PURDUE UNIVERSITY
GRADUATE SCHOOL
Thesis/Dissertation Acceptance

This is to certify that the thesis/dissertation prepared

By Suchana Akter Jahan

Entitled
OPTIMIZATION OF CONFORMAL COOLING CHANNELS IN 3D PRINTED PLASTIC INJECTION MOLDS

For the degree of Master of Science in Mechanical Engineering

Is approved by the final examining committee:

Hazim El-Mounayri
Chair

Andres Tovar

Jing Zhang

To the best of my knowledge and as understood by the student in the Thesis/Dissertation Agreement, Publication Delay, and Certification Disclaimer (Graduate School Form 32), this thesis/dissertation adheres to the provisions of Purdue University's "Policy of Integrity in Research" and the use of copyright material.

Approved by Major Professor(s): Hazim El-Mounayri

Approved by: Sohel Anwar 6/21/2016
Head of the Departmental Graduate Program Date

OPTIMIZATION OF CONFORMAL COOLING CHANNELS IN 3D PRINTED PLASTIC INJECTION MOLDS

A Thesis

Submitted to the Faculty

of

Purdue University

by

Suchana Akter Jahan

In Partial Fulfillment of the

Requirements for the Degree

of

Master of Science in Mechanical Engineering

August 2016

Purdue University

Indianapolis, Indiana

To God and my family.

ACKNOWLEDGMENTS

First, I would like to express my gratitude to my advisor, Dr. Hazim El-Mounayri for mentoring me and providing all the support throughout my Master's degree. I am also grateful to Dr. Andres Tovar, Dr. Jing Zhang and Dr. Razi Nalim for their guidance and help during my research endeavor. I would like to cordially thank Ms. Valerie Lim Diemer for her help in preparing this thesis.

My heartiest appreciation goes to my husband, Sayem, for always supporting me and helping me out during the long sleepless research nights. I am expressing my earnest gratefulness to my parents for loving me unconditionally and making me whatever I am today. I have made good friends with my lab-mates, Tong, Yi, Ehsan, Samuel, Mohamed and Rapeepan. Wishing them all good luck in their future.

This research effort is supported by Walmart and the Walmart Foundation. I and my team is highly grateful to them for this support and we are looking forward to work with them in future. Hewitt Molding Company (Kokomo, IN) provided the original injection mold model for this investigation. I appreciate their help and technical insight for my research. Financial and computational support from the Purdue School of Engineering and Technology at IUPUI is also acknowledged.

TABLE OF CONTENTS

Page

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Jahan, Suchana A. M.S.M.E., Purdue University, August 2016. Optimization of Conformal Cooling Channels in 3D Printed Plastic Injection Molds. Major Professor: Hazim El-Mounayri.

Plastic injection molding is a versatile process and a major part of the present plastic manufacturing industry. Traditional die design is limited to straight (drilled) cooling channels, which dont impart optimal thermal (or thermos-mechanical) performance. Moreover, reducing the cycle time in plastic injection molding has become significantly important to the industry nowadays. One approach that has been proposed is to use conformal cooling channels. With the advent of additive manufacturing technology, injection molding tools with conformal cooling channels are now possible. However, optimum conformal channels based on thermo-mechanical performance are not found. This study proposes a design methodology to generate optimized design configurations of such channels in plastic injection molds. Numerical models have been developed here to represent the thermo-mechanical behavior of the molds and predict the stress and cooling time. The model is then validated experimentally and used in conjunction with DOE (Design of Experiments) to study the effect of different design parameters of the channels on the die performance. Design of experiments (DOEs) is used to study the effect of critical design parameters of conformal channels as well as their cross section geometries. These DOEs are conducted to identify optimal designs of conformal cooling channels which can be incorporated into injection molds that are used to manufacture cylindrical and conical shapes of plastic parts. Though these are simplified forms, the study provides useful insight into the potential deign parameters for all kind of injection molds.Based on the DOEs, designs for best thermo-mechanical performance are identified (referred to as ”optimum”). The

optimization study is basically a trade-off and the solution is based on a specific sample size. This approach is highly result-oriented and provides guidelines for selecting optimum design solutions given the plastic part thickness.

1. INTRODUCTION

1.1 Background

In the present world, a wide variety of plastic products are used in everyday life. Injection molding is a major part of the plastic industry, consuming a large percentage of the total amount of plastics [1]. Plastic injection molding is a versatile process to obtain different complex sizes and shapes of high quality products from thermoplastic and thermosetting materials with the application of heat and pressure [2]. To obtain a better quality plastic part the design of the injection molding tooling, specifically the design of die core and cavity is very critical. It also plays an important role in the economic aspects of the business.

The cooling of injection molding tooling plays very important role in the total production cycle time of the injection molding process. Time is significant in the entire molding process, as it constitute about half of the time in the overall production cycle [3].Figure 1.1 shows a generic distribution of time in the total injection molding process.

Injection molding is a widely used and accepted manufacturing process for the production of plastic parts. Traditionally straight holes are drilled into the solid dies to cool the hot molten plastic inside the cavity. This cooling process takes a major portion of the production cycle, leading to high cost of production. At present, with the rising competition worldwide in the plastic product business, it has become very important to lower the production cost, one way of doing so is to reduce the production cycle time. Using conformal cooling channels is a good option for this purpose. Conformal cooling channels have the potential to improve the performance of the molding dies in terms of uniform and fast cooling, less warping and defects

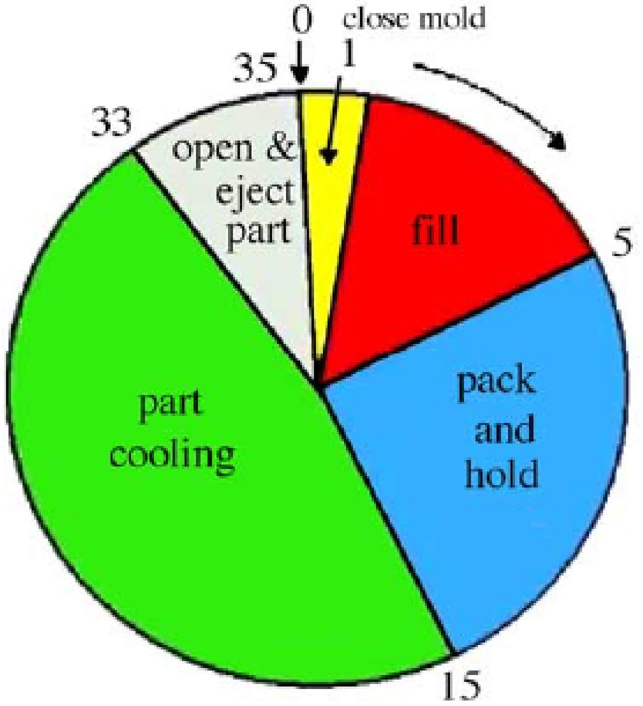


Fig. 1.1. Cycle time in injection molding.

etc., as any kind of channels could be produced using additive manufacturing process to create an optimal solution to this problem.

The use of cooling channels conformal in the molding cavity improves the control of mold temperature and part dimensions. This has been reported by a group at MIT in the 1990s [4]. A systematic, modular approach was presented by Xu and Sachs at MIT for the design of conformal cooling channels. They recognized cooling as local to the surface of the tool and divided the tool in different geometric regions and created the channel systems for each region. Mold surface temperature, pressure drop, mold material strength etc. were considered as design parameters in their study [4–6] Three dimensional printing was applied to the direct fabrication of tooling using metal powders. In their process of applying additive manufacturing technology, they provided improvement in the areas of thermal management, dimensional control, surface finishing and tool hardening. They used stainless steel powder with a resultant tooling hardness of 25-30 Rockwell C [7].

Ferreira and Mateus presented a study on rapid soft tooling for plastic injection molding. The main purpose of their study was to propose some original approaches to integrate the advanced processing technologies, with composite materials chilled by conformal cooling channels to manufacture injection molding tools [8]. The effect of conformal cooling channel to reduce cooling time and increase part quality, compared to traditional straight cooling channels was also presented by Meckley and Edwards. The used high density polyethylene and polycarbonate in their study and demonstrated the mold and melt temperature differences between the two materials to illustrate the conformal channels efficiency [9]. Hopkins and Dickens demonstrated the use of conformal cooling channels to both heat and cool a single injection molding tool. This provided potential of 3D printing technology to achieve successful production of complex geometries [10]. One of the advantages of rapid tooling methods in building conformal heating or cooling channels to enhance thermal control. An important issue of such tooling is to seal the channels rapidly and inexpensively. Yoo provided an investigation on this matter in 2008 [11].

Altaf et. al presented a technique of fabricating conformal cooling channels in an aluminum filled epoxy mold using rapid prototyping techniques. This paper provided an insight on conformal channel fabrication method, which is not possible using traditional drilling or machining process [12]. An investigation of the automation of preliminary design stage to the layout design stage of the cooling system design process is presented by Li et all. This study provides a configuration of straight cooling channels based on the size and shape of the plastic part design, and does not necessarily require additive manufacturing technique [13].

Though there have been a series of studies in the area of design and modeling of conformal cooling channels in injection molding tooling, the concept of simulating the designs cannot be rooted back to more than 10 years. Since then, different simulation packages have been used to analyze the tool and channel designs. Moldflow analysis in I-DEAS was used by Dimla et al. in 2005 to find the best position of the runner [3]. ABM Saifullah and SH Masood analyzed part cooling times using ANSYS thermal analysis software 2007 [14]. In 2009, this same group used MPI simulation software for part analysis and compared results for conventional and square section conformal cooling channels; concluding conformal channels render 35% less cooling time than conventional ones. They incorporated a square sectioned conformal cooling channel system for injection mold dies and provided comparative studies between conformal and traditional molds [15]. They also provided finite element analysis using ANSYS was presented for a mold with bimetallic conformal cooling channels. The performance was compared with a conventional mold and experimental verification was also provided with two different plastic materials being produced by miniature injection molding machine [16]. A quantitative guidance for tooling design was presented in 2009 by Xu and Sachs. Their proposed methodology was tested on a 3D printed benchmark tool with truss support. In their study, preliminary tests demonstrated the technical feasibility of using SFF process to fabricate low thermal inertia tools [17].

Sun et al provided a finite element study of milled groove insert method for cooling of plastic injection molds using a household iron plastic part. The numerical analysis technique was based on cooling and thermal stress modeling [18]. Gloinn et al. from Ireland performed FEA analysis to determine mold temperature using ABS polymer as molten material and water at 20C as cooling fluid [19]. Another study was conducted using Moldflow Plastic Insight 3.1 to investigate the thermal effects of cooling channel design on injection molding in 2007 by Au and Yu. [20].They proposed a novel scaffold for the design of uniform conformal cooling. In their study in 2013, Hsu et al identified that for cavities with irregular geometry, the distance between cooling channels and cavity varies throughout the part and causes local heat accumulation and product defects such as sink mark, warpage etc. They adopted a true three dimensional simulation technique to predict cooling time and compare the results with traditional molds [21]. Dang and Park adopted an algorithm for calculating the temperature distribution through molding thicken and presented a conformal channel with array of baffles to obtain uniform cooling over the entire free-form surface of molded parts [22]. They also provided an insight into the use of conformal cooling channels to provide a uniform cooling and reducing the cycle time for injection molding process. They presented U-shaped milled groove conformal channels and proposed an optimization process to obtain an optimal conformal channels configuration [23]. The comparative effect of conventional, series, parallel and additive parallel cooling channels was studied by Khan et al. in 2014 with respect to cooling time, total cycle time, volumetric shrinkage and temperature variance using AMI software [24].

Wang et al in 2011 presented an automatic method for designing conformal cooling circuits by establishing a relationship between the conformal cooling and the shape of the plastic body [25]. Choi et. al recognizes the higher degree of freedom in the design of conformal cooling channels with the application of 3D printing and concentrate on a branching law principle to improve the cooling efficiency in injection molds. They used Voronoi diagram algorithm and binary branching algorithm to create the design of conformal cooling channels [26]. A similar technique was also adopted by Park and Pham. They designed cooling channels for individual surfaces and then combined them to form overall conformal cooling channel system for the entire part [27]. Two years later, they designed conformal cooling channels for an automotive part using the algorithm they provided in their previous studies. In this paper, they conducted an optimization to minimize the cooling time with boundaries ensuring a realistic design for cooling system [28]. Wang et al introduced an approach to generate spiral channels for conformal cooling using an algorithm. With the help of boundary distance maps, their algorithm were investigated to generate evenly distributed spiral channels in the injection mold [29].

