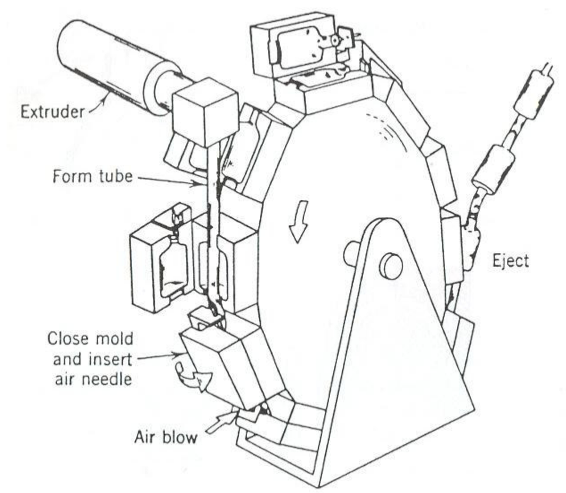


Figure 3: Vertical rotary wheel EBM machine [1].

On other machines the blow pin is at the bottom of the mould (Figure 4). This configuration is however not popular on the South African market. The modern machines manufactured and operated in South Africa are continuous shuttle EBM machines and have blow pins mounted at the top of the mould (Figure 5).

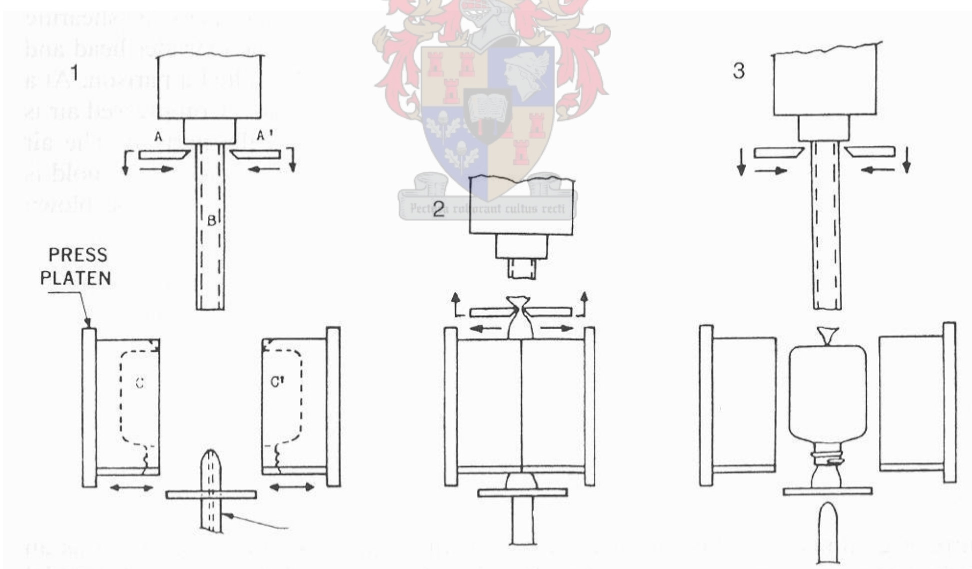


Figure 4: EBM layout [1].

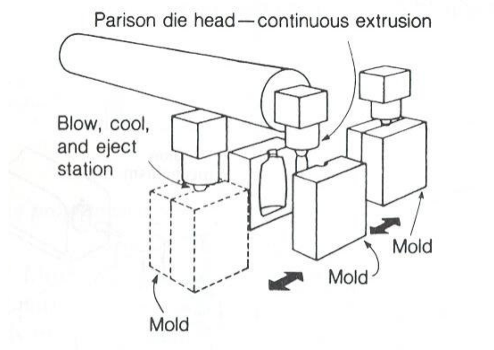


Figure 5: Continuous shuttle EBM [1].

After the mould halves close around the parison, the air, which is forced into the parison at around 6 Bar, inflates the parison to take on the form of the mould. In Figure 6 extrusion blow moulding is demonstrated with the use of a simulation package. A simulation view of parison expansion can be seen in Figure 7 and Figure 8.

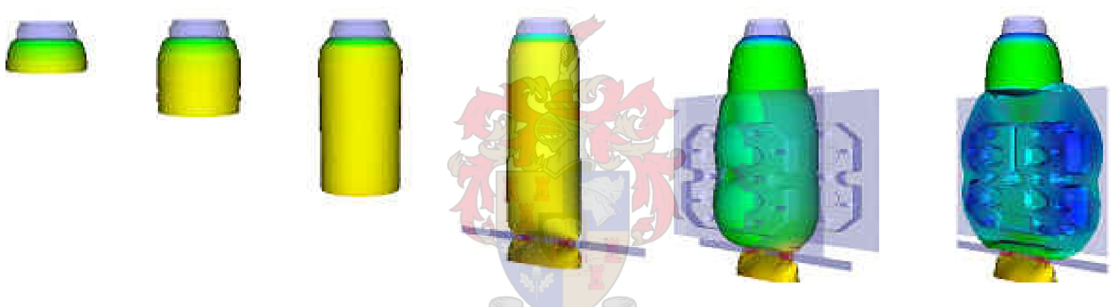


Figure 6: Simulation of the blow moulding [2].

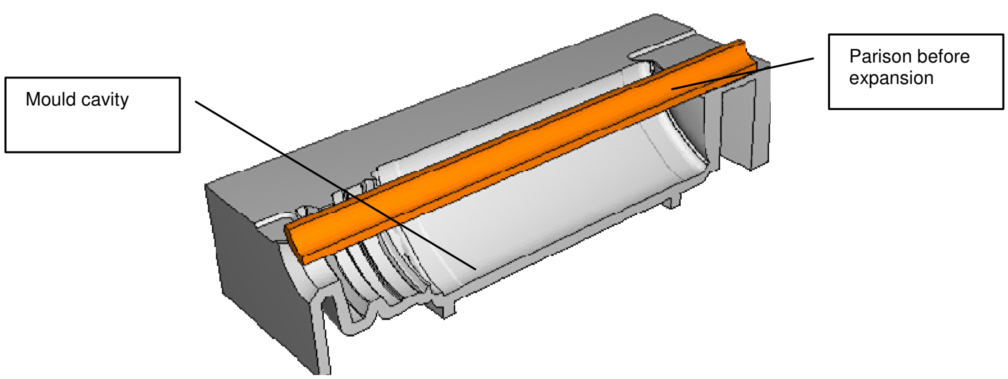


Figure 7: A simulation view of a quarter parison and mould.

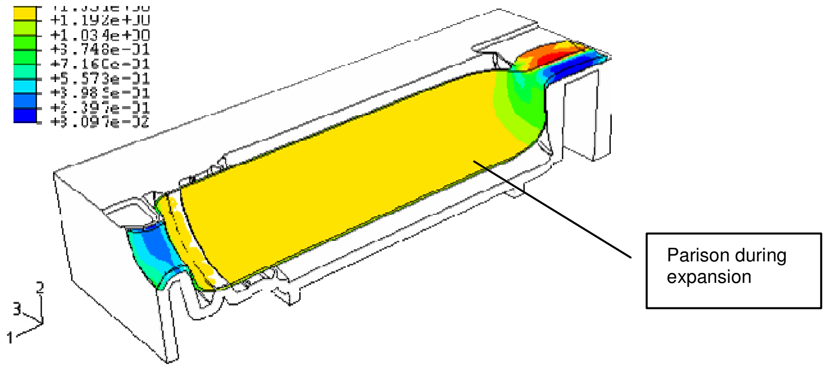


Figure 8: Simulated view of a quarter blown parison and mould.

Application of the different configurations

The two main forms of blow moulding are EBM and SBM.

EBM is mainly used to produce containers of lower value, such as detergent containers and medicine bottles. Typical plastics which are used in EBM are Polyvinyl Chloride (PVC), High-Density Polyethylene (HDPE) and Polypropylene (PP). The bottles produced with this method, when transparent, are not as transparent nor as crystal clear as that of glass or Polyethylene Terephthalate (PET) bottles produced with the SBM. The advantage of EBM is that the products can have very complicated shapes, including handles and goose necks.

The capital expenditure required to produce SBM containers is much higher than that of EBM, but the value of the containers is also much higher. This process competes with glass containers since the bottles produced are crystal clear and very strong, which makes it ideal for carbonated fluids. There is even a tendency for liquor companies to sell their products in PET bottles, especially the 50 ml bottles. The major limitations at this stage are that the bottles produced with SBM cannot be very complicated and can also not have a blown handle. Some innovative handle designs are being developed for the larger PET containers, but at the moment none are blown handles.

Forming cycle

All the machine movements and processes take time and all these added together is the total production cycle. The breakdown of the cycle time during the EBM process is illustrated in Figure 9. It is clear that the cooling of the product is by far the largest single component of the total cycle time. Figures of 60% to 90% are claimed in literature [3].

The cooling cycle time is determined by a number of factors of which none are controlled by the blow moulding machine. Most of these factors are either specified by the client (product mass, design and material) or governed by the mould design such as the mould cooling, material and parison diameter. All these factors play major roles in the cycle time, but some of them are given and cannot be changed, such as those specified by the client. The mould material is a given, because of reliability issues. The parison diameter also affects the quality, especially around the split line of the bottle. The larger the parison diameter, the longer the cut off area becomes and a cut-off has a sharp edge which may cause customer complaints.

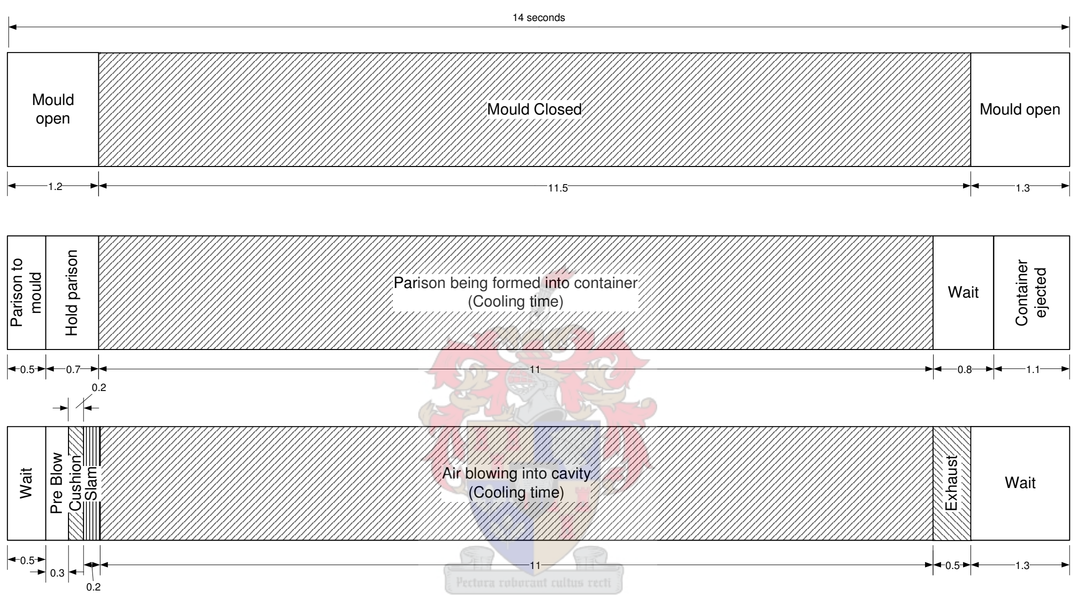


Figure 9: Typical manufacturing cycle breakdown of EBM [1].

<u>Controlling the wall thickness of the product</u>

One of the many challenges in EBM is to achieve a constant wall thickness in the final product. There are two methods of achieving this:

Parison programming

The first method is to ensure that the wall thickness of the bottle is uniform in it's length, this method is known as parison programming. The parison is formed with different wall thicknesses at different heights. Thus if the body of the bottle is very large, compared to the neck and the parison will have to expand significantly to fill the cavity without rupturing, then more material will be added in that region. The parison forming is done by moving the extrusion mandrel up and down, depending on the required wall thickness, during the extrusion process (Figure 10).

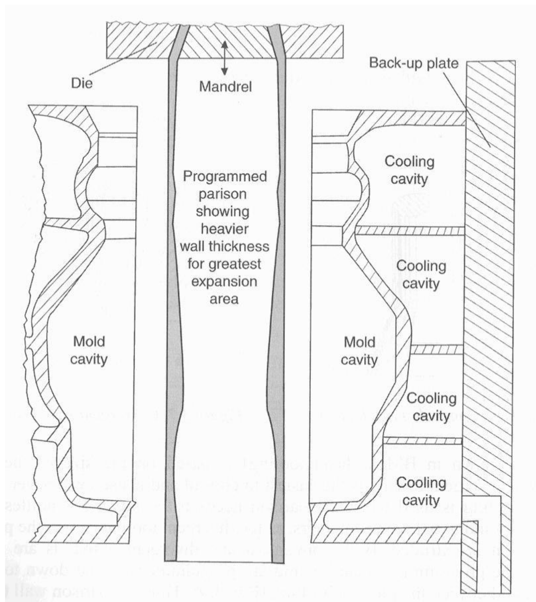


Figure 10: Programmed parison [1].

Extruder and die design

The second method is to achieve a uniform wall thickness on an oval shaped bottle. To do this the extruder and die is formed oval. This ensures that the parison has the basic shape of the bottle before blowing starts.

<u>Parison behaviour</u>

Die and mandrel design and setting

The extruder die and mandrel design are not only critical for the form of the parison, to ensure uniform wall thickness in the product, but also for the quality of the parison. If the die or mandrel is designed, manufactured or adjusted badly then the parison might have seam marks, it might curl to the one side or the wall thickness might vary at a particular height [1].

Parison sag

This is caused by the weight of the parison as it hangs from the extruder head. As it sags, the diameter and wall thickness change. This obviously posses a problem and the sagging must be taken into account when doing the parison programming. The temperature of the melt also influences the sagging significantly. The hotter the melt the more sagging will take place. The problem is that due to the viscoelasticity of the plastic there is no quantitative relationship between sag and viscosity [1].

Parison swell

Parison swell (Figure 11) starts to take place the moment the plastic exits the extruder head, but can continue for up to 10 minutes in some plastics like polypropylene [1]. And in high – density polyethylene (HDPE) at 170 ˚C, 70% to 80% of the swell takes place within the first few seconds after the parison exits the extruder. The remainder occur during the next 2 – 3 minutes.

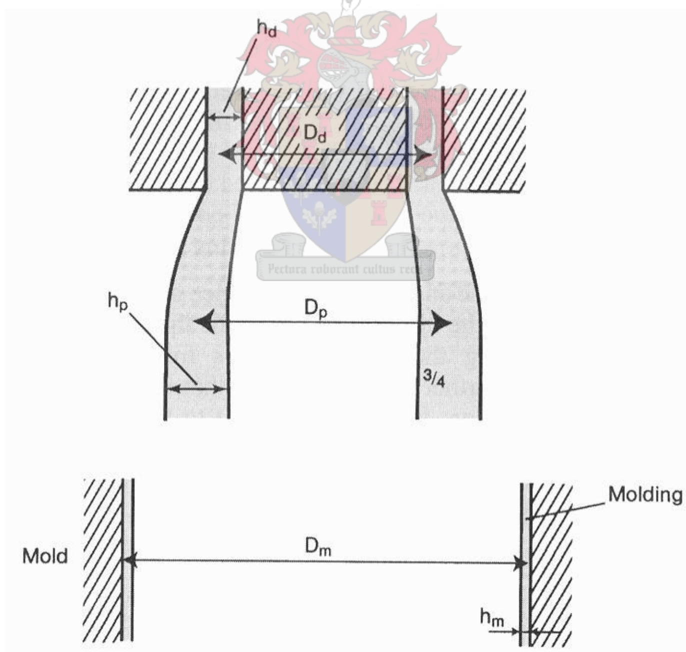


Figure 11: Parison swell [1].

The combined effect of parison swell and sag gives the shape of the final parison, which must then be a shape that will be expandable into the desired product shape. The effect of swell and sag are especially important when producing bottles with handles. It must be ensured that the parison fills the handle cavity sufficiently to ensure that the handle is formed properly.

2.1.2 Stretch blow moulding

In this process the parison or preform is stretched before it is inflated. This is done to orientate the molecule structure of the material in the same direction. The orientation of the molecule structure is one of the determining factors for the quality of the bottle [1]. The typical improved features of a product produced in stretch blow moulding are the following:

- Improved product clarity.
- Increased impact strength.
- Improved gas and water vapour barriers.
- Reduced creep.
- Improved electrical properties
- Increased stiffness

There are two different stretch blow moulding techniques: Stretch extrusion blow moulding (SEBM) and Stretch injection blow moulding (SIBM).

<u>Stretch extrusion blow moulding</u>

With SEBM the parison (Figure 12) is formed by the conventional extrusion process as used in EBM.

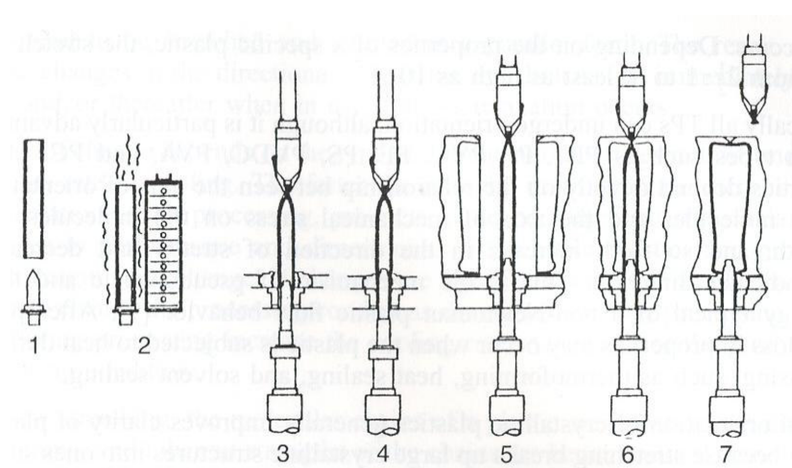


Figure 12: SEBM with the parison being pulled upwards [1].

The only difference is that the parison is stretched before the mould is closed, using a mechanical device. The device grabs the end of the parison and pulls it down, or up, to stretch it to the desired length.The stretching ratio depends on the plastic being used, but can vary from 2 ½:1 to 10:1 [1].

Stretch injection blow moulding

The main difference between SEBM and SIBM is that the product in SEBM is blown from a parison and in SIBM the product is formed from a preform. The preform is injection moulded and can then either be left to cool only to reheat it later for use or it can be used directly while it is still at the desired temperature [1]. Figure 13 illustrates how a preform is blown into a product after it is stretched.

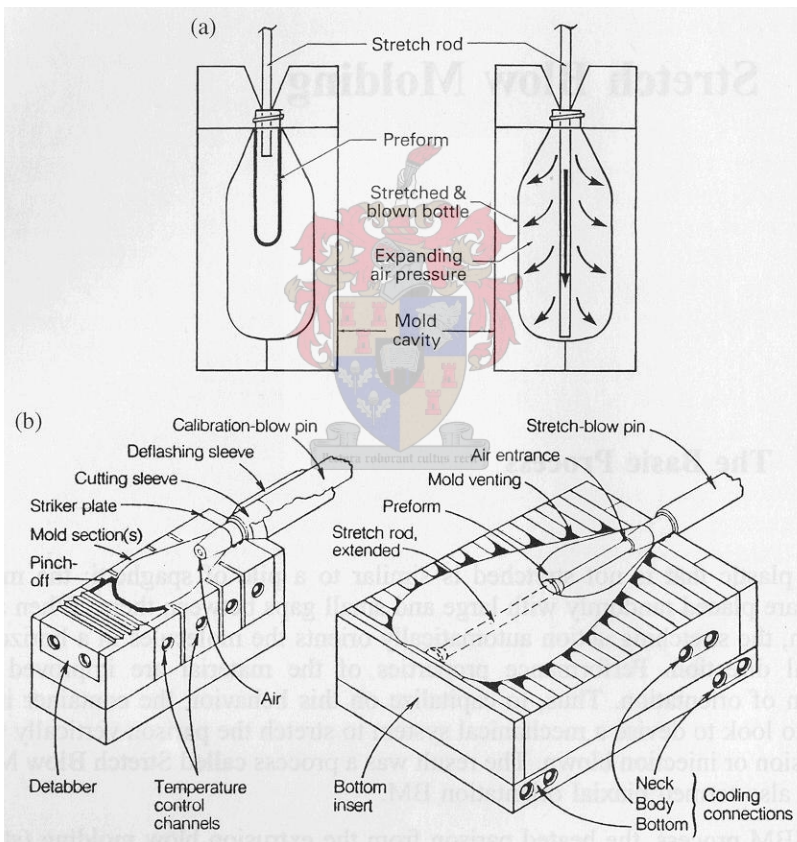


Figure 13: Stretch blow moulding using an injection moulded preform [1].

In high volume production layouts the preforms are normally produced in a dedicated preform machine. The preforms are then allowed to cool and are stored in mass containers, it must be reheated when needed for production. The reasoning behind this is that a large preform machine can supply a number of smaller SBM machines which produce different products from the same preform design.

2.1.3 Injection blow moulding

Injection blow moulding (IBM) uses fundamentally the same principle as SIBM except for the fact that the preform is not stretched before it is blown. The one major difference is that the preform and product are formed in the same machine. The mould must therefore be designed in such a way that it will accommodate the injection moulding of the pre - form and then change to allow for the blow moulding process (Figure 14).

In SIBM the preform and bottle are also produced in a single machine. The machine is designed in such a way that it has a stretch pin as with SBM.

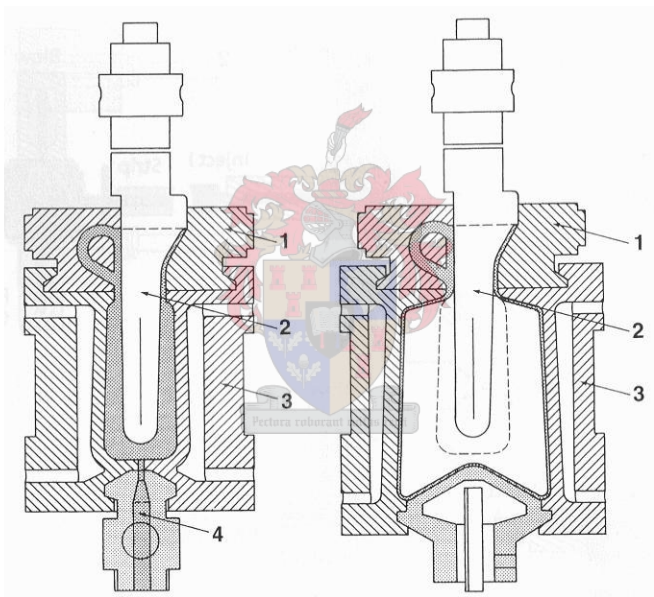


Figure 14: IBM mould layout [1].

(1) Mould neck; (2) Mandrel; (3) Injection / blow mould; (4) Injection nozzle

The cycle time distribution for IBM is shown in Figure 15. It is important that the injection and blowing cycle are of equal length since everything is done in the same machine and there are no buffer areas.

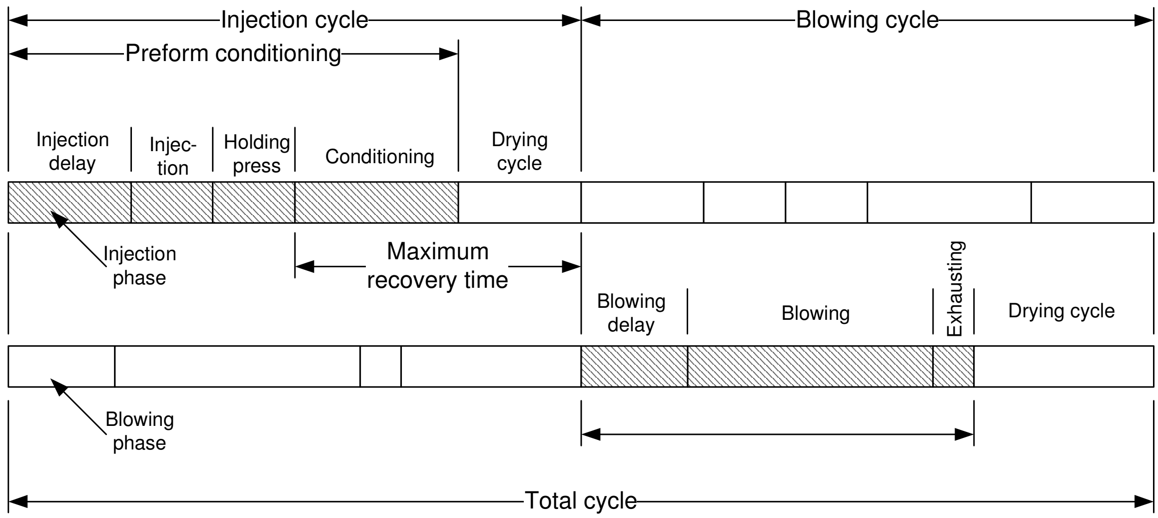


Figure 15: Typical IBM cycle time distribution [1].

This configuration is typically used for relatively small production runs. Since the tooling cost on these machines are low when compared to that of the large carousel type SBM machines. These large machines regularly take ten moulds, or more, and only operate with preproduced preforms which are produced in large and expensive preform machines. These carousel machines and the large preform machines, with large multi – cavity moulds, are designed to produce large volumes, whereas SIBM machines have a lower tooling cost and are more suitable for lower production runs.

2.2 Injection moulding

The process of injection moulding will be discussed in a broad sense. The complete process is very complicated and there are many applications, ranging from single to multi cavity moulds and different injection and clamping configurations.

2.2.1 The start of plastic conversion

Three different people from three different countries pioneered the first cellulose plastic product. They were Christian Schönbein (Swiss professor), Alexander Parkes (English inventor) and John Wesley Hyatt who was an American entrepreneur. They all developed an identical celluloid plastic and christened it Xylnite, Parkersine and Ivoride respectively.

The billiard ball makers of the day, Phelan & Collendar, advertised a reward of $10 000 in 1865 for an ivory replacement material in the making of billiard balls. At the time elephants were slaughtered at a rate of 70 000 per year to supply the demand. This led to exorbitant ivory prices and the extinction of the animal in many areas. Hyatt then developed Ivoride (1869) which was used as a substitute for ivory, imported from Africa. Instead of claiming the reward money, he started, with his brother Isaiah, their own business named "*Albany Billiard Ball Company*". This became Phelan & Collender's direct competition. Their next challenge was to develop a machine which could produce plate or rod like celluloid articles. They based their design on the patent of John Smith & Jesse Locke who patented the design to inject metal into a die, to create metal die castings (1870). And by 1872 the first injection moulding machine was developed and patented (Figure 16). They called it a stuffing machine [4].

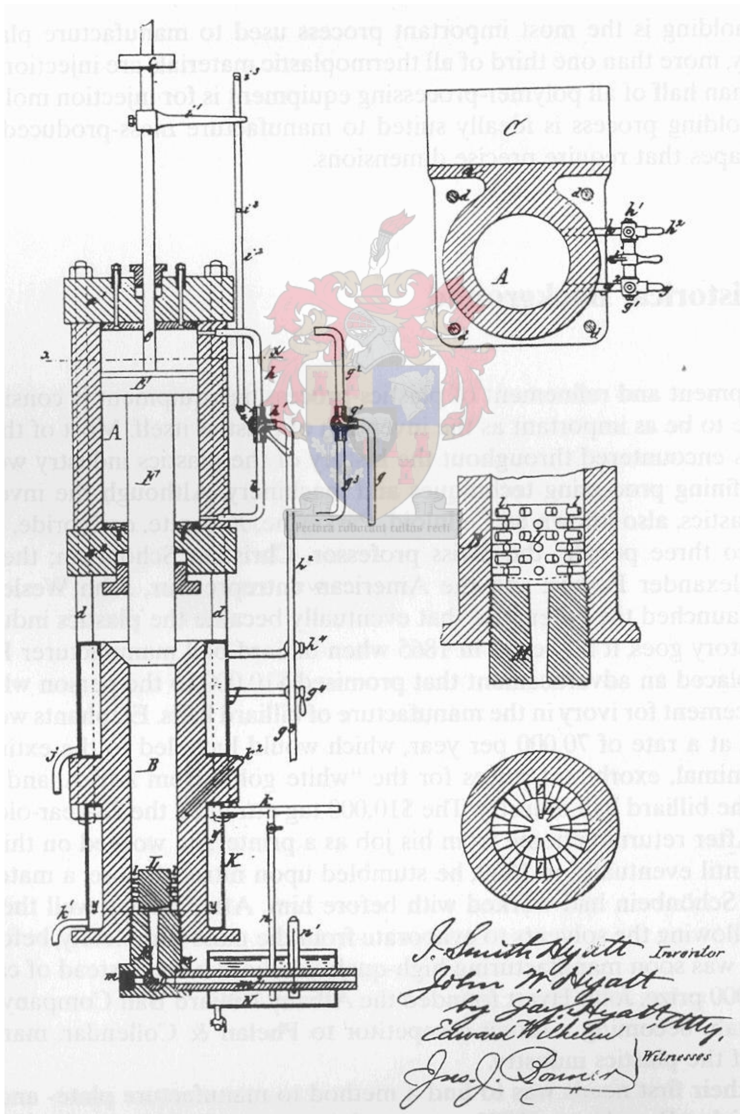


Figure 16: Original patent drawing of the Hyatt brothers' stuffing machine [4].

2.2.2 Injection moulding process

The IM machine has the following 3 basic subassemblies [4]:

- The plasticating and injection unit
- The clamping unit
- The injection mould / mould cavity

All injection moulding machines have these components, but all are not designed in the same way. There are major design differences especially in the clamping unit design, but not in the functioning. The same goes for the plasticating and injection units. There are numerous variations, but all perform the same task.

The plastication and injection unit

The design of the plastication and injection unit is very important. It must melt the plastic without destroying its mechanical properties and then inject the melt at the correct speed and pressure to fill the mould cavity. The injection pressures involved can range from as low as a 100 bar in heavy walled products, to 1800 bar in thin walled polycarbonate products. The injection pressure is determined by the wall thickness and type of plastic being injected.

The basic functions of the plastication unit are [4]:

1. Melt the polymer
2. Accumulate the melt in the screw chamber
3. Inject the melt into the mould cavity
4. Maintain a holding pressure during cooling

The main components in this unit are [4] (Figure 17):

- Hopper
- Screw
- Heating bands
- Check valve
- Nozzle

There are two basic injection designs:

Reciprocating screw design

The IM screw is basically the same as the single screw unit used in EBM machines, with the one significant difference in the reciprocating screw design. The IM screw can move backwards to accumulate the melt, which is needed for the injection and then move forward during the injection phase. This is necessary because the IM process is not a continuous process like the EBM process. The screw is therefore known as a reciprocating screw. There is a check valve at the end of the screw, which allows the screw to operate as a plunger during injection (Figure 17).

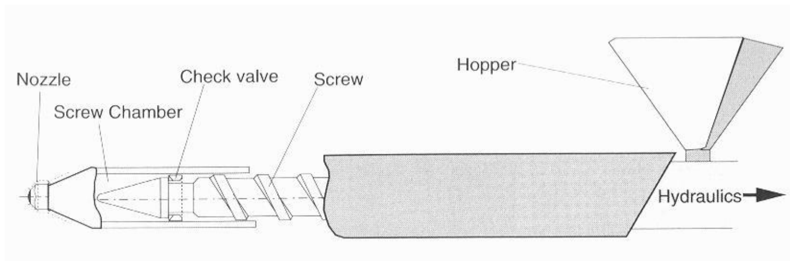


Figure 17: Typical plasticating unit of an IM machine [4].

The main disadvantage of this design is that the screw has to be stopped for the injection cycle, due to the excessive bearing loads. The screw can therefore only produce melt at between 60% and 80% of its rated cycle [5].

Pre – plasticizing machine

In this design the screw is not used as an injector plunger, it produces the melt on a continuous basis and fills an injection cylinder. The plastic is then injected from the injection cylinder by a dedicated plunger. This design has some advantages over the reciprocating screw design which can be summarised as follows [5]:

- The screw run continuously, thus utilising its capacity 100% of the time. Thus a smaller extruder is required for a similar production rate.
- The melt is better mixed because the extruder runs continuously.
- There is no check valve on the screw. The shot size in mechanically measured, giving greater accuracy and repeatability.
- The plastic can be filtered as it flows out of the screw into the injection cylinder, since the pressure drop over the filter will have no effect on the injection cycle.

The main disadvantages of the system are that it is more expensive than the reciprocating design. And PVC can not be used in this system, due to its heat sensitivity.

The clamping unit

The purpose of the clamping unit is to keep the mould shut during the injection process. As a rule IM machines are rated according to their clamping force. The clamping force determines the footprint of the part which can be moulded. The clamping forces range from about 30 tons to 12000 tons or more. High clamping forces are needed when producing large components or many small components in a multi cavity mould.

The two basic designs for mould closure are a mechanical toggle system and a hydraulic clamping system. Both have some advantages and disadvantages.

Mechanical toggle design

The toggle system (Figure 18) uses less hydraulic power to operate but will only apply its maximum clamping force when it is totally extended. This design needs major adjustment when a new mould is placed in the machine, since the stroke of the mechanism can, by design, not compensate for moulds of different thicknesses. One of the major advantages of this system is the reduction of mould speed just before the mould closes completely. Thus the mould is not slammed shut, but closed rather gently [4].

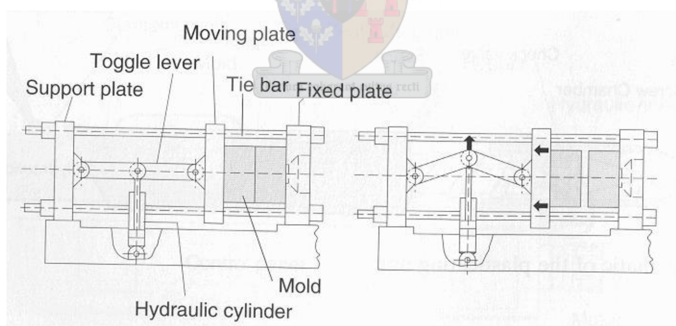


Figure 18: Generic mechanical toggle design [4].

Hydraulic clamping system

The hydraulic system (Figure 19) on the other hand can apply its force in any closing position. The major drawback of the hydraulic system is the initial cost. The cost can however be justified by calculation of the number of setups per year and the time it takes to make a setup. This will indicate the possible savings over a toggle system.

The design of the hydraulic system is such that it has a fast action stage which closes the mould quickly and then a second stage which apply the main clamping force. The hydraulic system also needs a better controlling system, than the toggle mechanism, which will ensure that the closing speeds are controlled properly.

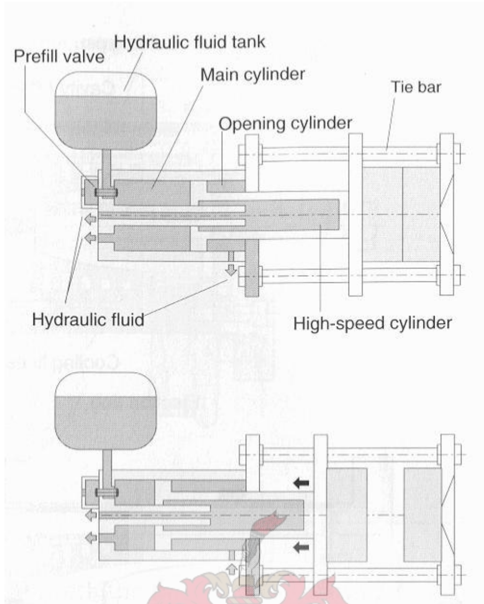


Figure 19: Generic hydraulic mould closing design [4].

<u>The injection mould</u>

The injection mould is an arrangement, in one assembly, of one, or more, hollow cavity spaces built to the shape of the desired product. The purpose of the injection mould is normally to produce a large number of identical plastic parts [5].

There are many different mould configurations and some questions must first be asked and answered to help the designer decide what design configuration will be best suited for the purpose. This will however be discussed in more detail in Chapter 4.

2.2.3 Injection moulding cycle

The basic description of the steps in a general IM cycle is shown below [5]:

- Close the mould.
- Inject the hot molten plastic into the cavity.
- Keep the mould closed and under pressure until the plastic has solidified sufficiently for ejection.

- Open the mould.
- Eject the finished part.

The number of injection cycles per hour at which a mould run is used becomes the indicator of the mould's performance [5]. The break down of a typical injection moulding cycle can be seen in Figure 20 and Table 1. If the cycle is analysed it will be clear that the cooling is the longest single activity in the total cycle time.

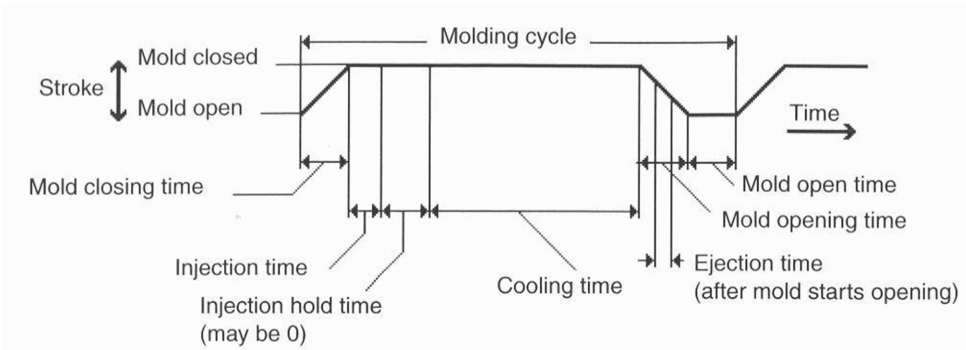


Figure 20: Injection moulding cycle time break down [5].

Cycle segment	Percentage of cycle time	Description
Mould closing	Typical 1% to 5%	This is dependant on the clamping system used on the machine.
Injection time	Typical 1% to 5%	Depending on the wall thickness and the capacity of the machine.
Cooling time	Typical 60% to 90%	This depends mainly on the cooling design, coolant temperature, wall thickness of part and type of plastic.
Opening time	Typical 1% to 5%	This is dependant on the clamping system used on the machine.
Mould open time	Determined by factors outside the machine	This depends on the amount of time required to prepare the mould for the next shot.

Table 1: Injection moulding cycle time breakdown.

Since the cooling time is the largest single part of the total cycle time it is very important to reduce the cooling time as much as possible. During the cooling time the machine does not move, the mould is in the closed position and the part is being cooled. If this cycle can be shortened it would have direct positive impact on the cycle time.

2.3 Conclusion

Good cooling is as relevant in injection moulding as it is to blow moulding, albeit that the processes differ significantly. The moulds however have many similar features and the cooling design of the moulds is constrained by the same parameters, also the cooling channel design has the same effect on the produced part.

The cooling time: i.e. the time the mould is closed to allow the part to cool down to a temperature where it would have sufficient structural strength to be ejected is regulated by the final product quality. If the quality of the part is poor or inconsistent, the natural way of improving it would be to increase the cooling time, thus increasing the total cycle time, which then decreases the productivity.

The percentage time spend on cooling in both processes are between 60% and 90% of the total cycle time. This is time, during each production cycle, in which the machine is actually just standing. Thus if this time can be reduced, it will add directly to the production capacity of the machine. If this is done through proper tool design which takes the cooling behaviour of the tool into account then this improvement can be made without significant capital expenditure. In order to bring about these improvements, there must be a proper understanding of the similarities and problems of both IM and EBM.

In order to achieve these improvements, the designer must first understand the blow and injection moulding cycles. This chapter explains the fundamentals of blow and injection moulding required to understand these process.

3. HEAT FLOW DISCUSSION

Heat conduction is the transfer of energy from the more energetic particles of a substance to the adjacent [6], thus the transfer of energy in a medium, typically in the mould material or in the plastic being cooled.

Convection is the mode of heat transfer between a solid (the mould) and an adjacent fluid (cooling water) or gas, which is in motion (flowing). Convection combines the effects of conduction and motion.

3.1 Heat conduction in moulds

When a moulded part is cooled the heat moves from the plastic, through the boundary intersection between the mould and the plastic, into the mould material, then through the mould material into the cooling water. There is also a boundary layer between the mould and the water. This boundary layer is influenced by several factors of which the velocity, water turbulence and the scale build – up on the surface in the water channels are the most important.

