Cycle Time Reduction in Injection Moulding through Simulation Study of Conformal Cooling Channels

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Abstract— Plastic injection molding is very used in today's manufacturing industry. In injection molding process, the cooling channel performance is one of the most vital factors because it has significant effect on both production rate and the quality of the plastic part. In order to reduce the cycle time and control the uniform distribution of temperature, it is necessary to create conformal cooling channels which conform to the shape of the mold cavity and core. Cycle time of a part in injection molding process is very important as the rate of production and quality of the products manufactured depends on it. Cycle time is the total time from beginning to the end of the process. Cycle time includes process time. This can be achieved through various techniques like external cooling, improve capacity of cooling tower, Install Flow Meters, Proper design of the cooling channel, Optimization Of Injection Molding Machine Parameters like Cooling Time, Back Pressure And Plasticizing Limit, Optimum Height for Counter Flow Cooling Tower.

Key words: Injection Molding, Conformal Cooling, Simulation, Mold Flow, Cycle Time, Injection Molding Machine Parameters

I. Introduction

Thermoplastic injection molding is an eminent process for manufacturing effortless and complex shaped products in short time and at low cost. Now a days there is a need for optimizing the processing parameters to intensify productivity. In the cycle time the cooling time can represent more than 60% of the injection cycle. Cutting down the cycle time for each part is a major concern in injection molding machine. In order to set the processing parameters, they commonly follow on experience and trial-and–error method. This process becomes inadequate and unpractical for complex products. As a consequence the designers need a more powerful tool to analyze and to optimize the process. This project is to design an experiment to optimize a cooling cycle time of product by using conformal cooling channel system. The motive of this paper is to study on the cooling in injection molding, since it has large impact on production cost and quality of produced part. Traditional mold cooling designed is practical experience and designer's knowledge. This method is simple and may be efficient in practice, but becomes less feasible for the complex part. Therefore many researchers have proposed some optimization methods to undertake this problem

In this work, the Plastic Pot was taken up to express the whole optimizing process. The modeling is done by one of the modeling software CATIA V5. It is then imported to Mold flow by IGES format. The plastic material used for the product is Polypropylene. The thickness of the product is 2.5mm & Part weight is 110 gram. There are three mesh types in Moldflow software including mid plane, 3D and Fusion. Due to the thickness of the plastic product, we adopt the surface meshes (Fusion) and used grid mesh tool to modify mesh defects.

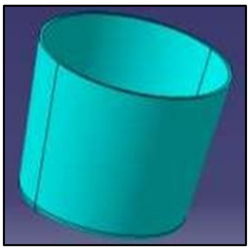


Fig. 1: Plastic Pot

In this project, positions of conformal cooling channel are considered as design parameter to minimize the cooling cycle time. Plastic Bowl thickness and material are assumed to be predetermined according to the strength requirements of the structure. Minimum cooling line to line distances recommended by the industry are considered. Cooling line diameter 4 mm considered.

It should be noted that processing parameters like coolant flow rate, barrel temperature, injection pressure, injection speed and process conditions like holding pressure, Holding time and cooling time have significant effect on the quality of the part in terms of warpage and shrink mark. In order to ensure the quality of the part, one should therefore consider these factors. However, the present study focuses only on the position of the conformal cooling lines. Selection of optimum processing parameters is outside the scope of this study.

II. Literature review

Various researchers work regarding the optimization in cooling time by using conformal cooling channel, improve capacity of cooling tower, Optimization Of Injection Molding Machine Parameters like Cooling Time, Back Pressure And Plasticizing Limit are discussed below,

Eric Boillat et al. [1] reported potential of layered manufacturing processes (LMP) is their capacity of producing injection tooling equipped with complex cooling systems. Tailored cooling systems may help to shorten the mold cycle time. They can also reduce the parts defects, like warpages or residual stresses, which are usually due to highly unfavorable cooling processes. The first objective of this paper is to present a methodology for the optimal design of cooling systems in three-dimensional injection molds. In the next part of this paper, they have compared a conventional mold and a mold equipped with a cooling system optimized by means of the proposed methodology. The conclusion is that the optimization of the cooling system doubled the productivity of the mold.

Eric Dimla [2] inspected the temperature profile along the mold cavity wall to improve cooling system design to find out optimum and efficient design. The Simulated models were made from Solidworks and Moldflow for straight and conformal cooling Channels.

K. Poornima et al. [3] have compared the straight drilling cooling channel (SDCC) with conformal cooling channels. This was done by investigating multi-cavity rectangular plate for inappropriate draft angles and nominal wall thickness. Designing of rectangular plate was done using Pro-E Wildfire 5 and imported to Autodesk Moldflow for analysis. They have conclude the spiral cooling channel needed the least cooling time.

James Henderson, Aaron K. Ball [4] By Manipulating cooling time, back pressure, and plasticizing limit on the injection molding machine to reduce the cycle time and keep the quality of the part that deal with problems such as shrinkage, flash, and other abnormalities.