In 2011, Au and Yu presented a methodology called visibility based cooling channel generation for automatic preliminary cooling channel design. This is a more geometric and theoretical method, rather than adopted in practical scenario [30]. After that, they provided the cooling channel distance modification based on adjustment direction and adjustment amount in 2014. Also, a simulation technique using moldflow plastic insight was adopted to demonstrate the feasibility of their proposed method [31]. A new methodology called Morpho Cooling was proposed by Agazzi et al for the design of cooing channels in injection mold.This technique provided better results in cooling in terms of higher uniformity of temperature and lesser part warpage [32].

Though there has been a lot of studies about the analysis of conformal cooling channels, the number of studies dedicated to the design parameters of conformal channels for various kinds of part design is very limited. Till date, most of the designs have been done based on the designers experiences. Also any kind of mix and match between the design parameters, cross section size and respective experimental analyses is pretty rare. Yet, some preliminary information could be gathered from the literature that act as a basis for further research in this project. For example, a simple relationship between 4 parameters for the design of conformal cooling channels using additive manufacturing is proposed by Mayer [33]. Some studies shows that the use of different cross section for channels other than circular might provide better cooling efficiency.

1.2 Scope of Research

From the literature review, it is evident that there has been a number of studies in the field of design an analysis of conformal cooling channels in injection molds. However none consider both thermal and structural performance when designing conformal cooling channels. This study addresses this limitation, and proposes a more systematic and comprehensive approach to the design of conformal cooling channels for dies for plastic injection molding. In addition, this work provides guidelines for the mold makers to design their injection molds with conformal cooling channels for best performance.

1.3 Research Objective(s)

The research objectives can be summarized as follows:

1.Develop simulation models for plastic injection molding on dies with conformal cooling channels (CCC).

2.Use Design of Experiments (DOE) to optimize the design of CCCs.

3.Provide guidelines for selecting best CCC designs in real life industrial cases.

To achieve the research goal, a CAD model of a generic injection mold was created. Three different numerical models, namely: thermal analysis model, the structural analysis model and the moldflow process model was developed to analyze the performance and operational behavior of this generic mold. These models were used to analyze various mold designs using Design of Experiments (DOE). The DOEs provided optimum solutions of the design of conformal cooling channels in injection molds, as well as design selection guidelines for mold designers.Once a specific design of mold with cooling channels is finalized, moldflow process model is run to predict key parameters for real-life plastic injection molding process. Figure 1.2 shows a schematic diagram of the research approach.It should be noted that the research goals are part of a more comprehensive research effort aimed at optimizing the topology of 3D printed dies with conformal cooling channels.

1.4 Chapter Contents

The background on conformal cooling channels and related previous research along with the scope of study of present thesis is discussed in Chapter 1. The development, application and validation of numerical models to analyze injection molds with conformal cooling channels is discussed in Chapter 2. Chapter 3 contains a design of experiments approach to identify a generalized method for designing conformal cooling channels in injection molds. This includes a number of DOEs to obtain optimized designs of conformal cooling channels based on thermo-structural analysis. The research project collaborates with a local plastic injection molding industry. A step by

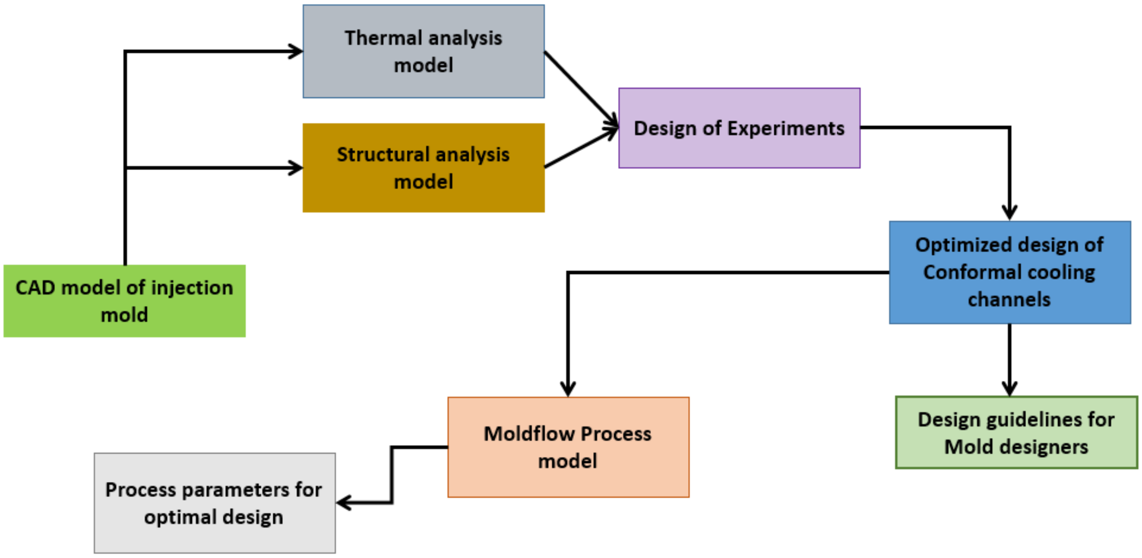


Fig. 1.2. The research approach.

step design approach has been adopted to replace the traditional cooling channel of an existing injection molding die of this industry. All these efforts constitute the contents of Chapter 3. In Chapter 4, a case study of the effect of channel cross section on the cooling performance of injection molds has been conducted. This leads to a final guideline for the mold designers to adopt a design technique on conformal cooling channels. Lastly, the conclusions and the recommendations of the present research are described in Chapter 5.

2. NUMERICAL MODEL FOR ANALYZING INJECTION MOLDS WITH CONFORMAL COOLING CHANNELS

2.1 Developing a Generic CAD Model of Injection Mold

The research aims at developing a methodology or guideline to create conformal cooling channels in injection molds that can provide fast and uniform cooling, structural stability of the mold, reduction in cycle time and overall improvement in part quality. With the application of additive manufacturing or 3D printing technology, it is possible to create cooling channels of any size and shape inside the injection molding cores and cavity, which has been impossible with the currently available traditional drilling and machining processes. The benefit of additive manufacturing in this area can be fully availed if an optimized design of conformal cooling channels can be incorporated into the molding tools and dies.

To obtain an optimized design of conformal cooling channels, it is necessary to numerically analyze the thermal and structural behavior of an injection molding core and cavity with different configuration of conformal channels and thus obtain an effective and well-functioning design. For this reason, it is important to develop a numerical or simulation model to analyze the mold behavior/ performance.

A typical injection molding machine contains different components such as clamping unit, injection unit, mold assembly etc. In fact the mold base contains a number of parts such as mold core, mold cavity, cooling channel inlets and outlets, ejector pin, ejector bar, support plate, sprue, runner, gate and so on [34]. As the study is concerned on the design of cooling channels, i.e.; replacing the traditional straight drilled cooling channels with conformal ones, the design details of sprue, runner, gate, ejection system etc. are beyond the scope of this research. It is reasonable to concentrate on the cooling channels inside the core and cavity to find an optimal configuration.

Hence a CAD model of a generic injection mold that contains the core and cavity with the cooling channels is developed to analyze the thermal and structural performance of it. This CAD model provides the initial basis of implementing the later developed numerical model for analyzing the behavior of an injection mold and its cooling system. The CAD model of generic injection mold with core and cavity is shown in Figure 2.1.

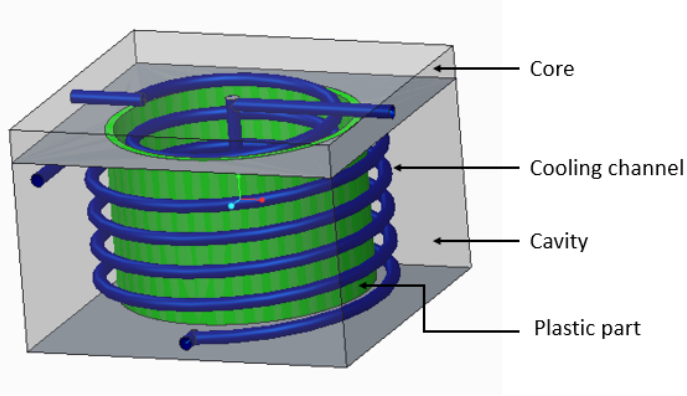


Fig. 2.1. CAD model of a generic injection mold with core, part and cavity.

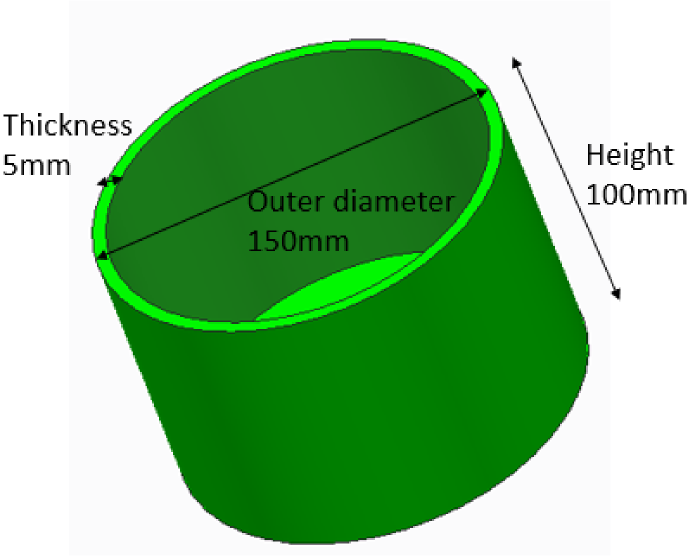


Fig. 2.2. CAD model of generic plastic part.

The design of a mold cavity and core depends on the design of the plastic part that is to be manufactured via the injection molding process. Hence, the design details of the plastic part is important and discussed herein. The CAD model of this part is shown in Figure 2.2. This is a simple cylindrical shaped bowl. The design is inspired from a part design used in literature [14]. The reason for choosing such a shape is that, it is a simple and symmetric design with no complex patterns, is easy to analyze and understand the effect of cooling channels. Also, cylindrical shape is a very common in today's injection molding industry that produces a lot of plastic bottle caps, simple containers of this same basic shape. This is inspired from previous work in this field. The dimensions of the plastic part is: outer diameter 150 mm, height 100mm and thickness 5 mm (uniform). The design as well as all the other CAD models that are discussed in this study are created using CREO parametric software.

The generic injection mold as shown in Figure 2.1 has a core, a cavity with the injected plastic part (green) inside the mold assembly. The solid body of the cavity is 200 mm × 190 mm × 115 mm, with a cylindrical hole of 150 mm diameter and 100 mm height at the center from top surface. On the other hand, the mold core has a rectangular solid body (200 mm× 190 mm × 20 mm) with a cylindrical protrusion (height 95 mm, diameter 140 mm) on the bottom surface. While the cavity and core are clamped together during injection molding process, the open space between them is filled up by injecting molten plastic polymer into it and thus the circular bowl of 5mm thickness is manufactured. Both the core and cavities have spiral shape conformal cooling channels in their solid bodies. The cooling channel is of 10 mm diameter and 20 mm pitch distance between two channels. The spiral channel inside the core and cavity is created using the helical sweep option in CREO. The plastic part is made of polypropylene and the mold core and cavity material is structural steel. These are important case setup parameters in the numerical model that is discussed in the following sections.

2.2 The Thermal Analysis Model

During the injection molding process, hot molten plastic is injected into the mold cavity via the injection unit and cooling water is passed through the cooling channels. The water serves two purposes. First, cool down the hot plastic and second, to warm up the cavity and core body. This warming up process is required to ensure minimum shrinkage of the plastic part being produced in the process. Hence this is understandable that the cooling waters temperature is needed to be above the temperature of the mold cavity and core, i.e.; room temperature. As the study is concerned on the cooling process and the phenomena happening after the molten hot plastic is inside the cavity; the time when the molten plastic is inside and cooling water starts running inside the channel is considered to be the initial condition while developing the thermal analysis model.

To analyze the thermal behavior of the mold with hot molten plastic inside the cavity and cooling water running through the channels a transient thermal analysis model is developed using ANSYS workbench 14.5. The model to be analyzed has three different solid bodies: cavity, core and plastic part. The core and cavity material is structural steel and the plastic material is polypropylene. The initial temperature of the molten plastic 168 °C. Water temperature at the inlet is 28°C. Convection heat transfer co-efficient is applied on the cooling channel surfaces. Fine meshing with medium smoothing is applied on the geometry using automatic mesh generator in ANSYS, where total 94,088 elements are created with 155,990 nodes. Minimum edge length is 0.75 mm. The material properties for thermal analysis and the boundary conditions numerical model are shown in Table 2.1 and Table 2.2 respectively. This numerical model has been discussed in previous publications of the author [35].