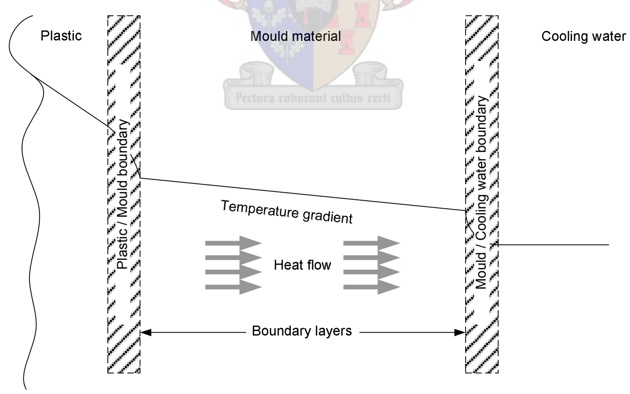


Figure 21: Heat flow in a mould across boundary layers.

3.2 Surface boundary conditions

A surface cannot store any energy, because it does not have any thickness or mass. Therefore if two surfaces are in contact they will have the same temperature at the point of contact. The theory of this is explained by Çengel [6] with the help of Figure 22.

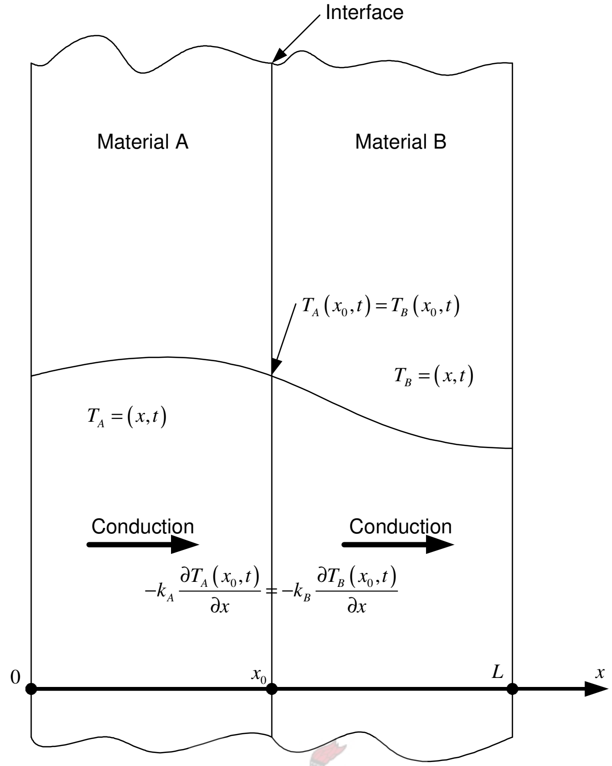


Figure 22: Interface boundary condition [6].

The values of k_A and k_B are the thermal conductivities of materials *A* and *B* respectively. With $\partial T_A(x_0,t)$ being the temperature of specimen A at distance x_0 at time *t* and $\partial T_B(x_0,t)$ being the temperature of specimen B at distance x_0 and time *t*. *L* is the total width of the combined specimen.

3.3 Convection

Convection is probably the most common boundary condition found in practice, since most heat transfer surfaces are exposed to the environment. The convection boundary is based on the surface energy balance expressed as [6]:

{ Heat conduction at the surface in a selected direction. } = { Heat convection at the surface in the same direction. }

According to Çengel the heat flow through a plate can be expressed with equation 1 and 2 as shown in Figure 23.

$$-k = \frac{\partial T(0,t)}{\partial x} = h_1 \left[T_{\infty 1} - T(0,t) \right] \quad (1)$$

$$-k = \frac{\partial T\left(L,t\right)}{\partial x} = h_2\left[T\left(L,t\right) - T_{\infty 2}\right] \quad (2)$$

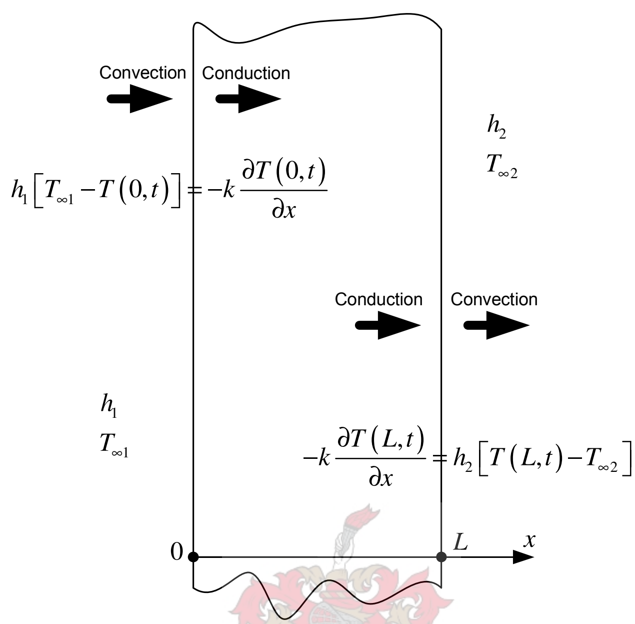


Figure 23: Convection boundary condition on two surfaces [6].

With h_1 and h_2 being the heat transfer coefficients and $T_{\infty 1}$ and $T_{\infty 2}$ the temperatures of the surrounding mediums on the two sides of the plate (Figure 23). The thermal conductivity of the specimen is given by *k*. *L* is the width of the specimen, with *x* being any point in the specimen between 0 and L and *t* is the instant in time.

3.4 Thermal resistance network

The heat flowing in a mould from the product cavity to the cooling channels can be analysed as one-dimensional. The temperature difference between the plastic and the water is the greatest, therefore will the heat flow in a straight line along the shortest route between these two entities. The heat flow could be described as done in Figure 24.

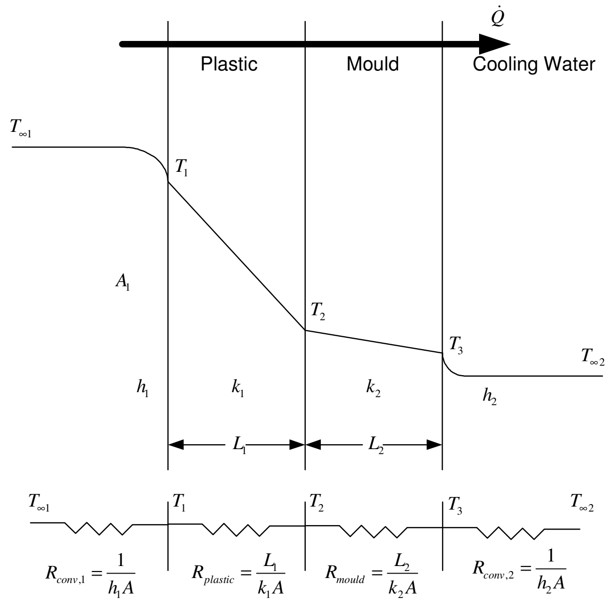


Figure 24: The thermal resistance network [6].

This explained in words gives [6]:

{Rate of heat convection into the wall} = {Rate of heat conduction through the wall} = {Rate of heat convection from the wall}

The heat flow is given by $\dot{Q}$ and equation (3) gives the total heat which will flow in Figure 24. The values of *R* are the thermal resistance, *L* the width and *A* the area of the specimens. The values of *k* represent the conductivity coefficient and h the convection coefficient of the different specimens.

$$\dot{Q} = h_1 A\left(T_{\infty 1} - T_1\right) = k_1 A \frac{T_1 - T_2}{L_1} = k_2 A \frac{T_3 - T_2}{L_2} = h_2 A\left(T_3 - T_{\infty 2}\right) \qquad (3)$$

Now equation (3) can be rearranged to give equation (4).

$$\dot{Q} = \frac{\left(T_{\infty 1} - T_1\right)}{1/h_1 A} = \frac{T_1 - T_2}{L_1/k_1 A} = \frac{T_3 - T_2}{L_2/k_2 A} = \frac{\left(T_3 - T_{\infty 2}\right)}{1/h_2 A} \qquad (4)$$

The factors below the line in equation (4) can be substituted by the resistance equations as shown in Figure 24 and as described by Çengel [6] p 131. This then gives equation (5).

$$\dot{Q} = \frac{\left(T_{\infty 1} - T_1\right)}{R_{conv,1}} = \frac{T_1 - T_2}{R_{plastic}} = \frac{T_3 - T_2}{R_{mould}} = \frac{\left(T_3 - T_{\infty 2}\right)}{R_{conv,1}} \qquad (5)$$

3.5 Multi layer walls

The basic principle for heat transfer in multi layer walls is the same as for single layer walls. The resistances are added together to make up the complete resistance of the compound wall. The total resistance of the wall in Figure 24 is given by equation (6) [6].

$$\begin{aligned} R_{total} &= R_{conv,1} + R_{wall,1} + R_{wall,2} + R_{conv,2} \\ &= \frac{1}{h_1 A} + \frac{L_1}{k_1 A} + \frac{L_2}{k_2 A} + \frac{1}{h_2 A} \end{aligned} \tag{6}$$

The total heat flow in a wall is given by equation (7) where $T_{\infty 1}$ and $T_{\infty 2}$ are the temperatures of the fluids flowing on the respective sides of the wall. And R_{total} is the total resistance of the wall including the boundary layers [6].

$$\dot{Q} = \frac{T_{\infty 1} - T_{\infty 2}}{R_{total}} \tag{7}$$

Now looking at Figure 24 the values of T_1, T_2 and T_3 can be determined by using equation (8), (9) and (10) respectively, provided that $\dot{Q}$ (total heat flow) is known [6].

$$\dot{Q} = \frac{T_{\infty 1} - T_1}{R_{conv,1}} \tag{8}$$

$$\dot{Q} = \frac{T_{\infty 1} - T_1}{R_{conv,1} + R_1} \tag{9}$$

$$\dot{Q} = \frac{T_{\infty 1} - T_1}{R_{conv,2}} \tag{10}$$

If $\dot{Q}$ is known then the heat flow equation can be written as shown in equation (11) [6]. Where as T_i is a known temperature at location *i* and $R_{total,i-j}$ is the total thermal resistance between location *i* and j.

$$\dot{Q} = \frac{T_i - T_j}{R_{tatal,i-j}} \tag{11}$$

3.6 One-dimensional heat flow simulation in a mould wall

3.6.1 The explanation and equations

In an effort to understand the relationship of the mould temperature and the plastic temperature during the moulding cycle the multi - layer heat flow equations were used to write a simulation program, which calculates the temperature at different wall depths in both the mould and in the plastic.

The problem is transient (time dependant), since the part is cooled down over time, during which the heat load on the mould changes continuously. The relevant equations must be solved with the use of integration with regards to time in order to calculate the heat flow at a given time instant and of more importance the temperature at a specific point in the wall. This method of calculating the values is very involved and it does not provide temperature values at different time intervals.

A simpler method of calculating the values was therefore devised, which used modified empirical equations and Visual Basic to solve the heat flow problem with regards to time. The basic approach was to divide the plastic and mould wall into sections and then with the help of the modified heat flow equations develop a time dependant problem, which can be solved over many small time steps.

The basic principle of the calculations will be explained below. The philosophy used is shown in Figure 25 with the temperature taken at the centre of the layer and the heat flow taken at the intersection between the layers as a function of the difference in temperatures. This approach gives a very good representation of what will really happen during the cooling process. The program was written in such a way that the number of layers and time steps could be changed as required.

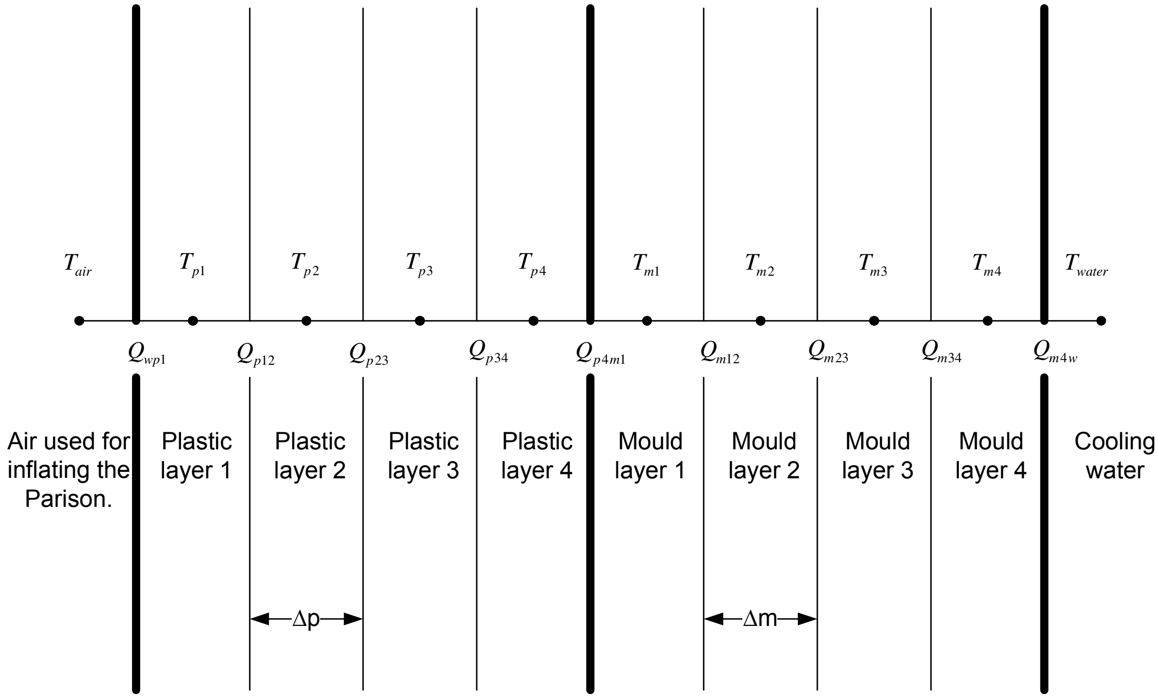


Figure 25: Heat flow in mould and plastic part.

The equation used to calculate the heat flow between the first layer in the plastic and the inflation air in the parison is given by equation (12).

$$\dot{Q}_{wp1} = h_1 A(T_{p1} - T_{air}) \tag{12}$$

Where as $\dot{Q}_{wp1}$ being the total heat flow between the air and the first layer of plastic and h_1 being the convection heat transfer coefficient between the air and the plastic. The temperature of the inflation air is given by T_{air} and the temperature of the first layer of the plastic is T_{p1}.

This equation is solved and the value of $\dot{Q}_{wp1}$ is then used to solve the temperature of the air after a predefined time step with the use of equation (13). The variables in the formula are as follows: P is the inflation pressure, V is the volume of the container and T is the initial temperature of the air when inflated. The constant volume specific heat is given by c_p and R is the gas constant. The time step is given by Δt which typically has a value of not more than 0.01 seconds to prevent instability in the calculations.

$$T_{air_{new}} = T_{air_{old}} + \frac{\Delta t}{\left(\frac{PV}{RT_{initial}}\right)c_p}\left(0 + Q_{wp1}\right) \tag{13}$$

The heat flow between the layers of plastic is given by equation (14) with $k_{plastic}$ being the thermal conductivity of plastic and Δp being the thickness of the layer in question (in either the plastic or mould, depending on what is being solved) and A the area normal to the conduction direction.

$$\dot{Q} = k_{plastic} A\left(\frac{T_i - T_j}{\Delta p}\right) \tag{14}$$

Equation (15) is used to determine the temperatures of the different layers with m_p the mass of the plastic layer and cp_p the specific heat capacity of the plastic.

$$T_{new} = T_{old} + \frac{\Delta t}{m_p c_p}\left(Q_{ij} - Q_{kl}\right) \tag{15}$$

These equations are used up to the point where the plastic and mould meet, where the heat flow across the interface is given by equation (16) with Δm the layer thickness in the mould.

$$\dot{Q}_{p4m1} = \frac{T_{p4} - T_{m1}}{\frac{\frac{\Delta p}{2}}{k_p A} + \frac{\frac{\Delta m}{2}}{k_m A}} \quad (16)$$

The temperature is however determined by the same equations as shown in equation (14) and the heat flow in the mould metal is also determined with similar equations as shown in equation (13) with the exception that the thermal conductivity must be that of the mould material instead of the plastic. These equations are solved for each layer up to the water where the heat flow between the mould and the water are given by the same equations as used for the heat flow between the plastic and the inflation air (equation (12)). The correct convection heat transfer coefficient must however be entered (normally around 1000 W/m^{2}°C for water). The assumption is also made that the water temperature stays constant, since the volume of water flowing through the mould, should be such, that the water temperature increase is neglectably small.

3.6.2 Results

The equations shown above were implemented using a Visual basic program, which makes use of Excel as the input and output of the data. The code of the program can be seen in Appendix A. The results from a typical simulation can be seen in Figure 26. This graph shows what the temperature curves would do if the first bottle is moulded. The start-up temperature in the mould is uniform as is the temperature in the plastic.

The different lines represent different layers in the mould and plastic respectively as shown in Figure 26. It is clear that the layer of plastic closest to the mould will cool quickest, while the layer furthest away will cool slowest. Thus there will be a temperature gradient across the plastic wall. The same can be said for the mould material, although the temperature gradient across the mould will be significantly less, due to the superior heat conductivity of the mould material.

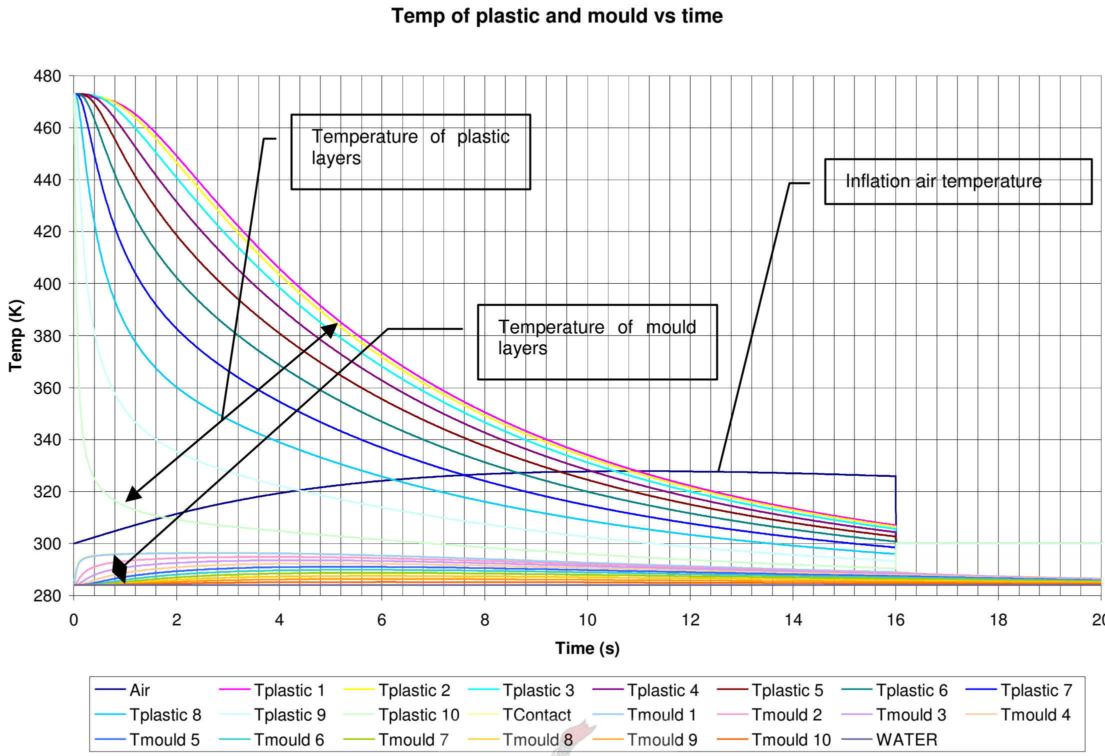


Figure 26: Plastic and mould temperature vs time.

During the production process the mould does not have time to cool completely to the cooling water temperature and will eventually heat up to a working temperature. This warm-up of a mould can be simulated if the moulding of a number of bottles is simulated. An example of such a simulation is shown in Figure 27. It is clear that this figure is a combination of a number of cycles as described in Figure 26. The mould seems to reach working temperature after about 130 seconds of operation, the mould temperature contours are shown on a larger scale in Figure 28.

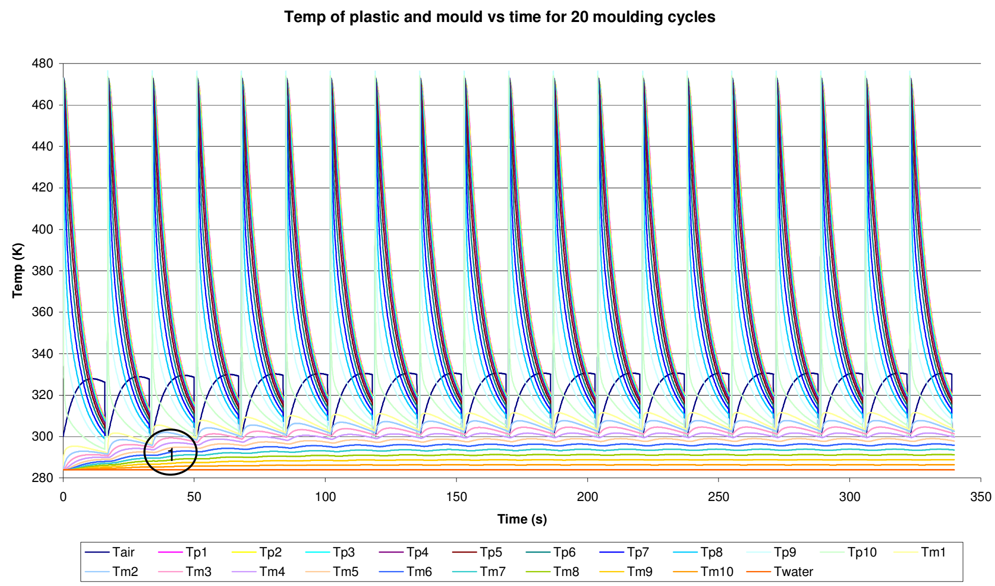


Figure 27: Temperature contours in the plastic and mould during showing the warm-up.

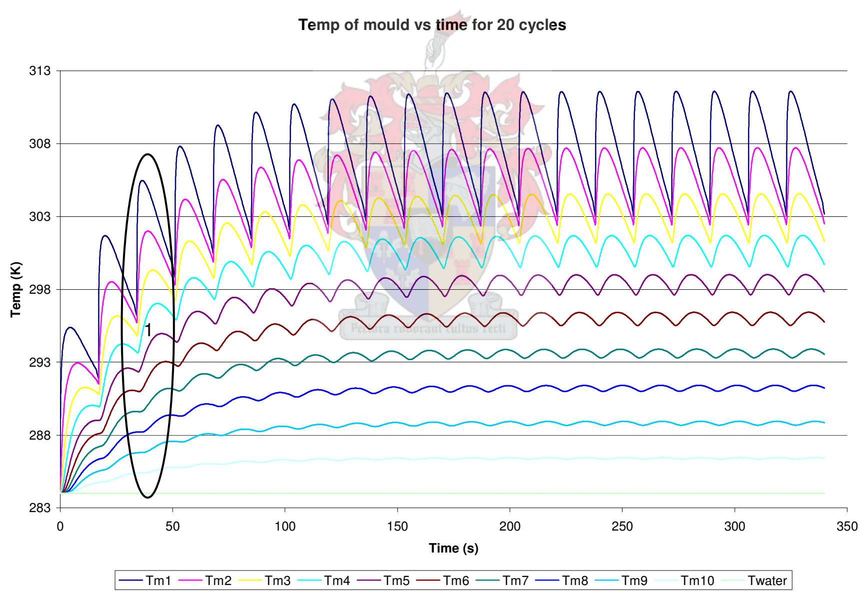


Figure 28: Temperature of different levels in a mould wall during warm-up.

Area 1 in Figure 27 and Figure 28 respectively are the same temperature lines, but plotted on different temperature scales. Figure 28 only indicates the temperature variations in the mould layers, whereas Figure 27 gives information on all the layers in the mould and plastic.

3.7 Conclusion

The understanding of basic heat transfer is important when designing the cooling layout of a mould. The fact that interfacing surfaces are at the same temperature allows for useful calculations to be made about the heat flow from the plastic to the mould. It is also important to understand the influence of the boundary layers on the mould, especially between the mould and the water. The designer must know that water flowing turbulently removes more heat from the mould than laminar flowing water.

The heat flow in the mould can be seen as one-dimensional, but it is dependant on time, since the temperature in the mould and part changes constantly throughout the cycle. The simulations done gave a good indication of the input parameters which had to be used in the CFD simulations. It also showed that the mould cavity temperature does not vary more than 8 °C, which is very low in comparison with the change in melt temperature. The CFD analysis could therefore be handled as a steady state instead of a transient problem, which requires much less preparation and solving time.

It is virtually impossible to measure the cavity surface temperature of a mould, because an infrared camera cannot measure accurately on a shiny surface and a thermocouple would not measure the surface temperature accurately either, thus the only way to obtain the temperature is to calculate it.

4. MOULD DESIGN CONSIDERATIONS

The mould design process consists out of a number of basic steps. The steps will be described in this chapter with the assumption that the product CAD design is already available. Figure 29 gives the basic design process chain.

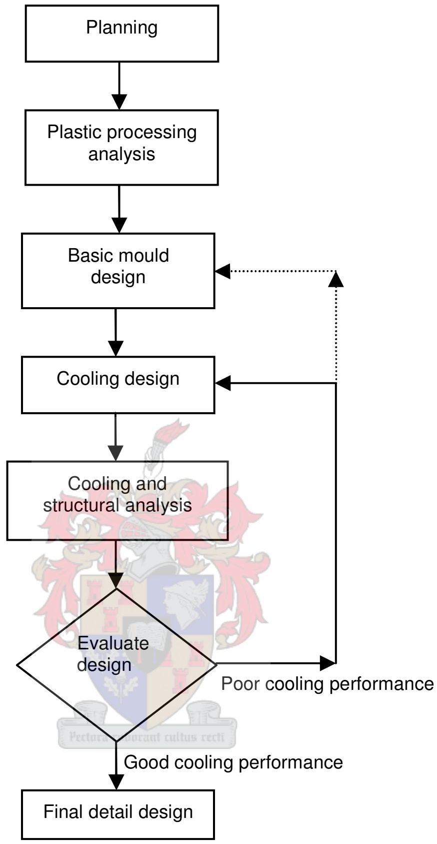


Figure 29: Basic mould design process chain.

4.1 Planning

In order to do the planning of the mould design, the following factors should be answered and considered [5]:

1. Part complexity.
2. Machine parameters.
3. Number of mould cavities.
4. Moulded material.
5. Batch size.

6. Product lifespan.
7. Anticipated cycle time.
8. Function of the moulded product.
9. Product tolerances.
10. Moulded material shrinkage.
11. Product draft angles and split lines.
12. Runner system.
13. Gate and ejector locations.
14. Permissible gate size and shape.
15. The required part finish.
16. Mould engraving.
17. Mechanical moulded part removal.
18. Project lead time.
19. Project budget.

The designer can use these questions to determine the precise requirements from his client as well as guide him to prevent elementary mistakes such as forgetting to allow for shrinkage.

The planning will allow the designer to determine his design envelope. If these questions are answered, he will have an idea of how big the mould would be and what material will be used.

4.2 Plastic processing analysis

There are some software packages available for the simulation of plastic processing. The most prominent area of development is injection moulding with blow moulding also receiving attention, but to a lesser extent. The blow moulding industry has been a lot slower to adopt simulation technology to improve their mould designs [7].

4.2.1 Injection moulding

Since injection moulding is one of the biggest applications of plastic processing and the moulds are also the most expensive, most of the development resources have gone into the development of simulation tools for this industry.

Plastic part simulation

Typical simulation packages are SIMUFLOW [8], MOLDFLOW [9], REM3D [10] and certainly some others. The typical analysis capabilities of these packages are as follow [8]:

- Variable injection rates
- Shear stress calculation
- Automatic weld line interpretation
- Automatic gas entrapment interpretation
- Flow vectors
- Hot runners
- Programmable gate injection time
- Gate modelling
- Fully integrated mould filling, packing and cooling analysis
- Automatic runner balancing
- Recommended cooling layout
- Cycle time determination
- Differential (cavity/core) cooling effects
- Etc.

This is to name a few of the more important features. The only injection moulding simulation package currently available at the University of Stellenbosch is MOLDFLOW. This is one of the most popular packages available and is very user-friendly.

This software is however not suitable for the analysis of BM problems. The fundamental difference between IM and BM simulation is that BM is a structural analysis and IM is a flow analysis. A common simulation package is not available yet, the main reason being these process differences.

Mould cooling simulation

The simulation capabilities of MOLDFLOW are confined to channels. A typical cooling layout suggested by MOLDFLOW for a cup is shown in Figure 30.

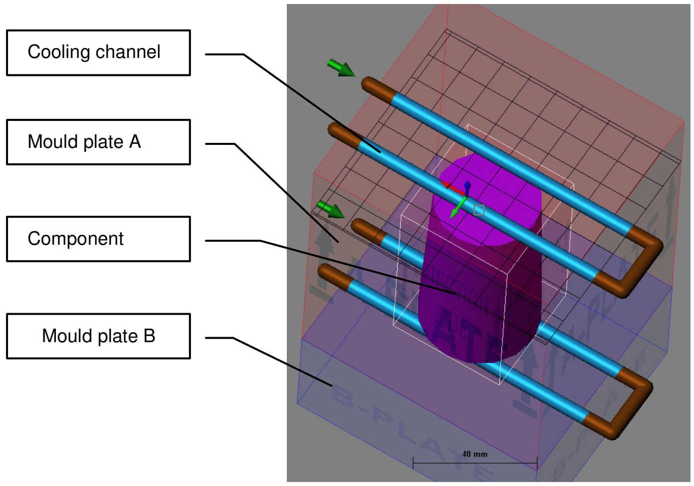


Figure 30: Typical MOLDFLOW cooling layout.

The design can also include bubblers and baffles, but all involve normal cooling mechanisms, which are typical of conventional machining. MOLDFLOW allows the designer to import custom designed wireframe networks as IGES lines, these lines can be spirals or any other complex curve. The curves are then converted to round or half round water channels but still there is no option for flood or conformal cooling.

4.2.2 Blow moulding

There are some blow moulding simulation packages available such as BLOWVIEW [11], POLYFLOW [12] and B-SIM [13]. As stated earlier the blow moulding industry is very reluctant to adapt simulation software. This could be partly due to the complexity of the software and the additional simulation time which is needed before the mould manufacture could commence. In the fast moving consumer goods industry where the latest and greatest detergent bottle must get to the market as soon as possible, there is often "*no time to do simulations*". This combined with the poor quality CAD models created in the low-end software which most of the mould designers use, hampers the simulation process even further.

Capabilities of POLYFLOW

POLYFLOW is being developed by the same company which develops FLUENT. FLUENT is a very well established and powerful fluid flow simulation package.

When a problem is solved by POLYFLOW then it provides the following information [14]:

- The effect of gravity on the sagging of the parison.
- The pinch-off and inflation process and possible blowabillity limitations.
- Influence of the operation parameters and material properties on the process sensitivity.
- The thickness and extension distribution, these results can then be transferred to structural simulation analysis software for further analysis.
- Cooling phase resulting from the contact mould, it also includes the crystallisation of the plastic.

The parison is modelled as a fluid and standard rheology data can be used in the simulations. The simulation can take the mandrel movement into account, thus allowing for varying parison thicknesses, this is then combined with the effect that gravity has on the parison. During the blowing phase the cooling is simulated as the plastic starts to touch the mould wall.

The one problem with POLYFLOW is that it can do full 3D blow moulding simulation, but this is very complex and its strength is mainly in 2D simulations, which is obviously only of use for the simulation of round containers. It can however simulate 3D expansion, but this was not achieved during the trial evaluation period of the software.

According to the distributors of POLYFLOW in South Africa, no one is using the software at the moment in South Africa, thus there is no support as yet. To use this software, the user has to go through a steep learning curve. No comparative studies were done on this, but the learning curve is definitely steeper than structural analysis or fluid flow analysis packages.

Simulation problems with blow moulding

According to the FLUENT website there are very specific problems when solving a blow moulding process [14].

The two major mathematical problems being the fact that the parison is dangling in open space during the extrusion and that the elements deform excessively during the expansion process. There is also the additional problem of virtually no heat conduction during the period when the parison is not touching the mould wall to a time where the plastic touches the mould wall and heat conduction starts. There is also the slipping of the material, as it expands, over the mould surface.

4.3 Basic mould design

The design of the mould will involve the layout of the cavities and the designer must decide, in the case of blow moulding, where to split the mould sections. Typical areas to split a mould are at the base and at the neck of a bottle as shown in Figure 31.

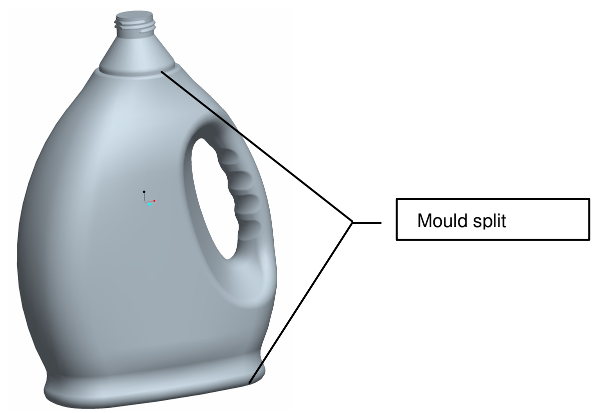


Figure 31: Bottle indicating splitting region for mould.

These areas are important since it will determine the shape of the cooling cavities in all the sections of the mould.

At this stage the designer will make decisions on design aspects like: the distance between the mould cavities, position of leader pins, fasteners and other ancillary items. This detail should however not be included in the cooling and structural simulation model, as it could cause unnecessary complications.

4.4 Cooling design

The cooling of moulds is a very important aspect of the design. The layout of the cooling channels is usually done empirically relying solely on the designer's experience. There is also the additional problem that the designer is normally not responsible for cooling performance of the mould, but only for the sturdiness and mechanical reliability. Therefore will he design a mould which is mechanically sound and then see where and how he can add the cooling channels. The following are some of the factors which influences the cooling performance of a mould

- The temperature difference between the inlet and outlet water.
- The volume flow of the water.

- The chemical composition of the water.
- The thermal conductivity of the moulded components.
- The temperature drop of the plastic from injection to ejection.
- The size and layout of the runner system.
- The type of runner system (hot or cold)
- The cooling channel geometry in the mould inserts.

4.4.1 Factors influencing moulding cycle time

The following factors influence the cooling performance of a mould and therefore the productivity of the mould.

Mould material

The type of material used to manufacture a mould greatly influences the cooling time. Taking steel as an example, its thermal conductivity is much lower than that of aluminium. This means steel will conduct less heat, measured in Watt, than aluminium under the same conditons.

So why don't we manufacture all moulds from a metal with a very high thermal conductivity? The answer is steel is strong and can take more pressure. It can guarantee far more cycles than that of a softer or weaker material. A softer material can however be feasible in low volume production runs or in stretch blow moulding where there are no cutting edges.

Water temperature

The water temperature can directly influence the cooling of the mould, the lower the water temperature the shorter the cooling time.

The water temperature can not be lowered infinitely, since defects in the plastic will occur. If the water temperature is too low, dew drops will form in the mould, which can cause corrosion in the mould cavity and marks on the bottles. Determining the optimal temperature can be done by trail and error, but in most blow moulding factories the water temperature is between 11 ˚C and 13 ˚C, throughout the plant.

Water flow

The flow of the cooling liquid (water) can influence the cooling time. If the volume flow through the mould is very low (resulting in low flow velocity), the water will heat and thus less heat transfer will take place, causing the cooling time to lengthen. On the other hand, if the flow is sufficient the water will not heat significantly and heat transfer can take place at a constant rate. There will be a certain truncation point for the flow volume in any mould. This happens at a point where the water will remove all the heat the mould and mould – fluid boundary layer can conduct to the water. Thus the constraint in the heat conduction chain is the mould’s conductivity.

Product mass

The product mass influences the cooling time of the part directly. The thicker the part, the longer it will stay too hot to eject. The thickness of every part differs depending on the specifications supplied by the client.

Type of plastic

The type of material used to manufacture the product influences the cooling as much as the mould material. Every type of plastic has a specific thermal conductivity and heat capacity that influences the heat flow, which in turn influences the cycle time.

Air temperature

The temperature of the air can play a small role in the cooling of the mould. Similar to plastics and metals air has a specific thermal conductivity. The low temperature of the air causes some heat transfer towards the air and thus decreases the amount of heat transfer towards the mould. The lower heat transfer to the mould means faster cooling. This however has no substantial influence. Figure 32 illustrates the heat transfer due to the air.

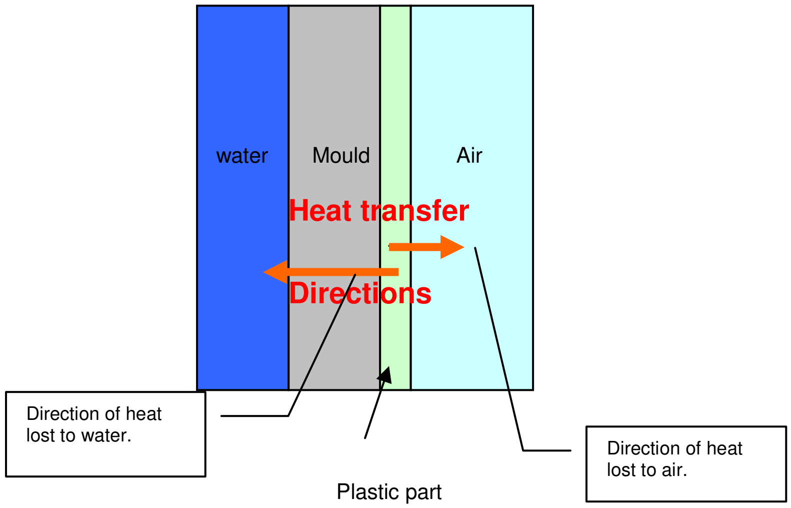


Figure 32: Heat transfer to air.

4.4.2 Cooling design guidelines

According to Rees [5] the mould designer does not have unlimited freedom to design as he would wish. He must still take into account that the mould must be economically manufacturable in the mould shop. For example, he can design the most elaborate cooling layout imaginable, but all this must be machined with a machine which can only use straight tools or work in 3 axes. Typical examples of such tools are drills, which can only drill straight holes although different straight holes can be combined at angles to allow it to follow some kind of a path.

The workshop restrictions are however becoming less of a problem with Layer Manufacturing (LM) becoming available [16] [17]. The modern LM machines can produce mould inserts, which can be used for high volume production (Figure 33). Some [17] even claim to be able to produce components with a hardness of up to 65 Rockwell without any additional plating.

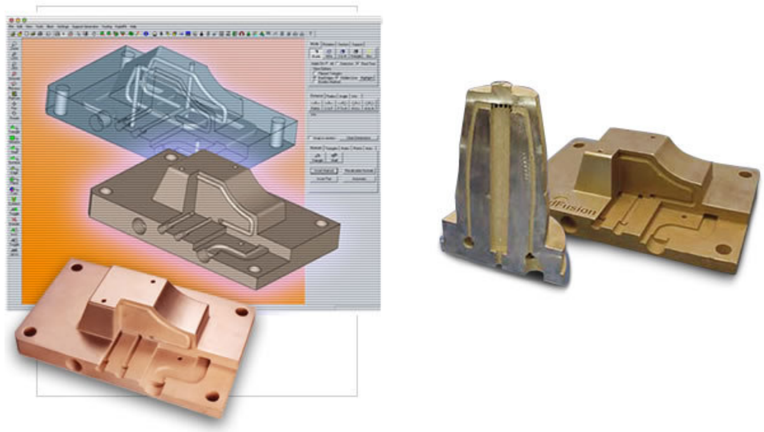


Figure 33: Mould insert grown on a ProMetal machine [17].

These machines are all relatively new developments and are not documented in mould manufacturing textbooks. Nevertheless the designers should keep these machines in mind when developing a mould.

The important advantage which these machines provide for tool making is the fact that the complexity of the part does not change the production price of the part. Which will allow the designer in future, to design elaborate cooling channels and water ways in the mould, without having to consider if it is manufacturable or not. In Figure 33 two typical moulds inserts are shown and the cooling design is visible. This cooling design, although not difficult to design, is very difficult to or even impossible to manufacture using conventional methods.

4.4.3 Analysis and critic on conventional cooling designs

The most popular way of cooling moulds is water, but air and oil can also be used. Air and oil are sometimes, but not always, used for moulds operating above 100 ˚C.