Menglei Wang [5] the air/water ratio has a direct impact on the efficiency. There is a linear relationship between them, and the greater the ratio, the higher the efficiency. The environment influences are shown in two characteristics: the quality and the flow rate of inlet air. They have a greater impact on the cooling capacity. It is found that the cooling capacity decreases with the increase of the inlet air enthalpy and the decrease of the inlet air flow rate.

III. Methodology

The introduction of conformal cooling significantly simplifies the injection molding cooling system design methodology. In the conformal cooling situation, the heat transfer is localized in a small region between two adjacent cooling channels. This feature suggests that we first design a cooling "cell" composed of the small region between the adjacent cooling lines and then map the solution to the entire mold. The flexibility of Solid State Fermentation (SFF) processes makes this modular approach possible by minimizing the manufacturing constraint that must be applied. This strategy simplifies the cooling line design by providing a sequential approach which provides a global solution by the addition of many local solutions. While the design process is simplified, the resulting cooling line designs can be quite complex and take full advantage of the flexibility of SFF processes. Fig. illustrates this design strategy by using a generic part with a hemispherical dome and a flat bottom. As shown in the Fig. 2, the part is first divided into two cooling Zones (a hemisphere and a flat surface) based on its geometry. Then in each cooling zone the conformal cooling surface is constructed and the cooling channel topological structure is defined. After that the system of cooling channels is further decomposed into small elements called cooling cells. The heat transfer analysis and the cooling system design is based on these cooling cells and is then mapped to the entire mold. This modularized design strategy is not sensitive to the part geometry therefore it keeps the same design simplicity no matter how complex the part geometry is.

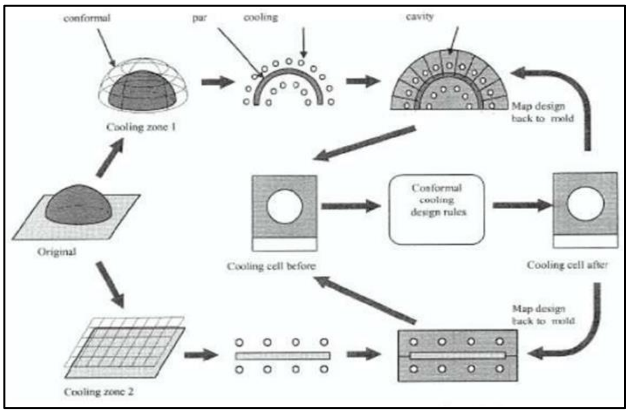


Fig. 2: Steps for the Modularized Cooling Line Design for a Generic Part

After the cooling system has been decomposed into simple cooling cells by the method discussed above, the design rules are applied to these cooling cells in order to obtain cooling channel design parameters and process conditions. In this, six design rules are proposed and design windows are constructed for the cooling line design based on individual cooling cells. These rules include design for conformal cooling condition, design for coolant pressure drop, design for coolant temperature uniformity, design for sufficient cooling, design for uniform cooling and design for mold strength and deflection.

A. *Design for Conformal Cooling Condition*

As the name implies, conformal cooling is used to signify cooling channels that conform to the surface of mould cavity. However, in this work, the term "conformal cooling" has a further significant that is related to the transient heat transfer within the mold. When a mold is started up it takes some time before the mold reaches a steady state operating temperature. Fig. 3 shows the mould surface temperature histories recorded by the thermocouples for both the mould with straight conformal cooling channels and that with straight cooling channels. As one can see from the Fig., the mold surface temperature of the core with straight cooling channels tracked over 25 successive injections starting from the coolant temperature of 12° C and reaching a cycle average steady state temperature of approximately 55° C. However, if the cooling lines are placed very close and conformal to the mold surface the steady state condition is reached very quickly. As illustrated in Fig. 3 the cycle average temperature of a conformal cooled core reaches its steady state value after one injection cycle. Our operational definition of conformal cooling then is that the cycle average temperature reaches its steady state value within one injection cycle. As shown by experiments, the difference of the mold surface temperature profiles we just discussed above significantly affects the part quality and productivity.

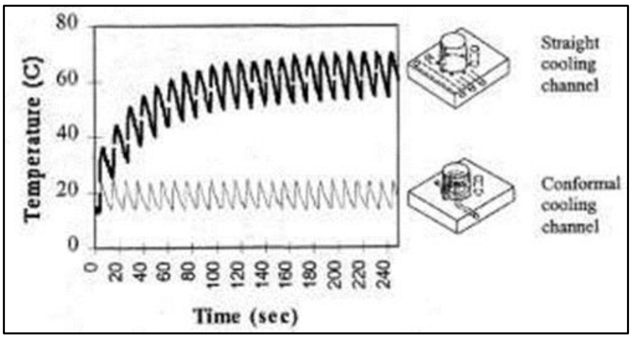


Fig. 3: Comparison of Mold Surface Temperature Histories for Straight Channel Cooling & Conformal Channel Cooling