2.3 Thermal Analysis on Generic Injection Mold Model

The numerical model as discussed in the previous section has been employed on the generic injection mold model. The objective is to analyze the thermal performance

Table 2.1
Properties of plastic and mold material

Material	Polypropylene	Structural Steel
Density (kg/m^3)	830	7850
Thermal Conductivity (W/mK)	0.14	60.5
Specific Heat (J/kgK)	1900	434

Table 2.2
Boundary conditions

Coolant Temperature (°C)	28
Molten Plastic (°C)	168
Ejection Temperature (°C)	50

of the mold, i.e.; determine the cooling time. To reach the ejection temperature 50°C, the generic mold with conformal cooling channel takes 17.77 s. This result offers an insight to the potential of conformal cooling channels to bring about an improvement in the plastic injection molding industry by reducing the cooling time significantly. Typically, the cooling time ranges from 25-40 s with the traditionally designed injection molds with straight drilled cooling channels. Figure 2.3 shows the temperature distribution on the plastic part at the time of ejection, i.e.; at 17.77 s, the maximum temperature on the part is 50.03 °C which is the allowable ejection temperature.

2.4 Validation Study

The developed numerical model as discussed in Section 2.2 is validated experimentally. This validation is important to proceed further in the research. An industrial collaborator of the research project uses traditional injection molds with straight

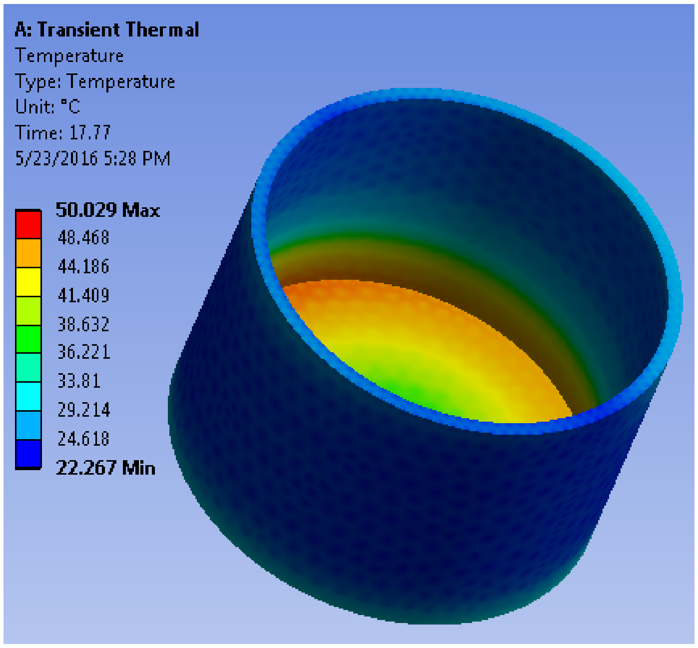


Fig. 2.3. Temperature distribution on plastic part(conformal mold).

drilled cooling channels to cool the plastic part in their manufacturing process. Figure 2.4 is a simplified version of their existing model of die core and cavity with straight cooling channels which has been selected for experimental validation study. The complicated actual mold design is discussed in the later parts of this dissertation. The single cavity mold as shown in Figure 2.4 is used to produce a simple plastic bottle cap of cylindrical shape. The die material is structural steel as mentioned earlier. The plastic part is made up of polypropylene. It takes 30 s to cool the molten injected plastic down to ejection temperature of 50°C. Hence, the cooling time 30 s is the experimental result.

For validating the developed numerical model, it is employed to analyze the thermal performance of the CAD model shown in Figure 2.4. The analysis predicts that with the given geometry, the plastic part here can be cooled down to the ejection temperature at 28.25 s. Thus, it can be stated that the results from experimental and numerical studies are very close (within 5%) and hence the developed numerical model can be considered to be valid. Figure 2.5 shows the temperature distribution

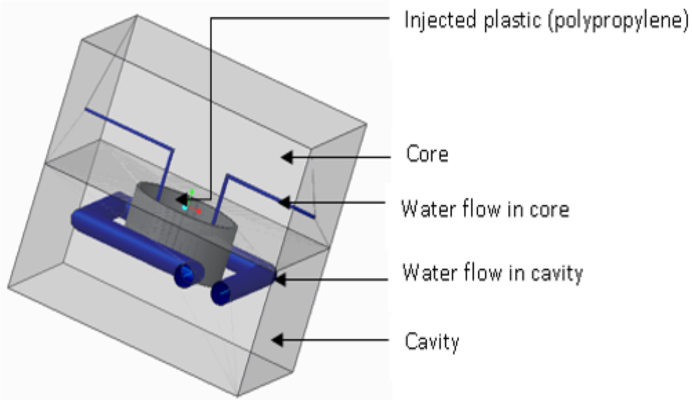


Fig. 2.4. Simplified version of a traditional injection mold .

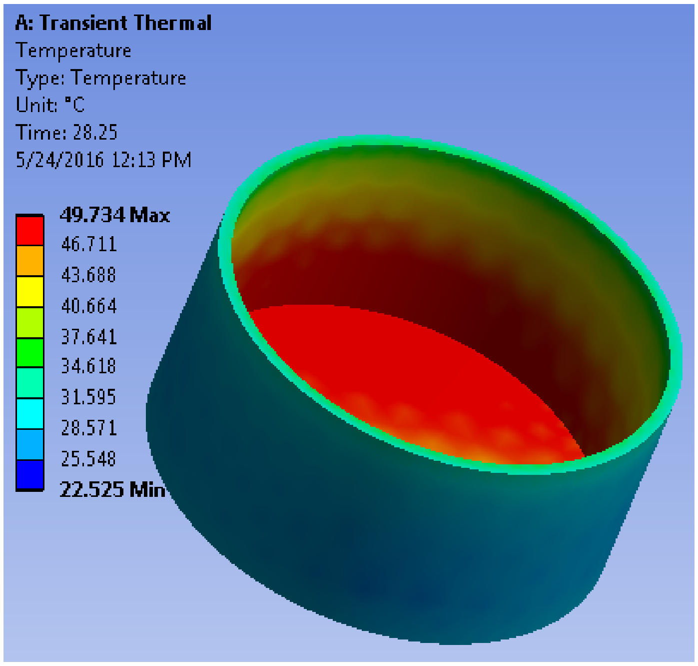


Fig. 2.5. Temperature distribution on plastic part(traditional mold).

on the plastic part that is manufactured by the traditional mold. It is also notable from Figure 2.3 and Figure 2.5 that, conformal cooling channel can provide more uniform temperature distribution of the manufactured plastic bodies, which is very important for the quality of production.

2.5 The Structural Analysis Model

To analyze the performance of an injection mold with conformal cooling channels, it I necessary to ensure the structural stability of the mold. By introducing conformal channels, the designer is creating more void space in the die cavity and core compared to a traditional mold which has limited void space. Hence the CAD models of molds are needed to be tested numerically in structural analysis. The research project has been collaborating with a local plastic injection molding company, and hence the authors have collected some industrial data regarding the loads and pressures that a mold encounters during an injection molding cycle. Using these setup conditions, a static structural analysis model has been developed in ANSYS Workbench 14.5. The clamping force is 110tn, which is applied to the top and bottom surfaces of the mold. Moreover, the 131MPA injection pressure is applied on the heating surface. The structural analysis predicts the deformation and distribution of Von-mises stress on the mold body. If the Maximum Von-mises stress is below the acceptable limit of yield strength of mold material, then the mold can be considered as structurally stable and functional.

2.6 The Structural Analysis of Generic Mold

In the structural analysis, the same CAD model of generic injection mold is analyzed with the static structural model. This study predicts that, at the ejection time, the maximum value of Von-mises stress is 159 MPa on the mold and the maximum value of total deformation is 0.019 mm. This result is within the acceptable range of material yield strength.This is important to note that,though the thesis title indicates that the study is for 3D printed injection molds, the material properties used in this study account for solid materials, not the 3D printed powder metals. The research project aims at printing a fully functional injection mold and to analyze its performance, 3D printed material properties would be incorporated into the numerical models in future.

2.7 The Moldflow Process Model

This model is developed in Autodesk Moldflow Insight.This software package is capable of analyzing process parameters and the complete injection molding process of a mold with conformal cooling channels. Once the specific geometry, positions of channel inlet and outlet, the material properties etc. are specified, several process parameters as well as mold performance can be predicted by this model.The generic mold has been analyzed with this numerical model to identify the process parameters for the proposed design solutions.

3. OPTIMIZING THE DESIGN OF CONFORMAL COOLING CHANNELS BY USING DESIGN OF EXPERIMENTS

3.1 An Existing Mold with Traditional Cooling

Present injection molding industry typically uses traditional machining process to create the mold core and cavity to produce the required design of plastic part. The cooling channels are drilled sometimes on the cavity body or sometimes on the base plate depending upon the size and placement constraints. The core body generally does not contain any cooling channels. The available technology and ease of fabrication that is offered by the additive manufacturing nowadays, enables us to design any kind of cooling channel design of any size and shape inside the core and cavity of injection molds. Here comes the question of what should be the design of conformal cooling channels to maximize the benefit.

A large variety of plastic parts are being produced everyday by injection molding process. They vary in size, shape, pattern, thickness, design complexity, material and so on. In this scenario, it is reasonable to start optimizing the conformal cooling channel configuration for a single design of plastic part and then move further to obtain a generalized method. In this process, a simple plastic part is chosen from an industrial collaborator of the research project. This local industry manufactures plastic products using injection molding process. It has been decided to redesign one of their existing die with conformal cooling channel to provide benefit to the business. A simple single cavity mold is selected from some industrial visits and discussions. The selected plastic part is a simple cylindrical bottle-cap. Figure 3.1 shows the CAD model of this body. This bottle cap has a height of 33 mm and thickness of 1.5 mm, and made of polypropylene.

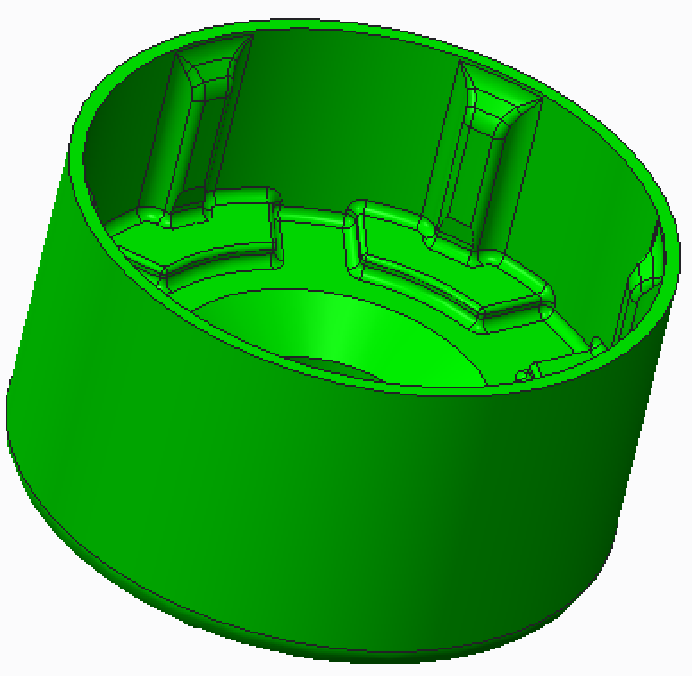


Fig. 3.1. CAD model of plastic part from Hewitt Molding.

The injection mold that is used to manufacture the plastic cap is made of structural steel. It has one cavity and one core. The cavity design is a rectangular block (127mm × 127mm × 60mm) has a cylindrical hollow space (height 33mm, diameter 59mm) inside it. The core has two parts, the rectangular block (127mm × 127mm × 60mm) and a cylindrical protrusion. The straightdrilled conventional cooling channels in the cavity are 11 mm in diameter and enables continuous water flow inside. The rectangular part of the core has one straight channel of 11mm diameter drilled inside. The conventional die design is shown in Figure 3.2. The purpose is to replace the conventional channels with an optimized configuration of conformal cooling channels, both in the core and the cavity.