In injection moulding and blow moulding operations, chemically treated water is normally used. The purpose of the chemical treatment is to reduce corrosion in the moulds and microbial build-up which could block pipes and small water lines.

The cooling hardware is very well documented in the available textbooks, but there seems to be less focus on the cooling design. The textbooks focus only on conventional cooling methods and do not describe alternatives such as conformal cooling. There are some papers looking at conformal cooling though. It is clear that the textbook authors have much design experience, but they seem to try and oversimplify the cooling of the moulds. Some of the examples given are very crude and can be misleading. Light will be shed on common mistakes made by the authors. Most of what they say is true, but they tend to step into the potholes by trying to oversimplify cooling.

The temperature differences in a mould should not be more than 5.5 ˚C. If the differences are larger the part may distort excessively [18]. This is caused by the uneven stress levels in the part which forms due to uneven cooling. Rees explains this with Figure 34 [5].

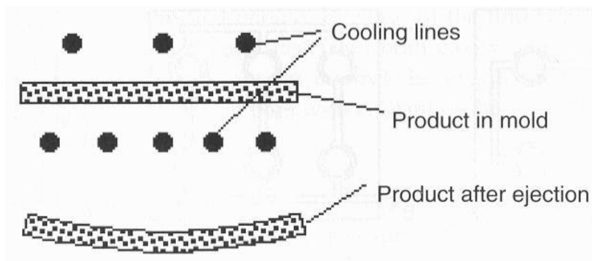


Figure 34: Explanation by Rees of how unequal cooling distorts a plastic product [5].

As stated above, the part should be cooled as uniform as possible. To do this the water channels must follow the cavity as close as possible. This is however easier said than done, because the water channels can only be drilled [18]. Some compromise can however be struck to cool a round object with straight drilled water channels, but this will still not solve the problem completely.

An analysis, of a cooling layout, as described by Bryce [18] was done. Figure 35, Figure 36 and Figure 37 were used to compare good and bad cooling designs. If a comparison is made between Figure 35 and Figure 36, which are used to describe poor and acceptable designs respectively, it is found that both are poor. The blue areas in Figure 35 represent the areas, which are properly cooled since it is cooled from two directions. The red areas on the other hand are poorly cooled, because it is far from any cooling channel. The design was changed to that being shown in Figure 36 and was then described as acceptable. This is not true, the design is somewhat different, but it still does not solve the actual cooling problems shown Figure 35. The design (Figure 36) was changed in such a way that it provides better cooling in an area already cooled and then neglects the poorly cooled area. The design in Figure 36 also neglects to cool the centre of the mould.

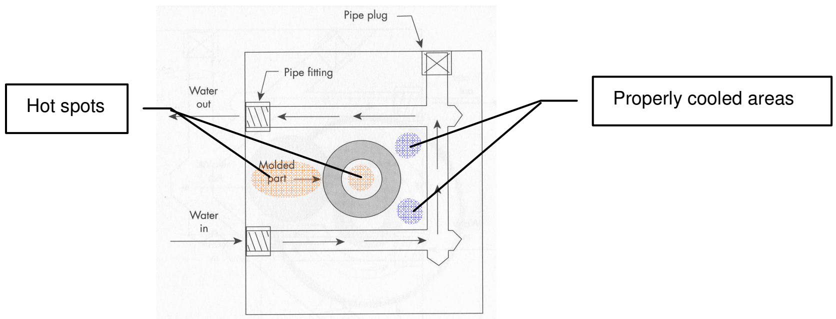


Figure 35: Poor cooling arrangement, according to Bryce [18].

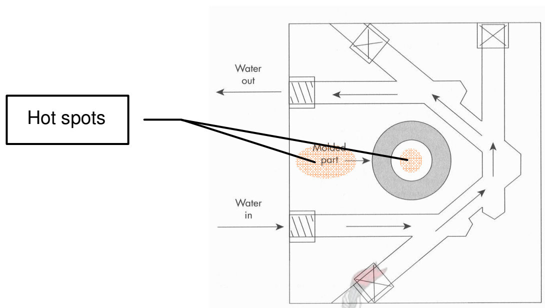


Figure 36: Acceptable cooling arrangement, according to Bryce [18].

The design in Figure 37 is described as a good design. It is agreeable that this design is better, because it solves the cooling problem better than the previous designs. The water channel should however be in the other half of the mould. In the current design only one side of the cooling channel touches the mould side needing the cooling. If the channel was cut into the opposite part of the mould, then the water touching three walls will contribute to cooling. Such a layout gives without any complications a 3 times bigger cooling water contact area. This is properly illustrated by Rees [5] with Figure 38. The centre (red dot) of the mould is however still not cooled.

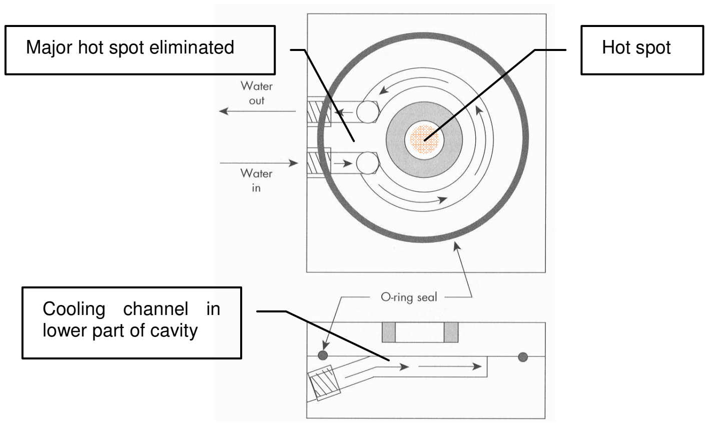


Figure 37: Good cooling arrangement, according to Bryce [18].

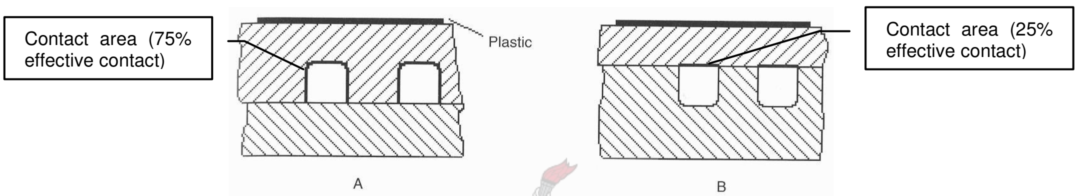


Figure 38: A has a 3 times bigger water contact area than B [5].

To demonstrate this, some simulations were conducted using identical material properties and boundary conditions. The simulation results of the designs shown in Figure 35 and Figure 36 are shown in Figure 39 and Figure 40 respectively. It is clear that there is no significant difference in the temperature contours, which suggests that there will not be any significant performance difference. It is also clear where the problem area is and that the change in design does not solve it in any significant way.

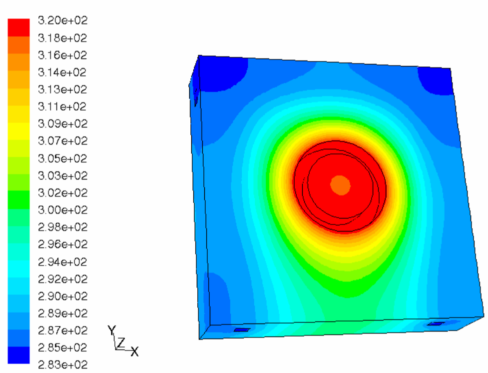


Figure 39: Simulation result of the design shown in Figure 35.

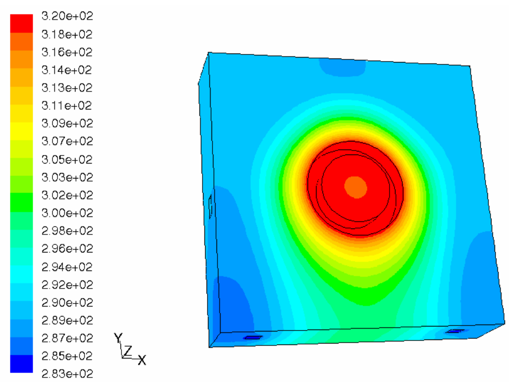


Figure 40: Simulation result of the design shown in Figure 36.

The difference between Figure 41 and Figure 42 is the contact area between the coolant and the cavity side of the mould. The design, of which the simulation results are shown in Figure 42, is a rework of the design shown in Figure 37 made by Rees [5]. The result shows a significant improvement and shows what can be achieved by making subtle changes.

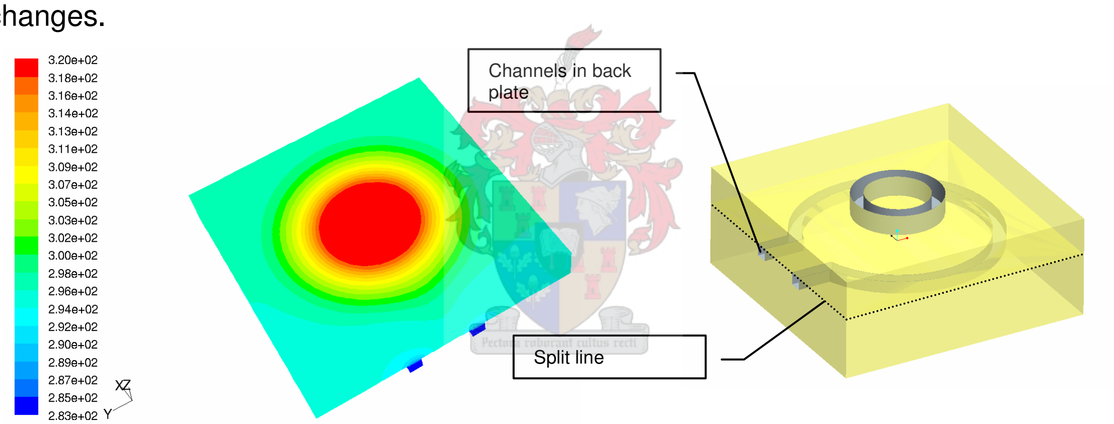


Figure 41: Simulation result of the design shown in Figure 37.

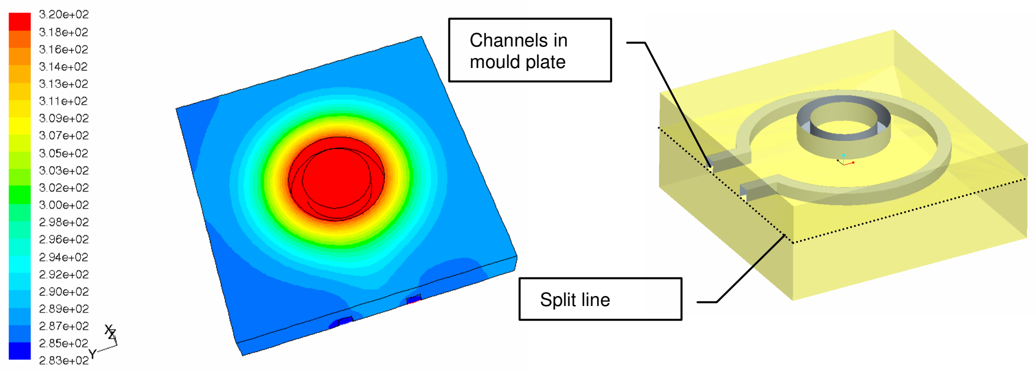


Figure 42: Simulation result of the design shown in Figure 37, but modified according to Figure 38.

What Bryce mentioned [18] is that care should be taken not to weaken the mould by drilling the water channels too close to the product cavity, since this could cause the mould to crack or fracture under the high injection pressures. He uses a rule of thumb that the water cavity should not be closer than 1.5 times its diameter from the mould cavity. Rees also states that the best cooling between two surfaces, which only touch and have no conduction enhancing substance between them, is about 50% compared to a similar piece of material with no joint.

Rees gives a more detailed description of how close the cooling channels may be to the cavity and to each other Figure 43.

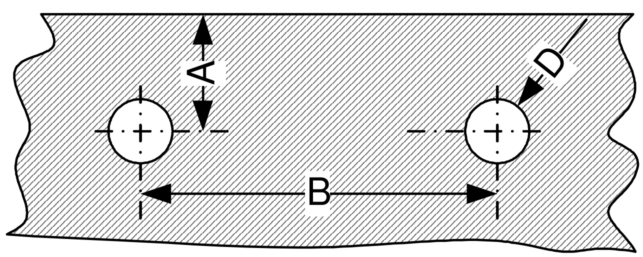


Figure 43: Sketch showing advised cooling channel spacing [5].

$$B \approx 2.5D \rightarrow 3.5D \qquad (17)$$

$$A \approx 0.8B \rightarrow 1.5B \qquad (18)$$

In an effort to explain cooling on a level understandable to mould designers in practice Rees, uses a number of graphs. The examples used by Rees will however mislead the designer due to the oversimplification of the mould cooling.

The examples Rees uses in his chapter on mould cooling will be shown, analysed and discussed below.

Rees starts off with what he calls, "a typical moulding cycle when using a slow machine" (Figure 44) and a mould with relative poor cooling. The different sections of the cycle are described as follows.

- A is the closing of the mould.
- B is when the plastic is injected.
- C is the cooling time.
- D is mould opening and ejection.

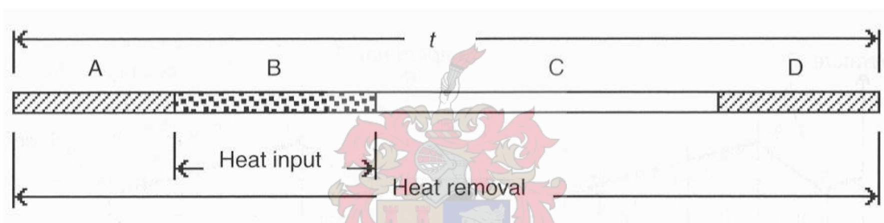


Figure 44: IM moulding cycle of a slow IM machine [5].

Although his example is only an illustration of what he wants to explain, it fails because of the scaling used. He states that the cooling cycle takes up to 80% of the total cycle time. Other literature suggests [3] that the cooling cycle in a blow moulding cycle is between 60% and 90% of the total cycle time. The example he used shows a cooling cycle of at the most 40%. Thus if he drew the figure on scale it would be something like the cycle in Figure 45. The assumptions made here are that the opening and closing of the mould are of the same length and also that the injection time is the same as an opening or closing cycle.

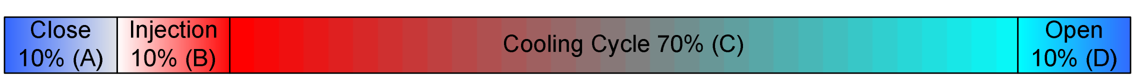


Figure 45: Typical IM cycle according to Rees (with exact scaling).

Rees also explains quite clearly that the cooling in the mould will continue even if the mould is not filled with plastic Figure 46. He also states that he makes the assumption that he will ignore the mould temperature rise and also the time lag between adding and removing heat from the mould cavity [5] (p284).

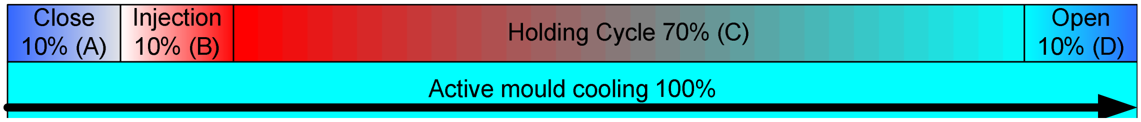


Figure 46: Typical IM cycle as Rees explains in his text.

Rees then makes the statement, with this assumption in mind, that: If a faster machine is used that the total cycle time will not decrease because the cooling part of the cycle will be longer; which he illustrates with Figure 47. Again the illustration which Rees uses (Figure 47) is not done to a proper scale. The heat will enter the mould when the hot melt is injected and this is a small part of the injection cycle. In Figure 48 an illustration of the same cycle is drawn to a more realistic scale. It is clearly illustrated that the machine open and closing cycles and the injection cycle are only a small part of the total cycle. The correct scale is important, since this gives the novice mould designer an idea of how large the holding (cooling) cycle is.

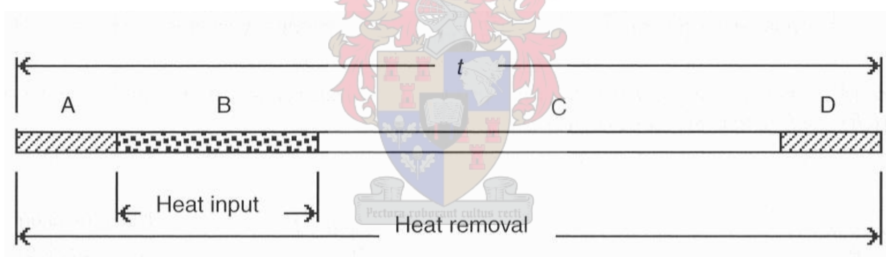


Figure 47: Rees's illustration that a faster machine will not improve the cycle time [5].

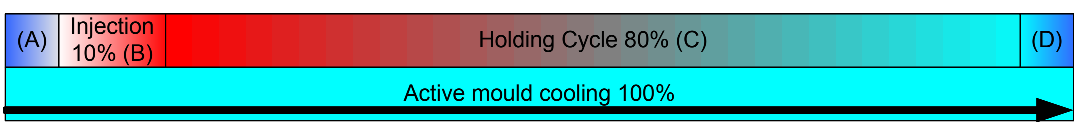


Figure 48: Figure 47 with realistic scaling.

The assumption which he makes by ignoring the mould temperature rise whenever heated plastic is cooled in the mould is however very crude, for the simple reason that there must be a temperature difference between the mould temperature and the water temperature if heat flow has to take place. Bryce [18] (p 121) states clearly that a temperature difference of as low as 5.5˚C in the mould will cause deformation. Thus small temperature differences in the mould are significant in the moulding process.

When the opening and closing cycle becomes shorter, and the injection and holding cycle stays the same, then the average mould temperature will increase. The bigger temperature difference between the mould and the cooling water will cause a higher heat transfer rate. Therefore the cycle shown in (Figure 47) will be shorter than that shown in Figure 44. The decrease in cycle time might however not be significant, depending on the cycle time difference between the slow and fast machine.

Rees also uses the graph in Figure 51 to illustrate the temperature change in the mould. This graph is not a true representation of what is happening in the mould cavity. As shown in Figure 22 the cavity surface will heat up instantaneously and heat flow will start to the rest of the mould. The graph in Figure 51 is roughly accurate if this is seen as the average temperature of the mould, but even then it is a crude estimate.

The cooling in the mould is dependent on the temperature difference between the plastic, the mould and the water. The bigger the temperature difference between the different elements in the mould the more energy will flow and the faster cooling will take place. To demonstrate this, the results of a typical one-dimensional, time dependant heat flow simulation can be seen in Figure 49. The simulation was done with ten finite elements in the mould and in the plastic. The element thickness in the plastic is 0.12mm which gives a total thickness of 1.2 mm. And the mould was taken as 10mm thick, thus having 1mm layers. The layers at the top indicate the temperature profile in the plastic at certain depths. A one-dimensional analysis is sufficient since the heat will follow the shortest route when flowing from hot to cold. And when conformal cooling is used in the design the distance between the part and the cooling channels must stay constant.

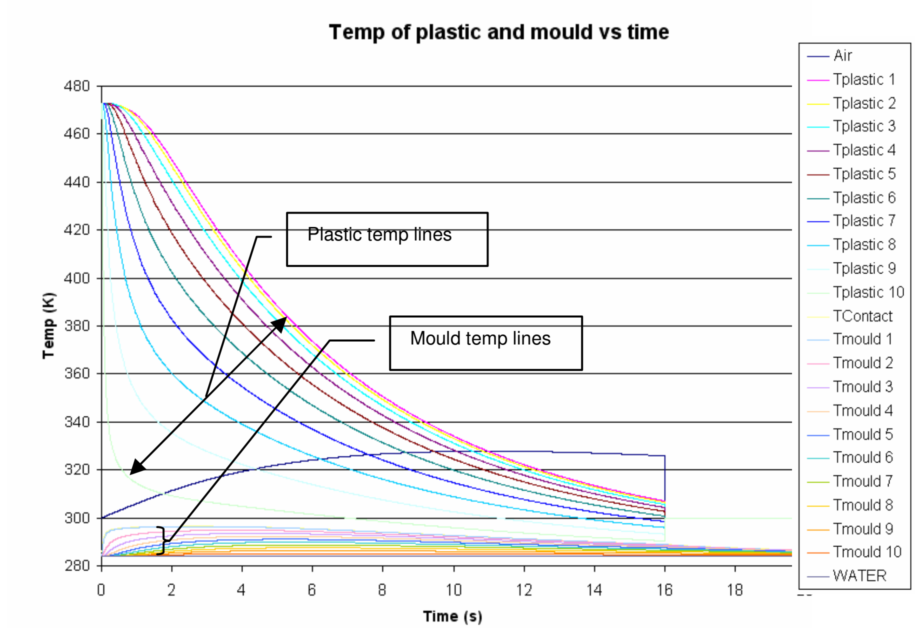


Figure 49: Demonstration of the cooling (holding) cycle in a mould.

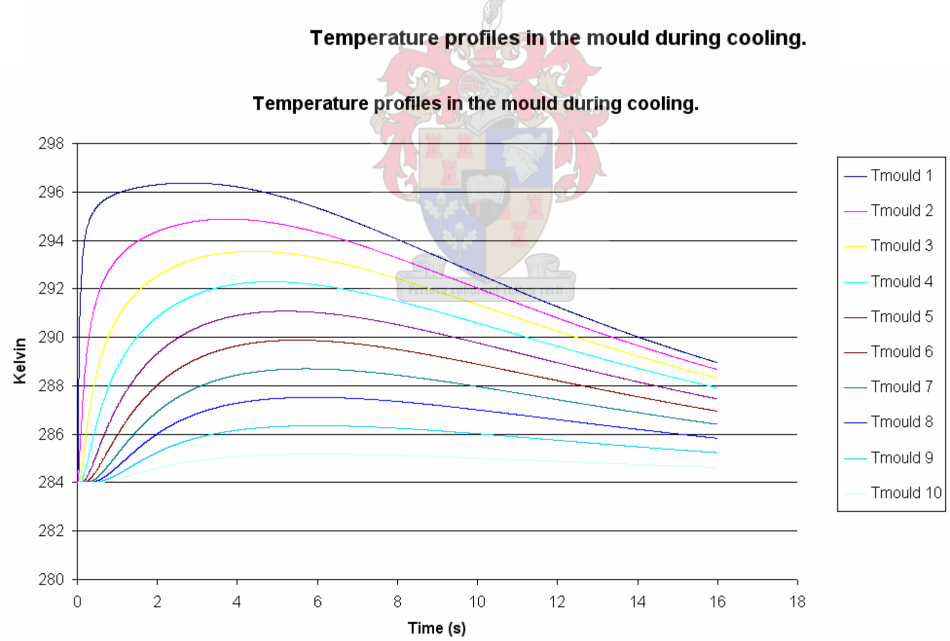


Figure 50: Mould temperature contours during cooling (holding) cycle.

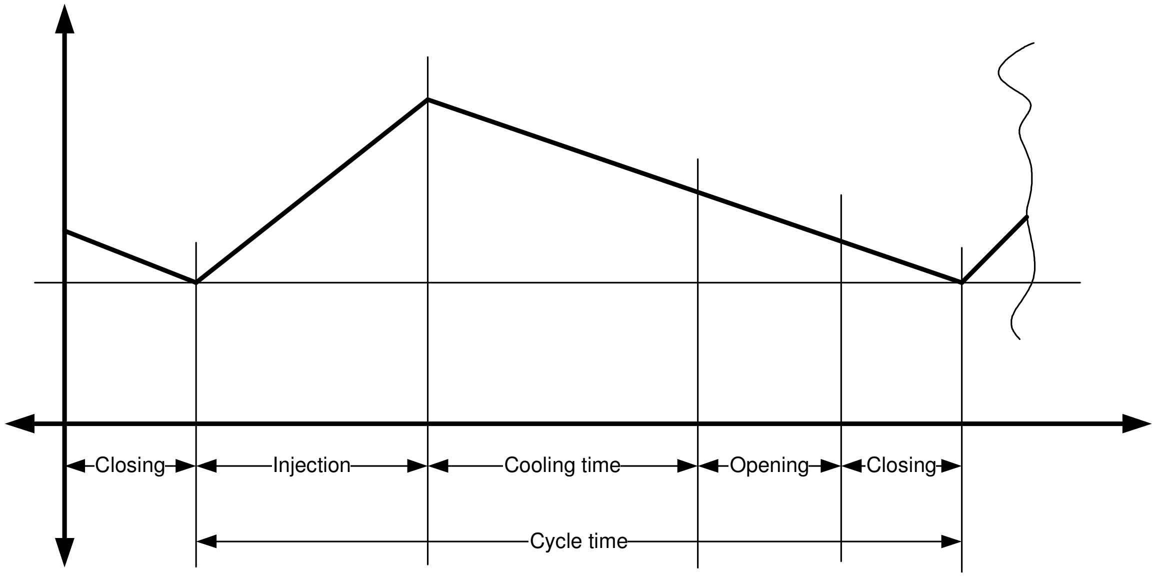


Figure 51: Mould temperature fluctuation according to Rees [5].

If the mould temperatures are magnified (Figure 50) then it is clear that the temperature in the mould closer to the part cavity changes more dramaticly during injection than those closer to the cooling channels. The temperature increase on the contact surface of the mould with the part is the most important aspect of the cooling. And the closer the cooling channels to this surface, the better the cooling will be, provided that the channel distribution is properly done.

According to Figure 51, which Rees [5] uses to explain the temperature change in the mould, he indicates the temperature rise in the mould as gradual. This is not true. The plastic is already hot when it is injected, around 480 K, thus the instant the plastic touches the mould cavity it would raise the temperature of the cavity at the point of contact, thus the temperature in the cavity would rise instantly to a maximum and then start to cool as the heat is dissipated, through the mould, to the water. The average mould temperature might show a gradual increase, but this will follow the patterns in Figure 49.

If the temperature contours of the plastic in Figure 49 are studied more closely it will be clear that there is a significant temperature drop over the plastic. This will explain the phenomena which occur when a part is taken from a mould. The surface will feel cool at first, but as time goes by the apparent temperature will increase. This is when the temperature in the part equalises.

Rees then goes on further to say with Figure 52 that if the cooling is improved then the total cycle time will be improved.

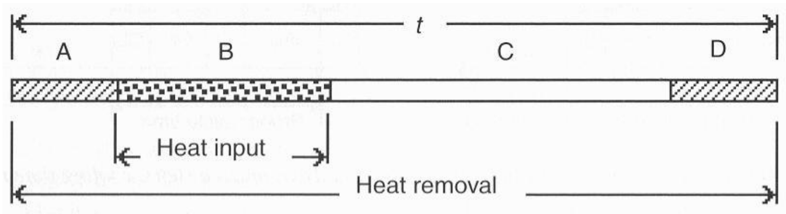


Figure 52: IM cycle with improved cooling on a fast machine according to Rees [5].

4.4.4 Cooling channel distribution

If drilled cooling channels are too close to the mould cavity, uneven cooling will develop, the influence of uneven cooling being distortion in the product [15]. This is known in industry as “hard cooling”. If the channels are further away from the cavity then “soft cooling” will exist. The heat from the plastic part is absorbed by the mass of the metal which is in turn cooled by the cooling channels which are much deeper.

The metal is not simply a conduction medium which conducts the heat to the water. It is rather like an accumulator which absorbs the heat quickly and evenly and then dissipates it to the water. This property is widely used in thin wall injection moulding where the mass of the product is relatively low. In thin wall injection moulding the melt flow distance to wall thickness ratio is in the region of 200 : 1 to 300 : 1.

4.4.5 Automated cooling design

There is also some research being done on automatic cooling layout design using algorithms for the heuristic search of the best cooling layout design. This process is however limited by the use of drilled channels [19]. It might have the advantage of supplying a quick cooling design, but it will not solve the cooling problem completely, since drilled channel cannot follow the form of a complex object. It will only be affective if it could be developed to enable the use of LM technology.

4.4.6 Conformal cooling

Conformal cooling in itself is not a completely new concept and has been used in many experiments and also in different applications.

The basic principle of conformal cooling, in its simple from, is a cooling system of which the cooling channels follow the cavity being cooled at a constant distance. There are also more complex layouts which use simulation to determine the exact route which the cooling channels should follow to allow for the uniform cooling of the mould cavity. In Figure 53 two different layouts are shown which were used in the design of two specific injection moulding tools [20].

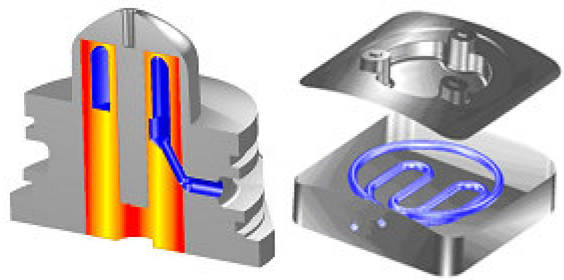


Figure 53: Conformal cooling channels in injection moulding tools [20].

Since conformal cooling is a cooling layout where the water channels follow the mould cavity closely, it is obvious that different designs would satisfy this requirement. The designs in Figure 54 are all conformal cooling designs albeit there are big differences in the shapes of the cooling channels [21].

The hybrid tooling (Figure 54 (a)) is produced with a combination of conventional mould manufacture and Selective Laser Melting (SLM). The base of the mould is manufactured using conventional methods, then with the use of SLM the top part of the mould is built on the machined part. Some finishing is done afterwards to ensure a good surface quality.

The cooling channels method (Figure 54 (b)) is used in this case for the top edge of a bucket where there are small ribs requiring cooling.

The cooling surface method (Figure 54 (c)) is a more expensive method of cooling moulds. The cooling is in a honeycomb shape and can be multi layered, where the one layer can be used for cooling and the second layer for heating. This is ideal for pulsed cooling. This method is advisable for high volume production and provides excellent performance. The only way this type of cooling can be created is with layer manufacturing.

Combined surface and channel cooling (Figure 54 (d)) are also a combination of conventional machining and SLM. The base of the mould core is machined and the channels are drilled after which the component is hardened. The top of the core is then grown on top of the machined part. After the part is grown, it must be machined to the final size.

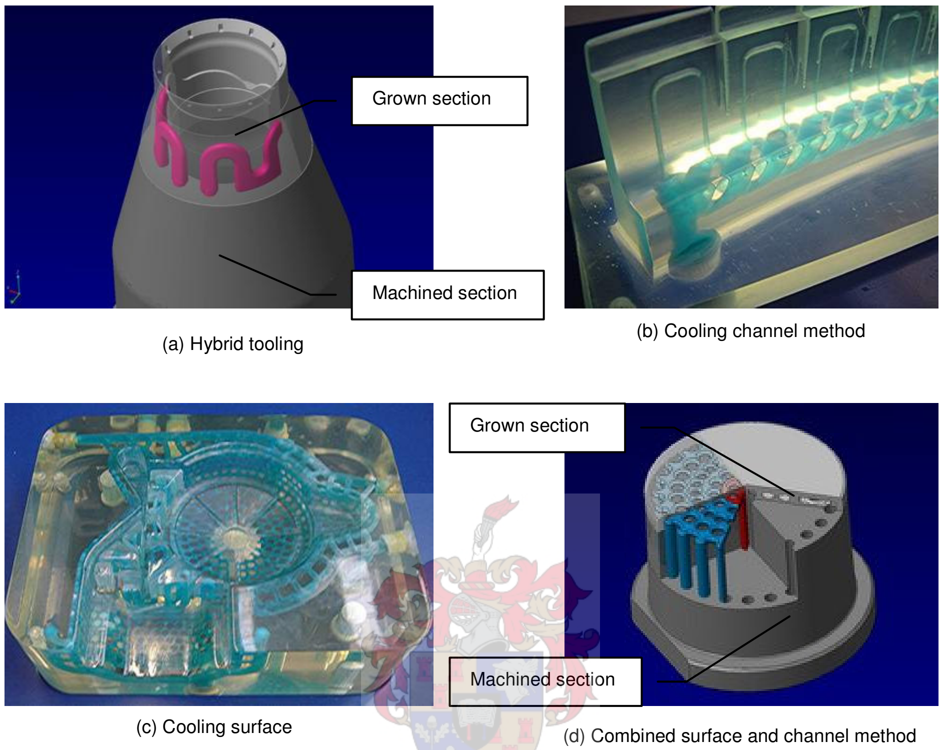


Figure 54: Different conformal cooling layouts [21].

The difference between conformal cooling and conventional cooling can be seen in Figure 55. In conformal cooling the cooling channels follow the mould cavity geometry at a constant distance, hence the name, since the shape of the cooling channel conforms to that of the cavity.

When looking at Figure 55 the cooling channels seem to be conformal, since it follows the mould cavity at a constant distance. This cooling layout only follows the mould cavity in one direction and if a 3D model is created the short comings become clear (Figure 56). The layout will typically cause uneven temperature distribution in the mould, which in turn causes the product to distort. Thus the design is actually not conformal cooling, but rather conventional cooling.

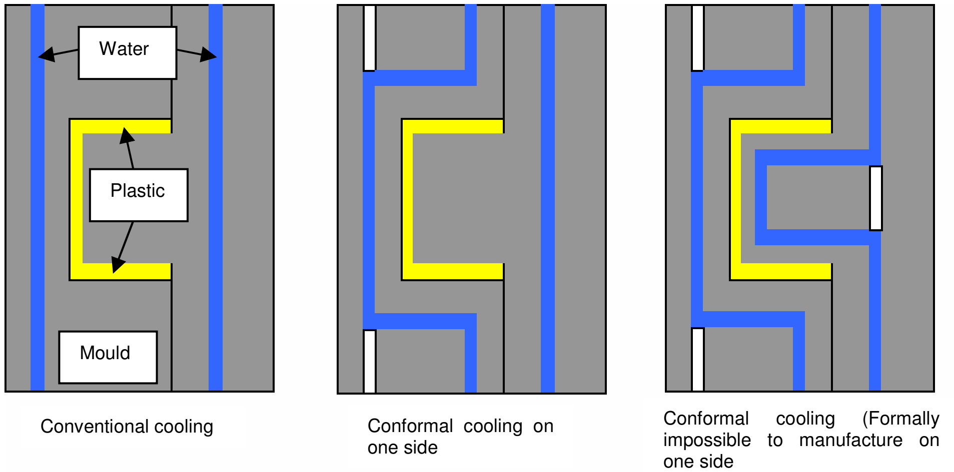


Figure 55: Comparison between conventional and conformal cooling [22].

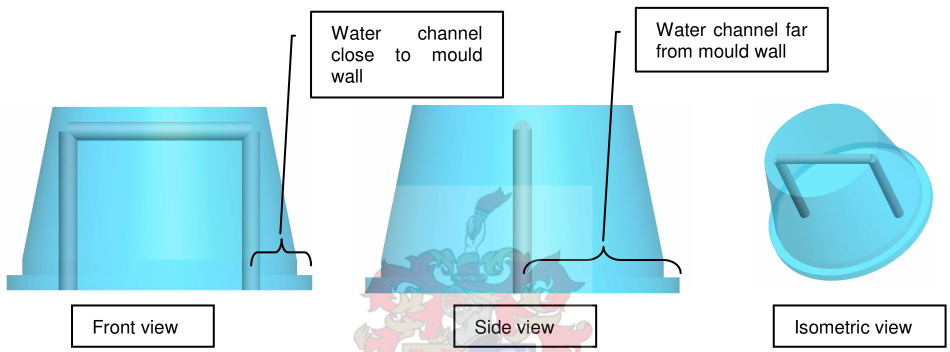


Figure 56: 3D model of Figure 55.

If channels are to be used to create a conformal cooling layout then a design as shown in Figure 57 can be used. To design such a cooling layout is relatively easy, but it is not as easy to manufacture. A design like this can only be manufactured using LM.

From Figure 58 it is easy to see that for conventional cooling channels, the thickness of the mould between the water channel and the mould face vary. Right across the channels the mould is 7 mm thick and in between the channels is 8.49 mm, if the channels are spaced 12 mm from each other. This effect leads to hotspots at these points, and causes the mould to take longer to cool down.

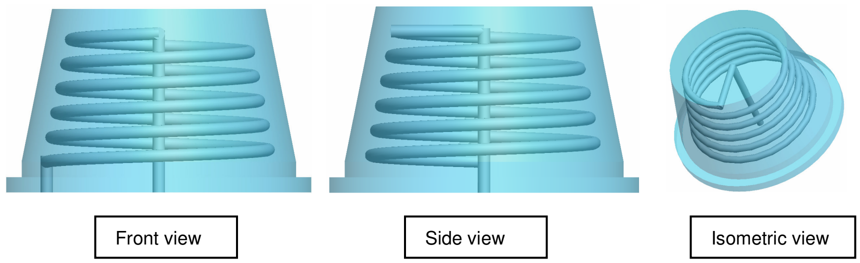


Figure 57: 3D model with a conformal cooling layout.

Hotspots are a major concern for the industry since it usually bring defects and longer cycle time. Eliminating all these hotspots will improve cycle time and defects.

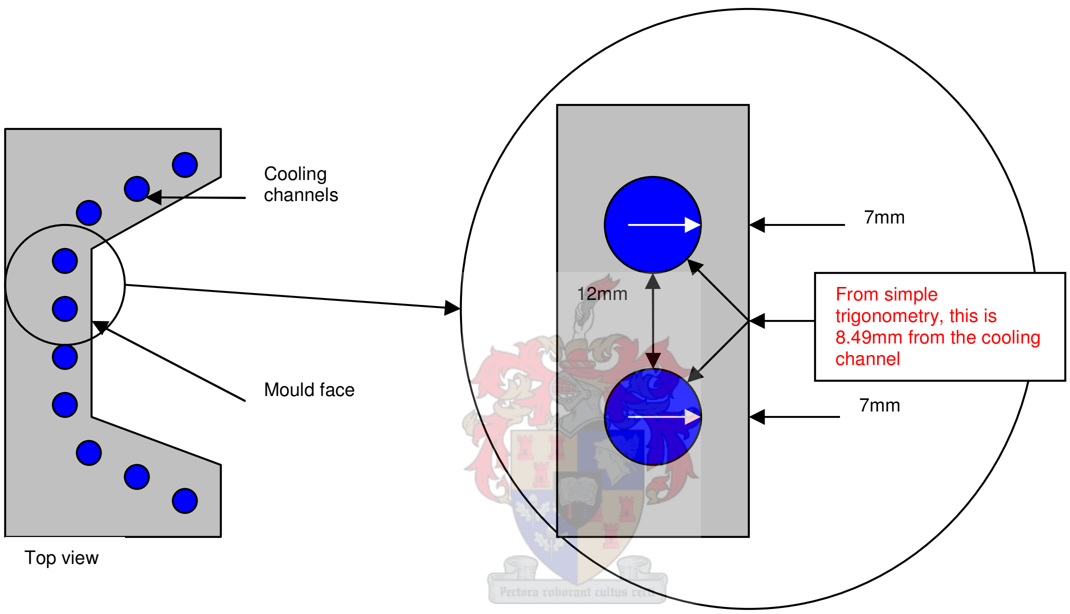


Figure 58 Cross section thickness of original mould.

Figure 59 provides a further illustration of the unequal cooling effect of drilled channels. The blue areas are the water channels and the bottom edge is where the heat is applied. As the heat dissipates to the water, temperature contours wrap around the cooling channels.

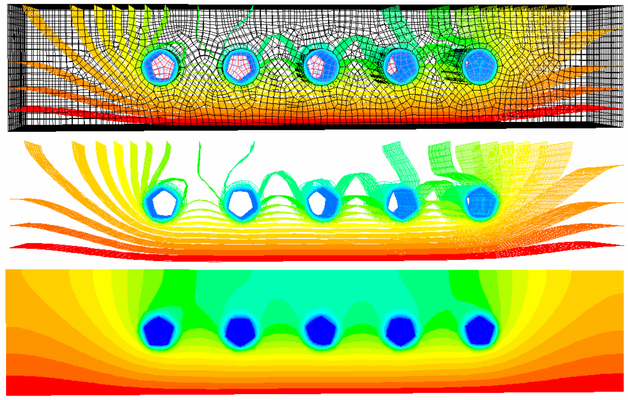


Figure 59: Illustration of unequal cooling in a mould with drilled holes.