The difference between two cases shown in Fig. 3 has to do with the rate of the energy transfer into the mold over successive injections and the thermal inertia of the mold. As the hot plastic comes in during each successive injection, heat transfer takes place across the plastic mould interface and a heat pulse is conducted through the mold maternal itself. This heat pulse warms up the mould material as it propagates toward the cooling channels and is eventually removed in the cooling water. If the cooling channels are far from the mold's surface, successive heat pulses keep raising the temperature of the mould until the heat pulse propagating in is balanced by heat extraction by the coolant. If the cooling channels are close to the mold surface, the effective thermal mass of the tool is confined to that region between the surface and the cooling channels and is much reduced. In addition, the conduction path from the surface of the tools to the cooling lines is reduced. As a result, the steady state condition is reached much more rapidly and can in fact be attained within one injection cycle.

An energy balance may be written for the active portion of the mold that is the portion between the surface and the cooling lines.

$$\rho_m C_m l_m \frac{dT_m}{dt} + \frac{h\pi K_m}{2K_m W + h\pi D l_m}(T_m - T_c) = \frac{\rho_p C_p l_p (T_{melt} - T_{eject})}{t_{cycle}} \quad (1)$$

The first term in Equation (1) captures the thermal mass of the tool and the build-up of heat as the temperature of the tool increases. The second term in Equation (1) captures the transfer of heat by conduction through the mold and then convection into the cooling fluid. The right hand side of Equation (1) captures the source of the heat, which is the cooling down of the plastic. This first order differential ordinary differential equation has the solution of the form shown in Equation (2) where Tms is the cycle averaged mold temperature at steady state and τ is the time constant of the system. Equations (3) and (4) give the expressions for cycle averaged mold temperature and the time constant respectively. Our definition of conformal cooling can now be stated formally by requiring that τ be less than or equal to one injection cycle time. Fig. 4 shows a prediction of Equation (2) superimposed on the experimental results previously shown in Fig. 3. As can be seen, there is reasonably good prediction with the cycle average temperature.

$$T_m(t) = T_{mo} + (T_{ms} - T_{mo}) e^{\frac{-t}{\tau}} \quad (2)$$

$$T_{ms} = T_c + \frac{\rho_p C_p l_p (2K_m W + h\pi D l_m)(T_{melt} - T_{eject})}{h\pi D K_m t_{cycle}} \quad (3)$$

$$\tau = \frac{\rho^m c^m l_m (h\pi D l_m + 2K^m W)}{h\pi D K_m} \quad (4)$$

A limiting case of Equation (4) is that where the heat transfer to the fluid is very efficient and we can then examine the limiting case where the heat transfer coefficient goes to infinity. In this case, the expression for the time constant reduces to the form shown in Equation (5). In this simplified expression we see that the important material property for the mold is the thermal diffusivity which is *Km/ Pm Cm.* We also see that the time constant is proportional to the square of the distance between the surface of the mold and the cooling channels. This simplified expression makes clear the importance of considering this as a transient heat transfer calculation. If this were a steady state heat transfer problem than doubling the thermal conductivity of the mold would allow the channels to be placed twice as far away. However, as we can see from Equation (5) if we double the thermal conductivity and place the channels twice as far away the time constant in fact increases by a factor of 2. Thus, while the material properties are important, the geometry (as seen by the square of the distance of Equation (5)) is even more important.

$$\tau = \frac{\rho_m c_m l^2_m}{K_m} \quad (5)$$

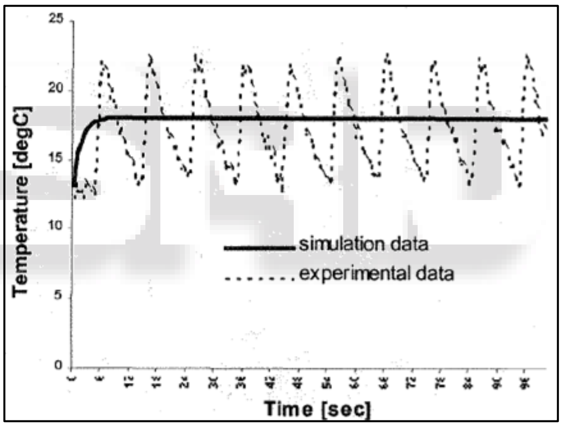


Fig. 4: Comparison of the Experiment Data Vs Simulation Data for the Mould Surface Temperature Profile during Successive Injections [8]

IV. INJECTION MOULDING PROCESS

Injection moulding is the most widely used polymeric fabrication process. It evolved from metal die casting however unlike molten metals, polymer melts have a high viscosity and cannot simply be poured into a mould. Instead a large force must be used to inject the polymer into the hollow mould cavity. More melt must also be packed into the mould during solidification to avoid shrinkage in the mould. The injection moulding process is primarily a sequential operation that results in the transformation of plastic pellets into a moulded part. Identical parts are produced through a cyclic process involving the melting of a pellet or powder resin followed by the injection of the polymer melt into the hollow mould cavity under high pressure. One disadvantage with injection molding is that the mold tends to be very expensive and modifications of the mold and the design of the part that are to be produced are common and cost-consuming.