3.2 Important Parameters for Design of Conformal Cooling Channels

To design the conformal cooling channels, it is necessary to identify the important design parameters of the configuration first. Conformal cooling channels can be of

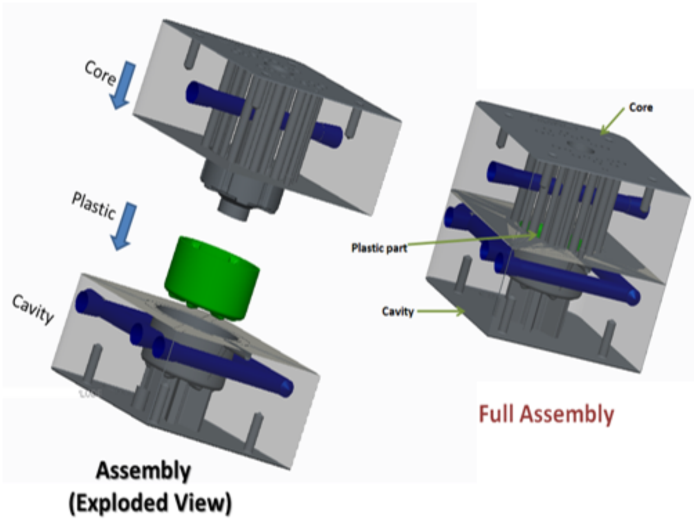


Fig. 3.2. CAD model of full mold from Hewitt Molding.

different configurations, that have been adopted and analyzed in different studies earlier, such as the single channel design [12], the modularized cooling channel [5], the continuous spiral design [21], the scaffolding architecture, the serpentine cooling channel [7], the cooling circuit [36] etc. Yet, no such design has been identified as the optimized and most effective of them all. In this study the spiral design of conformal cooling channels has been chosen for further analysis as in a recent study, it provided good potentials for being an effective solution in injection molding industry [37,38]. In [33], it has been identified a rule of thumb for the design of conformal cooling channels in injection molds based on their experience and existing state of the art. In their study, they identified a relation between the conformal channel design parameters (i.e.; channel diameter, pitch distance between two channels, the distance between channel centerline and mold wall) and the thickness of the plastic part to be manufactured by injection molding process. Their guideline is shown in Table 3.1. Moreover, channel cross section has been identified as an important criteria to consider while designing the conformal channel configuration by a number of studies [12, 14, 33, 38]. In this scenario, a number of design of experiments is conducted in this research to include all these parameters and finally obtain an optimum design of conformal cooling channels.

Table 3.1
Correlation between design parameter for conformal cooling channel

Wall thickness of molded part (mm)	Channel diameter, D (mm)	Pitch Distance, P(mm)	Channel centerline to mold wall distance, L(mm)
0-2	4-8	2D-3D	1.5D-2D
2-4	8-12	2D-3D	1.5D-2D
4-8	12-14	2D-3D	1.5D-2D

3.3 Design of Experiments: DOE-1

A design of experiments approach is adopted to identify an optimum design of cooling channels to incorporate into the industrially used traditional mold. (shown in Figure 3.2) is to conduct a design of experiments (DOE). As the plastic part to be produced is 1.5mm in thickness, the first row of the design parameters from Table 3.1 was selected to conduct a design of experiments.

3.3.1 DOE-1 Case Setup Details

A number of design of experiments have been carried out in the whole research, hence the first one is designated as DOE-1 for ease of understanding of the reader. In DOE-1, three design parameters are selected for consideration, namely: channel diameter (D), pitch distance (P), channel centerline to mold wall distance (L). These parameters are illustrated in Figure 3.3 by a schematic diagram of a simplified mold. Channels in cavity only is shown.

From Table 3.1, we can see that, for a plastic part which is 1.5 mm thick, the channel diameter (D) in the injection mold can be in the range of 4mm-8mm.The pitch distance (P) should be in a range of 2D-3D, in this case, in the range of 8mm

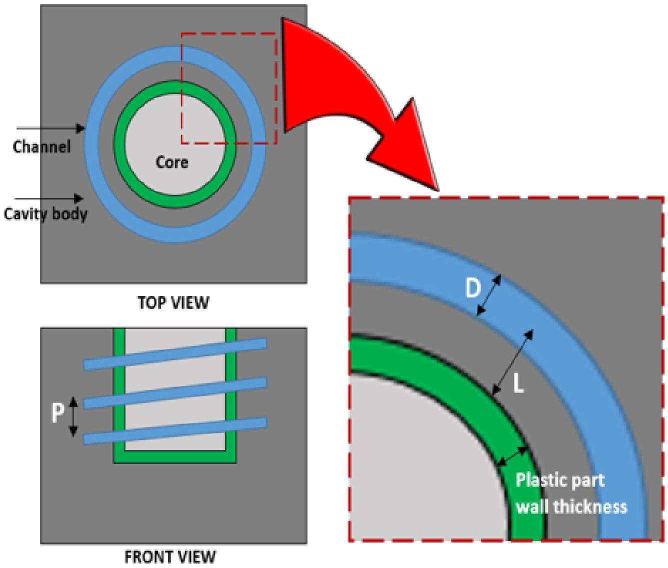


Fig. 3.3. Schematic diagram of a die cavity with parameter definition used in DOE

(lowest dimension 2D, i.e.; 2 × 4mm = 8mm) to 24mm (highest dimension 3D, i.e.; 3 × 8mm = 24mm). Similarly the range of L is 6mm to 16mm.

For the DOE-1, there are three parameters, D, P and L. These 3 parameters are divided into 5, 3, 3 levels respectively. Using the full factorial method, a total of 45(5 × 3 × 3) data points are set for performance analysis. First, a CAD model is created with the specific design parameters for a specific data point (e.g.; case 1.1), keeping all other design parameters of the die the same as the simplified version of manufacturers traditional mold model. Then the geometric model is imported to ANSYS workbench for transient thermal analysis using the same modeling technique described in the previous chapter in Table 2.1 and Table 2.2. This method is repeated for all 45 case scenario and later evaluated for cooling performance. Table 3.2 shows the setup parameters of the design cases in DOE-1 along with their thermal analysis results, i.e.; the cooling time in each case. For further clarification, it should be mentioned here that, all the design variables used in the DOE-1 are dependent on each other, not independent as one would expect them to be in typical design of experiments study.

3.3.2 DOE-1 Results and Findings

The comparative analysis of thermal behavior is done by numerical modeling in ANSYS. It shows the best result (in terms of cooling time) is obtained in case-1.1. As shown in Table 3.2, case 1.1 has design parameters as D = 4mm, P = 8mm, L = 6mm. With the smallest diameter, i.e.; 4mm, it allows the minimum pitch distance between the channels (P being a function of D). This in turn allows the longest conformal cooling channels possible in such circumstances, resulting in highest surface area of coolant in the core and cavity. Though the heat transfer co-efficient is a bit smaller in larger diameter channels with the same flow characteristics, the larger surface area causes the lowest cooling time, 14.38 s, which is considered the highest efficiency of the die in terms of cooling performance. Comparatively, in case 1.2, where the only difference from case1.1 is L being 7mm (vs. 6mm in case 1.1), cooling time is 14.5s, which is higher than the previous one. This is also explainable by the fact that with the same geometric conditions otherwise, the channels are situated far from the wall in case 1.2 than in case 1.1; and hence the increase in temperature.

For further details, in case 1.4, the pitch distance increases to 10 from 4 being in 1.1-1.3. This yields even a higher cooling time compared to case 1.1. This phenomenon describes the effect of the increased pitch and hence shorter cooling line. Similar explanations can be provided for the results from cases 1.5-1.9. This trend continues throughout the whole DOE, i.e.; up to case 1.45. These results and trends are graphically represented in Figure 3.4, 3.5. In Figure 3.6, the temperature distribution on the plastic part at the time of ejection for case 1.1 is shown. All the other design cases have similar trends of temperature distribution.

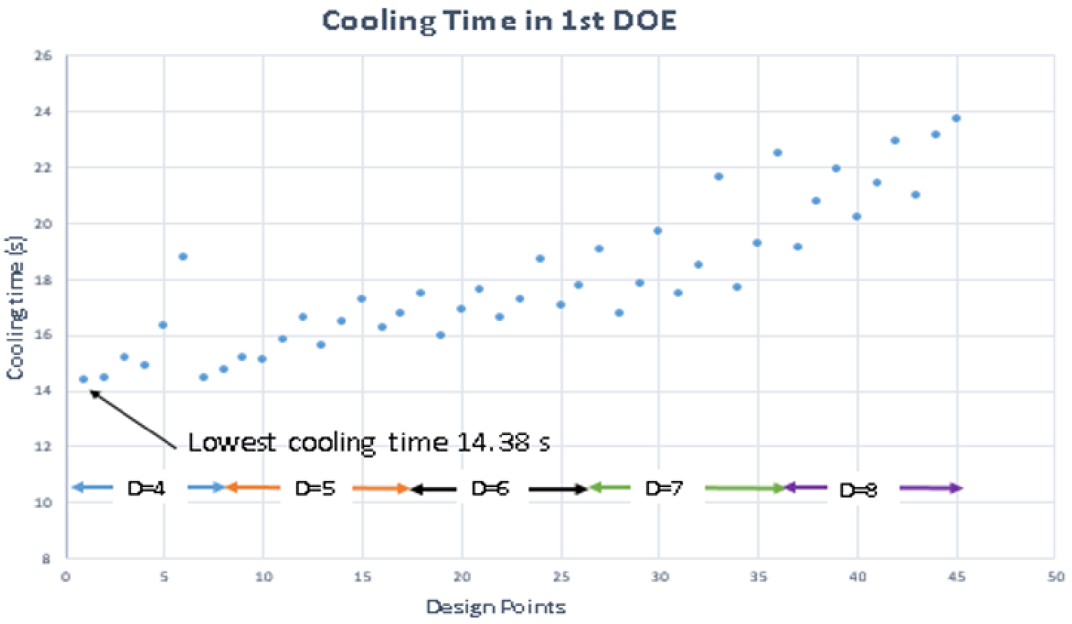


Fig. 3.4. Cooling time variation in DOE-1.

3.4 Design of Experiments: DOE-2

The results from the first set of DOE show that when the design parameters are coupled, the best design can be obtained from lowest value of D and P. This initiated the thought that a design with a minimum pitch distance of value and a ”maximum” value of D might provide even better results than the DOE-1. With this in mind, the design parameters (variables) are decoupled and a second set of design of experiments is initiated. This means, in DOE-1, P and L are functions of channel diameter D, whereas in DOE-2, they are not directly functions of D. These design parameters are decoupled in the new set and the whole range of parameters is considered for setting up the DOE-2 design cases. Here, in the second set of DOE, two parameters are chosen, channel diameter (D) and pitch distance (P). Instead of L, a new design parameter L1 was introduced here and kept constant as 4mm throughout. L1 is defined as the mold wall to channel wall distance. This value of L1 is derived from

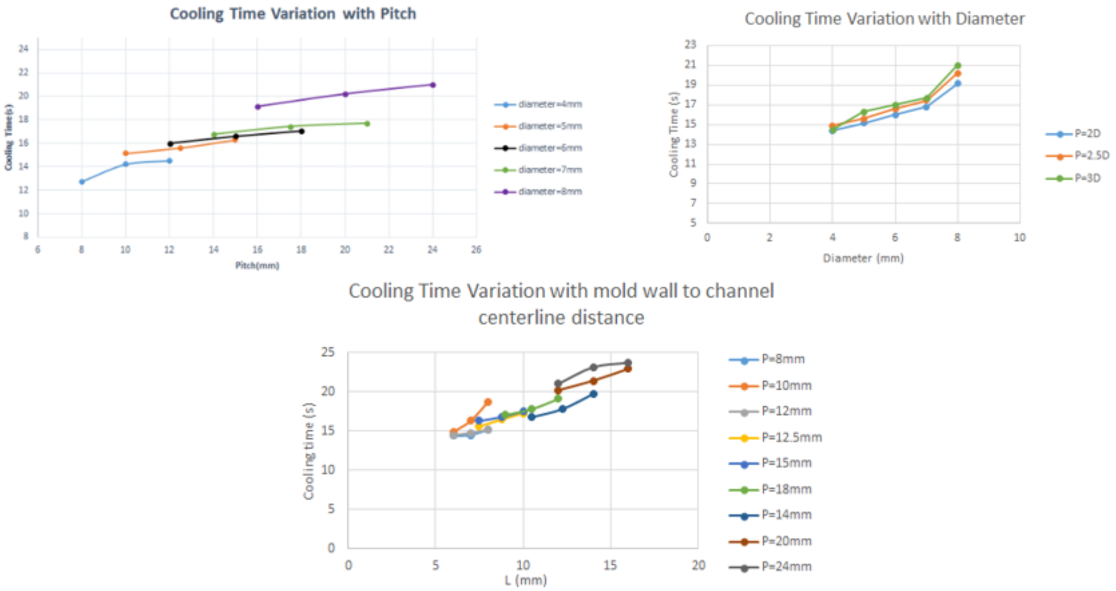


Fig. 3.5. Trend analysis in DOE-1.

the best case scenario in DOE-1, i.e.; case 1.1, where L = 6, so L1 = (6 - (D / 2)) = 4.