In order to show the differences in temperature contours between a conformal and conventional cooled mould, a hypothetical model (Figure 60) of a blow moulding object was constructed. Then the heat distribution was simulated using conventional (drilled) cooling channels (Figure 61(a)), as well as using a conformal cooling design (Figure 61(b)). Figure 61(b) shows clearly the equal distribution of the heat following exactly the contour of the cavity as a result of an adequate cooling as opposite to the picture shown on Figure 61(a).

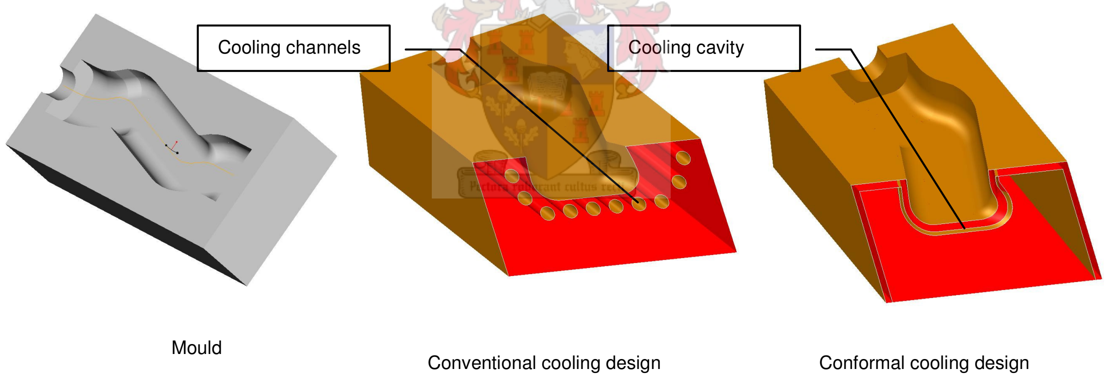
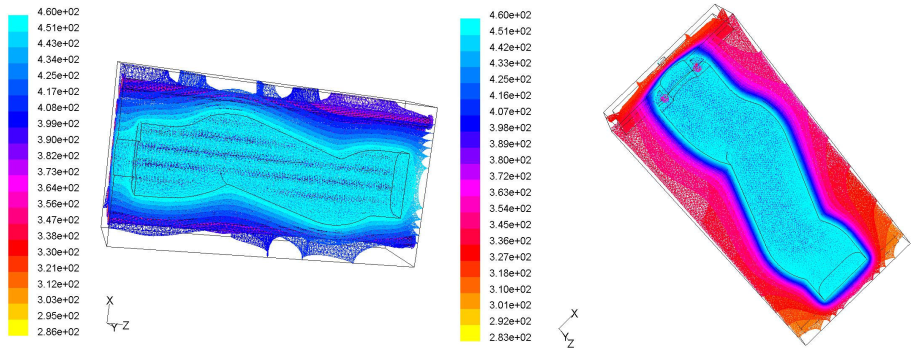


Figure 60: Hypothetical mould.



(a) Conventional cooling (b) Conformal cooling

Figure 61: Temperature contours.

<u>Conventional cooling limitations imposed by product geometry</u>

Another problem with the conventional cooling with regards to the cross section thickness is, if the part consists of a “fatter” part and “thinner” part (Figure 62). The cooling channels are drilled close to the fatter part which means that it will be further away from the neck area, which will cause the neck area to cool down slower. Figure 62 illustrates this problem and Figure 63 shows the results of an illustrative simulation. The simulation is of the mould layout used in Figure 62 and serves as an illustration of what is explained above.

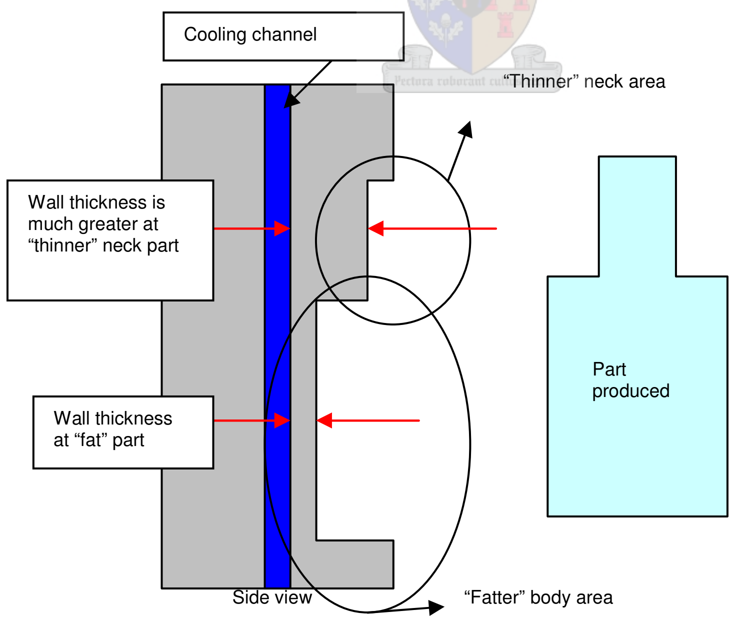


Figure 62: Side view of conventional cooling channels.

The irony in blow moulding is that the “thinner”/“narrower” part is always where the parison expands the least, thus the plastic in this area would be thickest, requiring the most cooling.

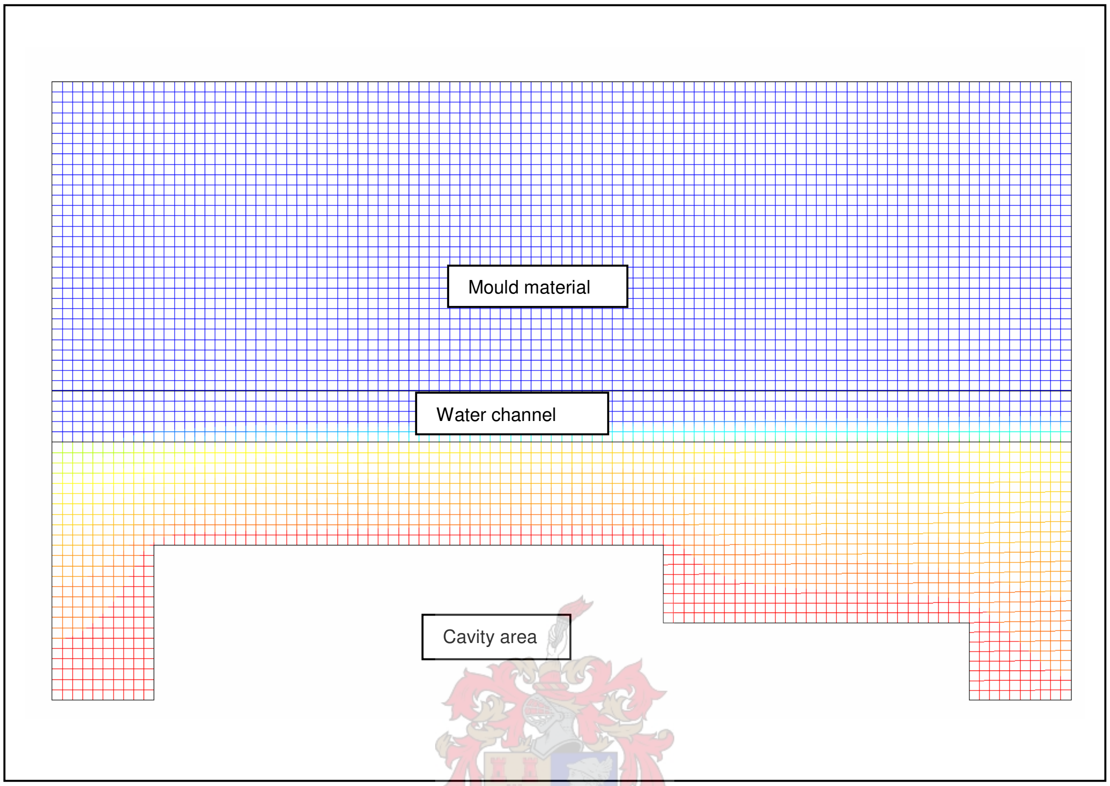


Figure 63: Heat distribution in mould with conventional cooling.

One of the major constraints in the design of conformal cooling channels is the manufacturability of it. There are some solutions to these problems, but it is not entirely solved. The different methods which can be used in manufacturing a conformal cooled mould are the following:

- Remove excess material to give the mould a uniform wall thickness and insert guides to help manipulate the water to ensure uniform cooling.
- Design the mould with cooling channels which can be investment cast into a near net shape for the mould.
- Design the mould with cooling channels which can be included when the mould is built in a LM machine.
- Mill out channels which follow the mould cavity at a set distance.

All these methods have their limitations and it is necessary to choose the correct method or combinations of methods.

A summary of the differences between conformal and conventional cooling can be seen in Table 2.

Criteria	**Cooling method**	
	Conformal cooling	**Conventional cooling**
Manufacturing cost	High, but will decrease as suitable LM technology becomes more affordable.	Low.
Manufacturability	Difficult	Simple
Efficiency	High (Independent of component geometry)	Low (Very dependant on component geometry)
Part quality	High	Usually lower than conformal cooling
Design difficulty	Difficult	Simple
Possible cooling complexity	High	Low

Table 2: Conformal vs conventional cooling.

4.5 Cooling and structural analysis

4.5.1 Cooling analysis

There is no package on the market with the capability of simulating the complete blow moulding process. Polyflow as mentioned earlier will simulate the parison forming in the mould. It supplies information such as component wall thickness and cooling time. The cooling time does however not allow for different cooling layouts.

Computational Fluid Dynamics (CFD) software on the other hand can simulate different cooling layouts, but not the parison formation. And the parison heat is the energy, which must be removed from the mould. The research done was to determine the benefits of conformal cooling thus was it more important to be able to analyze the cooling behaviour and not so much the parison formation. Some input parameters were needed to simulate the parison, the code in Appendix A was used to calculate this.

When designing traditional cooling channels, it's easy to predict what the water flow will be like and what the approximate heat convection would be between the channel wall and the water. With conformal cooling however it's not as easy, especially if a flooded cooling layout is used. In order to understand how the water would behave in the cooling cavity, a simulation is essential. In an effort to show the contrast in complexity of water flow in a large mould cooling cavity and conventional cooling channels an illustrative simulation was done (Figure 64). It is clear that the water flow in the cavity (Figure 64 (a)) is much more complex than that in the channels (Figure 64 (b)). The stagnant areas would typically yield poor cooling, whereas the areas of high velocity would ensure good cooling. The cavity design was done specifically to illustrate areas high velocity (red) and areas of low velocity (blue) and also some complex flow paths, which would be impossible to predict without the use of a simulation.

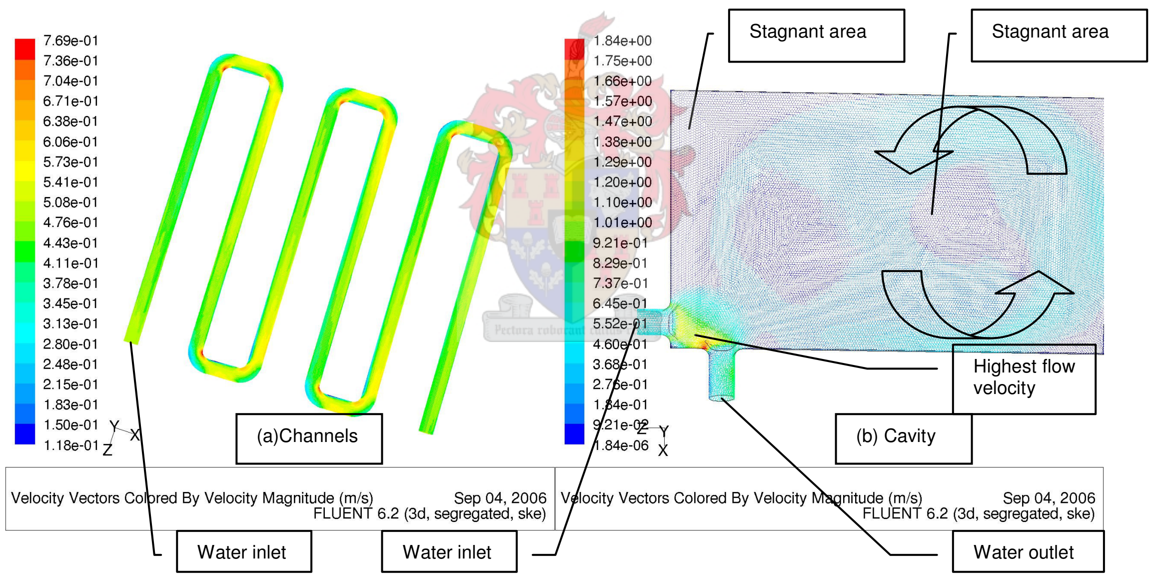


Figure 64: Illustrative comparison of flow in pipes with flow in cavities.

Three different CFD packages were used during the course of this research. These were STARCD, FLUENT and CFDESIGN.

<u>STARCD</u>

STARCD was the first package which was used during this project. It is a very powerful CFD package with strong pre and post processors. The pre and post processors were however not available at the time, which imposed severe constraints on the meshing of the CAD models.

STARCD is being developed by ADAPCO [23] and is used by a number of large role players such as the company developing the Pebble Bed Modular Reactor, Dassault Aviation and the Renault F1 team. It also developed STAR-Pro/E, STAR-NX, STAR-CATIA and STAR-WORKS, which is embedded into the user interfaces of the relevant CAD packages. ADAPCO also launched a product by the name of STAR-CMM+. This is one of the new generation CFD products that are much easier to use and still provide reliable answers.

<u>FLUENT</u>

FLUENT is like STARCD a traditional high end CFD package and like STARCD needs a 3rd party meshing package to create the mesh. It is however significantly simpler to use than STARCD.

Typical users of FLUENT [14] are Volkswagen (for the simulation of their BENTLEY designs), ADAM OPEL AG, RED BULL SAUBER and FORD to name a few. It is also extensively used in the aerospace industry.

<u>CFDESIGN</u>

CFDESIGN is different to STARCD and FLUENT in both the mathematics and usability. It is claimed to be very accurate, but much more usable than the traditional packages. The main mathematical difference between CFDESIGN and the traditional packages is that it calculates the relevant values at the nodes of the mesh elements, thus the shape of the element does not matter, whereas the traditional packages calculate the relevant values for the mesh elements.

Some of the major users of CFDESIGN are CUMMINS, PHILIPS, HEWLETT PACKARD, NORGREN and TOP FLITE who design and manufacture golf balls [24].

CFDESIGN is compatible with most main stream CAD packages, making it ideal for less advanced CFD users. A major time saver in the CFD analysis with CFDESIGN is the fact that the user does not have to create a CAD model of the simulated fluid anymore. It is created automatically. The second factor making it easier to use is the simplicity of the meshing procedure. The third factor is the simplicity of the user interface. The engineer can mesh, add constraints, solve and analyse the problem with the use of one user interface.

4.5.2 Structural analysis

The structural integrity of a mould is very important due to the large forces exerted on it during production. The cavity pressure in an injection mould can reach 600 Bar or more. This is usually not a problem when conventional cooling is used, because the drilled channels remove relatively small amounts of material thus leaving the structure of the mould virtually intact. When conformal cooling if used however this could become a problem. In both these cases a significant amount of material is often removed from the back of the mould.

The structural integrity of a blow mould could also be a problem if a large cooling cavity is used as shown in Figure 65.

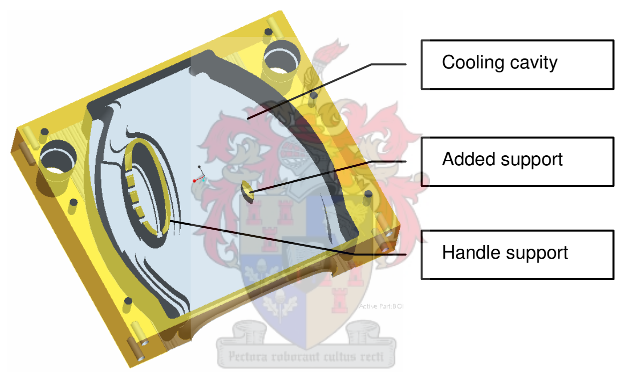


Figure 65: Typical blow mould with large cooling cavity.

In order to analyse the effect of the forces on the mould a number of software packages can be used. Most of the larger CAD vendors supply embedded Finite Element Analysis (FEA) packages or modules. These embedded FEA modules operate mostly in the elastic stress/strain range, which is sufficient for the solving of these problems. Since the mould is never suppose to operate in the plastic range in any event. If the mould should enter into the plastic range permanent deformation will occur and the mould would be of no further use. The following list gives the names of well established dedicated FEA packages and these will typically be able to operate in the plastic range:

- Nastran/Patran
- Abacus

- Cosmos

And the CAD packages, which have either embedded FEA capabilities as standard or as an option, are among others:

- Pro Engineer
- Unigraphics
- Catia
- Autodesk Inventor
- Solidworks
- Solidedge

As a demonstration of the use of such a package the results of an analysis can be seen in Figure 66. The FEA software was used to determine the deformation in the mould during parison inflation. The red area has the largest deformation.

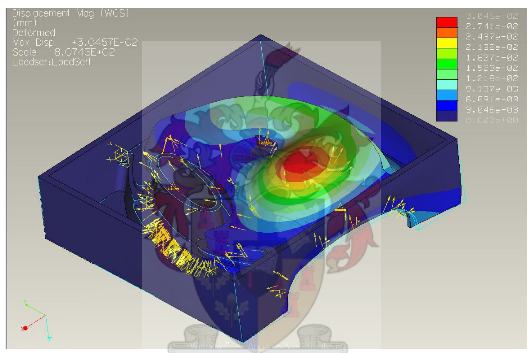


Figure 66: Study using FEA software.

The embedded FEA packages are as a rule not as powerful as the stand alone packages such as Abacus, but the geometry is usually parametric thus the simulation model will change if the CAD model is changed. This makes the iterative processes much quicker and is important to the designer.

4.6 Design evaluation

The evaluation of the basic mould design would be based on the structural and cooling behaviour of the mould. This behaviour prediction would be based on the simulations done on the mould using CFD and FEA. Typical scenarios arising from these analyses are the following:

- Hotspots present, but mould structurally sound.
- No hotspots, but mould structurally weak.
- Hotspots and mould structurally weak.
- No hotspots and mould structurally sound.

The reasons for the above mentioned results would normally depend heavily on the product geometry. Guidelines to determine the next step after the simulation results became available are shown in Figure 67.

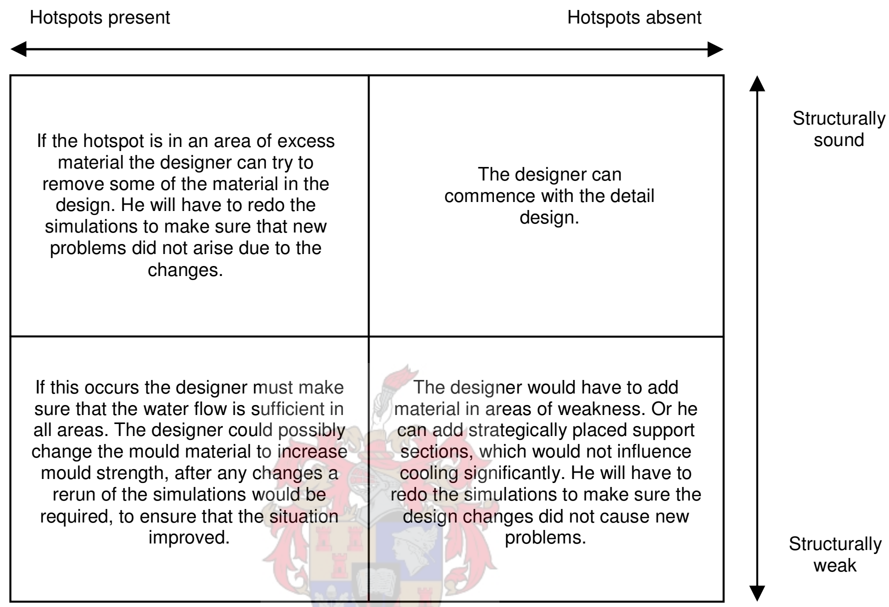


Figure 67: Evaluation matrix.

4.7 Mould manufacture

The important issues to remember are that a mould should always be sturdy enough to handle the process forces and it must be made accurate enough to allow for a good quality product. The three different process chains to manufacture moulds are:

- Conventional machining
- Layer manufacturing methods
- Casting

4.7.1 Conventional machining

With conventional machining a solid block of metal is used and the required cavities and channels are machined into it. This method normally produces a good quality product with a high accuracy.

Conventional machining methods include the following:

- Conventional milling
- CNC milling
  - Normal (3,4 and 5 axis)
  - High speed milling (3,4 and 5 axis)
- EDM
  - Wire cutting
  - Spark eroding
- Drilling
- Turning
  - Conventional
  - CNC
- Hand finishing

All these methods are subtractive, meaning that material is removed from a block of material. With new high speed machining methods it is relatively quick to produce a mould. Five axis high speed milling is especially effective, because it can be used to cut into hardened materials, with cutting tips for cutting steel of up to 65 Rockwell being available [25]. Previously this was the sole domain of the much slower spark eroding process. An additional advantage of High Speed Machining (HSM) is the good surface finish, thus reducing the hand finishing required in polishing the cavity surface.

The major drawbacks with subtractive manufacturing are that an area must be reachable in order to be machined. Thus drilled holes must be straight and undercuts kept within the machining capability limits.

4.7.2 Vacuum brazing method (VBM)

When producing a part with VBM the sheet metal layers are either cut from large sheets with a laser cutting machine and then brazed together [26]. Or the mould can be divided into sections. The cooling cavities are then machined into these sections before they are brazed together [27]. The method gives a strong mould with good cooling possibilities, since the designer has more design freedom than with conventional cooling design. This method is however better suited to larger tools especially where an intermediate casting would be required to created the tool.

4.7.3 Layer manufacturing methods

Layer manufacturing technology allows for the greatest flexibility when designing the cooling of a mould. The advantage being that the cooling channels will be incorporated in the model as it is being built. Some of the layer manufacturing methods used in mould manufacturing are the following:

- Direct Metal Laser Sintering (DMLS).
- Three - Dimensional Printing (3DP).
- Selective Laser Melting (SLM)

Direct Metal Laser Sintering [16]

This method uses a plastic coated metal powder, which is melted together in the shape of the CAD model, using a laser beam. The heat from the laser melts the plastic and this forms the bond between the powder particles. The part is then sintered in an oven and an infiltrant such as bronze is used to ensure that the density of the piece reaches 100%. Some finishing operations will typically be necessary in order to ensure that the surface quality meets the requirements.

Three - Dimensional Printing [17]

This process uses an uncoated metal powder and binds the particles together using glue. The parts are also sintered afterwards and infiltrated with bronze. After infiltration the piece will have a 100% density.

Selective Laser Melting [28]

This process uses a high energy laser to melt the powder particles together. In doing so the part reaches a 100% density without additional infiltration being required. Any powder such as titanium or stainless steel can be used. An added advantage is that the part produced is homogenous, thus it is suitable for post treatment such as case hardening etc. The layer thickness of this process is 30 µm, which ensures a good surface finish with little layering effect. For mirror finish parts, additional surface preparation would however still be needed.

4.8 Casting

For large moulds a near net shape casting is made and the cooling channels can be incorporated into this. The cooling channels can follow the cavity, thus conformal cooling is possible. A near net shape casting has the basic shape of the mould, but with additional material on the faces which must be machined. A major problem with casting is that the types of material which can be cast with ease are limited. Stainless steel especially is very difficult to cast

The second problem with cast moulds is that the designer first has to design the mould. After this he must add machining allowances and draft angles to make it cast-able. This places an additional burden on the designer and needs more time to complete, causing the manufacturing time to escalate.

4.9 Conclusion

The planning stages of the mould design are done to help the designer to determine the requirements, which the mould must meet during its operational lifecycle. The designer must ask some critical questions to define the work envelope of the mould.

The software packages developed for injection moulding are not suitable for the simulation of blow moulding thus were they not included in this study.

The blow moulding simulation software available on the market and those that were available for use in the simulation studies, are very complex and not really developed to such an extent that it is easy to simulate the formation of a 3D bottle in a blow mould. It is however relatively simple to simulate the 2D formation of a bottle.

The main advantage of these packages is that they can be used to simulate the wall thickness of a parison and also the wall thickness of the final part. This output can either be used to help set up the production or it can be used in further heat flow simulation studies.

It is clear from literature that uneven cooling causes distortion (or warpage) in plastic products. It is also clear that the available textbooks do not give the necessary attention to cooling and are not up to date with the latest technology and methods.

The solution in industry used to compensate for the distortion of the component is by modifying the mould cavity is such a way that the part would comply to the product specifications after distortion took place. This is however to a large extend, a trail and error method, since the software which can predict this type of distortion quantatively is expensive and not within the reach of the average mould designer. Distortion in components will take place when the cavity temperature varies with more than 5.5 °C.

The influence of subtle design changes is very important. The designer should always ensure that the cooling fluid contact area is as big as practically possible in the insert, which contains the mould cavity. The designer must keep in mind that the cavity must be cooled as uniformly as possible.

The cooling of the mould will continue as long as the mould temperature is above that of the cooling water. The more material there is between the mould cavity and the water channels the longer it will take to cool the cavity. The mould will also take longer to reach its operating temperature during start-ups. Such a mould could be very difficult to manage during stop/start operations.

The mould reliability is critical and the structural integrity of the mould is important during the cooling design phase. There are some guidelines for the design of conventional drilled cooling layouts, but for more elaborate designs such as conformal cooling FEA must be used in order to ensure the reliability of the mould.

The simulation of the different cooling systems was done with FLUENT. The temperature of the mould cavity was calculated with a piece of VBA code specially created for these simulations (Appendix A).

The FEA and CFD simulations will guide the tool designer by pointing out hotspots and stress concentrations. With the use of this information he can then design a reliable mould with good cooling characteristics.

There are basicly three different ways of manufacturing moulds. The first being subtractive manufacturing (cutting material away), the second being additive (adding material using LM) and the third is casting (sand and investment).

The best surface finish is produced by subtractive manufacturing, especially high speed machining, with layer manufacturing being very tolerant to complex geometry and casting being useful for producing of large near net shape moulds, which only need final machining.

Layer manufacturing is becoming a more viable option for the manufacturing of moulds and especially with its capability to produce complex geometry it gives the designer the option to design conformal cooling channels into the mould.

5. IMPLEMENTATION OF THE DESIGN APPROACH

5.1 Case study 1

This is the essence of the case study, the complete version is attached in Appendix B. The study was done on a mould for a particular Nestlé container. The purpose was to prove, through the use of simulation, that conformal cooling will improve mould performance.

5.1.1 Creating a simulation model

For simulation purposes a 3D solid model of the object is needed. This model of the mould was translated with the use of a STEP translator and imported into the relevant simulation package.

At this stage it has to be made clear that the usability of a model file depends mainly on the capability of the CAD package selected. It is true that an experienced CAD operator can positively influence the simulation results. To minimise the problems possibly caused by the CAD system a proper solid modelling package, which is set to tight tolerances, should be used (instead of a surface modeller) when the simulation model is developed.

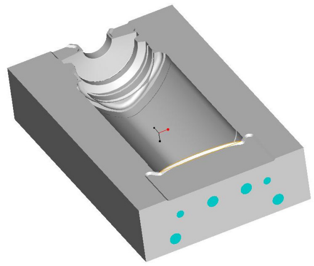
There is also a question about the reliability of the interface, which is employed to translate the data between CAD – systems and simulations packages. The well known IGES translator, for example, seems to be totally unsuitable for simulations purposes. It exports the geometry as surfaces. These surfaces need to be joined again in the meshing package in order to recreate the solid model, which is very time consuming and frustrating. Good results were achieved with the Unigraphics translator, which exports Parasolids. It works relatively well, although some difficulties were encountered especially with the surface of the solids. Problems such as lines not matching up appeared and this in turn made the surface meshing, which is necessary before the solid meshing can be done, very difficult and in some cases impossible. The best interface turned out to be the STEP translator. It translates the solid as a solid, thus the surface geometry of the model is of a better quality than is obtained using a Parasolid. The

STEP translation was still not perfect. However, a well designed solid could eliminate most of the potential problems.

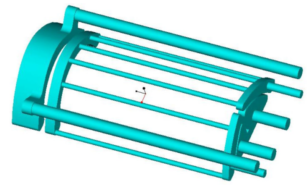
Figure 68 shows the virtual model of the existing production mould as used by the packaging manufacturer. While Figure 68(a) reflects the solid model of the mould, the picture right – Figure 68(b), shows the solid model of the water jacket related to the conventional cooling channels. Figure 68(c) on the other hand illustrates the velocity conditions in the three sections of the mould. Subsequently, Figure 68(d) shows the heat distribution throughout the mould. The inequality of this distribution is more than clear.

Based on an empiric approach a prototype mould for the same object was constructed. The cooling was performed using a flooded cavity in the back of the mould. The cavity was created by offsetting the mould cavity by 6 mm, which formed the conformal cooling layout. The cooling simulation of the prototype mould was carried out using the same input parameters as applied for the production mould. The results can be seen in Figure 69.

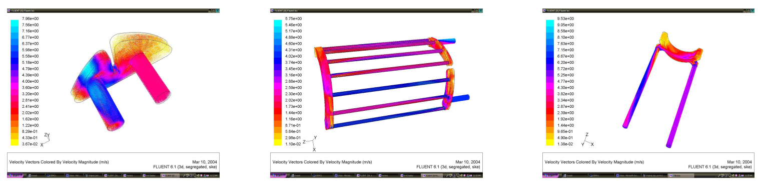
An observation of the cooling conditions on the prototype mould shows much stronger presence and equal appearance of the cooling fluid surrounding the mould cavity (Figure 69(a) & (b)). The velocity diagrams in the three sections can be interpreted as follows: the water enters the top cavity at a relatively high speed. It follows the shape of the bottle neck, which ensures relatively good cooling. The cooling is still not fully uniform, due to the fact that the water speed is not completely uniform over this section of the mould.



(a) Production mould

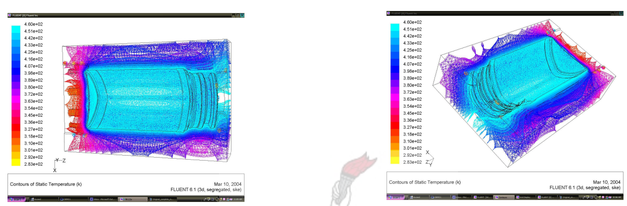


(b) Water jacket



Bottom cavity Central cavity Top cavity

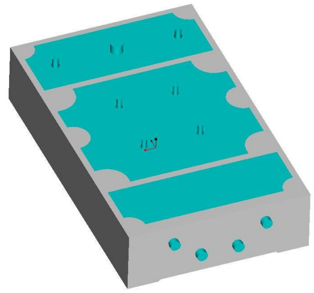
(c) Velocity diagrams.



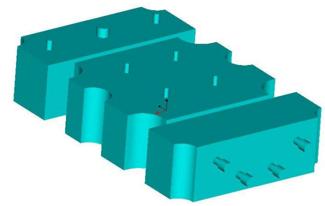
(d) Heat distribution of bottle cavity from different view angles.

Figure 68: Solid models, velocity diagrams and head distribution on the conventional production mould.

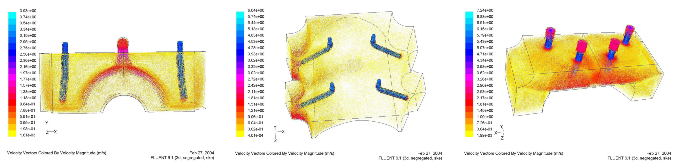
The water speed in the central cavity is relatively low, but it is uniform over the mould surface, which ensures uniform cooling. In the third mould section the water flows into the bottom of the mould cavity and hits the mould bottom at a relatively high speed, which will assure good cooling in this area. In the rest of the bottom cavity the water flow velocity is low, but uniform and will therefore cool the mould section equally. The heat distribution as shown in Figure 69(d) demonstrates the improved cooling as shown by the temperature contours which follow the cavity much closer.



(a) Prototype mould and cooling water

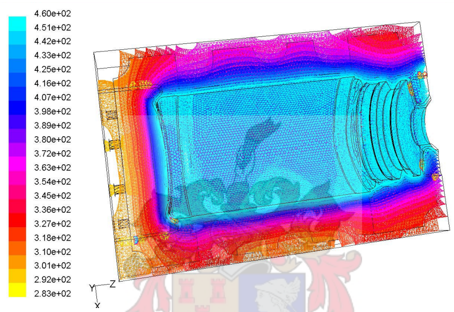


(b) Water cavities



Top cavity Central cavity Bottom cavity

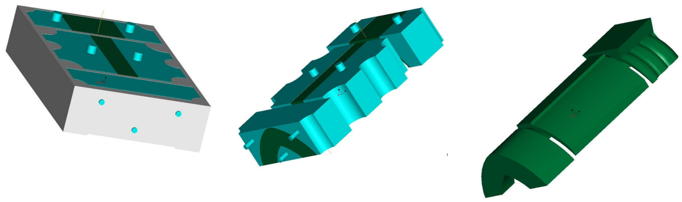
(c) Velocity diagrams of the cooling water in the different cavities.



(d) Heat distribution of the prototype mould using conformal cooling cavities.

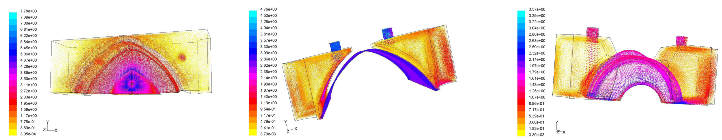
Figure 69: Solid models, velocity diagrams and head distribution on the prototype mould.

There are, however, substantial possibilities for further improvement as shown on the pictures below (Figure 70). Once again the pictures in (a) are reflecting the solid models of mould, water layout and possible inserts for better regulation of the water velocity. The velocity diagrams in Figure 70(b) show that the water flow can be manipulated to give a uniform surface velocity over the mould. In Figure 70(c) the temperature contours can again be seen. If Figure 70(c) is compared to Figure 69(d) a further improvement of the cooling can be clearly established.



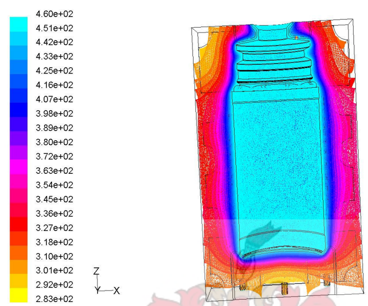
Mould Water and inserts Inserts

(a) Possible cooling layout of prototype mould for next iteration.



Bottom cavity Central cavity Top cavity

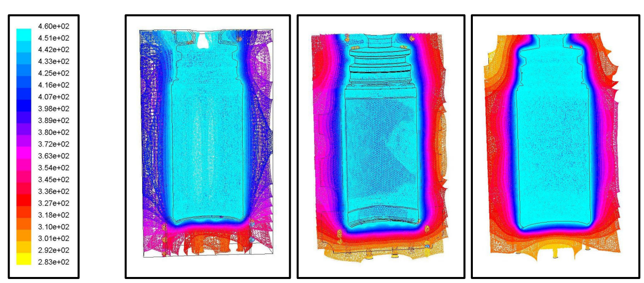
(b) Velocity diagrams of water in proposed cooling layout.



(c) Heat distribution of the bottle mould using the proposed cooling layout.

Figure 70: A possible further design iteration of the cooling layout.

The improvement is clearly visible if the simulation results are placed next to each other (Figure 71).



Temp scale (K) Original layout Prototype layout Proposed layout

Figure 71: Comparative layout of temperature contours.

5.2 Case study 2

In this case study a complete production mould was developed, for a 2 litre fabric softener bottle with a handle. The design incorporates conformal cooling, which was designed and analysed with CFD to ensure uniform coolant flow, FEA was used to ensure structural integrity. This is a summary of the case study and the complete version can be found in Appendix C

5.2.1 Design issues

The bottle is big, therefore is finite element analysis necessary to ensure that the mould will handle the pressure applied during parison inflation. The mould is divided into three sections, namely the base, body and neck section (Figure 72). The basics features of the mould are shown Figure 72. A rear view of the mould can be seen in Figure 73.

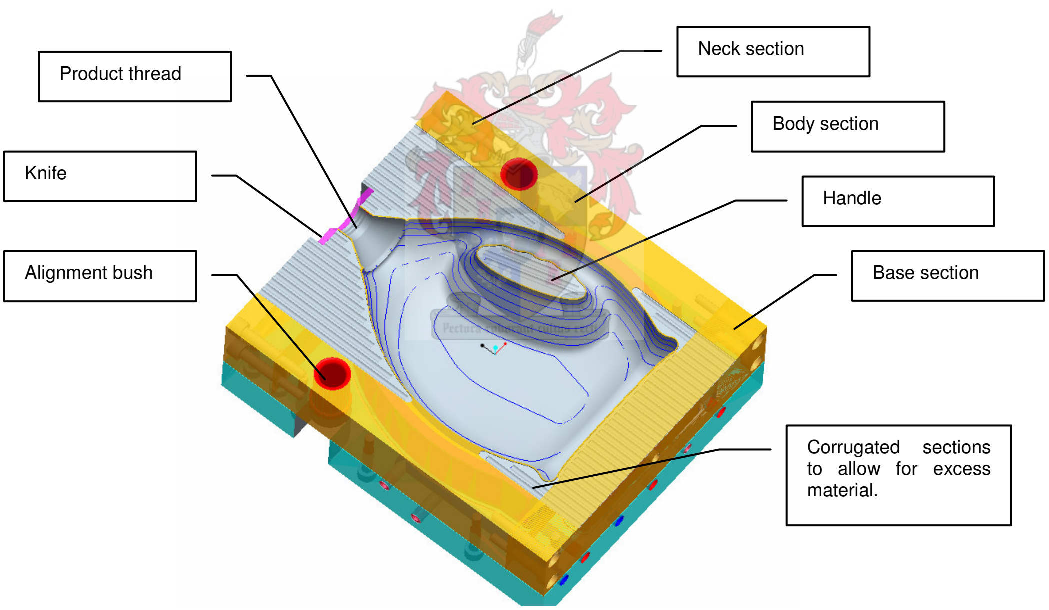


Figure 72: Front view of 2l bottle mould.

The design of the base water cavity is straight forward, since the base is a simple, nearly flat shape. The base was hollowed out and an insert was designed to ensure that the water flows in a 2 mm film over the part of the cavity which is closest to the base.

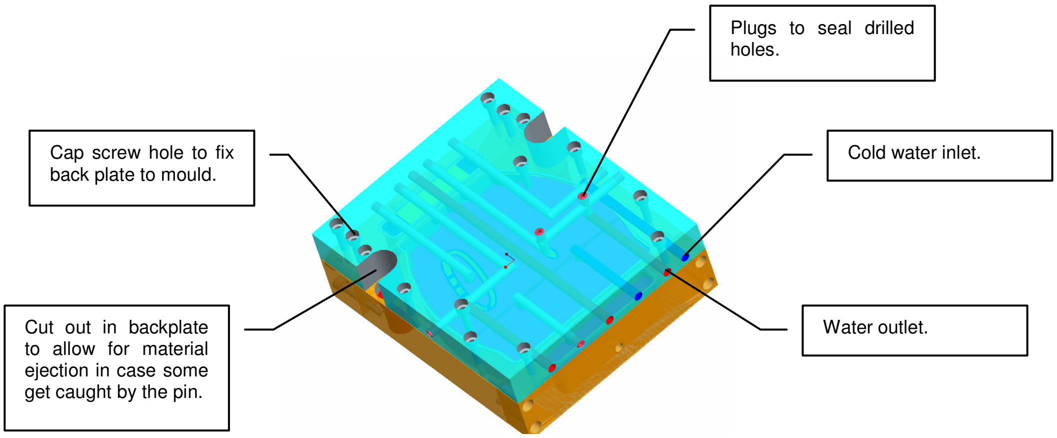


Figure 73: Rear view of 2l bottle mould.

The base has only one inlet and outlet for the water. The inlet is as shown in Figure 74 and the outlet goes into the back plate, from where the water is channelled to the body cavity. This is done to increase the water flow in the body cavity. The temperature of the water flowing through the base cavity does not increase significantly, thus the increased water flow serves to improve the cooling in the body section.