Computer-Aided Engineering (CAE) is an essential tool for simulation of the injection molding process. Its proper use will minimize the amount of redesign and retooling. There are three main stages in the injection moulding cycle: stage 1- injection followed by stage 2- holding pressure and plasticating and finally stage 3- ejection of the moulded part.

A. Stage 1: Injection of the Plastic Melt into the Mould

In stage 1, the mould is closed and the nozzle of the extruder is pushed against the sprue bushing of the mould. The screw not rotating at this point is pushed forward so that the plastic melt in front of the screw is forced into the mould. Sprue gate design and location as shown in fig. 7. The gate location analysis is done on the bowl with different location. The best gate location for the bowl is at the center of the part in order remove the defects like weld line, melt line and sticks. Sprue gate used for the bowl due to symmetry and single cavity part. The sprue gate diameter is ϕ6mm and length is 100mm.

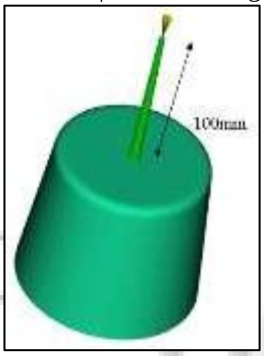
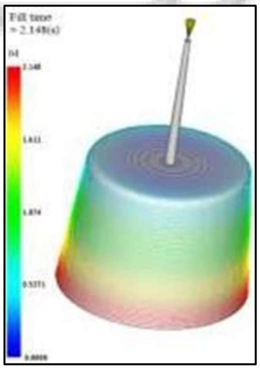


Fig. 7: Sprue gate location

As per the analysis report fill time required to fill all the material as per part profile it takes 2.148 second as shown in below fig. 8. The flow of the material start from the bottom root of the part and fill the part with symmetry along all direction.



Also the injection pressure required to fill the material at the injection location is shown in fig. 9.

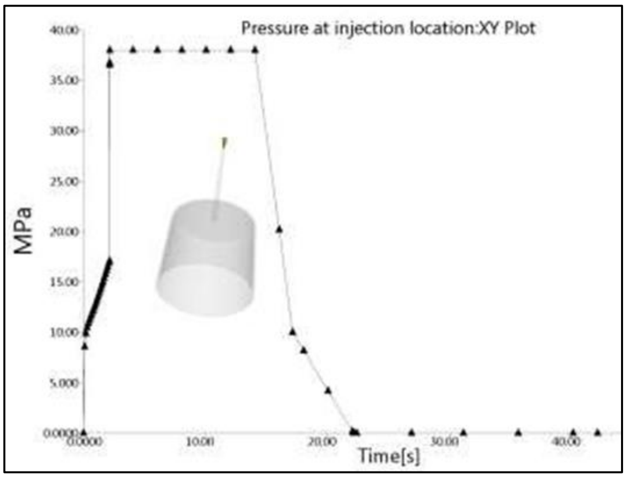
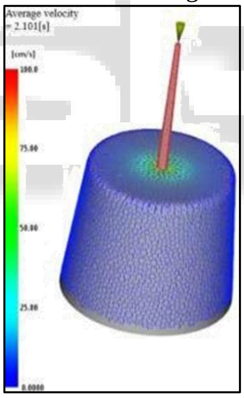


Fig. 9: Pressure at Injection Location

B. Stage 2: Holding Pressure & Plasticizing

When the mould is completely filled, the screw remains stationary for some time to keep the plastic in the mould under pressure, this is called the “hold” time. During the hold time additional melt is injected into the mould to compensate for contraction due to cooling. Later, the gate which is the narrow entrance into the mould freezes. At this point the mould is isolated from the injection unit. However, the melt within the mould is still at high pressure. As the melt cools and solidifies the pressure should be high enough to avoid sink-marks but low enough to allow easy removal of the parts.



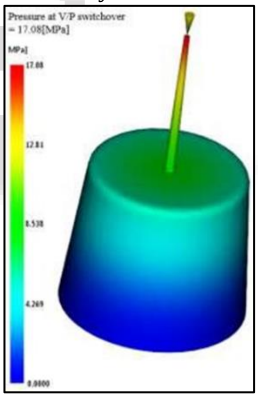


Fig. 10: Average Velocity Fig. 11: Pressure Switch Over

Maximum pressure observed at the gate area is 100cm/s and at part entry level it is 50 cm/s. In allover part uniform pressure of 12cm/s is observed. In fig. 11 vp switchover point shown. The top of the part is shown in blue color which is filled by velocity pressure conversion only. (i.e. injection pressure is 0). During the plastication stage, the material is pushed forward from the feed hopper through the barrel and towards the nozzle by a rotating screw. When the gate freezes, the screw rotation is started. The period of screw rotation is called screw “recovery”. The rotation of the screw causes the plastic to be conveyed forward. As the plastic moves forward, heat from the electric heater bands along the barrel and shear starts to melt the plastic. At the discharge en of the screw, the plastic will be completely melted. The melt that accumulates at the end of the screw pushes the screw backward. Thus the screw rotates and moves backward at the same time. The rate at which plastic melt accumulates in front of the screw can be controlled by the screw backpressure, that is, the hydraulic pressure exerted on the screw. This also controls the melt pressure in front of the screw. In fig. 12 it shows the clamping force required throughout the injection molding cycle.