3.4.1 DOE-2 Case Setup Details

As mentioned earlier, there are two design variables in DOE-2, namely channel diameter (D) and pitch distance (P). Both of them have 5 levels. As a result, there are 25 (5 × 5) design cases set in full factorial method for the DOE-2. The same procedure is followed for the CAD modeling and numerical analysis of these data points as described earlier in Section 3.3.1. Table 3.3 shows the setup parameters of the design cases in DOE-2 along with their thermal analysis results, i.e.; the cooling time in each case.

3.4.2 DOE-2 Results and Findings

From this analysis, the best thermal performance is obtained in case 2.11. As evident from Table 3.3, the case 2.11 has the values of D = 6mm and P = 8mm. It obtained the best result of cooling time = 12.76 s, which is even better than the best case scenario in DOE-1, i.e.; case 1.1.

Comparing cases 2.1 to 2.5, where the D is same with increase of P, the cooling time increases. In fact, with the increase of P, the channel length actually decreases hence the cooling time increases. Then again comparing case 2.3, 2.8, 2.13, 2.11, 2.23; where the P is same (= 16mm) but D's are increasing, an improvement performance, i.e.; a decrease of cooling time in observed. These results are shown in Figure 3.7, 3.8.

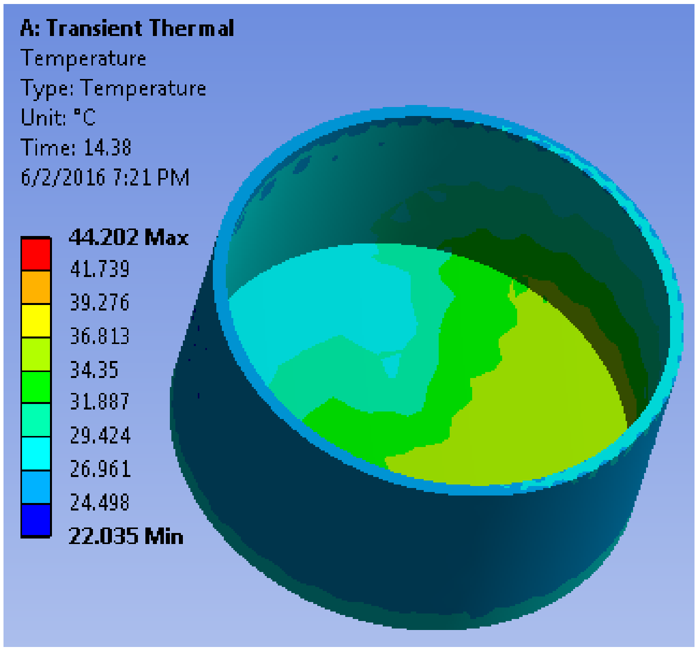


Fig. 3.6. Temperature distribution on plastic part in case 1.1.

Similar trend can be found from all other cases. This is an expected outcome with the increase in diameter, the surface area of cooling water increases, producing an opportunity to carry out higher amount of heat from the molten plastic and cool

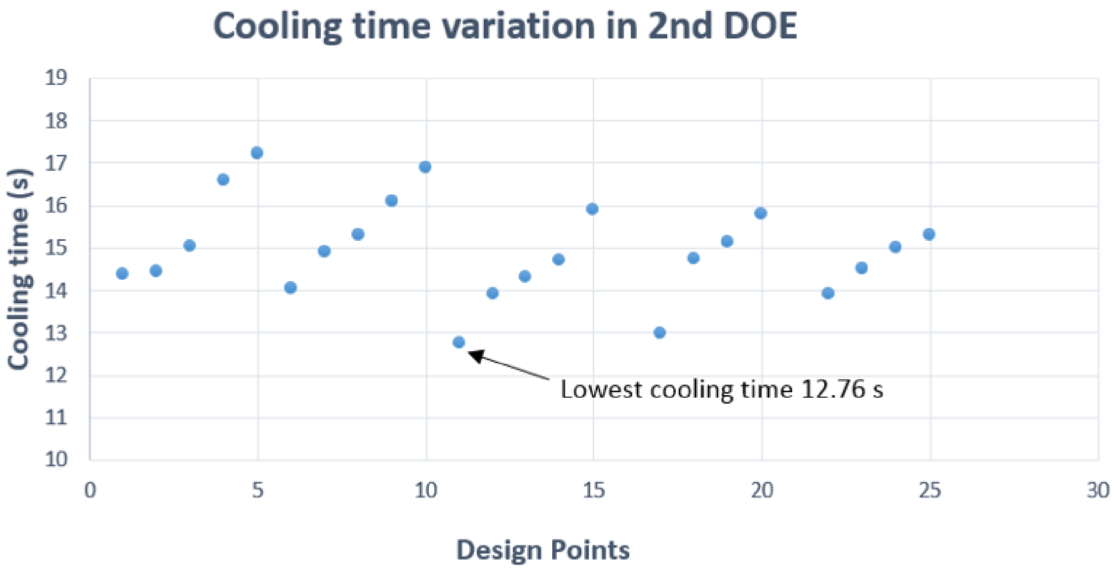


Fig. 3.7. Cooling time variation in DOE-2.

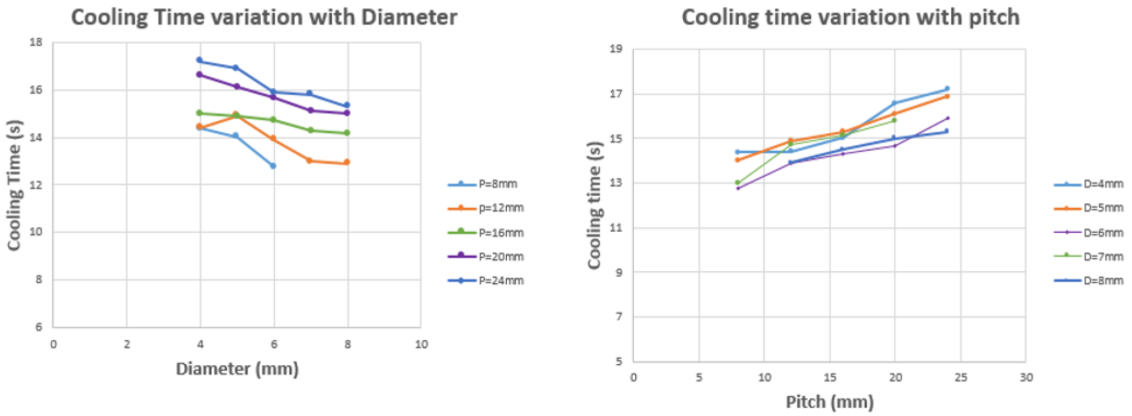


Fig. 3.8. Trend analysis in DOE-2.

it more quickly. Figure 3.9, the temperature distribution on the plastic part at the time of ejection for case 2.11 is shown.

It is to be noted here that case 2.16, 2.21 are not reproducible due to geometric limitation of the parameters. Thats why case 2.11 provides the best result, which means the circular channels diameter is 6mm, with a pitch distance 8mm and where the channel centerline is positioned at 6mm from the mold wall.

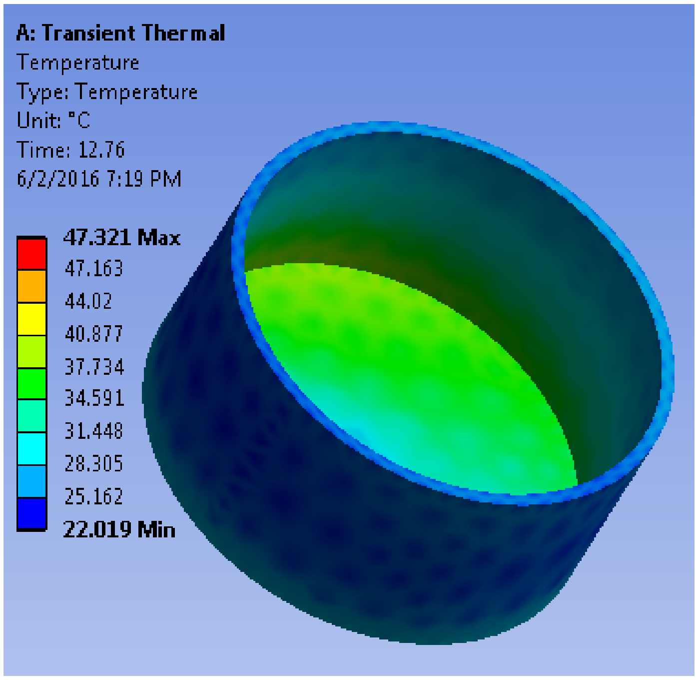


Fig. 3.9. Temperature distribution on plastic part in case 2.11.

3.5 Structural Stability Analysis

As mentioned earlier, the DOEs have been carried out to identify a suitable solution of creating conformal cooling channels to minimize the cooling time. Simultaneously, it is necessary to consider the structural stability of the mold. In this circumstances, the design cases in DOE-1 and DOE-2 are tested for structural stability. The mold structures to be stable enough, the stress and deformation developed within the body as a result of injection molding process should be below the yield strength of the mold material. It is to ensure that the mold will sustain the injection pressure of molten plastic and clamping force on the outer surfaces, will not deflect or deform beyond acceptable limit and will perform efficiently. The clamping force in 110 ton and the injection pressure is 131MPa. This is operational data obtained from the industrial collaborator of the research project. For the purpose of analysis, Von-mises Stress is identified. The results of this structural analysis shows that the stress values for all the cases are very close to each other with the range of 158MPa to 297MPa, which is very small compared to the acceptable limit. Also the total deformation ranges from 0.019mm to 0.026mm. Hence, the structural stability being ensured, design case 2.11 is still considered as the most suitable for the purpose of designing effective conformal cooling channel in injection mold for plastic part thickness 1.5mm. Figure 3.10 and Figure 3.11 show the structural analysis result of case 2.11. Other cases are not shown here, as all of them provide similar results and very small deformation and Von-mises stress.

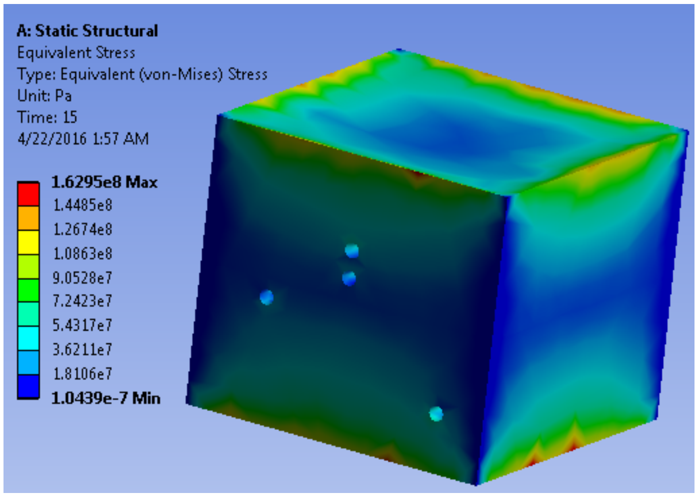


Fig. 3.10. Maximum von-mises stress on the mold for case 2.11.

3.6 Effect of Channel Cross Section

Earlier studies in the area of injection mold design show the use of different cross section of cooling channel other than the circular shape only. It is probable that other cross sections such as the rectangular or the elliptical cross section might be

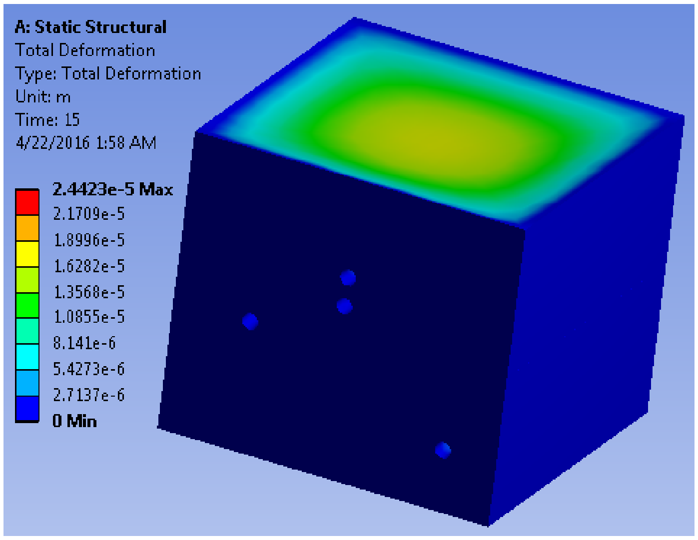


Fig. 3.11. Total displacement on the mold for case 2.11.

more effective than the circular ones. With the advantage of additive manufacturing technology, it is possible to create those channel cross sections too. For this reason, in this study, the effect of channel cross section is analyzed here. This is studied using the best case scenario obtained in the DOEs and replacing the circular channel with different shapes of cross section. Keeping the channel perimeter same, five sets of CAD models are prepared for this analysis, each having a different type of cross sectional shape of the channels, namely,1) Circular, 2) Square, 3) Rectangular, 4) Elliptical and 5) Semicircular, and these are analyze for thermal behavior. The channel designs are shown in Figure 3.12.