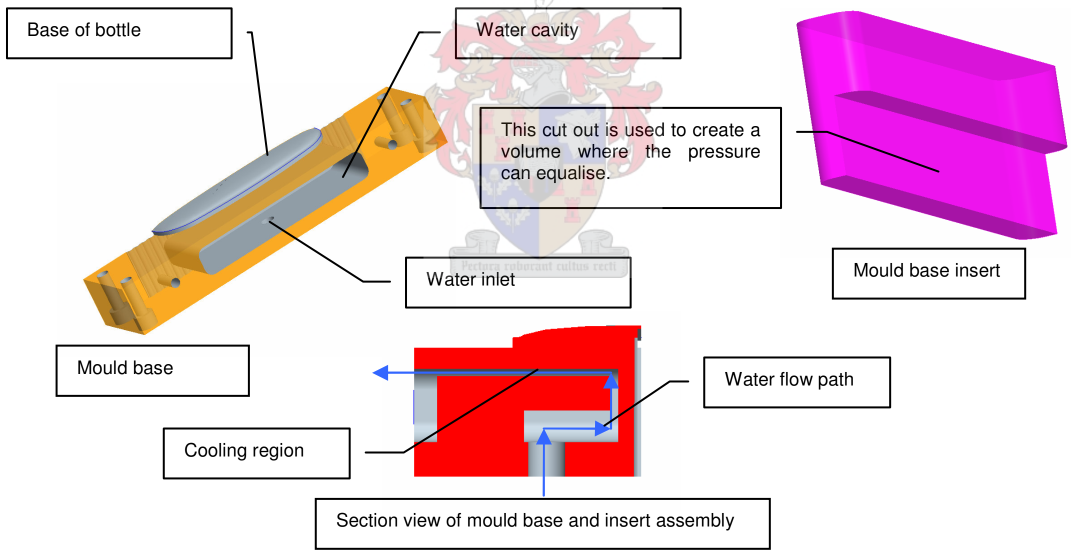


Figure 74: Proposed mould base and insert.

A major challenge when using conformal cooling, is to ensure that the water flow as fast and as uniform as possible over the total cooling area. With a large cavity it is often difficult to achieve high velocity flow since the water supply connection fittings are small (effective diameter of 5 mm in this particular case). In an attempt to minimize this restriction, the outflow from the base and neck combined with an additional inlet from the water mains is used to supply the body cavity with cooling water. In doing so, the water flow in the body increased three fold.

The design was started with first looking at all the critical areas of the product. These are the areas which will have the thickest plastic. The regions of concern are the handle and the tapering section of the neck.

It is also important to remember that the handle has a shutoff which must be cooled and supported structurally. The sharpness of the cutting edge will determine the forces exerted on the mould in that region when the plastic is pinched off. To overcome this problem a vertical wall following the cutting edge is left in the back. The cutting forces are conveyed via this wall to the back plate.

After the initial design of the mould a stress analysis simulation was done. This was required to determine what the deformation of the mould would be during the blowing cycle of the bottle. The inflation pressure in blow moulding is 6 Bar, thus this was used in the simulation. The areas in contact with the back plate were taken as fixed. One of the simulation results is shown in Figure 75.

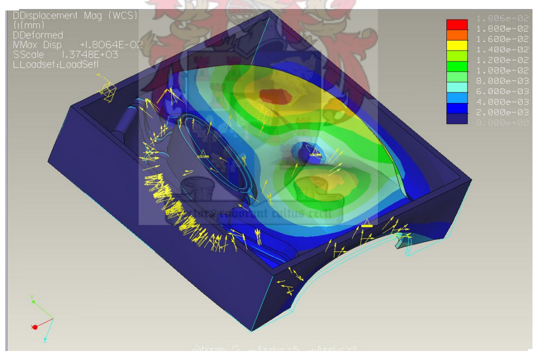


Figure 75: Result from FEA simulation.

In the initial simulation it was clear that there is a significant deflection of the body part of the mould and it was decided to add a support feature to the back of the mould. This feature had to be supportive of the mould cavity, yet it had to be small to reduce its influence on the flow of the cooling water as much as possible. According to the simulation a deflection of 18µm can be expected in the region coloured red. This is down from 50µm in the case of no support.

The final design of the mould can be seen in Figure 76 and it is clear that the design of the cooling cavity is not just an offset from the internal cavity, but is stepped with flat areas. This is the result achieved with the manual modelling of the surface offset.

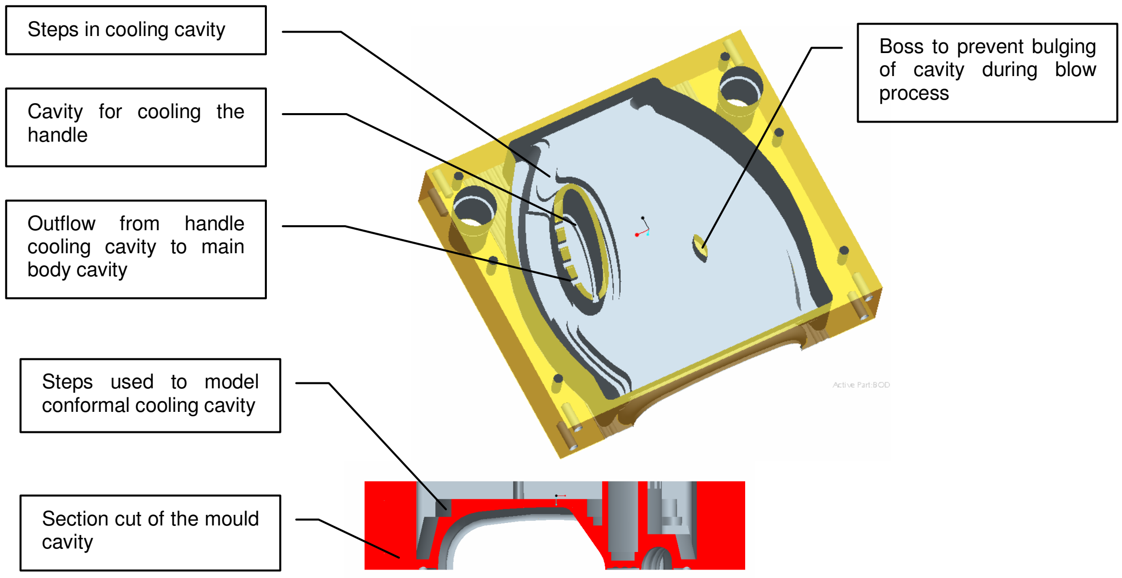


Figure 76: Cooling cavity of the body section of the mould.

A space of 2 mm was left between the mould and the mould insert. This ensures that a uniform film of water will flow over the mould back (Figure 77).

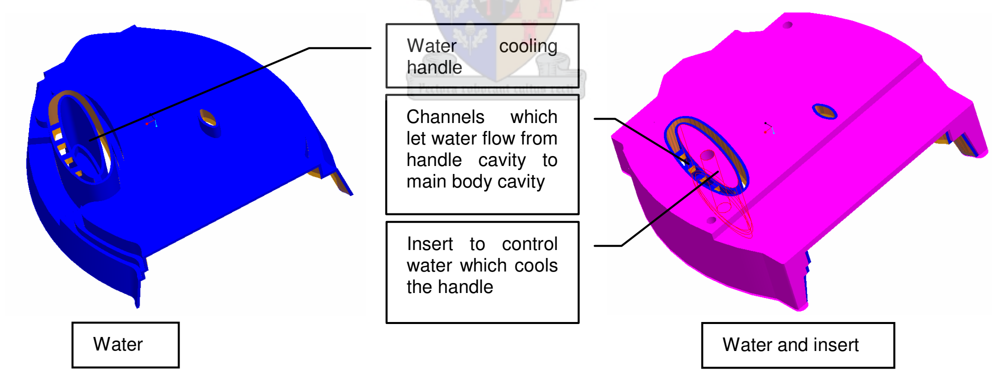


Figure 77: Body water and insert.

As for the base, the design of the cooling in the neck was relatively straight forward. The main concern was the holes necessary to hold the cut off knife. The cavity was modelled using standard cut functions. Fillets and rounds were used to create a smooth shape (Figure 78).

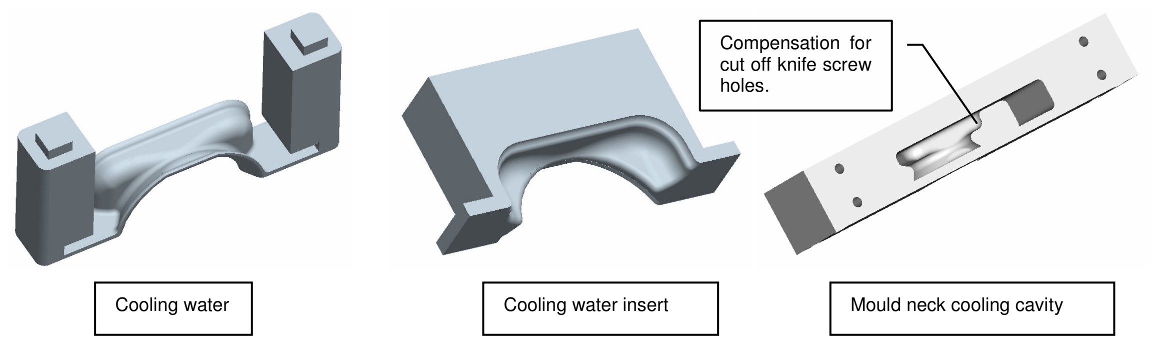


Figure 78: Mould neck cooling design.

Water flow simulation

CFD simulation showed that the base design had the desirable flow patterns. The flow patterns are shown in Figure 79 and it is clear that the colour distribution (which represents the flow velocity) is uniform. The factor causing the somewhat unequal flow is the placement of the outlet. The layout of the other channels in the back plate made it impossible to place the water outflow in the centre.

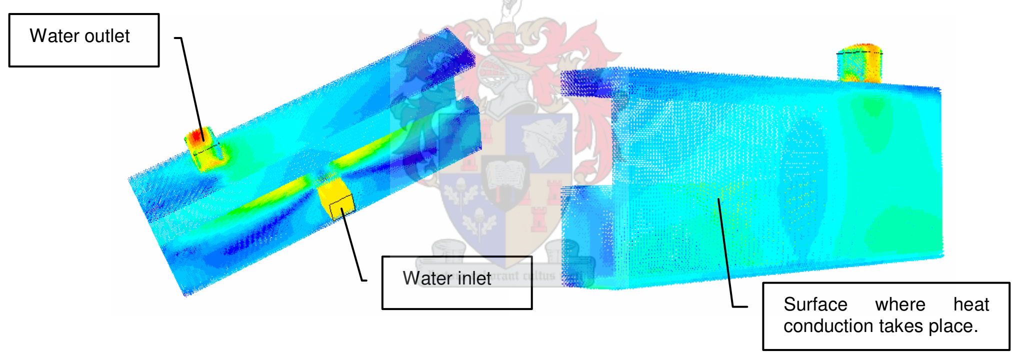


Figure 79: Flow velocity spread in the mould base.

The design of the water flow path for the body was more challenging because of the handle in the bottle. The major problem was to cool the handle shut-off area uniformly without disrupting the rest of the water flow in the cavity. This was done through the water, used to cool the neck. This water was channelled to the centre of the handle cooling cavity and the water then exits through the slots cut in the side of the support structure. The placement of the slots was done in such a way that their outflow complimented the flow in areas not sufficiently reached by the inflows from the other inlets (Figure 80).

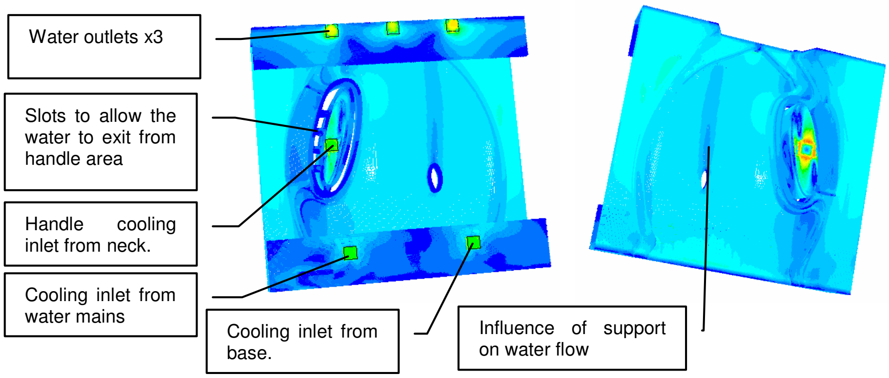


Figure 80: Flow velocity spread in the mould body cavity.

The design of the neck cooling cavity is straight forward as in the case of the base, because the area to be cooled is relatively small. There are areas of high velocity as well as areas of low velocity. The areas of velocity extremities (high and low) are relatively small. Therefore the influence of these areas is of little significance (Figure 81).

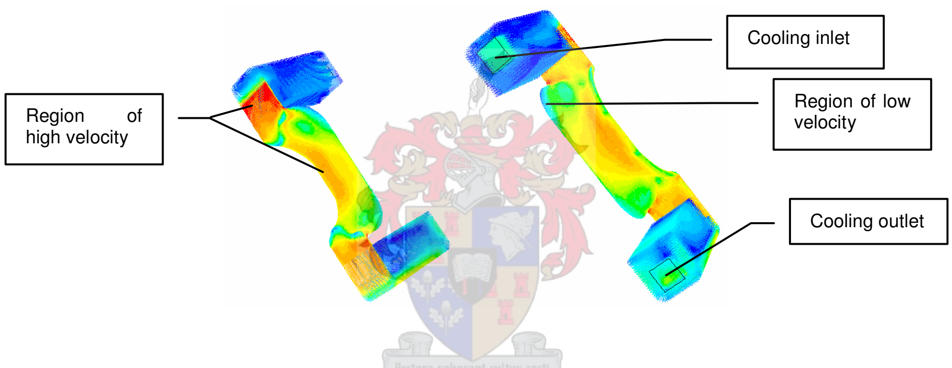


Figure 81: Water flow velocity spread in the mould neck cavity.

5.3 Case study 3

This case study involved the complete design chain as well as the manufacturing and testing of a mould. Simulations were done to compare the proposed design with the original design. Cycle time improvement simulations were then done using the code in Appendix A, this showed that a theoretical cycle time improvement of 33% is possible. With this information in hand, the proposed mould was designed, manufactured and a comparative experiment conducted to compare it with the original. A summary of the results from the experiment as well as the results from the cycle time prediction are given below. The complete case study is attached in Appendix D.

5.3.1 Cycle time improvement prediction

The shape of the bottle is such that the thickest part of the bottle is cooled by the part of the mould with the worst cooling. This area therefore governs the cooling cycle time and its parameters where used in the cycle time prediction.

The prediction showed that the use of conformal cooling will improve the cycle time by about 33.33% when compared to the original design. The product temperature at 18 s and 12 s respectively for the conventionally and conformal cooled mould are shown in Table 3. Graphs of the values were plotted and show the relation between the temperatures in the conformal and conventionally cooled mould (Figure 82).

	Cycle Time (seconds)					
	12	14	16	18	20	22
Neck section of conformal cooled mould (K)	302.1741	298.3022	295.328	293.0699	291.3623	290.0743
Neck Section of original mould (K)	312.4549	308.2743	304.8165	301.9701	299.6214	297.6754

Table 3: Product Temperatures.

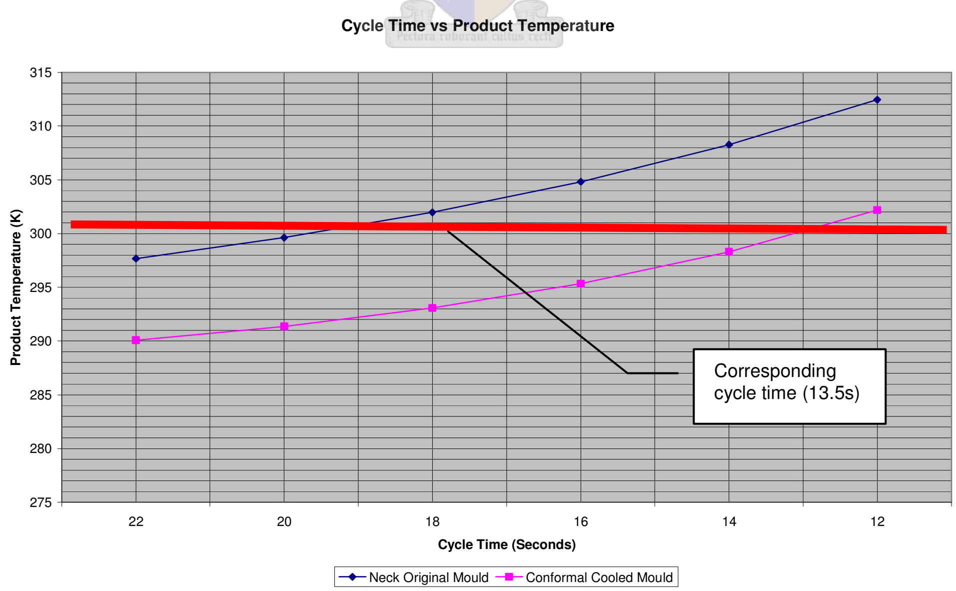


Figure 82: Theoretical cycle time prediction.

5.3.2 Design of experiment

After studying the existing mould in conjunction with the specifics of the blow moulding process, the factors that effect the cooling of a mould were identified as follows: Cross section thickness of mould (between plastic and water); Mould material; Water temperature; Water flow; Product mass; Type of plastic; Inflation air temperature; Cycle time; Inflation air pressure

5.3.3 Variables

The factors discussed above are not all controllable in the environment the experiment takes place. The factors that are controllable are:

- Water flow
- Product Mass
- Cycle time

All of the other factors are fixed for the experiment.

The cooling water temperature for the water at the factory where the experiment was conducted is fixed at 11 °C due to the capacity of the water chillers. For this experiment water temperature must be measured in order to make statistical correlations. The type of plastic used is predetermined since the product is made from Polypropylene (PP).

The output of the experiment was the product temperature (˚C) measured with an infrared camera. The brim fill volume was measured using water and a scale and a 3D tolerance check was done using a Coordinate Measuring Machine (CMM).

5.3.4 Factorial design of experiments

Different types of approaches to design experiments were researched (Taguchi, Fractional factorial, Factorial), and the decision was to do a full factorial experiment. A full factorial experiment is more appropriate to this application, because this was a small experiment with few variables. The other approaches are more suited to large experiments with many variables.

The purpose of the Taguchi approach is to lower the number of experiments. The total number of experiments worked out to be 45 for the full factorial approach. Since 45 experiments are not too many and time would allow it, a full factorial was designed.

Room was left in the experiment to do more tests if there was time left on the day of testing. These tests are to let the water flow unmeasured (full open) through the mould while the cycle time is reduced to a point where no more good bottles are produced. Table 4 shows all the controllable factors with selected levels of each and Table 5 shows the number of experimental runs with all the variables.

	Units	Level 1	Level 2	Level 3	Level 4	Level 5
CWV/H	l/h	150	190	250	Full open	
PT	mm	5	6	7	8	9
CT	sec	16	14	12	10	8

Table 4: Selected levels for the factors.

EN	CWV/H	PT	CT	EN	CWV/H	PT	CT
1	150	6	16	24	190	8	14
2	150	7	16	25	190	9	14
3	150	8	16	26	150	9	14
4	150	9	16	27	150	8	14
5	150	5	16	28	150	7	14
6	190	9	16	29	150	6	14
7	190	8	16	30	150	5	14
8	190	7	16	31	150	5	12
9	190	6	16	32	150	6	12
10	190	5	16	33	150	7	12
11	250	5	16	34	150	8	12
12	250	6	16	35	150	9	12
13	250	7	16	36	190	9	12
14	250	8	16	37	190	8	12
15	250	9	16	38	190	7	12
16	250	9	14	39	190	6	12
17	250	8	14	40	190	5	12
18	250	7	14	41	250	5	12
19	250	6	14	42	250	6	12
20	250	5	14	43	250	7	12
21	190	5	14	44	250	8	12
22	190	6	14	45	250	9	12
23	190	7	14				

EN – Experiment Number CWV/H – Cooling Water Volume / Hour

PT – Parison Thickness CT – Cycle Time

Table 5: Number of experiments with all levels.

5.3.5 Experimental set-up

In order to measure the controllable factors described in the experimental design above, the following measuring equipment was used:

- Flow meters were used to measure the water flow.

- The product mass is set with the blow moulding machine's controller.
- The product temperature was measured by an infrared camera.
- The cycle time is set and measured by the blow moulding machine's controller.
- The thermocouples were placed on specific points in both moulds and a data logger was used to log the temperatures at 0.5 second intervals.

Thermocouples

The purpose of the thermocouples is to measure the temperature of the mould throughout the whole experiment. Some points were selected by means of inspection of the Mandoza bottle. Mostly thicker areas on the bottle were selected since it is at these positions that defects are most likely to occur.

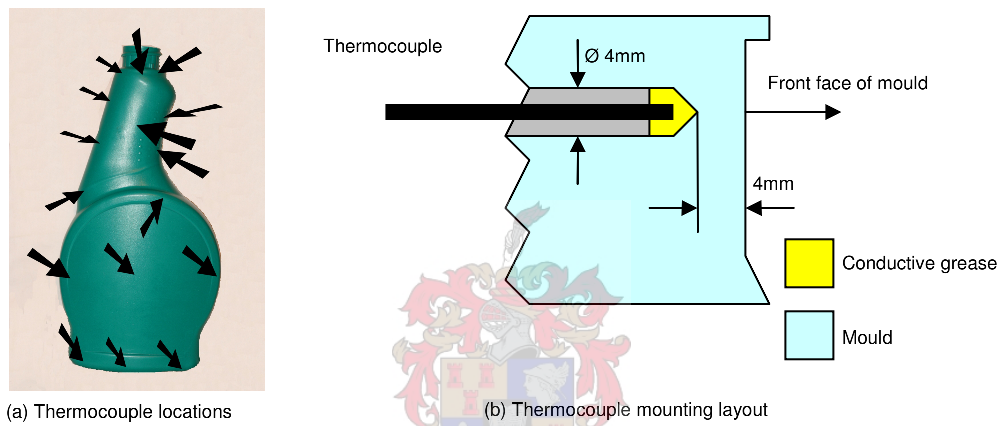


Figure 83: Thermocouple layout.

The locations are pointed out in Figure 83(a).These areas were identified on both the new mould and original mould. Holes were drilled at these points, from the back to a depth of 4 mm from the cavity of the moulds. Figure 83(b) illustrates how this was done.

Infrared camera

An infrared (IR) camera was used to get the bulk temperature [[32], [33]] of the bottles after ejection. An IR image of a bottle is shown in Figure 84. The temperature distribution in the plastic is clearly visible. Plastic is transparent to IR, thus the temperature given by an IR image is the bulk and not the surface temperature of the component. It has some advantages that you have an idea of what is the total temperature of the plastic, but it does not give an indication of the surface temperature of the product. This is a problem, since plastic with its low heat transfer coefficient has a very steep temperature gradient over a cross section of the wall. The accuracy of the IR camera is ±2 °C or 2%, whichever is greater. Refer to Appendix D for a full discussion.

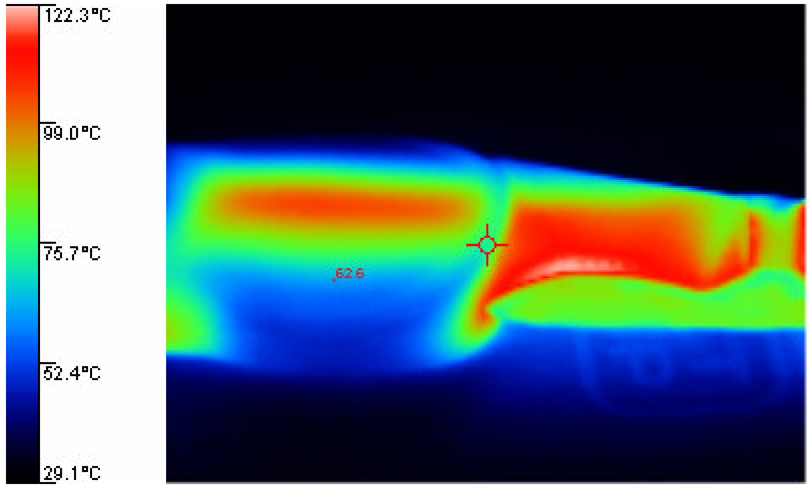


Figure 84: IR photo of Mandoza bottle just after ejection.

5.3.6 Discussion of results

In an effort to compare the capabilities of the two moulds as well as the influence of the different variables on the production process, statistical methods are used. In this comparison the influence of the mould design, water flow rate, parison thickness and cycle time are analysed. The comparison shows what the main differences between the two moulds are and how different variables influence them. The data analysis methods used are Analysis of Variance (ANOVA) and inspection.

<u>Brim fill volume</u>

In order to compare the quality of the bottles from the moulds, the brimful volume of the bottles was compared. The reasoning is that the cavity volume of the two moulds is identical and that the difference in the brim fill volume will be the result of the distortion of the bottle. In practice a brimful volume deviation of ±1% is acceptable, but this experiment aims to compare the cooling design of the two moulds. We are therefore more interested in the differences in brimful volume between the bottles, produced at the same production parameters, than the deviation of the bottles from the production specification. The theoretical volume of the bottle was determined by taking the volume of the CAD model and subtracting volume of plastic in the product. The results can be seen in Table 6, where the experimental parameters are also shown. It is clear that the redesigned (rpd) mould produced bottles with a brimful volume much closer to the theoretical, than that produced in the original mould (cinq).

Experiment #	Cycle Time (s)	Parison Thickness (mm)	Water Flow (l/h)	Mould Design	Volume (g)
4a	16	9	150	rpd	-4.89
4b	16	9	150	cinq	-23.78
5a	16	5	150	rpd	6.44
5b	16	5	150	cinq	8.67
11a	16	5	250	rpd	8.33
11b	16	5	250	cinq	-5.56
15a	16	9	250	rpd	-9.78
15b	16	9	250	cinq	-21.67
31a	12	5	150	rpd	0.56
31b	12	5	150	cinq	-12
35a	12	9	150	rpd	-18.89
35b	12	9	150	cinq	-30.78
41a	12	5	250	rpd	0.33
41b	12	5	250	cinq	-13.67
45a	12	9	250	rpd	-25.89
45b	12	9	250	cinq	-34.78

Table 6: Brimful volume differences.

ANOVA [[34], [35]] was used to compare the two moulds and to determine which parameters had the biggest influence on the volume of the bottle. The p values, as shown in Table 7, indicate which factor has an influence on the volume of the bottle. A value of 5% was predefined and if the calculated value is less than 5%, that factor does have a significant influence. If the calculated value is larger than the predetermined value (5%) then this variable does not have a significant influence.

When the values in the table are examined it is clear that there are 3 factors which played a significant role in the volume of the bottle during the tests. These being the cycle time, parison thickness and the mould design.

The influence of the cycle time is obvious, since panelling is a well known phenomenon during blow moulding when the cooling cycle is to short. The production manager will normally set the cooling cycle conservatively long to ensure only good bottles are produced.

In production the cycle time is actually governed by the quality of product. In the experiment the cycle time was changed to a number of predetermined values and the quality of the bottle checked. This different approach in the experiment was used because it showed the effect of cycle time on quality. And from this, conclusions are made to determine how the cycle time can be improved.

The influence of the parison thickness is also significant. If the parison thickness increases, more plastic has to be cooled. This is the same effect as shortening the cooling cycle. There is also more plastic in the product which brings with it more internal stresses. This causes the additional deformation of the product.

	SS	Degr. of Freedom	MS	F	p
Intercept	1966.036	1	1966.036	71.79361	0.000376
Cycle Time	539.168	1	539.168	19.68878	0.006782
Parison Thickness	1671.992	1	1671.992	61.05604	0.000550
Water Flow	49.070	1	49.070	1.79189	0.238335
Mould Design	503.778	1	503.778	18.39643	0.007796
Cycle T*Parison T	3.572	1	3.572	0.13044	0.732733
Cycle T*Water T	0.308	1	0.308	0.01125	0.919661
Parison T*Water T	0.013	1	0.013	0.00048	0.983317
Cycle T*Mould	1.501	1	1.501	0.05480	0.824198
Parison T*Mould	11.122	1	11.122	0.40615	0.551964
Water T*Mould	3.572	1	3.572	0.13044	0.732733
Error	136.923	5	27.385		

Table 7: Results from ANOVA showing the relationship between variables.

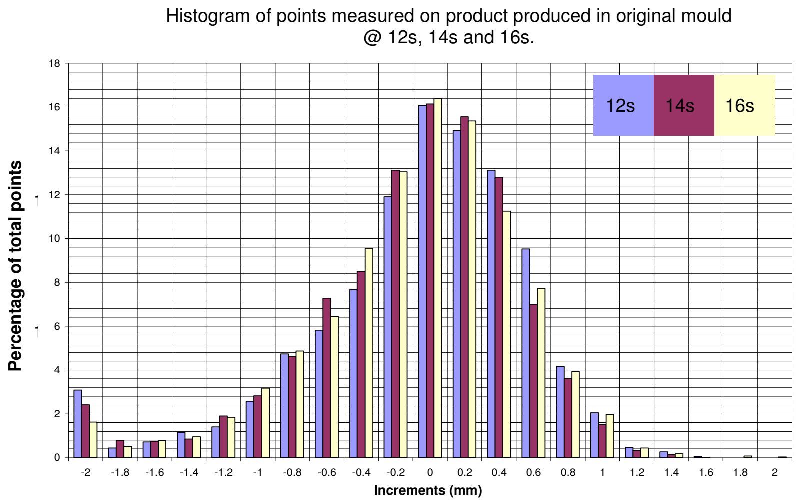
ANOVA shows that a combination of theses variables does not have a significant influence (Table 7).

The ANOVA shows that the mould's cooling design does have a significant influence on the quality of the bottle (Table 7). This emphasises why it is necessary to look critically at the design of the cooling channels of the mould.

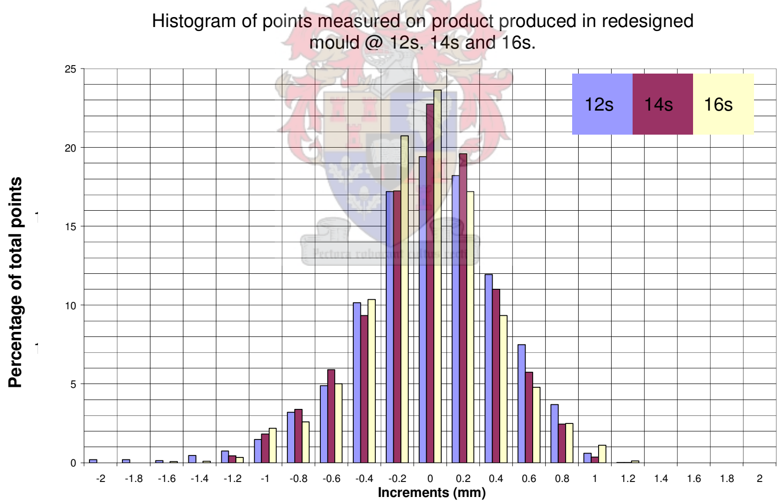
<u>Comparison of bottle vs CAD model</u>

The second method used, to determine the quality of the bottles, was a comparison of the actual bottles with the CAD model of the mould cavity. The measurements were done on a coordinate measurement machine (CMM). The CMM was programmed to measure about 385 points on each bottle. The program made it possible to measure similar points on each bottle.

The data were arranged in histograms, showing the percentage of points in each error category. In Figure 85a a comparison of the measured points on bottles, which were produced at different cycle speeds, can be seen. It is clear that there is a number of points which have errors of -2 mm and larger. The minus sign indicate that the point measured on the actual bottle is deeper than the same point on the CAD model. This indicates that part of the bottle is distorted inwards. It also indicates a possible brim fill volume problem.



(a) Bottles produced in original mould.



(b) Bottles produced in redesigned mould.

Figure 85: Histogram of measured points.

The same was done for the bottles produced from the mould designed by the RPD. In Figure 85b the comparison between the points, measured on bottles produced at different cycle times, can be seen. There are some points which are in the -2 mm region, but this is less than 0.5% of the total and only for the bottles produced at 12 s.

In Figure 86 a comparison is made between the measurements of the bottles produced in the original mould and that produced in the RPD mould. It is clear that the bottles from the RPD mould show much less deviation from the CAD model, than the bottles from the original mould. The CAD model is, by default, the representation of the mould cavity.

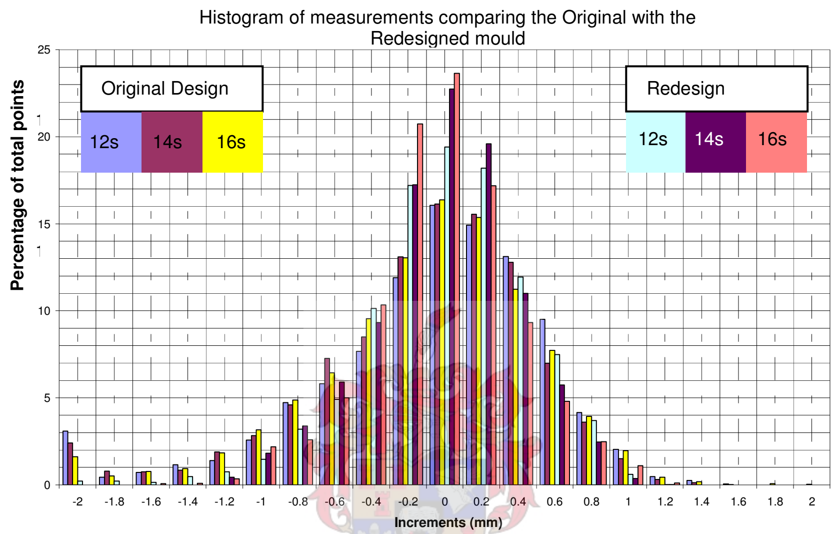
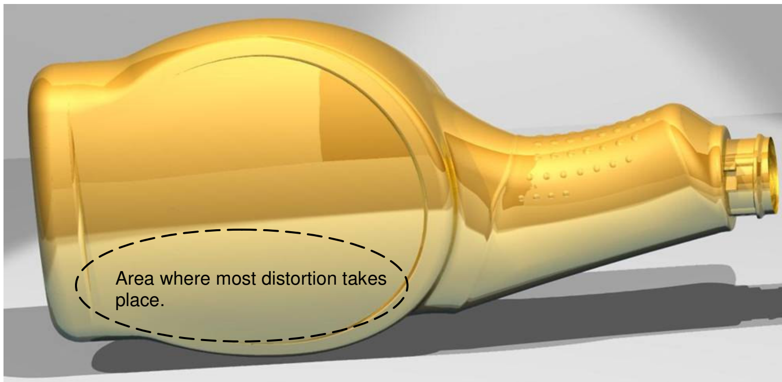
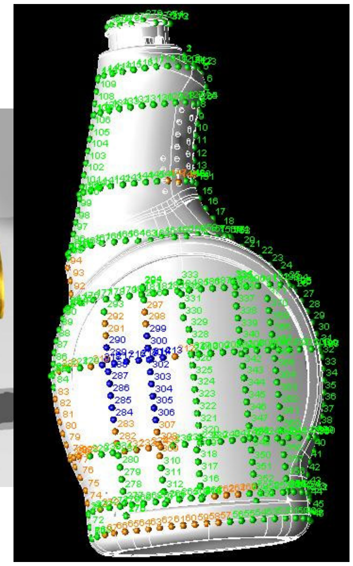


Figure 86: Comparative histogram of measured points.

There are certain regions on the bottles, which are more distorted than others. The side panels of the bottles tend to distort more, since it is large flattish areas, which have low strength characteristics by design (Figure 87(a)). The blue and brown dots in Figure 87 (b) give an indication of the other areas, where the bottles deviated from the CAD model.



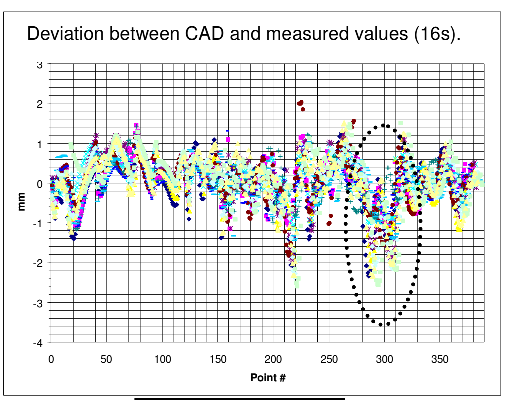
(a) CAD model of bottle



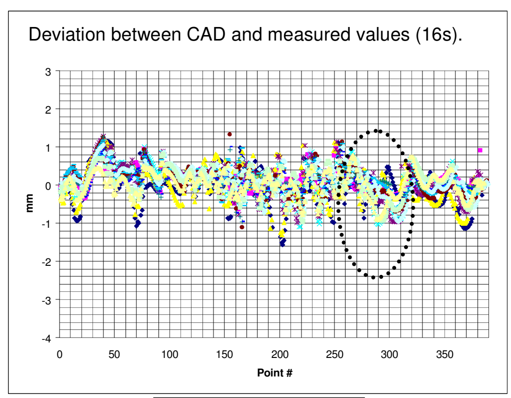
(b) Measured points locations

Figure 87: Indication of areas where the most distortion takes place.

The extent of the deformation can be illustrated further by comparing the graphs in Figure 88(a), Figure 89(a) and Figure 90(a). These figures are scatter plots of the total deviation between the CAD data and correlating measured points. The most deformation in all the cases was recorded in the region of point #280. The deviation became worse as the cycle time shortens. The values on the Y axis of each graph show the deviation from the CAD model in mm. If the value is negative, it is an indication that the measured point is deeper than the CAD model.



(a) Original design



(b) Redesign

Figure 88: Deviation between CAD and measured values at 16s.

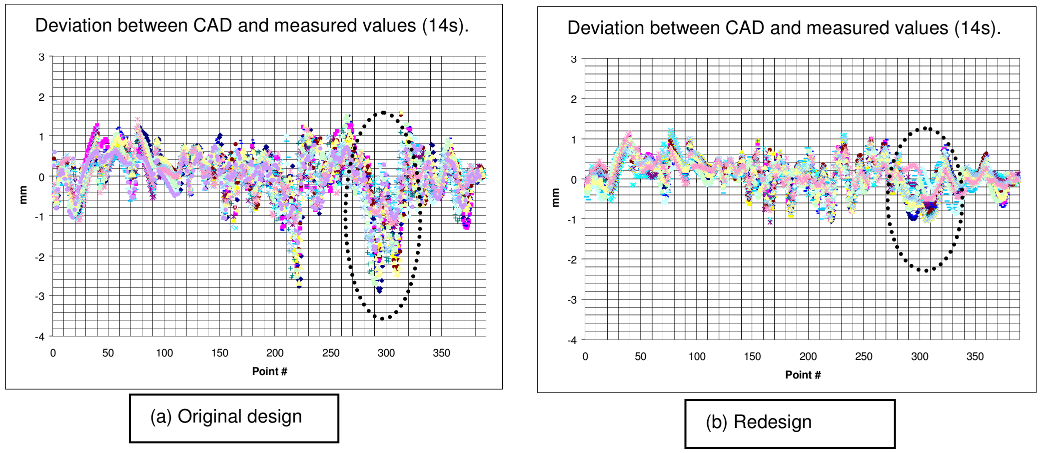


Figure 89: Deviation between CAD and measured values at 14s.

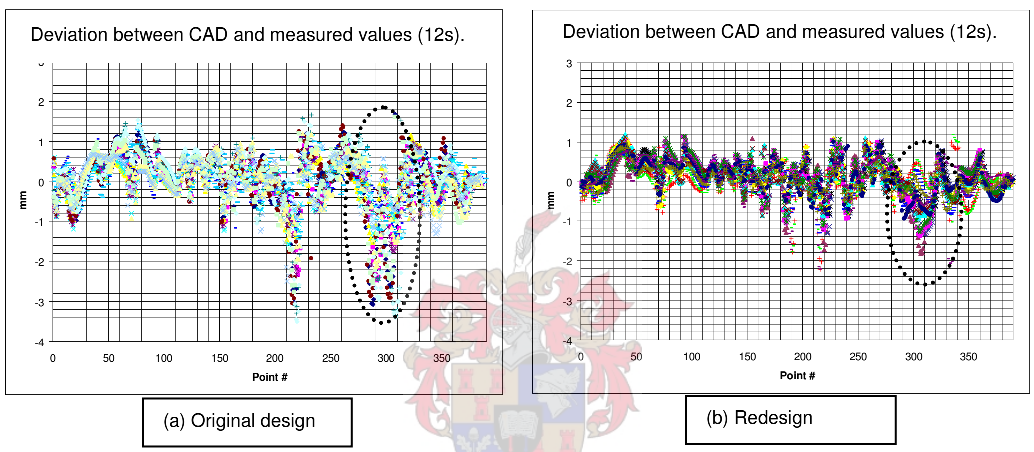


Figure 90: Deviation between CAD and measured values at 12s.