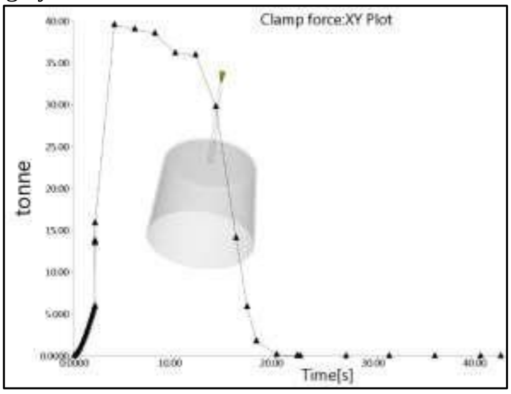


Fig. 12: Clamp Force Require for the Cycle

When sufficient melt gets accumulated in front of the screw, the rotation of the screw stops. During screw recovery the plastic in the mould is cooled but typically the cooling is not finished by the end of screw recovery. As a result, the screw will remain stationary for some period until cooling is completed. This period is often referred to as "soak" time. During this time additional plastic will melt in the extruder from conductive heating. Also, the melted material will reach more thermal uniformity, although the soak time is usually too short to improve thermal homsignificantly.

C. Stage 3: Ejection

When the material in the mould has cooled sufficiently to retain its shape, the mould opens and the parts are ejected from the mould. When the moulded part has been ejected, the mould closes and the cycle starts over again.

V. MOLD FLOW ANALYSIS

This chapter contains the simulation result and comparison. The simulation results are used for calculating the cooling time required for the plastic part. Single simple plastic part with four different cooling channel layouts is used for checking the cooling time and behaviour of the plastic part. The cooling time calculated from analysis result obtains from AUTO DESK mould flow. The cooling time for all four samples calculated from AUTO DESK mould flow result is shown in images,