Due to the limitations of 3D printing technology using metal powder, highly sophisticated channel cross sections; such as star shaped or hexagonal shaped channel designs are not considered as design cases, as they are more susceptible to damage, fracture and design failure inside the channels. These 5 cases are implemented on earlier mentioned DOE case number 2.11, which is yet considered as the best possible conformal cooling channel solution. For further understanding, these cases hold the same pitch distance (P) and mold wall to channel centerline distance (L) as in case 2.11. P and L is kept as 8mm and 6 mm respectively for all the five cases. These

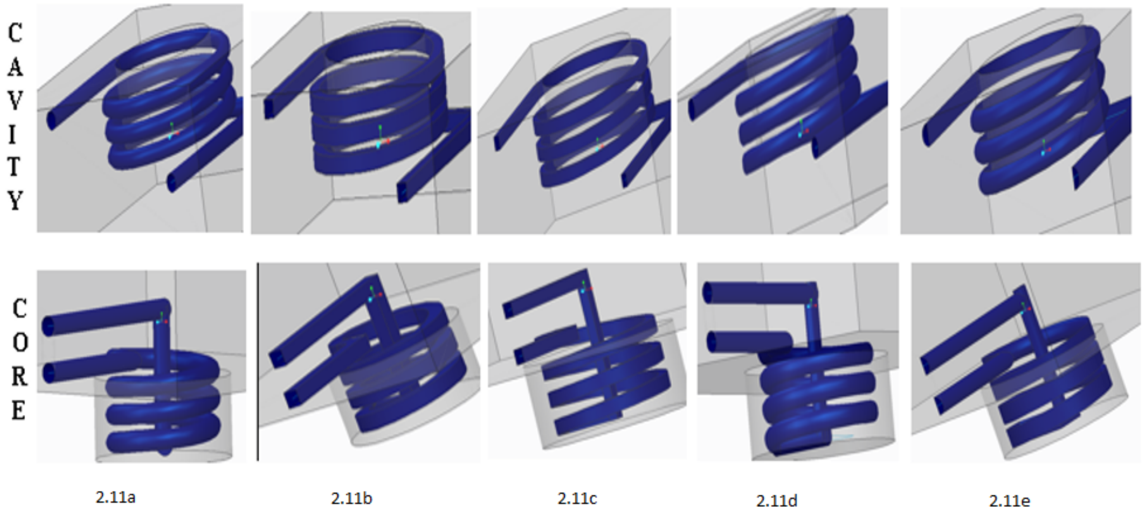


Fig. 3.12. CAD models of core an cavity with different channel cross section.

designs are named as 2.11a, 2.11b, 2.11c, 2.11d and 2.11e for better understanding in this section.

The thermal analysis in ANSYS of the above mentioned 5 cases provides five different cooling times, that indicates there is certain effect of the cooling channels shape on the cooling efficiency of the injection molds. The Temperature vs. Time curve is shown in Figure 3.13 for these cases for time up to 20s. This shows with the case 2.11c (rectangular channel), the plastic part reached its ejection temperature earlier than others. Hence this design can be termed as the best among the designs under consideration. Moreover, from Table 3.4 it is visible that the cooling time with rectangular cross section of channel is 10.15s which is smaller than all the other cases. The fact to be noted is that the longer edge of the rectangle is parallel to the plastic part body. This indicates that, it is better for the conformal cooling channel profile to follow the shape of injected plastic body. This is an interesting idea that the mold designers may need to consider while designing the cooling channels for cavity and core.

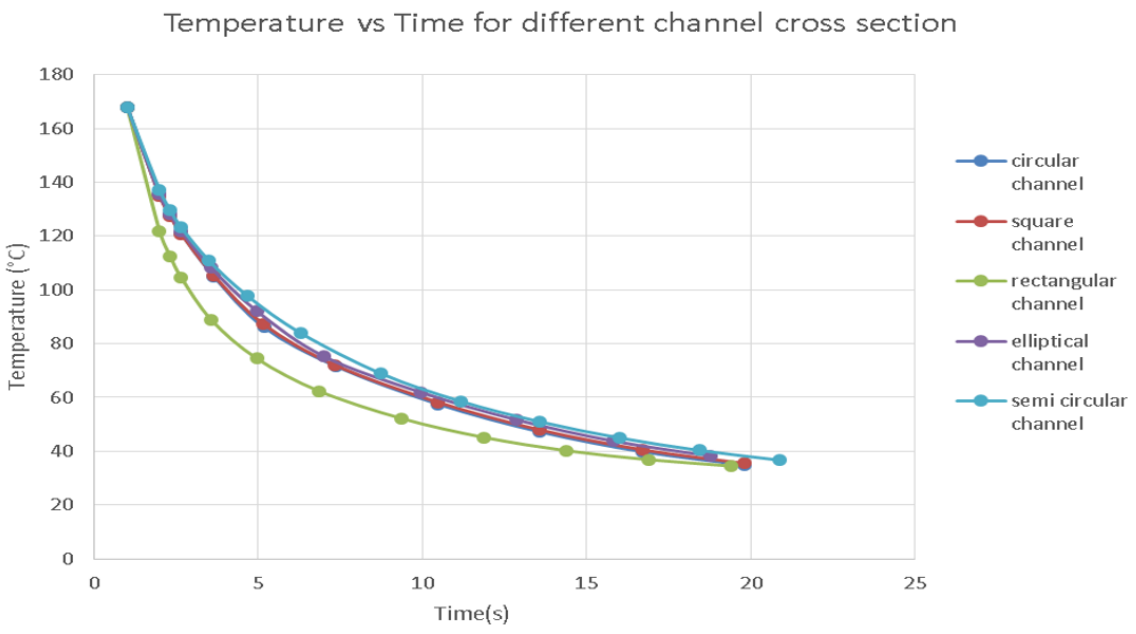


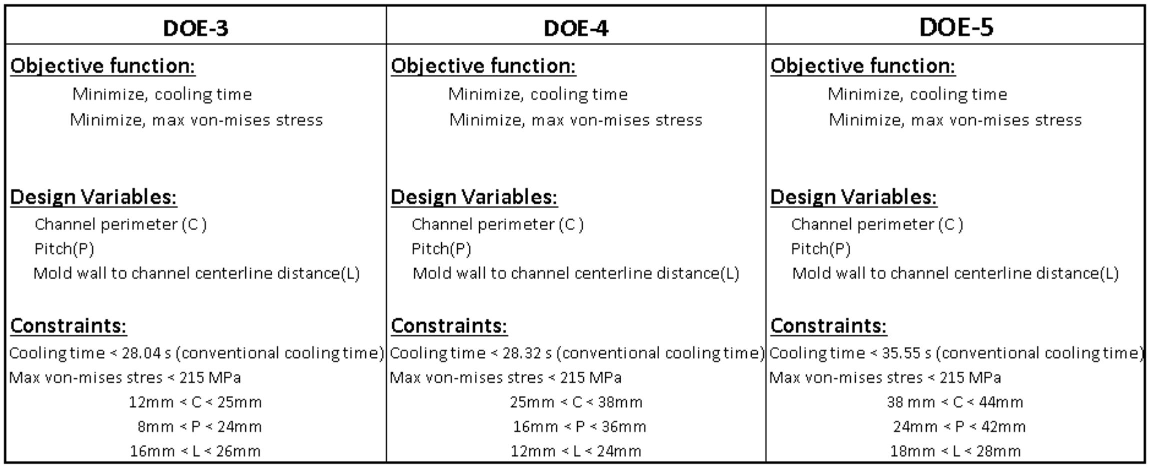
Fig. 3.13. Effect of channel cross section on cooling performance.

3.7 Redesign the Traditional Tool

The industrial mold that has been discussed herein is redesigned with the optimum conformal cooling channel design obtained in the previous section. In the redesigned mold, the traditional straight drilled circular channels of 11mm diameter is replaced with rectangular channels with 5.7mm × 3.8mm cross section with a pitch distance 8mm. The channel centerline is situated 6mm from the mold wall.

3.8 Generalized Design of Conformal Cooling Channels

An optimum design solution for creating conformal cooling channels in an existing mold has been obtained in the previous sections in this chapter. This design is entitled for a specific design (a cylindrical body, 1.5mm thickness) of plastic part that can be manufactured via injection molding process. But in general, the manufacturable plastic part design varies a lot; as people are using various types of plastic products in everyday life. The variation comes in form of part shape, thickness, pattern, material etc. Though the full range of variety is beyond the scope of this research, it is possible to develop a general method for the design of conformal cooling channels that can provide a guideline for the mold designers while creating conformal channels in the injection molds for the specific plastic part design under concern. In the following sections in this chapter, design of conformal cooling channels for producing cylindrical plastic parts of 3 different thicknesses are developed and analyzed. This variation of thickness is a common phenomenon in todays injection molding industry.



DOE-3	DOE-4	DOE-5
Objective function: Minimize, cooling time Minimize, max von-mises stress	**Objective function:** Minimize, cooling time Minimize, max von-mises stress	**Objective function:** Minimize, cooling time Minimize, max von-mises stress
Design Variables: Channel perimeter (C) Pitch(P) Mold wall to channel centerline distance(L)	**Design Variables:** Channel perimeter (C) Pitch(P) Mold wall to channel centerline distance(L)	**Design Variables:** Channel perimeter (C) Pitch(P) Mold wall to channel centerline distance(L)
Constraints: Cooling time < 28.04 s (conventional cooling time) Max von-mises stres < 215 MPa 12mm < C < 25mm 8mm < P < 24mm 16mm < L < 26mm	**Constraints:** Cooling time < 28.32 s (conventional cooling time) Max von-mises stres < 215 MPa 25mm < C < 38mm 16mm < P < 36mm 12mm < L < 24mm	**Constraints:** Cooling time < 35.55 s (conventional cooling time) Max von-mises stres < 215 MPa 38 mm < C < 44mm 24mm < P < 42mm 18mm < L < 28mm

Fig. 3.14. The optimization problem statements.

3.8.1 Setting Up Design of Experiments for Generalized Design

A design of experiments approach is taken to obtain a generalized guideline for the design of conformal cooling channels. For the design of cooling channels, initial consideration is the design of the plastic part to be molded. In this scenario, a basic shape of plastic parts are considered, i.e.; Cylindrical shape. This is then categorized into three different thicknesses: 1mm, 3.5mm, and 6mm. As a result, 3 sets of DOE are prepared and analyzed in this study. These are DOE-3 for thickness 1mm, DOE-4 for thickness 3.5mm and DOE-5 thickness 6mm.

The information of part thickness provides the basic outline of channel design parameters such as diameter (in circular channels), pitch distance, channel centerline to mold wall distance etc. The range of analysis for each DOE has been determined from literature and general rule of thumb of mold designers [33]. After deciding on the design variables (pitch, wall to wall distance etc.), next comes the factor of channel cross section. Though circular channel is the most common amongst all, from the results of section 3.5, it is evident that the rectangular channel might be a good option for the conformal channels, as they provide shorter cooling time compared to circular ones. For this reason, all the design cases are created with rectangular shaped cooling channels.

The DOE parameter details are mentioned in Table 3.5, 3.6, and 3.7. The design cases are designated as 3.1, 3.2, 4.1, 5.1 etc. as earlier.

For DOE-3, the plastic part thickness is 1mm. According to the guideline in Table 3.1, the channel diameter should be in the range of 4mm- 8mm. The perimeter of such channels would be 12.6mm to 25.13mm. Keeping the perimeter same, the circular channels are converted into rectangular ones, and thus their cross sectional dimensions are calculated. For example the circular channel with 4mm diameter was converted to a rectangular channel with a cross section of 3.8mm × 2.5mm and the channel with 8mm diameter is converted into a 7.5mm x 5mm section channel. There are 3 design variables in each of DOE- 3, 4 and 5. They are channel cross section (a × b), pitch distance (P) and mold wall to channel centerline distance (L). The first two variables have three levels and the third one has two levels of design. As a result, DOE-3 has $3 \times 3 \times 2 = 18$ design cases. Similarly DOE-4 has 18 and DOE-5 also has 18 design cases. The CAD modeling process is same as mentioned for the previous design of experiments (DOE-1 and DOE-2). The channel design parameters, such as pitch distance, cross section dimensions are same for both cavity and core in a single design case.