The measured data for the bottles, produced in the RPD mould, are plotted in the same way as that of the bottles produced in the original mould. The graphs can be seen (right hand side) in Figure 88(b), Figure 89(b) and Figure 90(b). It is clear that the bottles which were produced at cooling cycle times of 16 and 14 seconds have less deviation, especially in the region of point # 280, than those produced in the original mould. The deviation comparison of the bottles produced at a cooling cycle time of 12 s also indicates that the RPD mould produces bottles with less deviation from the CAD model than those produced in the original mould.

There is a clear indication that the RPD cooled mould has a better bottle surface than the original mould. The feature, which gives an indication of this, is the heat marks formed on the body of the bottle when a bottle is ejected at a high temperature. In Figure

91(a) to (d) is it very clear that the heat marks on the RPD bottles (right hand side) are much smaller than those on the bottles from the original mould (left hand side). The production parameters for these bottles can be seen in Table 5.

These heat mark differences do not give a quantative result, but do give a qualitative idea of the surface cooling which takes place in the mould.

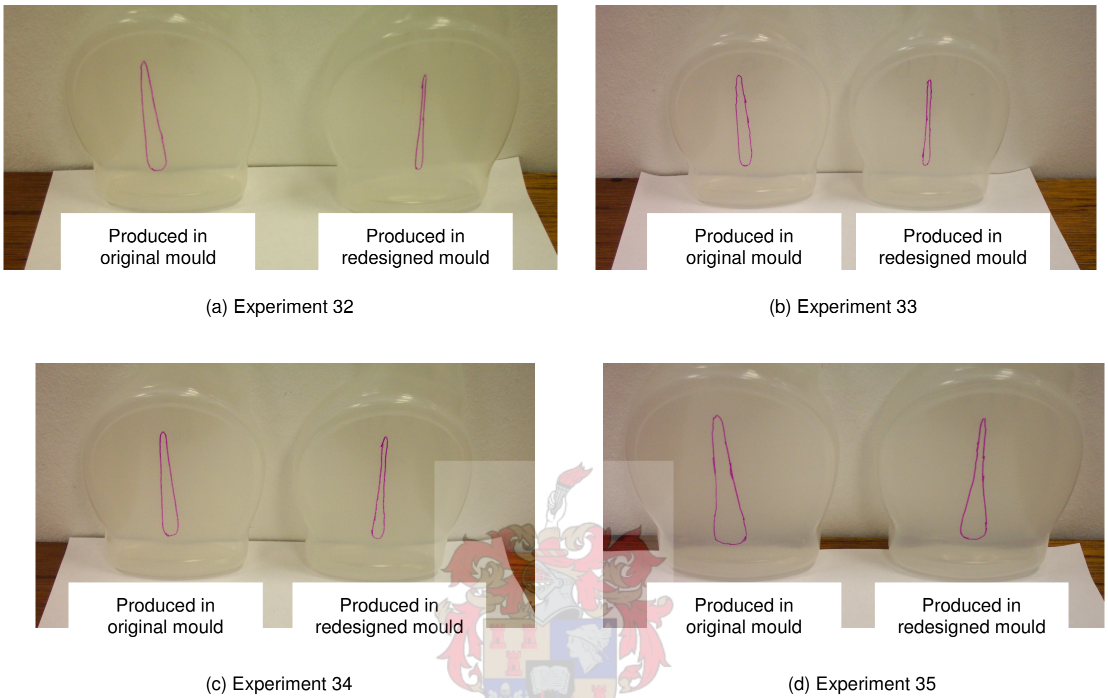


Figure 91: Heat marks marked in purple.

6. CONCLUSIONS AND RECOMMENDATIONS

Layer manufacturing is the future of mould making and if it is cleverly combined with conventional machining then toolmakers will produce very complex, high quality moulds with relative ease.

The utilisation of simulation tools demonstrates clearly how mould design changes can drastically influence the cooling parameters of a mould and therefore the reduction of cycle times.

The question is, what cycle time reduction is achieved? This can, in part, be answered by comparing the left hand graph in Figure 88(a) with the right hand graph in Figure 90(b). This will indicate that the bottles produced in the redesigned (with conformal cooling) mould, with a 12 s cooling cycle, are of the same or better quality than the bottles from the original (with conventional cooling) mould produced at 16 s. The total cooling cycle saving is 4 seconds, which is 25% of the total cycle time.

As a further comparison, Figure 92 shows that a bottle from the original mould (cooling cycle time of 16 s) differs more from the CAD model than the bottle produced from the redesigned mould (cooling cycle time of 12 s). The green line shows what happened to the bottle from the original mould, which was produced at the same parameters as the redesigned mould. It is very clear that the original mould produced a bottle with much bigger deviation than the redesigned mould.

This test provided ample evidence that the cooling design does have a big influence on the quality of the bottle. The improved design enables the production of bottles, with acceptable quality, at a cycle time reduced by 25% from the current cycle time. This improvement contributes directly to increased production capacity, without any capital expenditure. Since the price of the redesigned mould is the same as that of a conventional design.

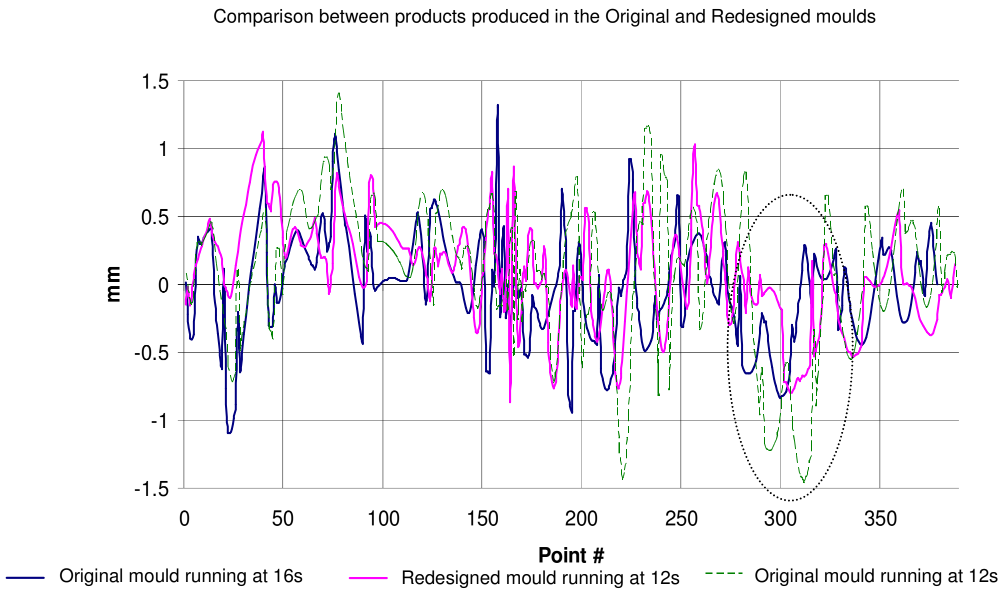


Figure 92 : Comparison between 39g bottle produced at 16s in CINQPLAST mould and 12s in RPD mould.

If the cycle time improvements are converted into monetary values then it becomes clear what saving will be achieved. If a production year of 320 days is assumed with production running 24 hours per day, then the extra available capacity on a single machine will be:

$$320days \times 24h \times 0.25_{improvement} = 1920h$$

If an hourly rate of R 500/h is assumed for such a machine, then the saving is R 960 000 per year. It can also be interpreted the other way around, for every 4 machines utilising this improvement, a fifth machine will be saved.

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APPENDIX A: VBA CODE FOR ONE-DIMENSIONAL HEAT FLOW

Appendix A: VBA Code for one-dimensional heat flow

```
Option Explicit
Public Qad(), TempMould(), TempPlastic() As Double

Sub Itterate()
Dim KMould, MouldThick, Area, TempAir As Double
Dim TempPlasticBegin, TimeSteps, CpAir, AirMass As Double
Dim Layers, KPlastic, HLug, PThick, PlasticMass, Cpp As Double
Dim MouldMass, CpMould, MouldClosed, OpenMould, R, TempCoolW As Double
Dim B, TempMouldBegin, PressAir As Double
Dim HeatAW, PlasticDensity, MouldDensity, PLayerThickness As Double
Dim MLayerThickness, L, ArrayLenght, AirVolume, t As Double
Dim j, fqad, BottleCount, n, k, RAir As Double

'Start temperature of the mould in Kelvin
TempMouldBegin = Worksheets("a").Cells(1, 2)
'Start temperature of the plastic in Kelvin
TempPlasticBegin = Worksheets("a").Cells(2, 2)
'Start temperature of Air in bottle
TempAir = Worksheets("a").Cells(4, 2)
'Air pressure in Pa
PressAir = Worksheets("a").Cells(32, 2)
'R value of air j/kg.K
RAir = Worksheets("a").Cells(33, 2)
'Temprature of cooling water in Kelvin
TempCoolW = Worksheets("a").Cells(3, 2)
'Heatflow rate from mould to water(w/(sqm*K))
HeatAW = Worksheets("a").Cells(5, 2)
'Plastic thickness (m)
PThick = Worksheets("a").Cells(8, 2)
'Plastic density
PlasticDensity = Worksheets("a").Cells(11, 2)
'Mould Density
MouldDensity = Worksheets("a").Cells(9, 2)
'Mould thickness (m)
MouldThick = Worksheets("a").Cells(29, 2)
'Number of layers in the mould excluding the water or air as a layer
Layers = Worksheets("a").Cells(28, 2)
'Plastic layer thickness
PLayerThickness = PThick / Layers
'Mould layer thickness
MLayerThickness = MouldThick / Layers
'Conductivity of mould material
KMould = Worksheets("a").Cells(30, 2)
'Conductivity of Plastic material
KPlastic = Worksheets("a").Cells(24, 2)
'h van die lug w/sqmK
HLug = Worksheets("a").Cells(34, 2)
'Lenght of mould speciman (m)
L = Worksheets("a").Cells(35, 2)
'Width of mould speciman (m)
B = Worksheets("a").Cells(36, 2)
'Area of mould
Area = L * B
'Volume of air kg
AirVolume = (22 / 7) * (B / 2) ^ 2 * L
'Mass of air in container
AirMass = (PressAir * AirVolume) / (RAir * TempAir)
'Heat capacity of Plastic (J/kgK)
Cpp = Worksheets("a").Cells(12, 2)
'Heat cacpacity of mould material (J/kgK)
CpMould = Worksheets("a").Cells(10, 2)
'Heat capacity of the air J/kgK
CpAir = Worksheets("a").Cells(37, 2)
'The size of the itteration time steps
TimeSteps = Worksheets("a").Cells(25, 2)
'Closed mould time duration (s)
```

```
MouldClosed = Worksheets("a").Cells(38, 2)
'Open Mould time duration (s)
OpenMould = Worksheets("a").Cells(39, 2)
'Number of bottels to be simulated
BottleCount = Worksheets("a").Cells(40, 2)
' Set r equal to 1
R = 1
'Mass of plastic in the mould
PlasticMass = Area * PThick * PlasticDensity
'Mass of the metal in the mould
MouldMass = Area * MouldThick * MouldDensity
'Determine the lenght of the arrays
ArrayLenght = ((MouldClosed + OpenMould) * BottleCount) / TimeSteps
'Fill matrix Qab with 0

ReDim Qad(1 To ArrayLenght + 1, 1 To Layers * 2 + 1)
ReDim TempPlastic(1 To ArrayLenght + 2, 1 To Layers + 1)
ReDim TempMould(1 To ArrayLenght + 2, 1 To Layers + 1)

For fqad = 1 To Layers * 2 + 1 Step 1

Qad(1, fqad) = 0

Next fqad

'Fill matrix TempPlastic with TempPlasticBegin
For j = 1 To Layers + 1

TempPlastic(1, j) = TempPlasticBegin

Next j

'Fill Matrix TempMould with TempMouldBegin
For j = 1 To Layers + 1

TempMould(1, j) = TempMouldBegin

Next j

'Set temprature of air in TempPlastic(1) array
'TempPlastic(r,1)=TempAir

'Number of bottles per itterated
B = 0

'Mould
'(KMould,MouldThick,TempMould,Area,TempAir,TempPlasticBegin,TimeSteps,CpAir,Qad,AirMass,Layers,KPlastic,HLug,PThick,PlasticMass,Cpp,MouldMass,CpMould,MouldClosed,OpenMould,r,TempCoolW,BottleCount,b,TempPlastic)

'End Sub
'---------------------------------------------------------------------------

'Sub Mould()
'(KMould, MouldThick, TempMould, Area, TempAir, TempPlasticBegin, TimeSteps, CpAir, Qad, AirMass, Layers, KPlastic, HLug, PThick, PlasticMass, Cpp, MouldMass, CpMould, MouldClosed, OpenMould, r, TempCoolW, BottleCount, B, TempPlastic)

For B = 1 To BottleCount Step 1

   'Fill Plastic matrix first line for new itteration with begin tempratures
      For j = 1 To Layers + 1 Step 1

       TempPlastic(R, j) = TempPlasticBegin

       Next j
```

```
'Set Air temp for Air in TempPlastic (1) array
TempPlastic(R, 1) = TempAir

'loop to do the itterations for the closed mould
For t = 0 To MouldClosed Step TimeSteps

   'Insert water temp into Mould temp
   TempMould(R, Layers + 1) = TempCoolW

   'Calculate the heat movement to the Air
   Qad(R, 1) = (Area * HLug) * (TempPlastic(R, 1) - TempPlastic(R, 2))

   TempPlastic(R + 1, 1) = TempPlastic(R, 1) + (TimeSteps / (AirMass * CpAir)) * (0 - Qad(R, 1))
      'Calculate the heat movement in the plastic layers
      For j = 2 To Layers Step 1

        Qad(R, j) = KPlastic * Area * _
          ((TempPlastic(R, j) - TempPlastic(R, j + 1)) / (PThick / (Layers - 1)))

        TempPlastic(R + 1, j) = TempPlastic(R, j) + TimeSteps / _
          ((PlasticMass / (Layers)) * Cpp) * (Qad(R, j - 1) - Qad(R, j))

      Next j
   'Calculate the Heatflow in the intersection between plastic and mould

   Qad(R, Layers + 1) = (TempPlastic(R, Layers + 1) - TempMould(R, 1)) / _
     ((((PThick / (Layers)) / 2 / (KPlastic * Area))) + _
     (((MouldThick / (Layers)) / 2 / (KMould * Area))))

   TempPlastic(R + 1, Layers + 1) = TempPlastic(R, Layers + 1) + _
     (TimeSteps / ((PlasticMass / (Layers)) * Cpp)) * (Qad(R, Layers) - Qad(R, Layers + 1))

   'Calculate the Heatflow in the mould

      For j = Layers + 2 To Layers * 2 + 1 Step 1

        k = j - (Layers + 1) 'The mould temperatures start from 1 to Layers

        Qad(R, j) = KMould * Area * _
          ((TempMould(R, k) - TempMould(R, k + 1)) / (MouldThick / (Layers - 1)))



        TempMould(R + 1, k) = TempMould(R, k) + TimeSteps / _
          ((MouldMass / (Layers)) * CpMould) * (Qad(R, j - 1) - Qad(R, j))

      Next j


   R = R + 1

Next t
'---------------------------------------------------------
 ' Calculate heatflow for open Mould
 R = R - 1
For t = 0 To OpenMould Step TimeSteps

   ' Set temperatures of mould to be the same as suround air
     For n = 1 To Layers + 1 Step 1

      TempPlastic(R, n) = TempAir

      Next n
     'Set temperatures of the water in the mould matrix to that of water
   TempMould(R, Layers + 1) = TempCoolW
```

```
        Qad(R, Layers + 1) = (Area * HLug) * (TempPlastic(R, Layers + 1) - TempMould(R, 1))

        'calculate the cooling of the mould while it is open

         For j = Layers + 2 To Layers * 2 + 1 Step 1

           k = j - (Layers + 1) 'The mould temperatures start from 1 to Layers

           Qad(R, j) = KMould * Area * _
             ((TempMould(R, k) - TempMould(R, k + 1)) / (MouldThick / (Layers - 1)))



           TempMould(R + 1, k) = TempMould(R, k) + TimeSteps / _
             ((MouldMass / (Layers)) * CpMould) * (Qad(R, j - 1) - Qad(R, j))
         Next j

      R = R + 1


   Next t


      For j = 1 To Layers * 2 + 1 Step 1

      Qad(R, j) = 0
      Next j

   TempMould(R, Layers + 1) = TempCoolW

Next B
Call plot(Qad, TempPlastic, TempMould, ArrayLenght, Layers)
End Sub
Private Sub plot(Qad, TempPlastic, TempMould, ArrayLenght, Layers)

Dim counter, SkipLines, j, L As Double
SkipLines = Worksheets("a").Cells(31, 2)
j = 1
For counter = 1 To ArrayLenght Step SkipLines
   'write data to sheet
   For L = 1 To Layers * 2 + 1

   Worksheets("Qad").Cells(j, L) = Qad(counter, L)

   Next L
   'write data to sheet
   For L = 1 To Layers + 1

   Worksheets("TempMould").Cells(j, L) = TempMould(counter, L)

   Next L
   'write data to sheet
   For L = 1 To Layers + 1

   Worksheets("TempPlastic").Cells(j, L) = TempPlastic(counter, L)

   Next L
   j = j + 1
Next counter
   End Sub
```

APPENDIX B: CASE STUDY 1 (NESTLÉ CONTAINER)

Appendix B: Case study 1 (Nestlé container)

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1.1 Introduction

The first mould investigated was a mould which is used to produce the bottles for Nestlé. The container is used for powder products such as Milo, Hot chocolate and Nesquik. The cycle time of the original mould was about 16s

The mould was designed in software which was developed for the manufacturing of blow moulds and not for layer manufacturing or simulation purposes.

1.2 File problems

The original design was done in a software package known as Cimatron. Cimatron is mainly a surfacing package which was developed specifically for designing and machining of moulds [29]. According to Cimatron's website, the data translators used in the package can handle any type of data which it is presented with. Experience showed Cimatron files are not useable with other packages although it may be able to handle files created in other packages such as Pro Engineer, Unigraphics, Catia, PowerShape, Inventor, SolidEdge, etc. One possible explanation for the problems is how the users use the program and the internal tolerances of the program. Then there is also the question of the accuracy of the data translators used to convert the data.

The original design can be seen in Figure 1. It is clear that this is not a solid CAD model which can be used for simulations or layer manufacturing. For both layer manufacturing and simulation purposes a solid model is needed and this model is a combination of wire frame and surface modelling. The cooling channels are not shown in this drawing, but the original models showed the start and end of the cooling channels as wire frame circles.

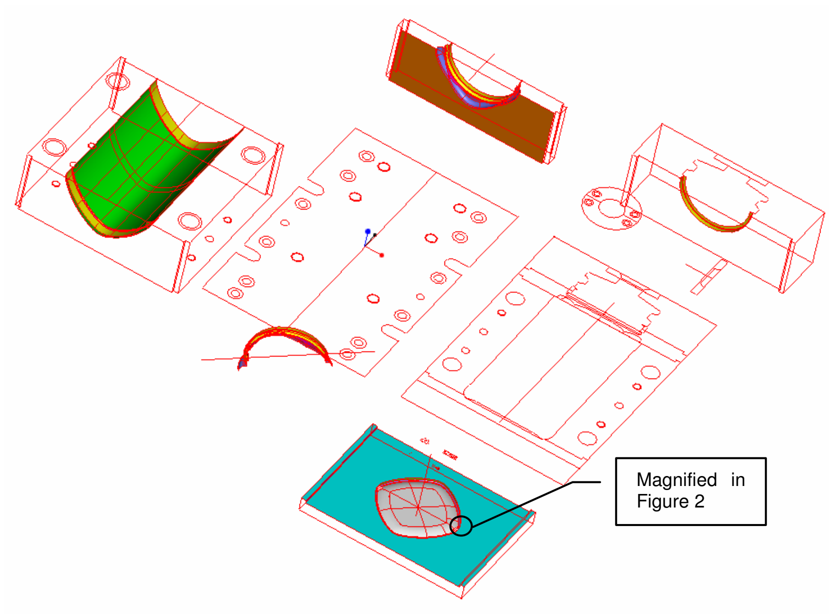


Figure 1: IGES Model and drawing combination as received for experimental purposes.

The major problem with the CAD model is that the surface edges do not match up. In Figure 2 there is a magnified view, of a surface boundary of the IGES file shown in Figure 1, showing a difference of at least 0.5mm between the edges. The accuracy normally used by a CAD package is in the region of 0.01mm and packages such as Pro Engineer and simulation packages use much tighter tolerances, thus if a CAD model is produced with a loose tolerance, then a CAD package with tight tolerance will not be able to use that file without significant repairs being needed. And that would also be the reason why a package like Cimatron can read in other data formats without problems.

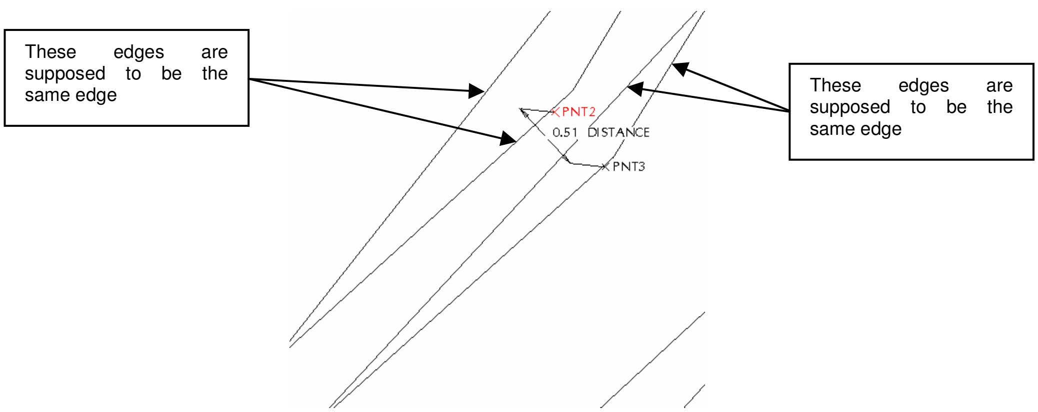


Figure 2: Surface mismatch.

These gaps are however irrelevant when the file is used for machining purposes, since the cutter path would not be influenced significantly by such a mismatch.

All these problems must first be fixed before the CAD model can be used for simulation and LM purposes.

1.3 Quality of the CAD model

A high quality CAD model is important if it is to be used for simulation purposes. There are different factors, which influences the quality of CAD model, some of the factors are:

- Method of translation (IGES, Parasolid, STEP, etc.)
- Accuracy to which part was modelled.
- Type of model (Wire frame, Surface, Solid).
- Short cuts taken by designer.

The ideal is to be able to use the native CAD model directly in the simulation package, but this is not always possible although most of the CAD and simulation vendors are working towards that. This however only solves the translation problem and to a lesser extent the accuracy problem to which the component was modelled. The accuracy problem is solved for the user, since the software developers would solve this problem during the development phase.

If a CAD model consists out of wireframe and surfaces entities, it can not be used for simulations, since a solid is required.

When a CAD modeller is in a hurry to complete a project, due to various reasons, he will create CAD models, which are not of good quality, but since he is in a hurry he would not care. When the simulations have to be done however, these problems catch up with him.

1.4 Method of translation

The translator used to do the translation influences the number of errors in the resulting CAD model. These errors normally have the largest affect on the meshing of the part. The developers of the various meshing software packages (ie. Gambit, etc) and solid modelling CAD developers devote a lot of research and energy in creating wizards and automated tools to handle and eliminate these errors. To them it is necessary to have a water tight model (obvious only up to their preferred tolerance), or else the model cannot be solid.

1.4.1 IGES translators

The IGES translator is one of the oldest translators around and it is still widely used, especially for transferring models for machining. And since almost all the modern tools are machined on CNC machines everyone uses this.

IGES is very suitable for transferring surface and wire frame models and the tolerances are normally in the region of 0.01mm → 0.001mm.

The problem comes in when a FEM or CFD simulation must be done. To illustrate the problem a piece of geometry (Figure 3) which was created in Pro Engineer and then exported via IGES and then imported back into Pro Engineer is shown. The errors are clear in Figure 4 (black lines) and before these errors are not fixed no simulation can be done. Some of these errors are very subtle and difficult to find and rectify.

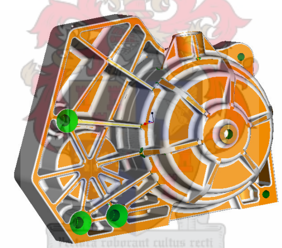


Figure 3: Part designed in Pro Engineer and exported as IGES.

This example shows the problems caused by an IGES translator only. In order to illustrate the problems a Pro Engineer model was exported using the Pro Engineer IGES translator and imported back into Pro Engineer using the same translator.

This particular part was designed to be used in high pressure die casting and is typically what is used in mould shops to design moulds.

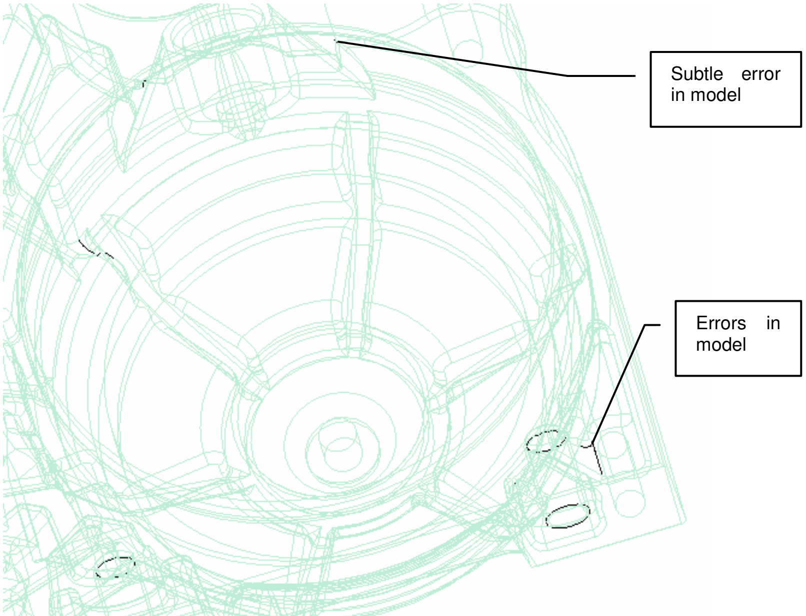


Figure 4: Wire frame IGES.

1.4.2 STEP translators

If parts such as the one shown in Figure 3 are designed in a solid modelling package which is set to the same or tighter tolerance as the one into which it will be imported, then the model will normally import as a solid. This is however not guaranteed. Pro Engineer is widely regarded as one of the best STEP translators and it is advisable to use STEP translation to and from Pro Engineer.

1.4.3 Parasolid translator

This is also a solid geometry translator and was developed in the Unigraphics stable. It translates the models well especially to packages using the same kernel (Solid Edge), but some problems are often encountered when translating to Pro Engineer.

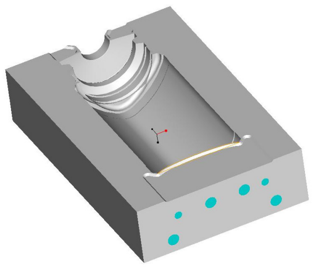
1.5 Creating the simulation model

The next step contains the modelling of the production mould for the container as used by the particular packaging manufacturer. For simulation purposes a 3D solid model of the object is needed. This model of the mould was translated with the use of a STEP translator and imported into the relevant simulation package.

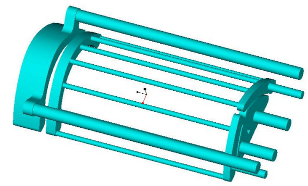
At this stage it has to be made clear that the usability of a model file depends mainly on the capability of the CAD package selected. It is true that an experienced CAD operator can positively influence the simulation results. To minimise the problems possibly caused by the CAD system a proper solid modelling package, which is set to tight tolerances, should be used (instead of a surface modeller) when the simulation model is developed.

There is also a question about the reliability of the interface, which is employed to translate the data between CAD – systems and simulations packages. The well known IGES translator, for example, seems to be totally unsuitable for simulations purposes. It exports the geometry as surfaces. These surfaces need to be joined again in the meshing package in order to recreate the solid model, which is very time consuming and frustrating. Good results were achieved with the Unigraphics translator, which exports Parasolids. It works relatively well, although some difficulties were encountered especially with the surface of the solids. Problems such as lines not matching up appeared and this in turn made the surface meshing, which is necessary before the solid meshing can be done, very difficult and in some cases impossible. The best interface turned out to be the STEP translator. It translates the solid as a solid, thus the surface geometry of the model is of a better quality than is obtained through Parasolid. The STEP translation was still not perfect. However, a well designed solid could eliminate most of the potential problems.

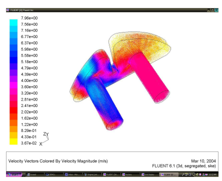
Figure 5 shows the virtual model of the existing production mould as used by the packaging manufacturer. While Figure 5a reflects the solid model of the mould, the picture right – Figure 5b, shows the solid model of the water jacket related to the conventional cooling channels. Figure 5c on the other hand illustrates the velocity conditions in the three sections of the mould. Subsequently, Figure 5d shows the heat distribution throughout the mould. The inequality of this distribution is more than clear.



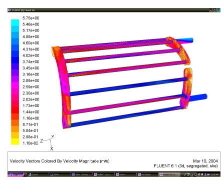
a) Production mould



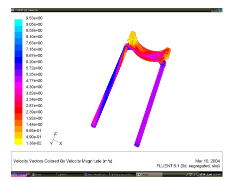
a) Water jacket



Bottom cavity

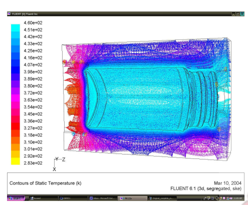


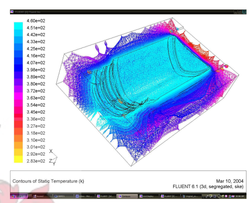
Central cavity



Top cavity

c) Velocity diagrams.





d) Heat distribution of bottle cavity from different view angles.

Figure 5: Solid models, velocity diagrams and head distribution on the conventional production mould.

Based on an empiric approach a prototype mould for the same object was constructed. The cooling was performed using a flooded cavity in the back of the mould. The cavity was created by offsetting the mould cavity by 6 mm, which formed the conformal cooling layout. The cooling simulation of the prototype mould was carried out using the same input parameters as applied for the production mould. The results can be seen in Figure 6.

An observation of the cooling conditions on the prototype mould shows much stronger presence and equal appearance of the cooling fluid surrounding the mould cavity (Figure 6a & b). The velocity diagrams in the three sections can be interpreted as follows: the water enters the top cavity at a relatively high speed. It follows the shape of the bottle neck, which ensures relatively good cooling. The cooling is still not fully uniform, due to the fact that the water speed is not completely uniform over this section of the mould. The water speed in the central cavity is relatively low, but it is uniform over the mould surface, which ensures uniform cooling. In the third mould section the water flows into the bottom of the mould cavity and hits the mould bottom at a relatively high speed, which will assure a good cooling in this area. In the rest of the bottom cavity the water flow velocity is low, but uniform and will therefore cool the mould section equally. The heat distribution as shown in Figure 6d demonstrates the improved cooling as shown by the temperature contours which follow the cavity much closer.

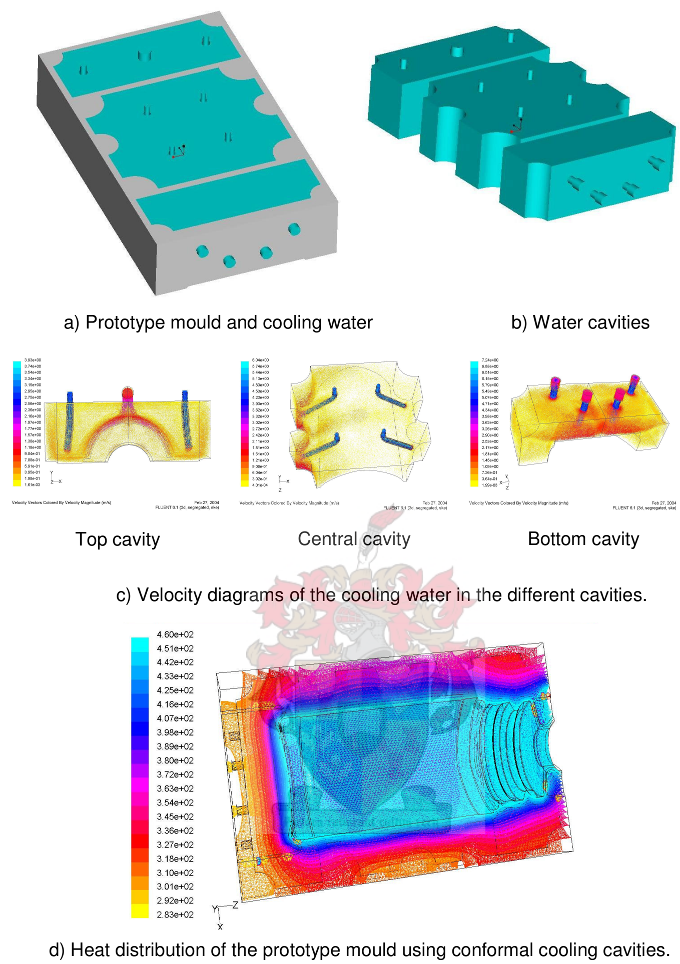
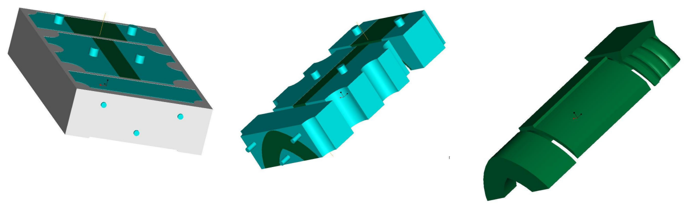
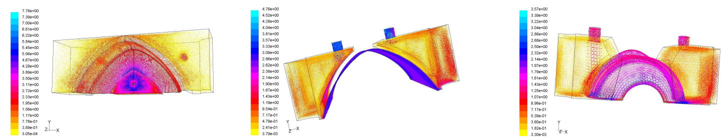


Figure 6: Solid models, velocity diagrams and head distribution on the prototype mould.

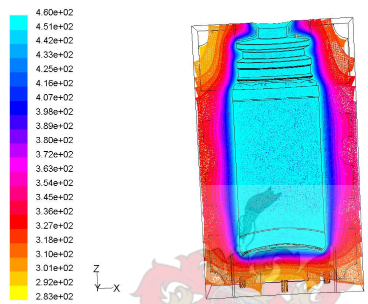
There are, however, substantial possibilities for further improvement as shown on the pictures below (Figure 7). Once again the pictures in (a) are reflecting the solid models of mould, water layout and possible inserts for better regulation of the water velocity. The velocity diagrams in Figure 7(b) show that the water flow can be manipulated to give an uniform surface velocity over the mould. In Figure 7(c) the temperature contours can again be seen. If Figure 7(c) is compared to Figure 6(d) a further improvement of the cooling can be clearly established.



a) Possible cooling layout of prototype mould for next iteration.



b) Velocity diagrams of water in proposed cooling layout.



c) Heat distribution of the bottle mould using the proposed cooling layout

Figure 7: A possible further design iteration of the cooling layout.

1.6 Mould manufacture

The original mould was designed in a surfacing package. Due to the loose tolerance setting of this package the model was unusable for simulations and prototyping purposes. The basic cavity design is relatively simple. It was therefore possible to create a complete new solid model using appropriate software package such as Pro Engineer. This formed the foundation for the conformal cooling layout. Thereafter the cooling side of the mould was divided into three water pockets. These water pockets were placed in such a way that it separated the three critical cooling areas in the mould.

An ".stl" file was created as an input for a layer manufacturing device using the 3D Printing process. In this way time consuming milling and EDM operations were avoided. The two halves of the mould, fabricated on the 3D printing machine in plaster based powder, were used as pattern for sand moulds. The sand castings of the mould cavities were subsequently machined to final tolerance and finished by hand as required. The cooling water was supplied through the back plate which helped to keep the mould geometry simple. This also allowed for cooling layout flexibility.

1.7 Conclusion

The utilisation of simulation tools demonstrates clearly how mould design changes can drastically influence the cooling parameters of a mould and therefore the reduction of cycle times.

The simulation of the cooling behaviour of both the production and the prototype moulds, whereby in the later some conformal cooling design ideas based on empiric assumptions were implemented, shows that the prototype mould has a better cooling than the production tool currently used. This can be clearly seen when looking at the figures showing the temperature distribution contours. The physical comparative tests between the production mould and the prototype confirmed qualitatively this observation through the fact that the bases of the bottles produced in the prototype mould deformed less. None of the bottles from either mould showed signs of any side deformation, but this was to be expected due to the simple geometry of this part of the product. The duration of the tests, however, was only a few hours, which was extremely insufficient with regards to gaining reliable data for comparison and further conclusions. Therefore proper experiment procedures have to be designed and sufficient time for comprehensive tests, in the region of 72 hrs, allocated.

The use of simulation tools showed good possibilities for further substantial improvements. It is recommended that this or a similar version of the mould is produced in order to carry out proper comparative tests, and to get calibration data regarding extrusion, solidification, and ejection temperatures of mould and parison. Only in this way a prediction of the cycle times and their quantitative variations will be possible. On the other hand, some steps of the manufacturing process could be tested using new materials available in layer manufacturing and more specifically in 3D Printing.

Based on these experiments and trials a generalized heat flow prediction methodology can be developed.

APPENDIX C: CASE STUDY 2 (FABRIC SOFTNER CONTAINER)

Appendix C: Case study 2 (Fabric softner container)

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1.1 Introduction

After the success of the achieved with the Mandoza container the company CINQPLAST – PLASTOP (Pty) Ltd / Astrapak (CINQ), supplied a second bottle. The container has a handle and is therefore an ideal design to illustrate the advantages of conformal cooling.

1.2 Product

The product for which the mould was designed is a handle bottle with a 2 litre capacity (Figure 1). The handle and teardrop shape, make it difficult to cool with conventional cooling.

Figure 1: 2 litre bottle with handle.

1.3 Problem areas

The problem areas in the bottle are around the neck of the bottle. There will be a concentration of plastic since a parison with a large diameter must be used to ensure that there is enough plastic in the mould to form the handle, thus the parison does not stretch much in this region resulting in very little thinning of the plastic, leaving a thick section of material to be cooled. The plastic caught in the pinch off area must also be cooled and carries a large amount of heat.

1.4 Design issues

The bottle is big, therefore is finite element analysis necessary to ensure that the mould will handle the pressure applied during parison inflation. The mould is divided into three sections, namely the base, body and neck section (Figure 2). The basics features of the mould are shown below. A rear view of the mould can be seen in Figure 3.

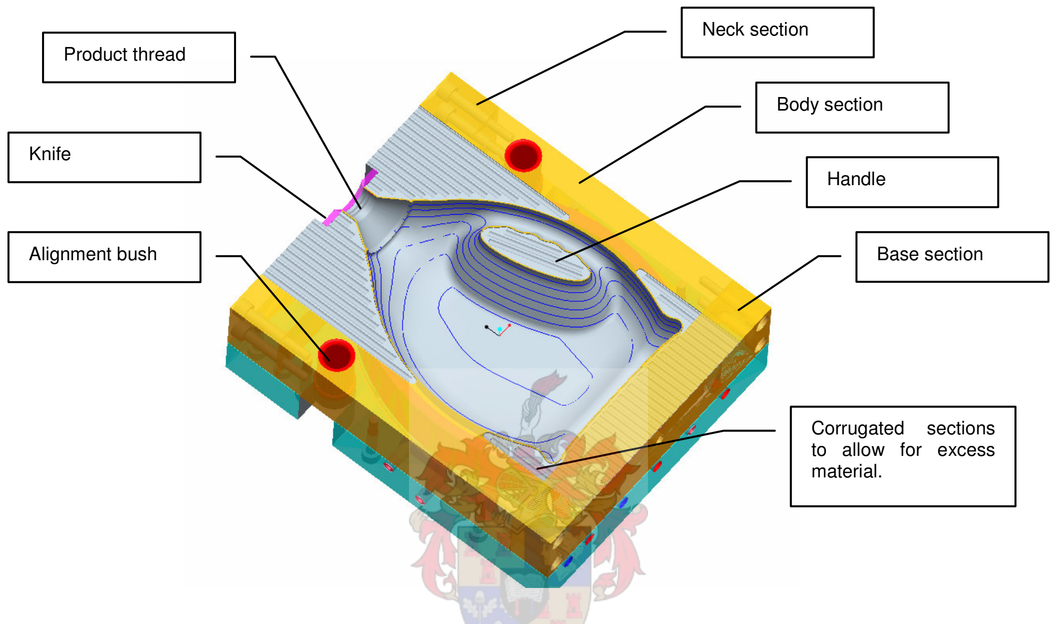

Figure 2: Front view of 2l bottle mould.