A. Conventional Cooling Systems in the Cavity & Core Sides

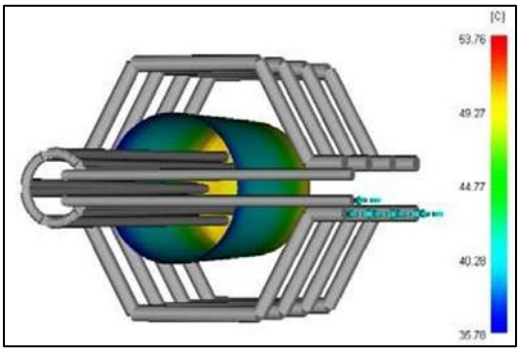


Fig. 13: Temperature Distribution On

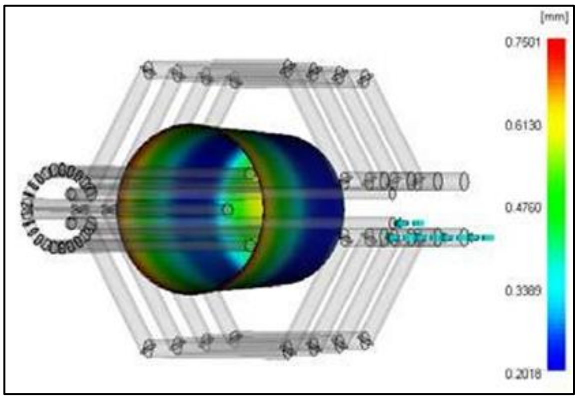


Fig. 14 Part's Deflection the Part's Surfaces

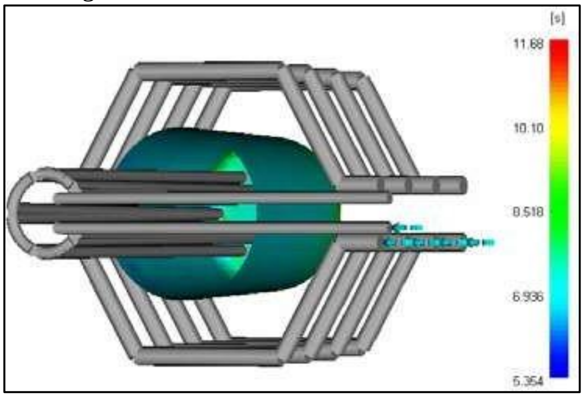


Fig. 15: Part's Cooling Time

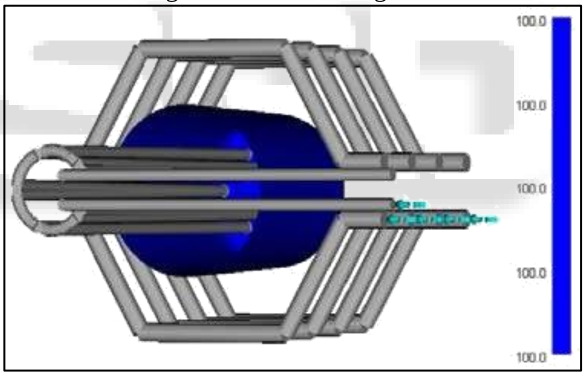


Fig. 16: Percentage Frozen Layer

B. Baffle Cooling Systems in the Cavity & Core Sides

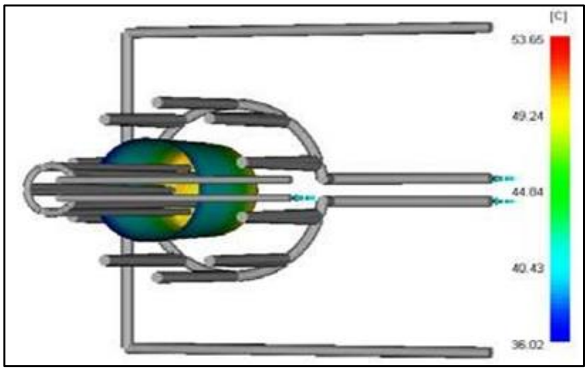


Fig. 17: Temperature Distribution

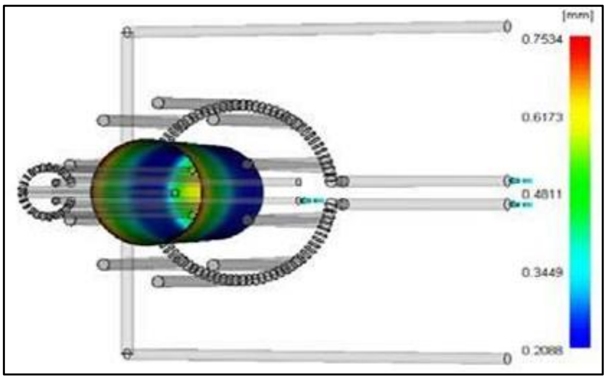
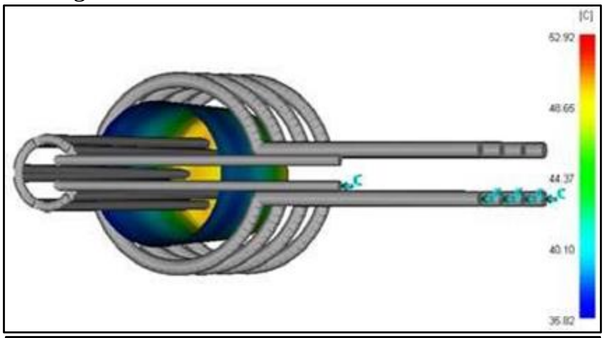