3.8.2 Thermo-Structural Optimization

In the previous DOEs, the numerical analysis and design decisions regarding the performance of conformal cooling channels in injection molds have been conducted with the single consideration of fast cooling. In addition to that, static structural analysis was also conducted on the DOE cases to ensure the structural stability of the mold cores and cavities with conformal channels. In the study of generalized design of conformal cooling channels, a more comprehensive approach to determine the mold performance has been adopted. Both thermal and structural analysis have been performed on all the design case studies and an optimization or trade-off between thermal and structural performance is done to find the best possible design to serve the purpose.

Theoretically a solid mold with a single straight drilled channel is structurally stable and can withstand large amount of stress compared to a mold with conformal channels due to higher void space within the body. On the other hand, the 'conformal channel' mold can cool off the molten plastic quickly and uniformly compared to the traditional mold due to the presence of conformal channels at the vicinity of plastic part. Here comes the issue of optimization. The design cases as mentioned in Table 3.5, 3.6, and 3.7 are analyzed for both thermal and structural behavior using the simulation technique mentioned earlier and an optimization method is conducted for each DOE to obtain the best suitable design scenario. Figure 3.14 shows the optimization problem statements for the DOE-3,4 and 5.

3.8.3 Results and Findings from DOE-3, DOE-4 and DOE-5

Table 3.8, 3.9 and 3.10 shows the thermal and structural results of DOE 3, 4 and 5 respectively. The results are in terms of cooling time and maximum von-mises stress at the time of ejection. The objective is to obtain the minimum cooling time and also the minimum stress. In Table 3.8, it is seen that for DOE-3, the minimum cooling time is 14.32s in case 3.1, whereas the minimum vale of maxm von mises stress occurs in the case 3.10, which is 107MPa. Hence neither case 3.1 nor case 3.10 is acceptable as the most optimized design case scenario. Similar phenomena happens for DOE-4 and DOE-5 too. In DOE-4(Table 3.9), minimum cooling time, i.e.; 21.39 s occurs in case 4.7, whereas minimum stress 161MPa occurs in case 4.5. Again, from Table 3.10, for DOE-5, case 5.13 and case 5.6 have the best thermal (27.47s) and best structural (162MPa) result respectively. Hence a trade-off is necessary to obtain the most effective design case in all these DOEs.

It is notable that the value of minimum cooling time increases from DOE-3 to DOE-5. This is an expected behavior as the thickness of the plastic part also increases there. Though the cooling time increases, in each case they show better results than their respective traditional mold design scenario. This comparison is conducted by creating three traditional mold designs with straight drilled cooling channels and analyzing them for thermal and structural performance. These cases are named as 3-conventional, 4-conventional and 5-conventional for the easy understanding of the reader. These design cases are created for plastic parts of thickness 1mm, 3.5mm and 6mm respectively to be comparable with their conformal design cases. Table 3.11 shows the cooling time for these conventional cases along with the respective conformal design cases, which indicate positive improvement with the application of conformal cooling channels in all the cases. The thermal analysis results for these design cases are shown in Figure 3.15. It shows the temperature distribution on the respective plastic parts at the time of ejection.

The selected top three design cases are listed in Table 3.12.

Figure 3.16 shows the variation of cooling time and stress distribution with pitch distance (P) and mold to channel centerline distance (L) for DOE-3. Figure 3.17 and Figure 3.18 shows the similar trends for DOE-4 and DOE-5. These figures show expected patterns that with the increase in p, the cooling time increases for the similar cases. Same phenomena is also true for L. From these figures, it can be noted that with the increase in part thickness, the variance among cooling times decrease. Hence, the thicker is the plastic part, the more it is critical to obtain a best suited conformal cooling channel design. For the temperature distribution of thicker plastic parts (Figure 3.15 c and e), the part temperature is higher in the inner surface than the outer surface. Hence, it can an interesting idea for the thicker parts to keep the distance of the channels to the mold wall smaller in core compared to the same in the cavity.

Analyzing the thermal and structural results, it is noted that though the cooling times vary a lot for all the DOE sets, the value of maximum von mises stress occurred are very close to each other. Also these stress values are much below the acceptable limit of yield strength. Moreover, some of the design cases such as case 3.4, 3.6, 4.2, 4.4, 4.18, 5.6, 5.9 etc. have higher cooling time than their respective conventional design cases, which completely violates the benefit of using additive manufacturing to create conformal channels to reduce cooling time. Thus, it is reasonable to emphasize more on the thermal behavior than the structural behavior here to choose the optimum design cases. In addition, all the design cases do not provide a single trend for the relationship between cooling time, stress and design variables, yet, the results provide important insight for the mold designers to choose from this design cases to create their own designs of injection molds. In practical world, there are also some constraints in the mold design such as position of ejector pins, runner, gate, inlet and outlet port etc., which are needed to be considered while designing any mold with conformal cooling channels. For the benefit of mold designers, Top three design cases from each set of DOE (shown in Table 14) are chosen to be most optimized ones.

Table 3.2
Case studies in DOE-1

Case number	D (mm)	P (mm)	L (mm)	Cooling time (s)	Case number	D (mm)	P (mm)	L (mm)	Cooling time (s)
1.1	4	8	6	14.38	1.24	6	15	12	18.69
1.2	4	8	7	14.5	1.25	6	18	9	17.05
1.3	4	8	8	15.2	1.26	6	18	10.5	17.8
1.4	4	10	6	14.89	1.27	6	18	12	19.08
1.5	4	10	7	16.3	1.28	7	14	10.5	16.78
1.6	4	10	8	18.74	1.29	7	14	12.25	17.81
1.7	4	12	6	14.5	1.30	7	14	14	19.74
1.8	4	12	7	14.76	1.31	7	17.5	10.5	17.45
1.9	4	12	8	15.2	1.32	7	17.5	12.25	18.49
1.10	5	10	7.5	15.13	1.33	7	17.5	14	21.66
1.11	5	10	8.75	15.82	1.34	7	21	10.5	17.73
1.12	5	10	10	16.6	1.35	7	21	12.25	19.29
1.13	5	12.5	7.5	15.6	1.36	7	21	14	22.53
1.14	5	12.5	8.75	16.46	1.37	8	16	12	19.15
1.15	5	12.5	10	17.3	1.38	8	16	14	20.78
1.16	5	15	7.5	16.28	1.39	8	16	16	21.94
1.17	5	15	8.75	16.78	1.40	8	20	12	20.22
1.18	5	15	10	17.5	1.41	8	20	14	22.94
1.19	6	12	9	16	1.42	8	20	16	21.02
1.20	6	12	10.5	16.93	1.43	8	24	12	21.02
1.21	6	12	12	17.59	1.44	8	24	14	23.15
1.22	6	15	9	16.6	1.45	8	24	16	23.72
1.23	6	15	10.5	17.3					

Table 3.3
Case studies in DOE-2

Case number	D(mm)	P(mm)	Cooling time(s)	Case number	D(mm)	P(mm)	Cooling time(s)
2.1	4	8	14.38	2.14	6	20	14.7
2.2	4	12	14.42	2.15	6	24	15.89
2.3	4	16	15.03	2.16	7	8	N/A
2.4	4	20	16.6	2.17	7	12	12.99
2.5	4	24	17.2	2.18	7	16	14.73
2.6	5	8	14.03	2.19	7	20	15.13
2.7	5	12	14.9	2.20	7	24	15.8
2.8	5	16	15.3	2.21	8	8	N/A
2.9	5	20	16.1	2.22	8	12	13.9
2.10	5	24	16.89	2.23	8	16	14.5
2.11	6	8	12.76	2.24	8	20	15
2.12	6	12	13.9	2.25	8	24	15.3
2.13	6	16	14.3				

Table 3.4
Cooling time for variable cross section of channels

Case number	3.1	3.2	3.3	3.4	3.5
Channel cross section	circular	square	rectangular	elliptical	semi-circular
Cooling time(s)	12.74	12.96	10.15	13.49	13.96

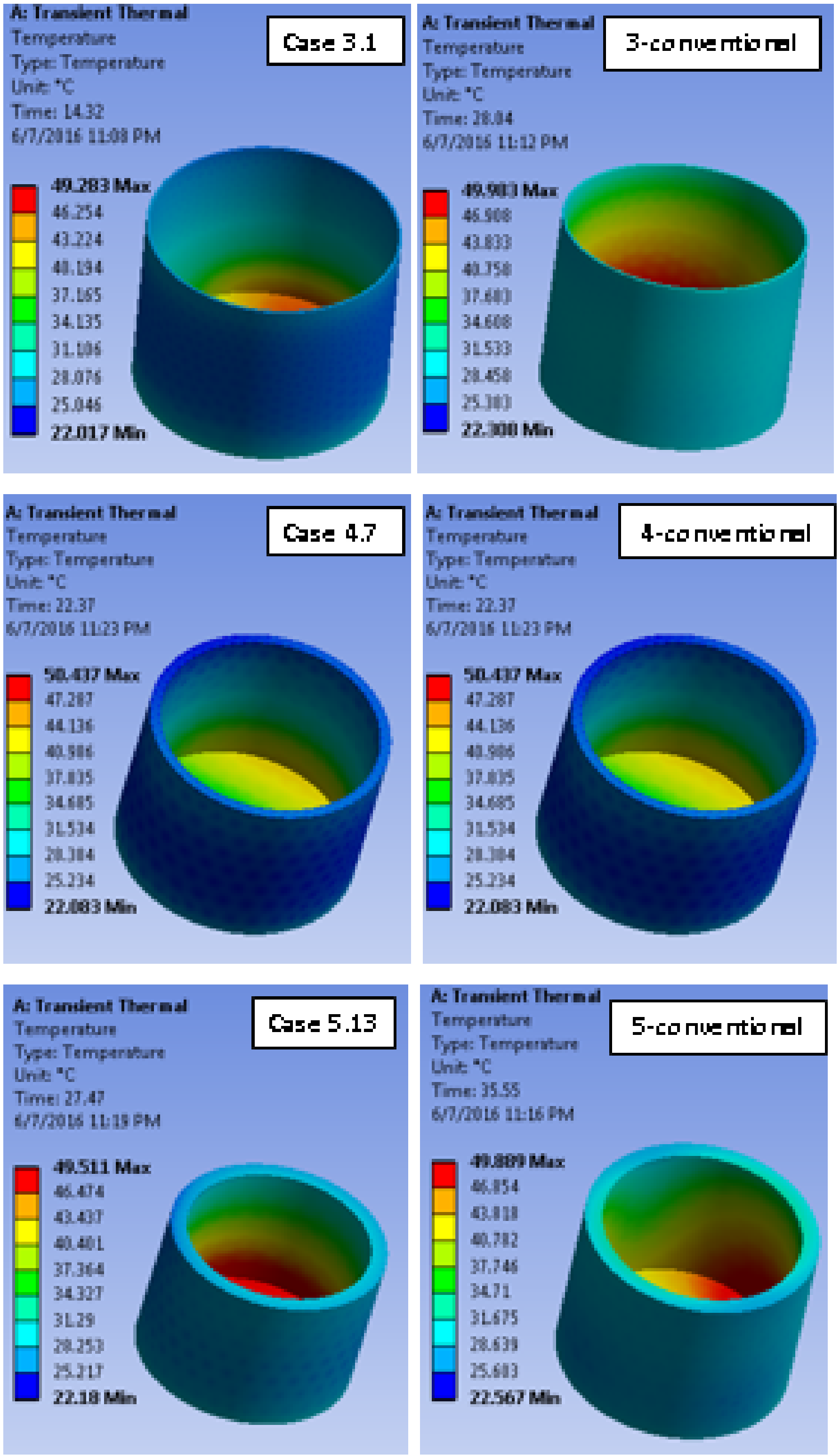


Fig. 3.15. Temperature distribution on plastic parts for comparable conformal and conventional cases.