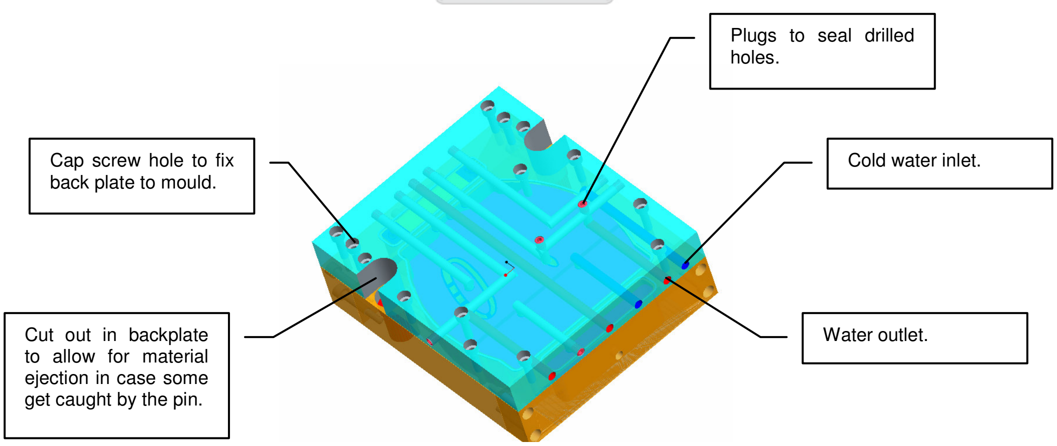

Figure 3: Rear view of 2l bottle mould.

1.4.1 Designing the water cavity in the base

The design of the base water cavity is straight forward, since the base is a simple, nearly flat shape. The base was hollowed out and an insert was designed to ensure that the water flows in a 2 mm film over the part of the cavity which is closest to the base.

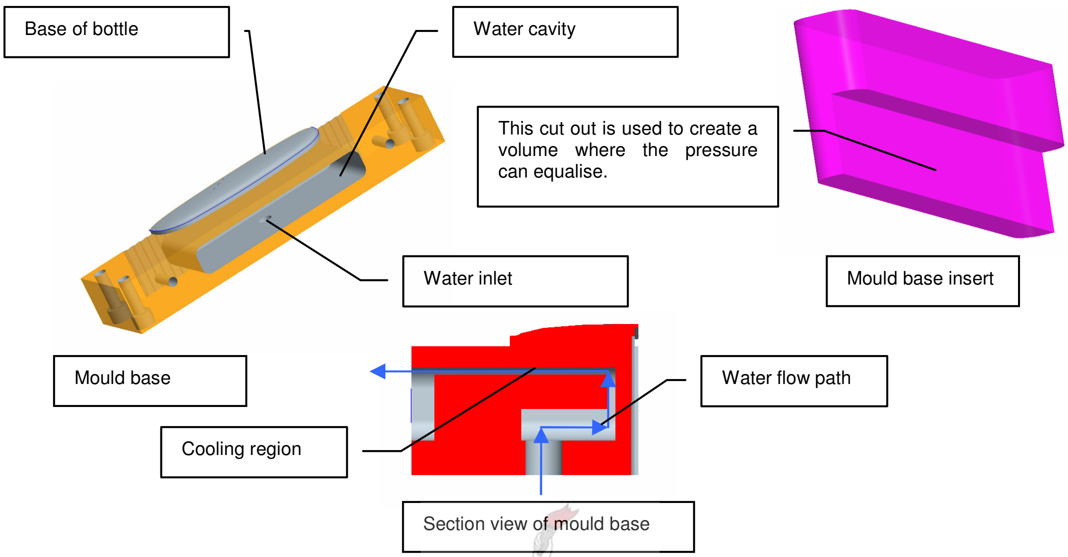

Figure 4: Proposed mould base and insert.

The base has only one inlet and outlet for the water. The inlet is as shown in Figure 4 and the outlet goes into the back plate, from where the water is channelled to the body cavity. This is done to increase the water flow in the body cavity. The temperature of the water flowing through the base cavity would not increase significantly, thus would the increased water flow serve to improve the cooling in the body section.

1.4.2 Designing water cavity in the body

A major problem when using conformal cooling, is to ensure that the water flow as fast and as uniform as possible over the total cooling area. With a large cavity it is often difficult to achieve high velocity flow since the water supply connection fittings are small (effective diameter of 5mm in this particular case). In an attempt to minimize this restriction, the outflow from the base and neck combined with an additional inlet from the water mains is used to supply the body cavity with cooling water. In doing so, the water flow in the body increased three fold.

Starting point

The design was started with first looking at all the critical areas of the product. These are the areas which will have the thickest plastic. The regions of concern are the handle and the tapering section of the neck.

It is also important to remember that the handle has a shutoff which must be cooled and supported structurally. The sharpness of the cutting edge will determine the forces exerted on the mould in that region when the plastic is pinched off. To overcome this problem a vertical wall following the cutting edge is left in the back. The cutting forces are conveyed via this wall to the back plate.

In an effort to form the conformal cooling surface the standard offset feature of Pro Engineer was tried, but failed. PowerShape was able to produce an offset usable for machining purposes after model alterations (Figure 5). The problem with PowerShape is that the adjacent surfaces tend to move away from each other when they are offset, creating gaps. This might not be a problem for machining, but cause serious difficulties for simulation.

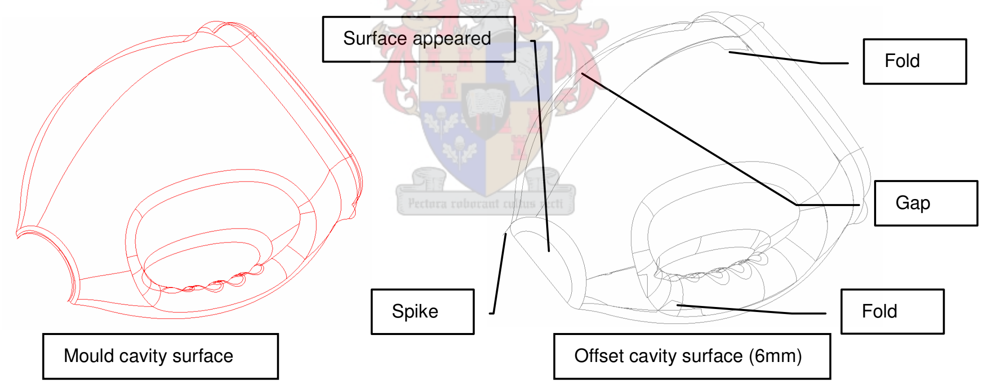

Figure 5: Mismatches created by a PowerShape offset.

Design iterations

After the initial design of the mould a stress analysis simulation was done using Pro Mechanica, which is the finite element analysis software embedded in Pro Engineer. This was done to determine what the deformation of the mould would be during the blowing cycle of the bottle. It is important, because most of the support material in the mould back is cut away to accommodate the cooling, which reduces the structural strength of the mould. The inflation pressure in blow moulding is 6 Bar, thus this was used in the simulation and the areas in contact with the back plate were taken as fixed. The clamping force exerted on the mould when it is closed was ignored during the simulations. The reason being that thick support material, extending up to the back plate, is left behind all the pinch-off edges and along the mould periphery.

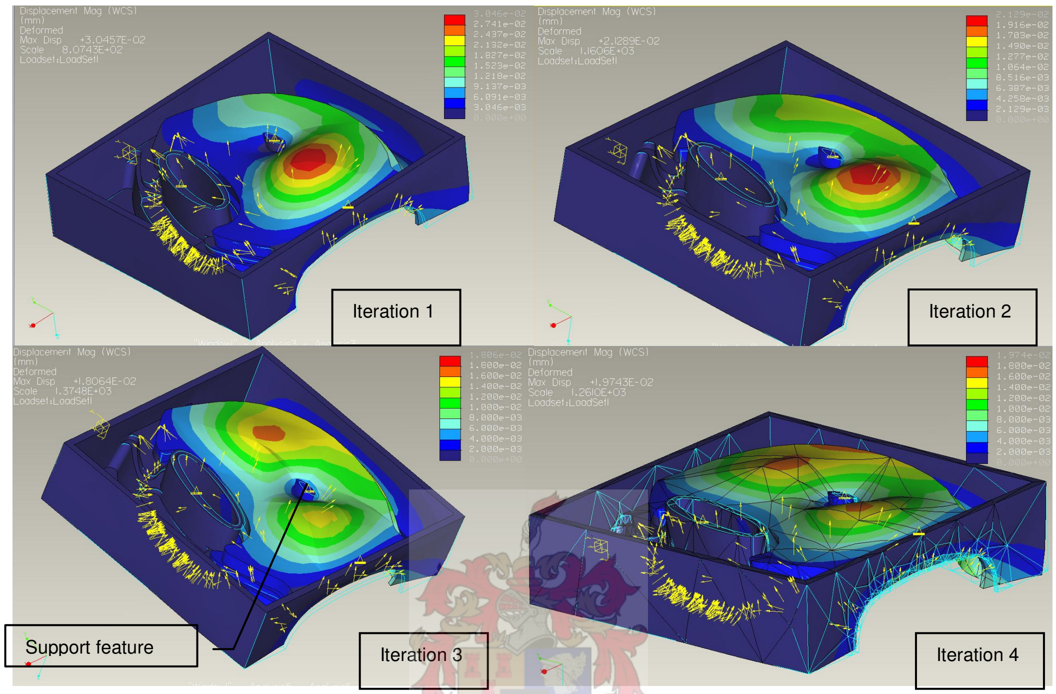

Figure 6: Design iterations to determine placement of support feature.

In the initial simulation it was clear that there is a significant deflection of the body part of the mould and it was decided to add a support feature to the back of the mould. This feature had to be supportive of the mould cavity, yet it had to be small to reduce its influence on the flow of the cooling water as much as possible. The feature was moved around in the back of the mould (Figure 6) in a number of iterations until the deflection did not decrease any more. The design as shown in Iteration 3 in Figure 6 was selected. According to the simulation a deflection of 18µm can be expected in the region coloured red, the first iteration showed a maximum deflection of 30µm.

<u>Final design</u>

The final design of the mould can be seen in Figure 7 and it is clear that the design of the cooling cavity is not just an offset from the internal cavity, but is stepped with flat areas. This is the result which was obtained with the manual modelling of the surface offset.

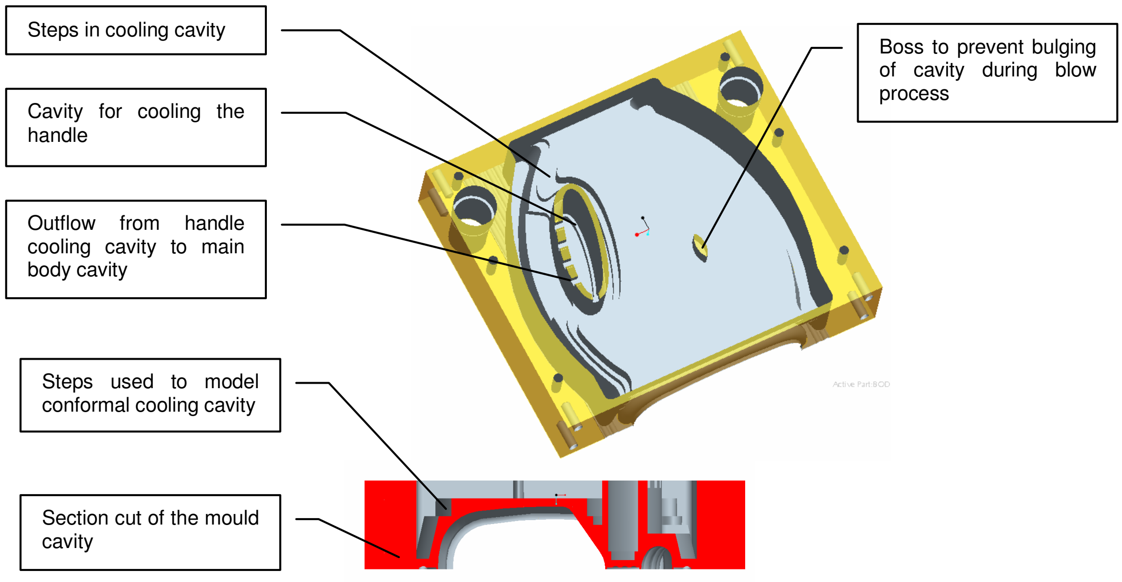

Figure 7: Cooling cavity of the body section of the mould.

Cooling insert design

The surface of the cooling cavity was offset by 2mm, allowing space for the cooling water. The insert which goes in the cooling cavity was created by taking the outside surface of the water as the inside of the insert (Figure 8). The cooling cavity walls were then taken as the boundary of the insert. The top of the mould was designed to allow for an open area where the cooling water enters into, ensuring good pressure distribution.

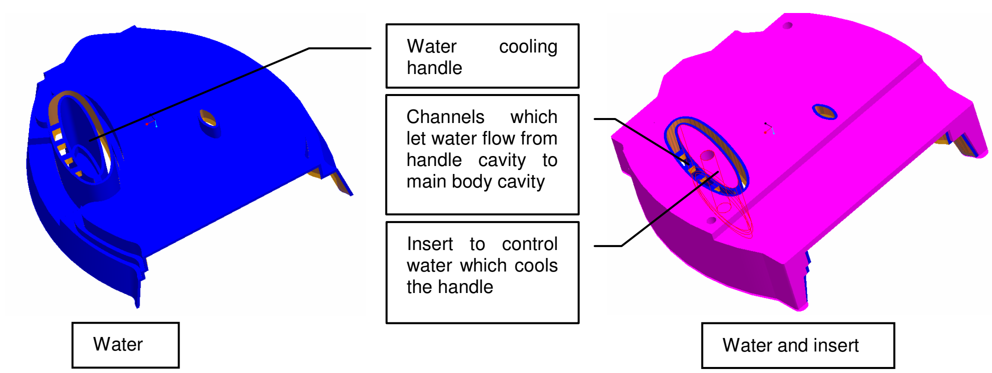

Figure 8: Body water and insert.

1.4.3 Designing the water cavity in the neck

As for the base, the design of the cooling in the neck was relatively straight forward. The main concern was the holes which is necessary to hold the cut off knife in the neck in place. The cavity was modelled using standard cut functions in Pro Engineer. Fillets and rounds were used to create a smooth shape (Figure 9).

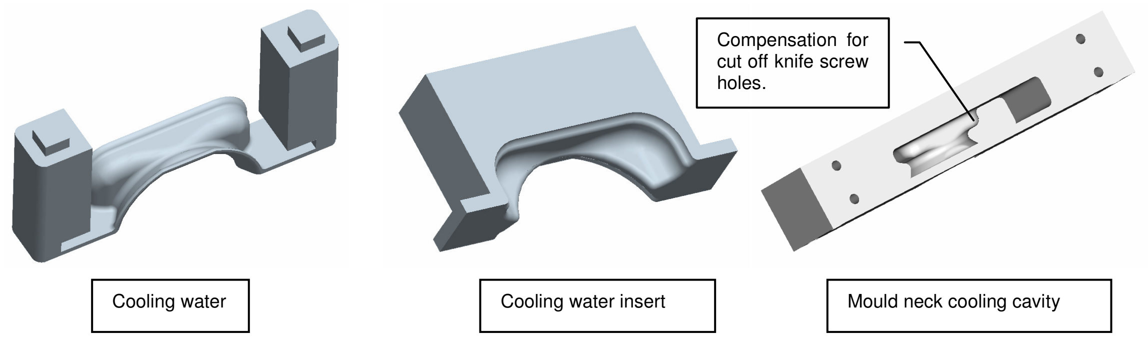

Figure 9: Mould neck cooling design.

1.5 Water flow simulation

1.5.1 Mould base

After the mould base was designed a flow simulation of the water was done. This simulation was used to determine if the flow patterns in the base are as desired. The flow patterns are shown in Figure 10 and it can be seen that the colour distribution (which represent the flow velocity) is uniform although some improvement is possible. The factor causing the somewhat unequal flow is the placement of the outlet. The layout of the other channels in the back plate made it impossible to place the water outflow in the centre.

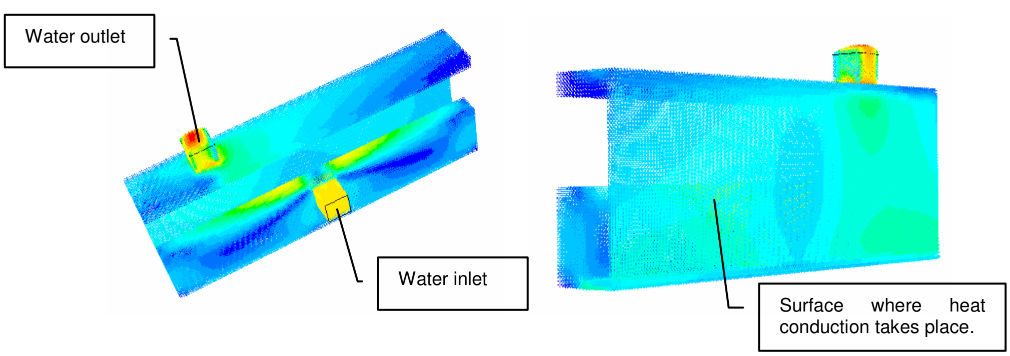

Figure 10: Water flow velocity spread in the mould base.

1.5.2 Mould body

The design of the water flow path for the body was more challenging because of the handle in the bottle. The major problem was to cool the area uniformly without disrupting the rest of the water flow in the cavity. This was done through the water, used to cool the neck. This water was channelled to the centre of the cooling cavity and the water then exits through the slots cut in the side of the support structure. The placement of the slots was done in such a way that their outflow complimented the flow in areas which is not sufficiently reached by the inflows from the other inlets. Simulation played a major part in this design as the placement of the slots were changed a number of times until a good solution was found (Figure 11). The influence on the cooling water by the support feature preventing the mould from bulging during inflation is also clear.

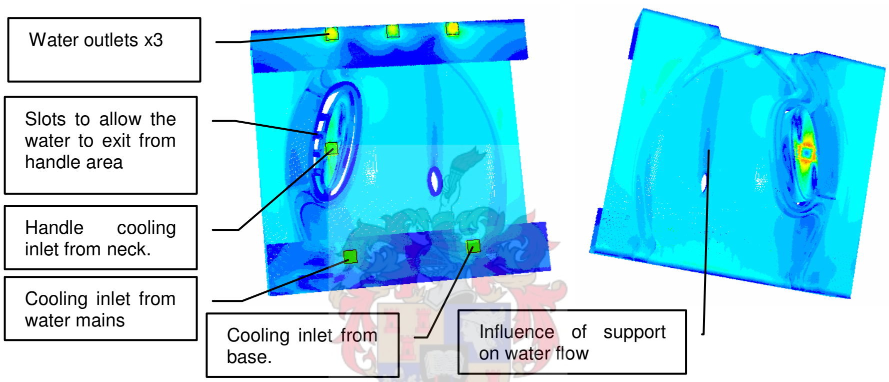

Figure 11: Water flow velocity spread in the mould body cavity.

1.5.3 Mould neck

The design of the neck cooling cavity is straight forward as in the case of the base, because the area to be cooled is relatively small. The design had to take the fastening screws of the cutting knife into account, but except for this there was no other problem. There are areas of high velocity as well as areas of low velocity. The areas of velocity extremities (high and low) are relatively small. Therefore is the influence of these areas of little significance (Figure 12).

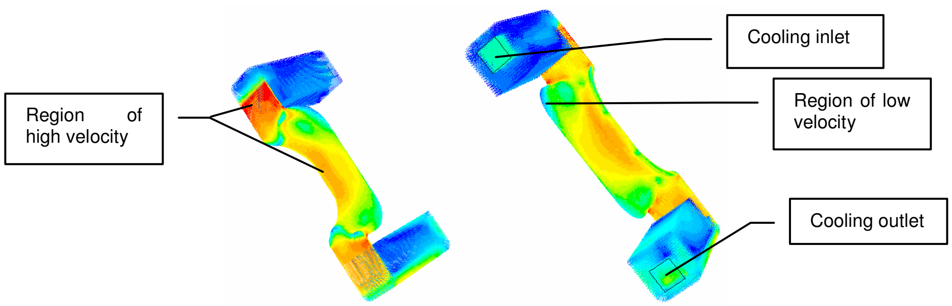

Figure 12: Water flow velocity spread in the mould neck cavity.

1.6 Conclusion

The design for this mould was ready for manufacture. The project was however cancelled, because the customer decided to use a different shape bottle. By then the project was so urgent that Cinqplast ordered their tool room to create the new design.

It is therefore very important to streamline this method of conformal cooling design to the point where the total design cycle can compete with the conventional cooling design cycle.

The simulations during the design process showed that the mould has uniform cooling. This cooling layout is superior to conventional cooling layouts, especially in the handle area; therefore can superior cycle times be expected.

APPENDIX D: CASE STUDY 3 (MANDOZA CONTAINER)

Appendix D: Case study 3 (Mandoza container)

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1.1 Introduction

The specific objective of the project is to determine if the claimed cycle time reductions are possible and what design processes are necessary to achieve this.

In a comparison of Figure 7 and Figure 8 the thinning of the parison can be seen during the inflation process. In this case a fairly simple cavity was used, but if the cavity is more complex like the Mandoza bottle, some unequal expansion will take place. This will cause the parts which expanded more than other to be thinner. This in itself is not a problem as long as the customer's specifications for the bottle are met. The parts which expand less are however a problem, because these regions have excess material which must be cooled. In the case of the Mandoza bottle there is a significant thickness difference between the material which expanded most and least.

The one advantage of a parison with a large diameter is that the parison can be thinner since less expansion is needed, which will ensure a more uniform wall thickness. This constitute to a lower maximum wall thickness, while keeping the same minimum wall thickness, resulting in a more uniform wall thickness. And a product with a uniform wall thickness is easier to cool uniformly. The trade-off will however be between cycle time and split line quality.

The area which this project will look at will be the layout of the mould. The challenge is to reduce the cycle time without compromising product quality. This area is the only place, which can give a reduced cycle time without a decrease in quality.

1.2 Aim of the experiment

The aim of the experiment was to demonstrate what improvements can be achieved, in terms of cycle time and product quality, when using the developed method of mould design.

The deliverables include the simulation of the original mould, the redesign of the cooling and the manufacture of a new mould. The new mould will be used to compare the advantages of the proposed cooling layout with that of the conventional cooling layout. An experiment was designed to do this comparison.

The aim of the experiment is two fold. The first is to determine what effect each of the moulding parameters have on the cycle time. And the second is to determine the influence of the cooling design on the cycle time.

1.3 Design process chain

In an attempt to develop a mould which is conformal cooled, the following design steps were taken:

- Analyse existing mould to determine problem areas.
- Design new mould.
- Analyse new design.
- Optimise the cooling layout of the new mould design.
- Manufacture the new mould.
- Test the new mould.

1.3.1 Discussion and analysis of the existing mould

The existing mould was designed with drilled cooling channels. These cooling channels are drilled in straight lines as shown in Figure 1. This does not allow for uniform cooling of the mould cavity, especially in the neck area (concave area) and on the narrow side of the body.

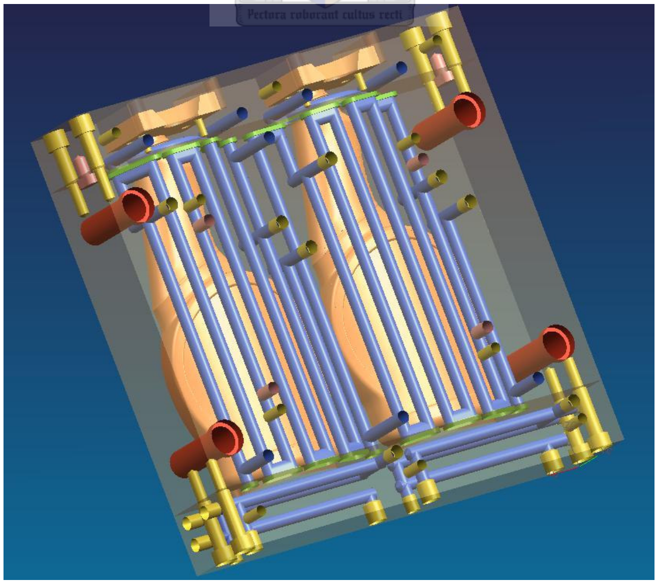


Figure 1: Original mould cavity, with drilled water channels.

The temperature distribution contours can be seen in Figure 2, this also shows the cooling problem areas. In Figure 2 it is very clear that the cooling channels do not cool the mould uniformly. If we take a look at the closes edge of the mould (red area), we would see some warm areas in the mould. This is because there is no cooling in this area.

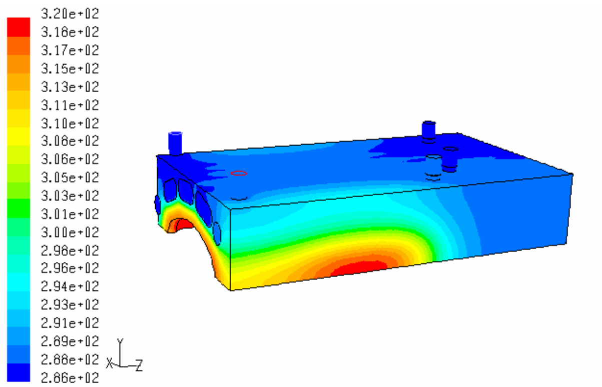


Figure 2: Temperature distribution in mould.

1.3.2 Design of new mould

The cooling of the new mould was designed based on the conformal cooling approach.

The original mould's CAD model as supplied by Spec Tool and Die, was used to develop the conformal cooled mould. The basic design started by hollowing the back of the mould out to a uniform wall thickness. This proved to be a challenging task, since none of the available software modelling packages (Pro Engineer & Unigraphics) were able to make an useable offset of the cavity surface. An approximation of the offset had to be constructed using normal modelling commands. This method returned a cooling cavity which does not follow the product cavity exactly, but still proved to be sufficient (Figure 3).

Inserts were designed to guide the water in the cooling cavity. The insert allows a constant 3mm water layer to follow the cooling cavity. The water flows in at the bottom of the cavity an out at the top. This was done to ensure that the cavities are always filled with water. The inserts were machined from aluminium and bolts onto the back plate (Figure 4).

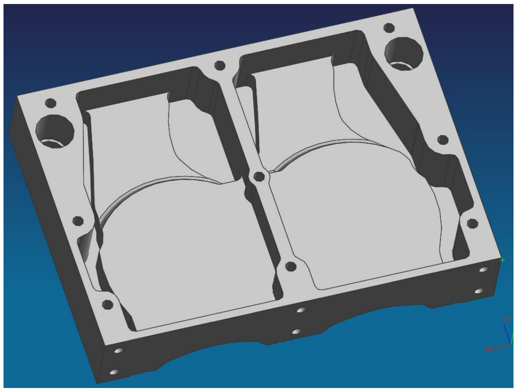


Figure 3: Cooling cavity in conformal cooled mould.

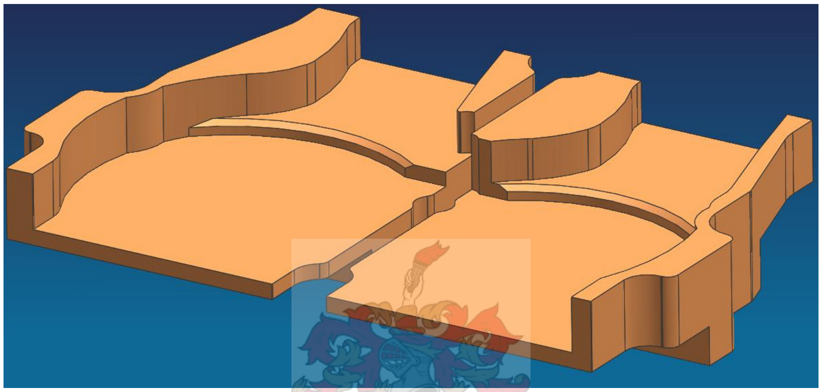


Figure 4: Inserts to guide to cooling water in the cooling cavity.

Due to the design of the mould, no cooling water channels could be drilled into the mould itself and the water had to be routed through the back plate (Figure 5).

With the space restrictions brought about with the cooling cavity design, only two guide pins, instead of the usual 4, were used in the design.

The cooling of the mould was simulated using Computational Fluid Dynamics (CFD), this showed that the new design ensured that the water flows uniformly in the cooling cavity, which is essential in uniform cooling. It also shows a very uniform and good heat distribution in the mould (Figure 6).

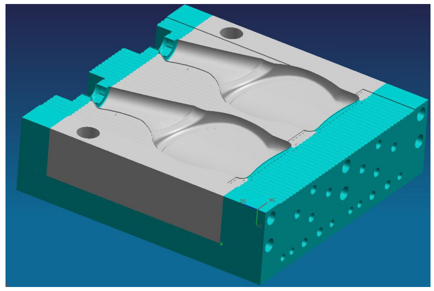


Figure 5: Mould assembly showing base and back plate with water in- and outlets.

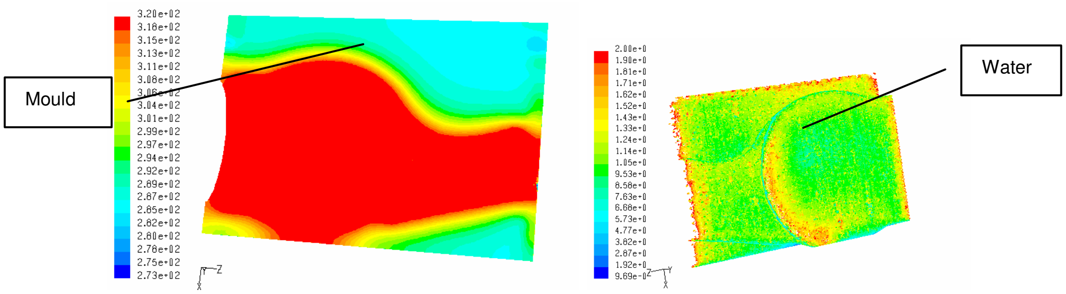


Figure 6: Conformal cooled mould, showing uniform cooling and water flow.

1.4 Design of experiments

"We design experiments as opposed to using trail and error methods, to gain both effectiveness and efficiency in knowledge acquisition" [30]. After studying the existing mould in conjunction with the specifics of the blow moulding process, the factors that effect the cooling of a mould were identified as follows:

- Cross section thickness of mould (between plastic and water)
- Mould material
- Water temperature
- Water flow
- Product mass
- Type of plastic
- Inflation air temperature
- Cycle time
- Inflation air pressure

1.4.1 Cross section thickness of mould (wall thickness)

This is the actual thickness of the mould between the plastic and the water cavity. Obviously the thicker the mould the longer it will take to cool down. Thus by minimizing this factor, a shorter cooling time can be achieved. This factor can only be changed in the design of the mould and can not be altered once the mould has been manufactured.

Looking at the original mould, the thickness varies since the cooling channels are drilled at specific distances from each other. To better illustrate this effect look at Figure 58.

1.5 Variables

From the factors discussed above, not all are controllable in the environment the experiment takes place. The factors that are variable are:

- Water flow
- Product Mass
- Cycle time

All of the other factors are fixed for the experiment.

At the CINQPLAST plant the water temperature is 11˚C, and this figure we can not adjust. Thus the water temperature is not a variable factor in this experiment. For this experiment water temperature must be measured in order to make statistical correlations. The type of plastic used is fixed since the experiment can only take place with PP.

The output of the experiment was the product temperature (˚C), which was measured using an infrared camera. The brim fill volume was measured using water and a scale. To measure the three dimensional accuracy of the bottles, the bottles was compared with the CAD model with the use of a Coordinate Measuring Machine (CMM).

1.6 Factorial design of experiments

Different types of approaches to design experiments were researched (Taguchi, Fractional factorial, Factorial), and the decision was to do a full factorial experiment. A full factorial experiment is more appropriate to this application, because this was a small experiment with few variables. The other approaches are more suited to large experiments with many variables.

	Units	Level 1	Level 2	Level 3	Level 4	Level 5
CWV/H	l/h	150	190	250	Full open	
PT	mm	5	6	7	8	9
CT	sec	16	14	12	10	8

Table 1: Selected levels for the factors.

EN	CWV/H	PT	CT	EN	CWV/H	PT	CT
1	150	6	16	24	190	8	14
2	150	7	16	25	190	9	14
3	150	8	16	26	150	9	14
4	150	9	16	27	150	8	14
5	150	5	16	28	150	7	14
6	190	9	16	29	150	6	14
7	190	8	16	30	150	5	14
8	190	7	16	31	150	5	12
9	190	6	16	32	150	6	12
10	190	5	16	33	150	7	12
11	250	5	16	34	150	8	12
12	250	6	16	35	150	9	12
13	250	7	16	36	190	9	12
14	250	8	16	37	190	8	12
15	250	9	16	38	190	7	12
16	250	9	14	39	190	6	12
17	250	8	14	40	190	5	12
18	250	7	14	41	250	5	12
19	250	6	14	42	250	6	12
20	250	5	14	43	250	7	12
21	190	5	14	44	250	8	12
22	190	6	14	45	250	9	12
23	190	7	14				

- EN – Experiment Number
- CWV/H – Cooling Water Volume / Hour
- PT – Parison Thickness
- CT – Cycle Time

Table 2: Number of experiments with all levels.

The purpose of the Taguchi approach is to lower the number of experiments [31]. The total number of experiments worked out to be 45 for the full factorial approach. Since 45 experiments are not too many and time would allow it, a full factorial was designed. Room was left in the experiment to do more tests if there was time left on the day of testing. These tests are to let the water flow unmeasured (full open) through the mould while the cycle time is reduced to a point where no more good bottles are produced. Table 1 shows all the controllable factors with selected levels of each and Table 2 shows the number of experimental runs with all the variables.

1.7 Experimental set-up

In order to measure the controllable factors described in the experimental design above, the following measuring equipment were needed.

- Flow meters were required for the measurement of the water flow.
- The product mass is set with the blow moulding machine's controller.
- The product temperature were measured by an infrared camera.

- The cycle time is set and measured by the blow moulding machine's controller.
- The thermocouples were placed on specific points in both moulds and a data logger was used to log the temperatures at 0.5 second intervals.

1.7.1 Thermocouples

The purpose of the thermocouples is to measure the temperature of the mould throughout the whole experiment. Some points were selected by means of inspection of the Mandoza bottle. Mostly thicker points on the bottle were selected since it is at these positions that defects are more likely to occur. These points are pointed out in Figure 7.

Figure 7: Critical points on the Mandoza bottle.

These points were identified on both the new mould and original mould. Holes were drilled at these points, from the back to a depth of 4mm from the cavity of the moulds. Figure 8 illustrates how this was done.

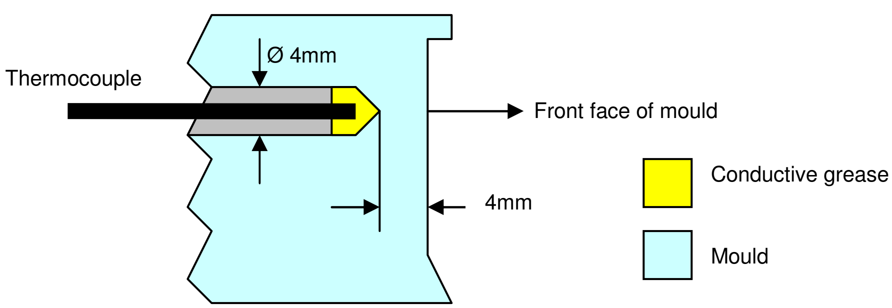
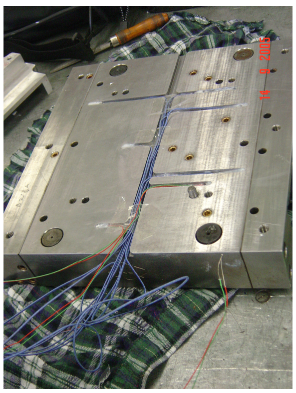


Figure 8: Drilled holes for thermocouples.

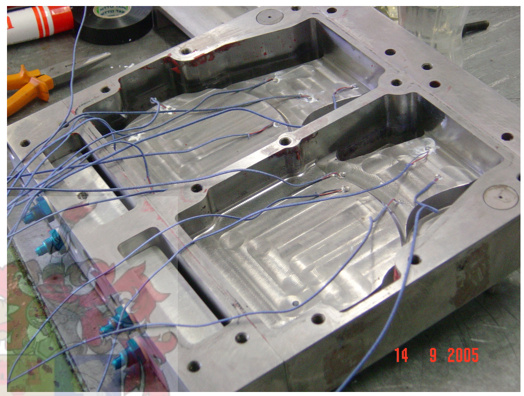
Conductive grease was inserted into the holes and the tip of the thermocouples was placed inside the conductive grease. The thermocouples were then glued in place with a strong epoxy.

Figure 9(a) shows the thermocouple set up on the original mould and Figure 10(b) the set up of the new mould.

For the new mould the thermocouples had to be fed through holes at the side of the mould. This proved quite a problem since the holes had to be sealed water tight so that no cooling liquid could escape. Epoxy was dripped in the holes, dried and sealed again with a lot of silicone. The mould was heated to speed up the drying of the epoxy.



(a) CINQPLAST mould



(b) RPD mould

Figure 9: Thermocouple set-up.

The measurements from the thermocouples will be used to calibrate simulations in future and not as much in determining the quality of the bottles. It also gives a good indication of when the mould temperature stabilises during an experiment. If the mould temperature stabilises during the experiment, it means the cavity is running at its operating temperature. Only bottles produced at operating temperature are usable for quality analysis.

1.7.2 Flow meters

The flow meters helped with the regulation of the water in the mould. It helped to ensure that the flow of water through both moulds was kept identical and constant. This was needed to eliminate the chances of a flow restriction in one of the cooling system pipes hampering the experiment or going unnoticed. It also ensures that water flow can be measured and this information can later be used in simulations. A manometer flow meter was build and calibrated (Figure 10) to fulfil this regulating role.

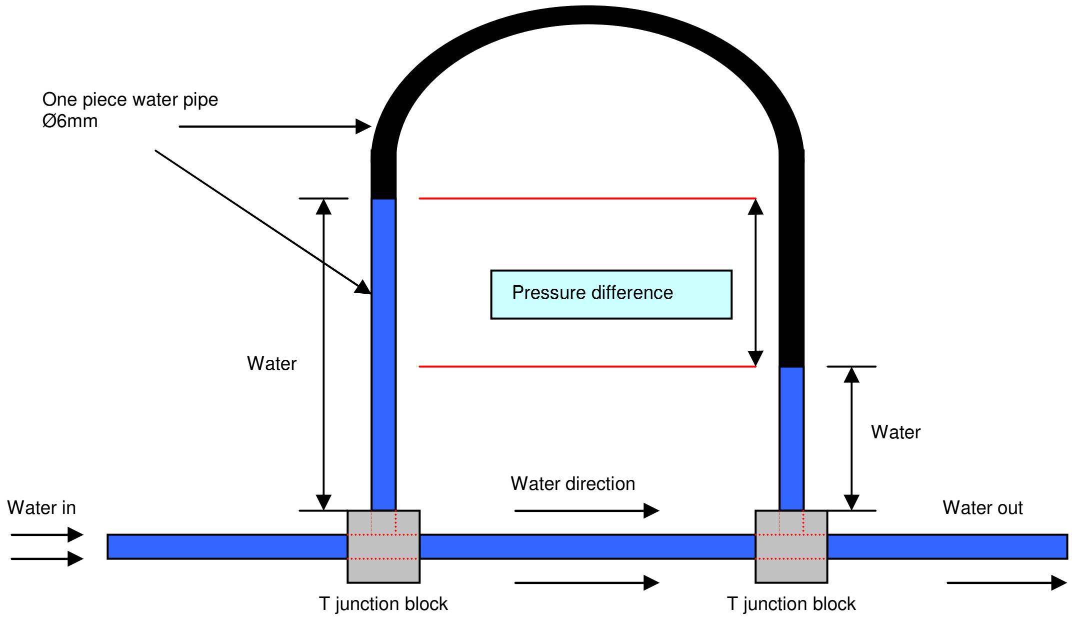


Figure 10: Basic construction of a manometer flow meter.