Fig. 18: Part's Deflection on the Part's Surfaces



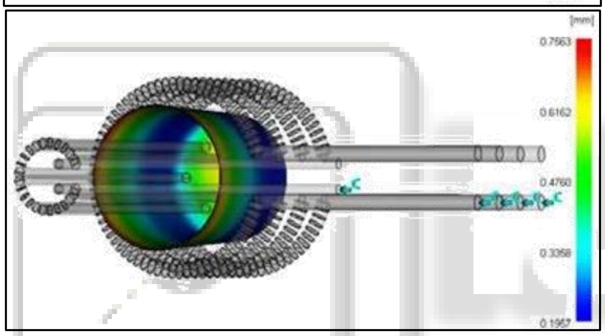


Fig. 20: Percentage Frozen

C. Conformal & Baffle Cooling Systems in the Cavity & Core Sides, Respectively

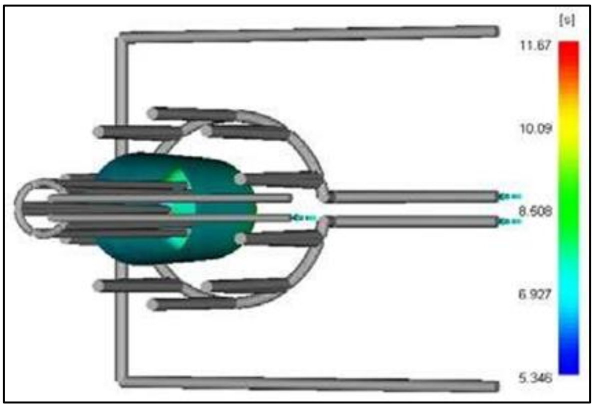


Fig. 21: Temperature Distribution

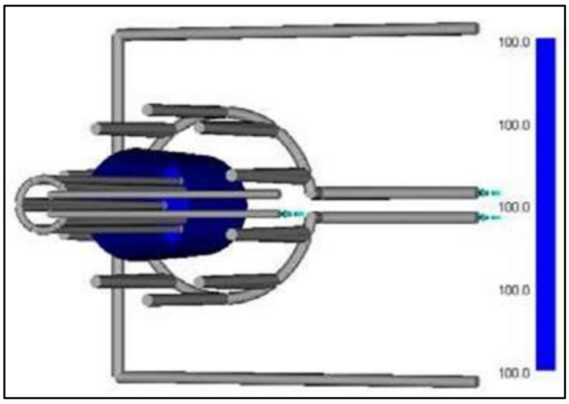


Fig. 22: Part's Deflection on the Part's Surfaces

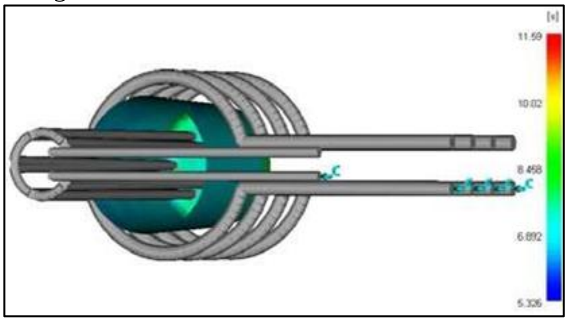


Fig. 23: Part's Cooling Time

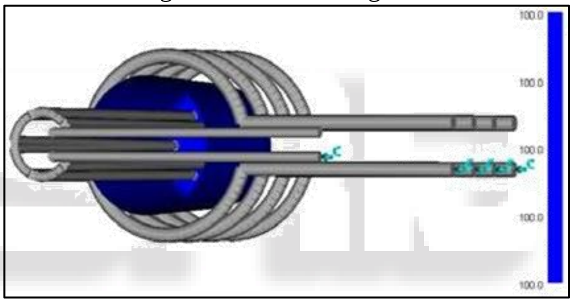


Fig. 24: Percentage Frozen

D. Conformal Cooling System in the Cavity & Core Sides

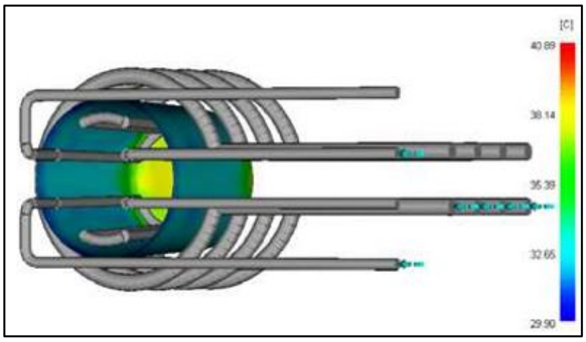


Fig. 25: Temperature Distribution

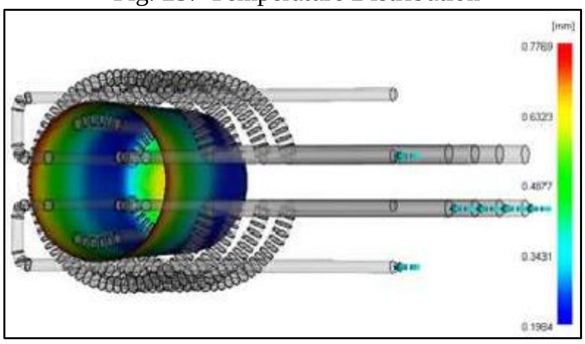


Fig. 26: Part's Deflection on the Part's Surfaces

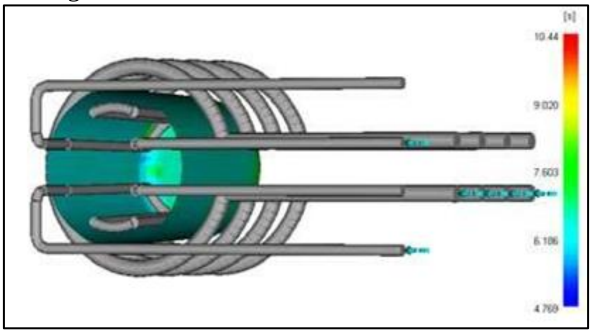


Fig. 27: Part's Cooling Time

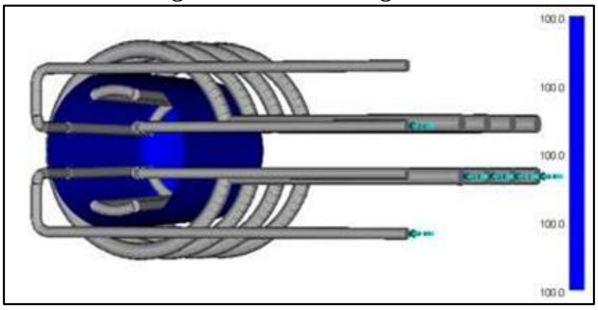
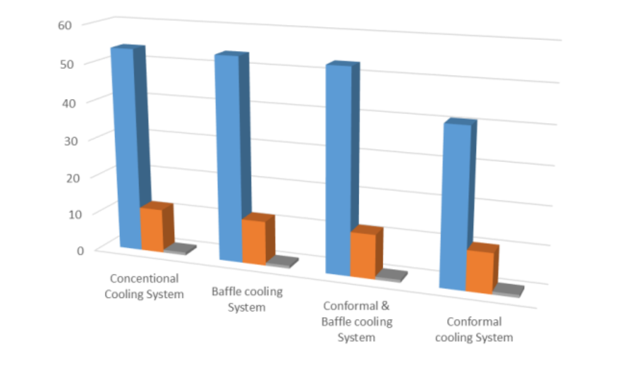