The flow for the experiment was regulated to three different settings as shown in Table 1.

1.7.3 Infrared camera

The infrared (IR) camera was used to get the bulk temperature [32][33] of the bottles after ejection. An IR image of a bottle is shown in Figure 11. The temperature distribution in the plastic is clearly visible. What must be remembered when looking at the image (Figure 11) is that the image indicates the bulk and not the surface temperature of a plastic product. This is because plastic material is transparent to IR rays. It has some advantages that you have an idea of what is the total temperature of the plastic, but it does not give an indication of the surface temperature of the product. This is a problem, since plastic with its low heat transfer coefficient has a very steep temperature gradient over a cross section of the wall.

The accuracy of the IR camera is ±2℃ or 2%, whichever is greater.

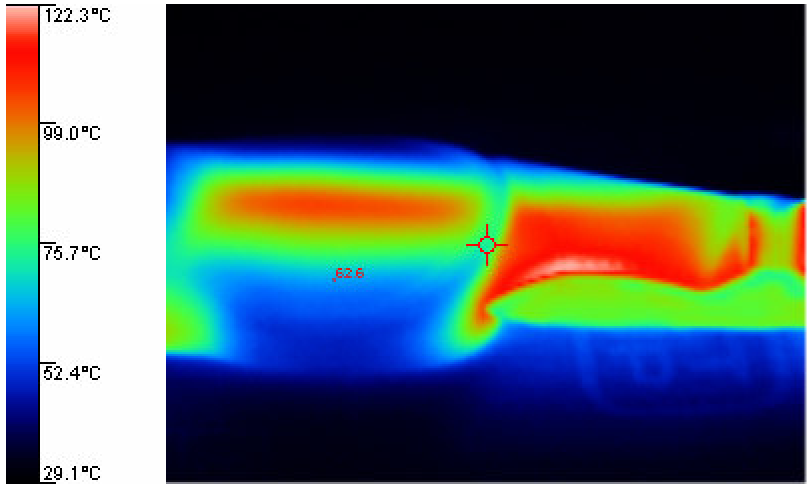


Figure 11: IR photo of Mandoza bottle just after ejection.

1.7.4 Parison control

The experiment was to compare the moulds in similar conditions. Thus the number of parameters, which have an influence on the process, had to be minimised. One of the important parameters is the melt temperature as it comes out of the extruder head. In Figure 12 a temperature profile of the parisons can be seen. The graph at the bottom represents the red line in the figure, which gives an indication that the parisons are not of the same temperature. This causes the parisons to stretch differently under its own weight.

To eliminate any uncertainties about different parison temperatures, the same parison was used to manufacture the bottles from the different moulds. The parison on the left was used during the experiment.

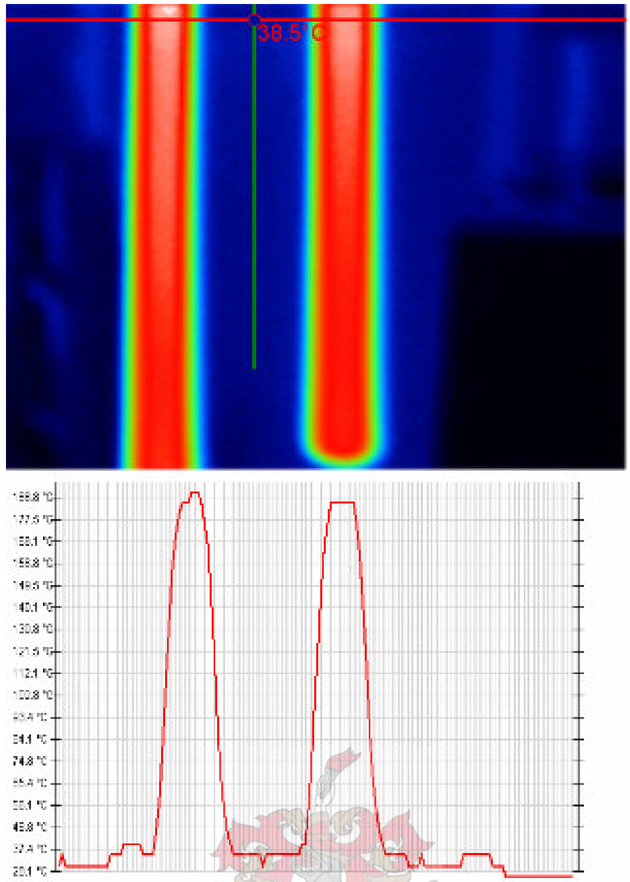


Figure 12: Temperature profile of the parison just before experiment started.

1.8 Discussion of results

In an effort to compare the capabilities of the two moulds as well as the influence of the different variables on the production process, statistical methods are used. In this comparison the influence of the mould design, water flow rate, parison thickness and cycle time is analysed. The comparison shows what the main differences between the two moulds are and how different variables influence them.

The data analysis methods used are Analysis of Variance (ANOVA) and inspection.

1.8.1 Brim fill volume

In order to compare the quality of the bottles from the moulds, the brimful volume of the bottles was compared. The reasoning is that the cavity volume of the two moulds is identical and that the difference in the brim fill volume will be the result of the distortion of the bottle. In practice a brimful volume deviation of ±1% is acceptable, but this experiment aims to compare the two moulds. We are therefore more interested in the differences in brimful volume between the bottles, produced at the same production parameters, than the difference of the bottle from the production specification.

The theoretical volume of the bottle was determined by taking the volume of the CAD model and subtracting volume of plastic in the product. The results can be seen in Table 3, where the experimental parameters are also shown. It is clear that the RPD mould produced bottles with a brimful volume much closer to the theoretical, than that produced in the CINQPLAST mould.

Experiment #	Cycle Time	Parison Thickness	Water Flow (l/h)	Mould Design	Volume deviation
4a	16	9	150	rpd	-4.89
4b	16	9	150	cinq	-23.78
5a	16	5	150	rpd	6.44
5b	16	5	150	cinq	8.67
11a	16	5	250	rpd	8.33
11b	16	5	250	cinq	-5.56
15a	16	9	250	rpd	-9.78
15b	16	9	250	cinq	-21.67
31a	12	5	150	rpd	0.56
31b	12	5	150	cinq	-12
35a	12	9	150	rpd	-18.89
35b	12	9	150	cinq	-30.78
41a	12	5	250	rpd	0.33
41b	12	5	250	cinq	-13.67
45a	12	9	250	rpd	-25.89
45b	12	9	250	cinq	-34.78

Table 3: Deviation of actual brim filled volume vs. theoretical brim filled volume.

ANOVA [34][35] was used to compare the two moulds and to determine which parameter had the biggest influence on the volume of the bottle. The p values, as shown in Table 4, indicate which factor has an influence on the volume of the bottle. A value of 5% was predefined and if the calculated value is less than 5%, that factor does have a significant influence. If the calculated value is larger than the predetermined value (5%) then this variable does not have a significant influence.

When the values in the table are examined it is clear that there are 3 factors which played a significant role in the volume of the bottle during the tests. These being the cycle time, parison thickness and the mould design. The water flow volume should also play a significant role, but not in the volume range which was used during the experiment.

The influence of the cycle time is obvious, since panelling is a well known phenomenon during blow moulding when the cooling cycle is to short. The production manager will normally set the cooling cycle conservatively long to ensure only good bottles are produced.

In production the cycle time is actually governed by the quality of product. Not like the experiment where the cycle time was changed and the quality of the bottle checked. This different approach in the experiment was used because it enabled us to determine how cycle time affects quality. And from this, conclusions are made to determine how the cycle time can be improved.

The influence of the parison thickness is also significant. If the parison thickness increases, more plastic has to be cooled. This is the same effect as shortening the cooling cycle. There is also more plastic in the product which brings with it more internal stresses. This causes the additional deformation of the product.

	SS	Degr. of Freedom	MS	F	p
Intercept	1966.036	1	1966.036	71.79361	0.000376
Cycle Time	539.168	1	539.168	19.68878	0.006782
Parison Thickness	1671.992	1	1671.992	61.05604	0.000550
Water Flow	49.070	1	49.070	1.79189	0.238335
Mould Design	503.778	1	503.778	18.39643	0.007796
Cycle T*Parison T	3.572	1	3.572	0.13044	0.732733
Cycle T*Water T	0.308	1	0.308	0.01125	0.919661
Parison T*Water T	0.013	1	0.013	0.00048	0.983317
Cycle T*Mould	1.501	1	1.501	0.05480	0.824198
Parison T*Mould	11.122	1	11.122	0.40615	0.551964
Water T*Mould	3.572	1	3.572	0.13044	0.732733
Error	136.923	5	27.385		

Table 4: Results from ANOVA showing the relationship between variables.

ANOVA shows that a combination of theses variables does not have a significant influence (Table 4).

The ANOVA shows that the mould's cooling design does have a significant influence on the quality of the bottle (Table 4). This emphasise why it is necessary to look critically at the design of the cooling channels of the mould.

1.8.2 Comparison of bottle vs CAD model

The second method used, to determine the quality of the bottles, was a comparison of the actual bottles with the CAD model of the mould cavity. The measurements were done on a coordinate measurement machine (CMM). The CMM was programmed to measure about 385 points on each bottle. The program made it possible to measure similar points on each bottle.

The data were arranged in histograms, showing the percentage of points in each error category. In Figure 13 a comparison of the measured points on bottles, which were produced at different cycle speeds, can be seen. It is clear that there is a number of points which has errors of -2 mm and larger. The minus sign indicate that the point measured on the actual bottle is deeper than the same point on the CAD model. This indicates that part of the bottle is distorted inwards. It also indicates a possible brim fill volume problem.

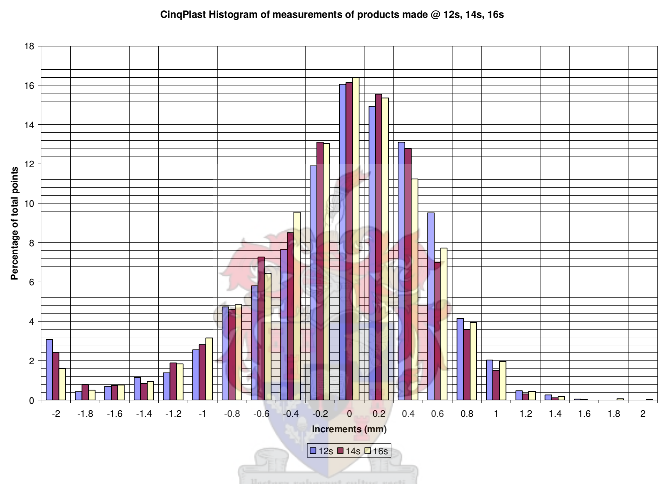


Figure 13: Histogram of measured points on bottles produced from CINQPLAST mould.

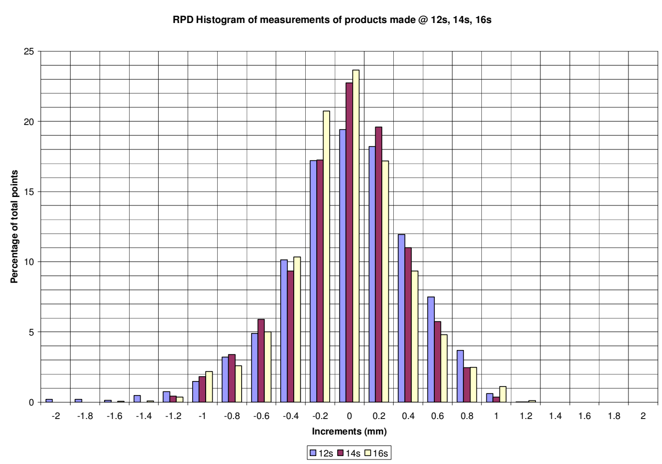


Figure 14: Histogram of measured points on bottles produced from RPD mould.

The same was done for the bottles produced from the mould designed by the RPD. In Figure 14 the comparison between the points, measured on bottles produced at different cycle times, can be seen. There are some points which are in the -2 mm region, but this is less than 0.5% of the total and only for the bottles produced at 12s.

In Figure 15 a comparison is made between the measurements of the bottles produced in the CINQPLAST mould and that produced in the RPD mould. It is clear that the bottles from the RPD mould show much less deviation from the CAD model, than the bottles from the CINQPLAST mould. The CAD model is, by default, the representation of the mould cavity.

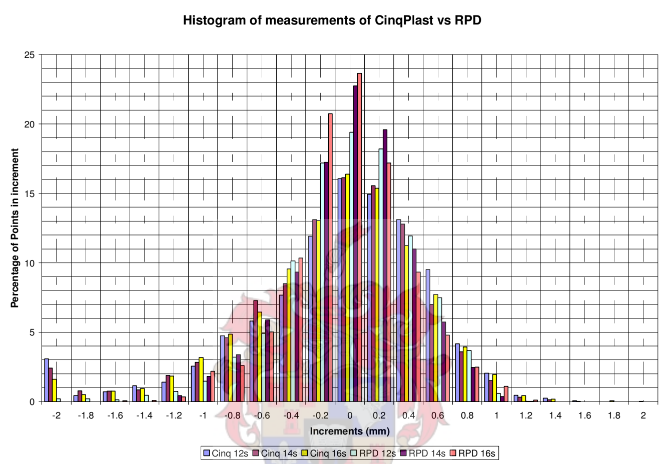


Figure 15: Comparison between measurements of bottles produced in CINQPLAST mould and that produced in RPD mould.

There are certain regions on the bottles, which are more distorted than others. The side panels of the bottles tend to distort more, since it is large flattish areas, which has low strength characteristics by design (Figure 16). The blue and brown dots in Figure 17 give an indication of the other areas, where the bottles deviated from the CAD model.

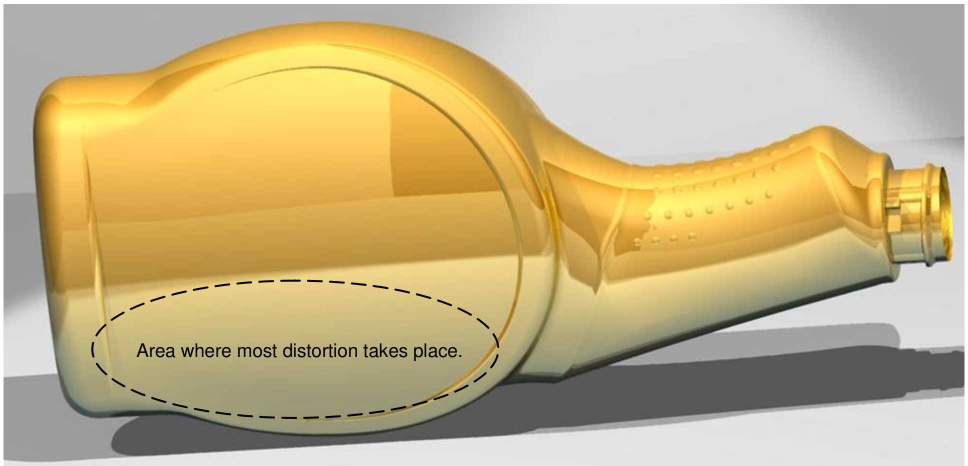


Figure 16: Indication of areas where the most distortion takes place.

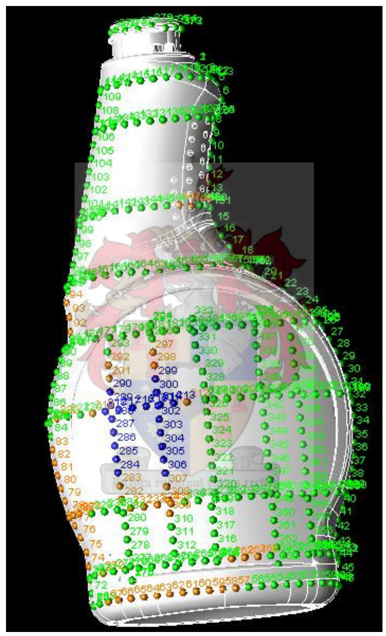


Figure 17: Measured points on sample bottles.

The exact location of the measured points can be seen in Figure 18, Figure 19 and Figure 20. This can then be compared with the graphs in Figure 21, Figure 22 and Figure 23 which help to understand where the distortion in the bottles takes place.

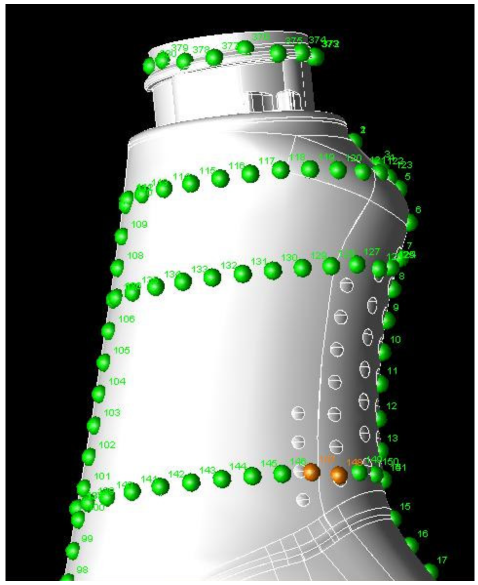


Figure 18: Points measured in the neck area of the bottle.

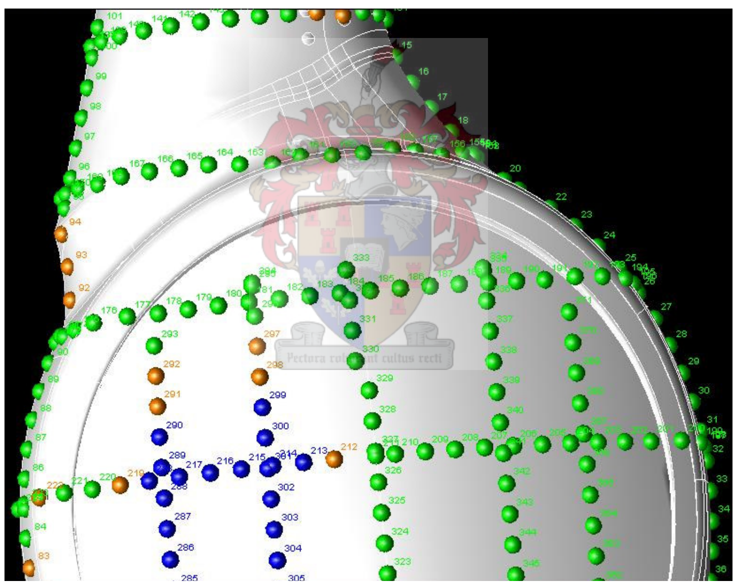


Figure 19: Points measured in the middle section of the bottle.

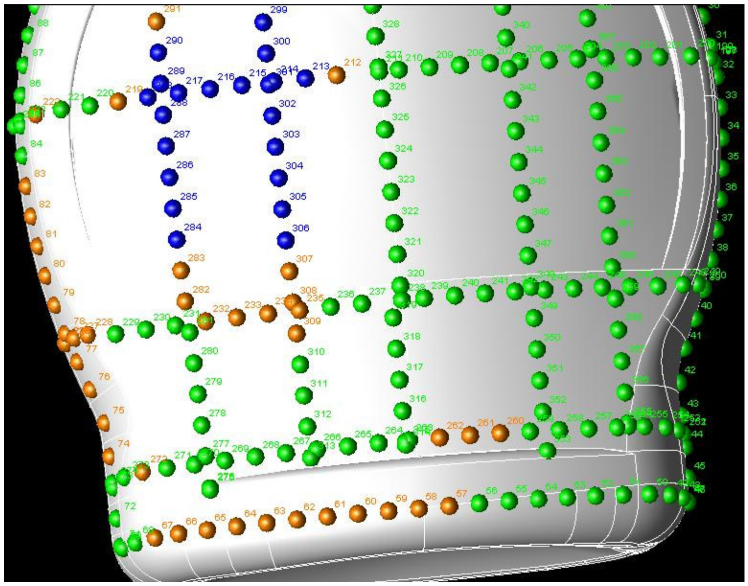


Figure 20: Points measured in the base area of the bottle.

The extend of the deformation can be illustrated further by comparing the graphs (left hand side) in Figure 21, Figure 22 and Figure 23. These figures are scatter plots of the total deviation between the CAD data and correlating measured points. The most deformation in all the cases, was recorded in the region of point #280. The deviation became worse as the cycle time shortens. The values on the Y axis of each graph show the deviation from the CAD model in mm. If the value is negative, it is an indication that the measured point is deeper than the CAD model.

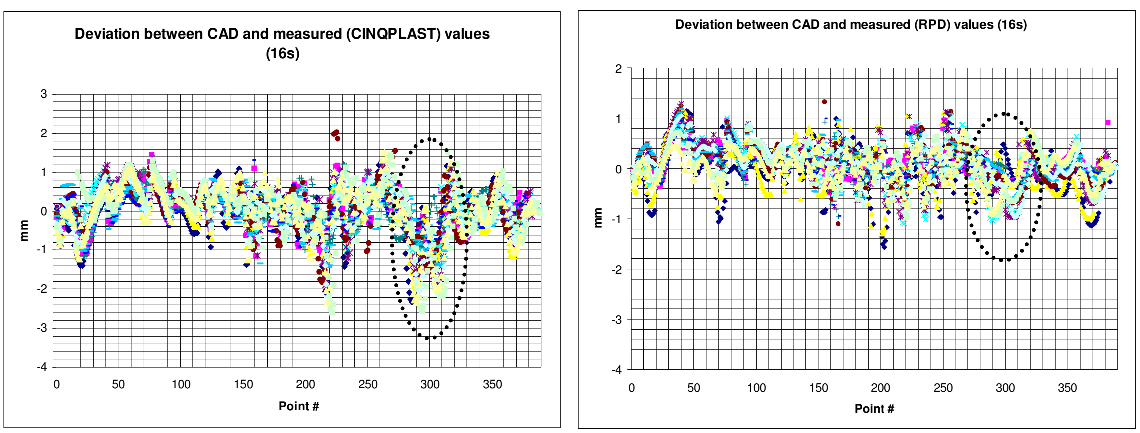


Figure 21: Deviation between CAD and measured values at 16s.

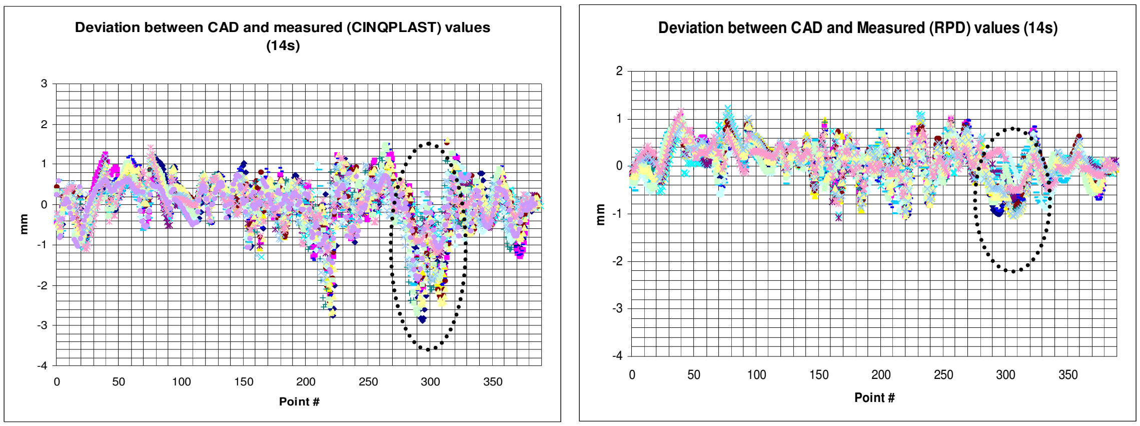


Figure 22: Deviation between CAD and measured values at 14s.

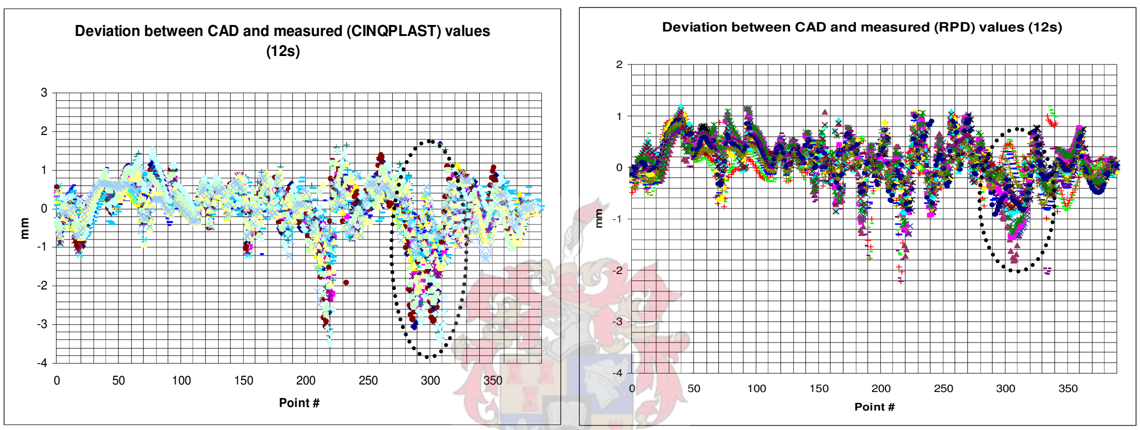


Figure 23: Deviation between CAD and measured values at 12s.

The measured data for the bottles, produced in the RPD mould, are plotted in the same way as that of the bottles produced in the CINQPLAST mould. The graphs can be seen (right hand side) in Figure 21, Figure 22 and Figure 23. It is clear that the bottles which were produced at cooling cycle times of 16 and 14 seconds have less deviation, especially in the region of point #280, than those produced in the CINQPLAST mould. The deviation comparison of the bottles produced at a cooling cycle time of 12s also indicates that the RPD mould produces bottles with less deviation from the CAD model than those produced in the CINQPLAST mould.

1.8.3 Comparison of IR photos

The infrared photos supplied good information on the distribution of the heat within the product. It shows all the hot spots. These hot spots are in the regions, where the plastic is the thickest. Many photos were taken, but the ones of interest are those of the bottles which have the same wall thickness as the production bottle, but produced at different cooling cycle times.

The first comparison can be made on the bottles as shown in Figure 24 and Figure 25. The comparison shows that the bulk temperature of the bottle produced in the CINQPLAST mould is cooler than the one produced in the RPD mould.

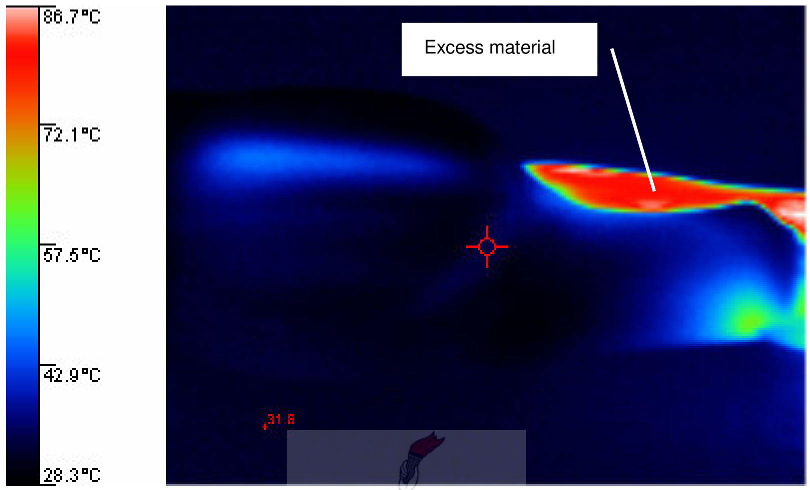


Figure 24: Bottle from RPD mould produced at 16s, with 39g product mass.

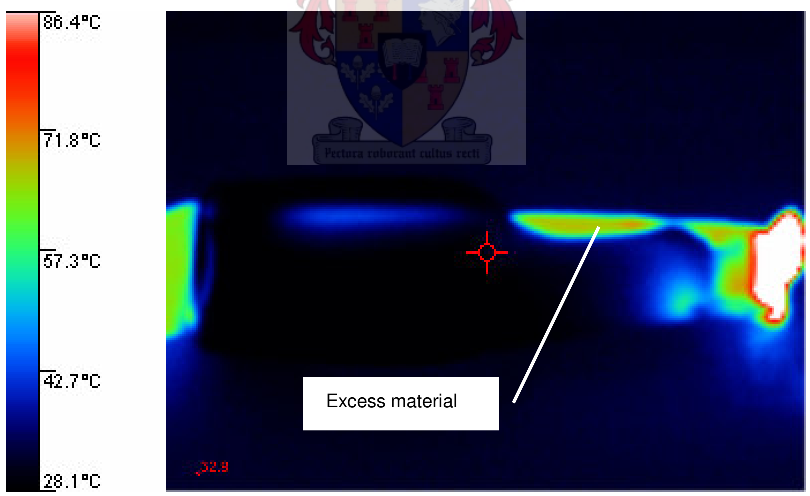


Figure 25: Bottle from CINQPLAST mould produced at 16s, with 40g product mass.

The main temperature differences are in the areas, where the excess material, is cooled. This is true for all the bottles and is the result of the design of the mould. The reason for this is that the grooves, where into the excess material goes during the pinch-off operation, are spaced differently on the two moulds. On the CINQPLAST mould the grooves on the one side of the mould are spaced at an offset of 50% to those on the other mould halve (Figure 26). This shortens the distance between the plastic centre and the cold metal considerably when compared with the design of the RPD mould (Figure 27) which has no offset.

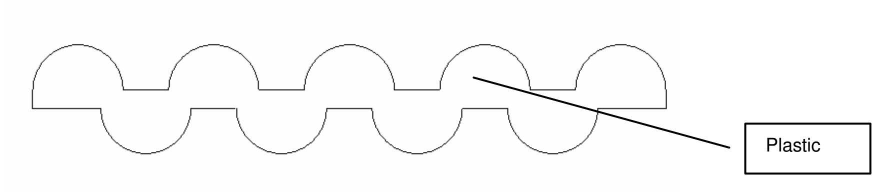


Figure 26: Pattern of excess material on CINQPLAST mould.

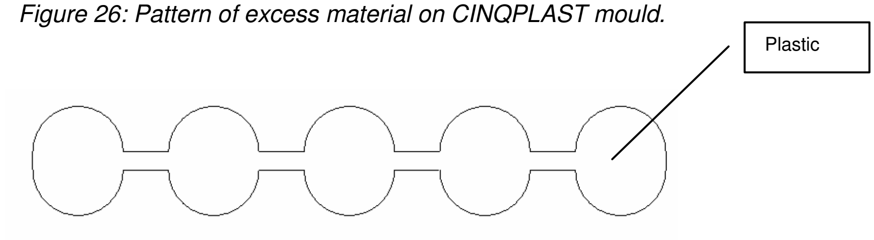


Figure 27: Pattern of excess material on RPD mould.

During the experiment this, however, did not prove to be a problem and it did not influence the cooling performance of the mould, but this was not in the scope of the experiment.

If bottles produced at 12s are compared (Figure 28 & Figure 29), then it is also clear that the excess material temperature differs considerably. The neck from the bottle produced in the CINQPLAST mould seems cooler than the same area on the RPD bottle, although only just, but again this is bulk temperature and does not say anything about surface temperature.

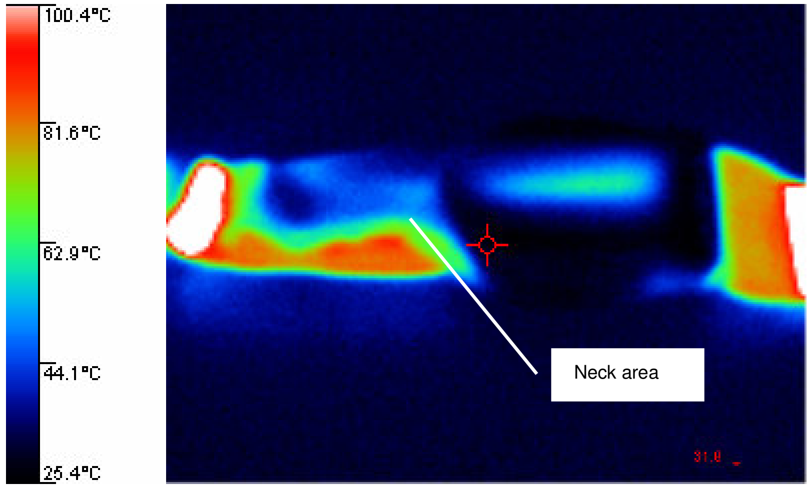


Figure 28: Bottle from CINQPLAST mould produced at 12s, with 39g product mass.

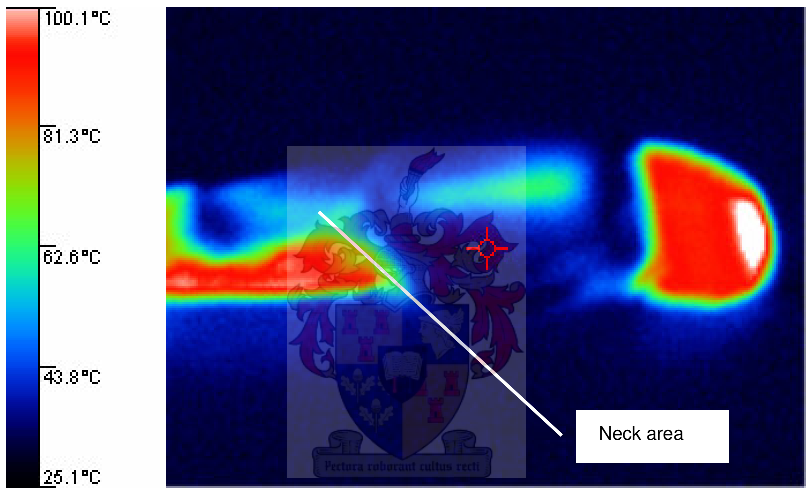


Figure 29: Bottle from RPD mould produced at 12s, with 39g product mass.

There is a clear indication that the RPD mould cooled the bottle surface better than the CINQPLAST mould. The feature, which gives an indication of this, is the heat marks formed on the body of the bottle when a bottle is ejected at a high temperature. In Figure 30 to Figure 33 is it very clear that the heat marks on the RPD bottles (right hand side) are much smaller than those on the bottles from the CINQPLAST mould (left hand side). The production parameters for these bottles can be seen in Table 2.

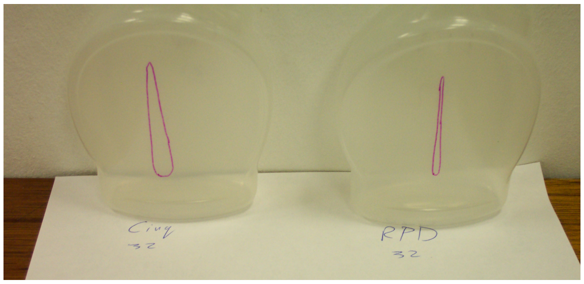


Figure 30: Heat marks marked in purple on bottle from experiment 32.

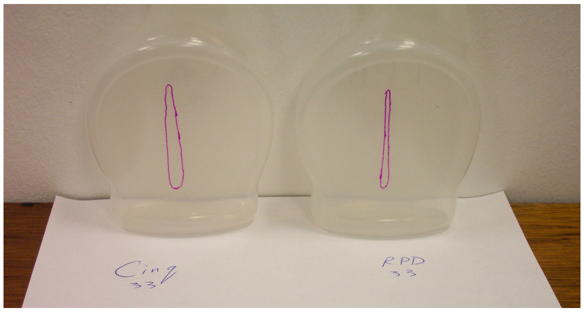


Figure 31: Heat marks marked in purple on bottle from experiment 33.

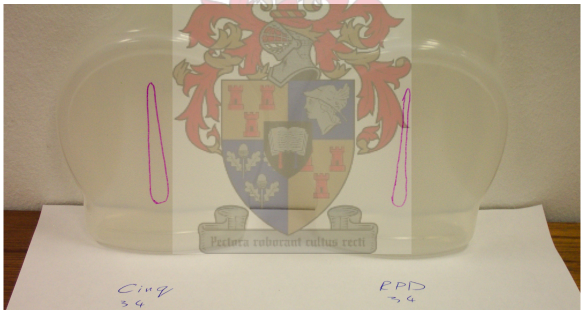


Figure 32: Heat marks marked in purple on bottle from experiment 34.

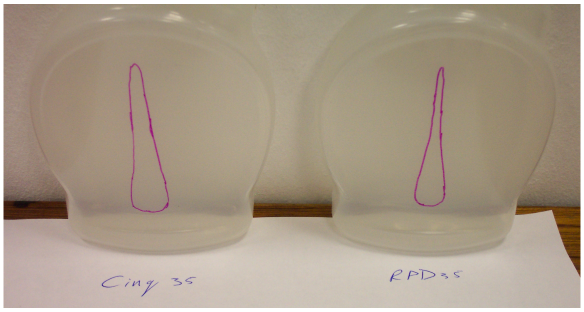


Figure 33: Heat marks marked in purple on bottle from experiment 35.

These heat mark differences do not give a quantative result, but it does give a qualitative idea of the surface cooling which takes place in the mould. I

1.9 Conclusion

The question is, what cycle time reduction is achieved? This can, in part, be answered by comparing the left hand graph in Figure 21 with the right hand graph in Figure 23. This will indicate that the bottles produced in the RPD mould, with a 12s cooling cycle, are of the same or better quality than the bottles from the CINQPLAST mould produced at 16s. The total cooling cycle saving is 4 seconds, which is 25% of the total cycle time.

As a further comparison, Figure 34 shows that a bottle from the CINQPLAST mould (cooling cycle time of 16s) differs more from the CAD model than the bottle produced from the RPD mould (cooling cycle time of 12s). The green line shows what happened to the bottle from the CINQPLAST mould, which was produced at the same parameters as the RPD mould. It is very clear that the CINQPLAST mould produced a bottle with much bigger deviation than the RPD mould.

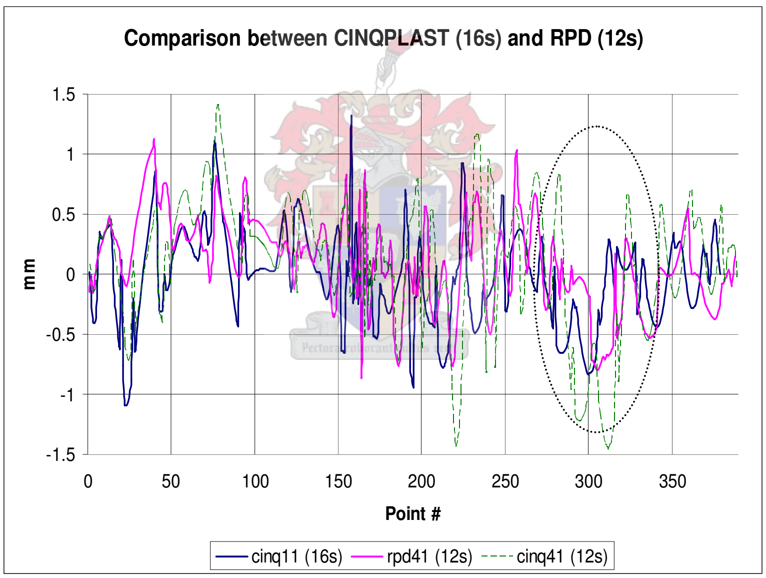


Figure 34:Bottle quality comparison.

The infrared photos shows that the bulk temperature of the bottles produced in the CINQPLAST and RPD mould are very close to identical. The heat marks on the bottles show clearly the surface temperature of the bottles produced in the RPD mould is much lower than that produced in the CINQPLAST mould.

This test provided ample evidence that the cooling design does have a big influence on the quality of the bottle. The improved design enables the production of bottles, with acceptable quality, at a cycle time reduced by 25% form the current cycle time. This improvement contributes directly to increased production capacity, without any capital expenditure. Since the price of the mould is the same as that of a conventional design.

If the cycle time improvements are converted into monetary values then it becomes clear what the saving will mean to CINQPLAST. If a production year of 320 days is assumed with production running 24 hours per day, then the extra available capacity on a single machine will be:

$$320 days \times 24h \times 0.25_{improvement} = 1920h$$

If an hourly rate of R500/h is assumed for such a machine, then the saving is R 960 000 per year. It can also be interpreted the other way around, for every 4 machines utilising this improvement, a fifth machine will be saved.