Fig. 28: Percentage Frozen

VI. RESULT & DISCUSSION

On the basis of comparison of the results shown in Fig., it can be concluded that conformal cooling channel is the most suitable cooling system for the plastic part among other cooling channels. It leads to better cooling properties due to exhibiting the lower volumetric shrinkage and the lower sink mark percentage. It also provides the lowest time to reach the ejection temperature, which translates to lower cooling time and reduced overall cycle time. In addition, the analysis also shows that fully conformal cooling (both in cavity and core) also reduces the warpage in the parts compared to the case of conventional (in cavity) with conformal (in core) and also compared to the case of conformal (in cavity) with baffles (in core). The conformal cooling channel shows uniform cooling that makes it most favorable cooling system. Conformal cooling channels requires less cooling time and provides near uniform cooling of parts because these cooling lines are located to follow the part geometry in the mold. Use of an injection molding analysis software provides valuable information for plastic product and mold design in reducing time and cost of production especially for complex parts. For the comparison of all the different analysis review are mentioned in below chart.



	Concentional Cooling System	Baffle cooling System	Conformal & Baffle cooling System	Conformal cooling System
part surface temperature	53.76	53.65	52.92	40.89
cooling time(.c)	11.68	11.67	11.59	10.44
Deflection(mm)	0.7501	0.7534	0.7563	0.7769

Fig. 29:

To demonstrate the temperature distribution, fig. 13 shows temperature profile for normal cooling channel. Since Part surface temperature is 53.76°C in all types of cooling channels, as a result, the normal cooling channel has non-uniformity of temperature distribution within the range from 35.78°C to 53.76°C as shown in fig. 13 which means that lowest value (35.78°C) is more than mold surface temperature which is 53.76°C. In contrast, small temperature variation from 40.89°C - 29.90°C is with the use of conformal cooling combination as can be seen in fig. 25.

In baffle cooling, temperature distribution lies within the range from 36.02°C to 53.02°C as shown in fig. 17. These cooling channels cannot provide the uniformity for all portions of part. Furthermore, we notice that the highest temperature in the whole analysis is reduced by more than 36%. Therefore, it can be concluded that this result gives clear evidence that conformal cooling channel provides better temperature consistency and uniformity than other cooling channels even in complex part.

The result of warpage analysis shows that minimum warpage (deflection) of 0.7501 mm was occurring with the use of normal cooling channels as can be seen in fig. 14, which is the lowest value as compared to other cooling channels. With the use of conformal cooling channel combination, the value of warpage increases to 0.7769 mm as can be seen in fig.26, because there was excessive and uniform cooling between the surfaces of the part. On the other hand, warpage increases significantly to 0.7534 mm with the use of baffle cooling channels as shown in fig. 18. It is because there was non-uniform cooling between the surfaces of the part. Furthermore, the results in fig. 22 shows that with the use of conformal cooling channel with baffle cooling channel, the warpage increases to 0.7563 mm.

However, in comparison between the conformal cooling channel and normal cooling channel, the value of warpage (deflection) in conformal cooling channel is slightly higher than that of normal cooling channels, due to normal cooling design solves the part distortion problem in a better way in some cases depending on the complexity and geometry of the part, such as the part in our case study. However, in conformal cooling channel, this slight increase in warpage is not a big issue that could influence the main function of cooling due to having more advantageous conditions of lowest time required to freeze, lowest volumetric shrinkage and lowest sink mark. These advantages organs of using conformal cooling channel outweigh the losses or disadvantages of such modest increase in warpage.

VII. CONCLUSION

The present study was analyzing the cooling channel layouts and their arrangement effects on cooling time. In order to improve productivity and to reduce the occurrence of defect in PIM, cooling channel design is of great importance. Optimization approach applied to cooling channels design optimization were suggested direct simulation-based optimization. Four different layout of cooling channel studies demonstrated to show the feasibility of the proposed optimization methods. Cooling design optimization of injection molding for a complex free-form molded part requires a complicated analysis steps, optimization strategy and appropriate computer aided tools. This Paper presents a systematic method for optimizing the cooling channels in order to obtain the target mold temperature and reduce the cooling time and the non-uniformity of temperature distribution of the molded part. To increase the computational effectiveness, both analytical method and simulation-based method were used successively.

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