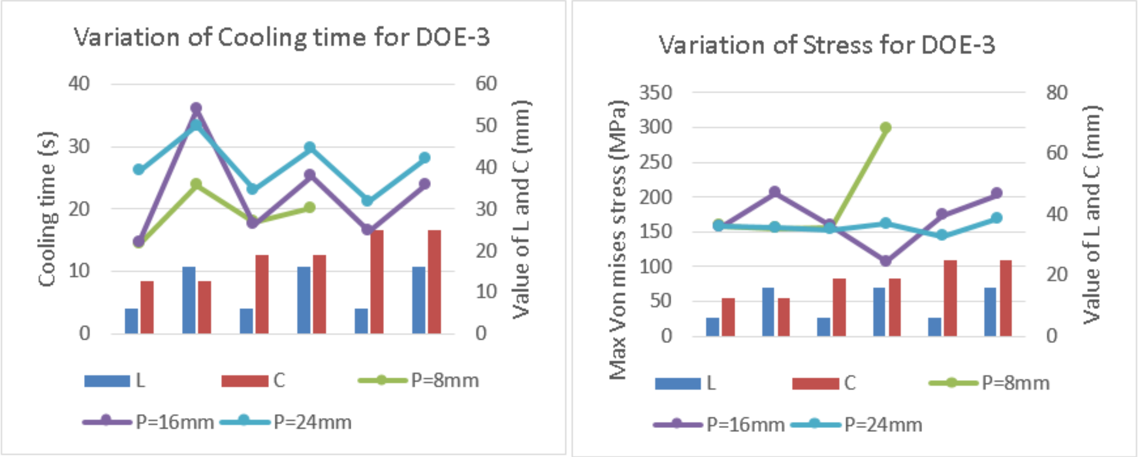


Fig. 3.16. Trend of cooling time and stress variation for DOE-3.

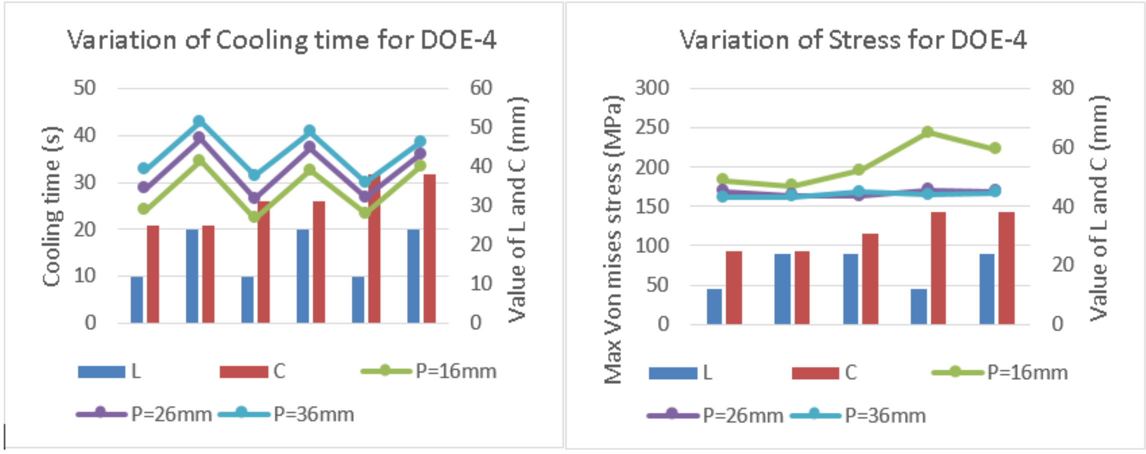


Fig. 3.17. Trend of cooling time and stress variation for DOE-4.

Table 3.5
Channel dimensions for DOE-3

Case number	cross section (mm × mm)	P (mm)	L (mm)
3.1	3.8 × 2.5	8	6
3.2	3.8 × 2.5	8	16
3.3	3.8 × 2.5	16	6
3.4	3.8 × 2.5	16	16
3.5	3.8 × 2.5	24	6
3.6	3.8 × 2.5	24	16
3.7	5.6 × 3.8	8	6
3.8	5.6 × 3.8	8	16
3.9	5.6 × 3.8	16	6
3.10	5.6 × 3.8	16	16
3.11	5. × 3.8	24	6
3.12	5.6 × 3.8	24	16
3.13	7.5 × 5	8	6
3.14	7.5 × 5	8	16
3.15	7.5 × 5	16	6
3.16	7.5 × 5	16	16
3.17	7.5 × 5	24	6
3.18	7.5 × 5	24	16

Table 3.6
Channel dimensions for DOE-4

Case number	cross section (mm × mm)	P (mm)	L (mm)
4.1	7.5 × 5	16	12
4.2	7.5 × 5	16	24
4.3	7.5 × 5	26	12
4.4	7.5 × 5	26	24
4.5	7.5 × 5	36	12
4.6	7.5 × 5	36	24
4.7	9.4 × 6.3	16	12
4.8	9.4 × 6.3	16	24
4.9	9.4 × 6.3	26	12
4.10	9.4 × 6.3	26	24
4.11	9.4 × 6.3	36	12
4.12	9.4 × 6.3	36	24
4.13	11.3 × 7.5	16	12
4.14	11.3 × 7.5	16	24
4.15	11.3 × 7.5	26	12
4.16	11.3 × 7.5	26	24
4.17	11.3 × 7.5	36	12
4.18	11.3 × 7.5	36	24

Table 3.7
Channel dimensions for DOE-5

Case number	cross section (mm × mm)	P (mm)	L (mm)
5.1	11.3 × 7.5	24	18
5.2	11.3 × 7.5	24	28
5.3	11.3 × 7.5	33	18
5.4	11.3 × 7.5	33	28
5.5	11.3 × 7.5	42	18
5.6	11.3 × 7.5	42	28
5.7	12.3 × 8.2	24	18
5.8	12.3 × 8.2	24	28
5.9	12.3 × 8.2	33	18
5.10	12.3 × 8.2	33	28
5.11	12.3 × 8.2	42	18
5.12	12.3 × 8.2	42	28
5.13	13.2 × 8.8	24	18
5.14	13.2 × 8.8	24	28
5.15	13.2 × 8.8	33	18
5.16	13.2 × 8.8	33	28
5.17	13.2 × 8.8	42	18
5.18	13.2 × 8.8	42	28

Table 3.8
Thermal and structural results of DOE-3

Case number	Cooling time (s)	Maximum von-mises stress (MPa)
3.1	14.32	159
3.2	23.83	155
3.3	14.68	157
3.4	35.97	206
3.5	26.07	158
3.6	33.36	156
3.7	17.97	165
3.8	20.08	299
3.9	17.53	159
3.10	25.22	107
3.11	23.04	153
3.12	29.64	161
3.13	N/A	N/A
3.14	N/A	N/A
3.15	16.49	174
3.16	23.88	204
3.17	21.21	144
3.18	28.1	169

Table 3.9
Thermal and structural results of DOE-4

Case number	Cooling time (s)	Maximum von-mises stress (MPa)
4.1	24.01	183
4.2	34.59	176
4.3	28.57	169
4.4	39.22	164
4.5	32.63	161
4.6	42.87	162
4.7	22.37	203
4.8	32.59	196
4.9	26.55	166
4.10	37.33	163
4.11	31.37	215
4.12	40.71	168
4.13	23.58	244
4.14	33.45	222
4.15	26.75	171
4.16	36.03	169
4.17	29.98	165
4.18	38.57	167

Table 3.10
Thermal and structural results of DOE-5

Case number	Cooling time (s)	Maximum von-mises stress (MPa)
5.1	28.48	179
5.2	31.91	180
5.3	32.52	173
5.4	35.39	170
5.5	35.04	172
5.6	37.15	162
5.7	28.35	197
5.8	30.78	174
5.9	36.60	184
5.10	34.24	168
5.11	33.99	174
5.12	36.35	171
5.13	27.47	176
5.14	30.52	189
5.15	30.75	186
5.16	33.35	177
5.17	33.45	177
5.18	35.65	175

Table 3.11
Comparative thermal and structural results of DOE-3,4,5

DOE number	Conformal cooling time (s)	Conventional Cooling time (s)	Conformal Max stress (MPa)	Conventional Max stress (MPa)
DOE-3	14.32	28.04	159	153
DOE-4	22.37	28.32	203	167
DOE-5	27.47	35.55	176	168

Table 3.12
Selected top three optimum cases from DOE-3,4,5

DOE number	Selected Cases
DOE-3	3.1, 3.3, 3.9
DOE-4	4.1, 4.9, 4.17
DOE-5	5.1, 5.8, 5.13

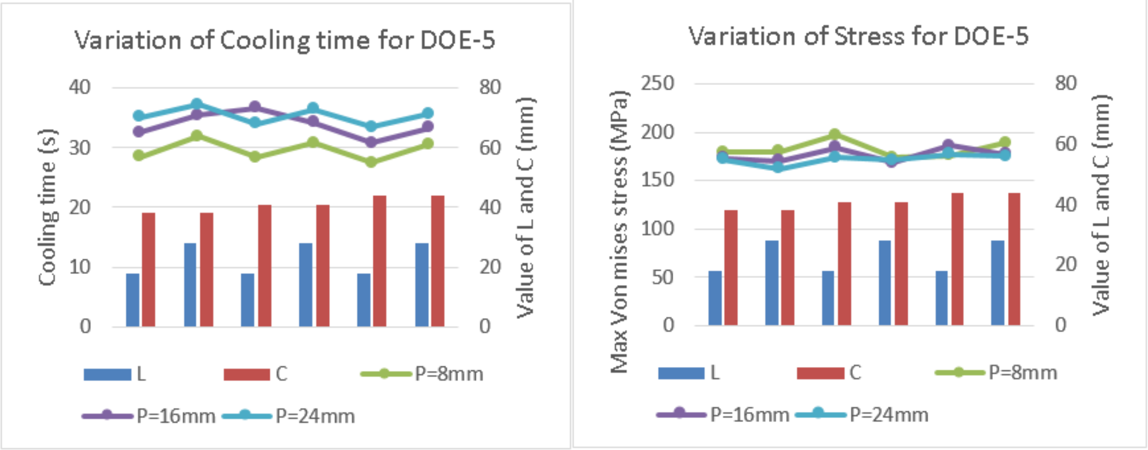


Fig. 3.18. Trend of cooling time and stress variation for DOE-5.

4. A DETAILED CASE STUDY ON CHANNEL CROSS SECTIONS AND GUIDELINE FOR DESIGNING CONFORMAL COOLING CHANNELS

4.1 Rationale

In Chapter 3, the optimum designs of conformal cooling channels in injection molds have been identified that can be used to manufacture plastic parts with different thicknesses. The analyses were conducted for cylindrical plastic parts and molds with rectangular x-section of conformal channels only. Recent studies [7,29] show that many different cross sections of channels can be effective for the purpose of injection mold design. This brings us to the content of the current chapter. With the optimal designs obtained in Chapter 4 is here implemented with different cross sections to identify the most effective solutions for designing conformal cooling channels. Moreover, the study is further extended to design for conical shaped plastic parts too, as the cylindrical and conical are the most commonly used designs under concern; both in literature and practical injection molding business [4–6, 14].

Recalling the discussion in Chapter 3, Section 3.5, with the five types of cross sections of cooling channels, the minimum cooling time was provided by the rectangular shape conformal cooling channel. The other two top designs were the circular and the square shaped ones (refer Table 3.4). As the comparative study was for a single design case, it is probable that rectangular channels might not always provide the best thermal performance in all sizes and shapes of plastic parts. Also the most suitable design cases in DOE-3, 4, 5 may not provide the same result while they are used for different shapes of plastic part designs. For this reason the results obtained in Chapter 3 are combined with the cross section variations and six new sets of design of experiments are conducted and discussed in this current chapter.

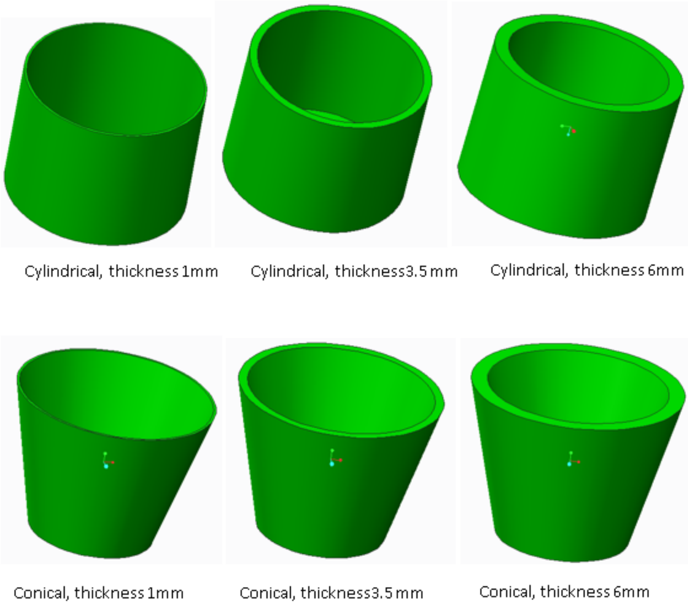
In this scenario, the top three optimized designs of cooling channels for each of the different thicknesses (as obtained in Chapter 3) are chosen for further analysis in this chapter, and all three different channel cross sections are incorporated into those. Moreover, designs are analyzed for conical part too as mentioned earlier. These are the significant parameters that influence the setup of all the subsequent design of experiments of this chapter, and are discussed in the following section.

4.2 Plastic Part Designs for DOEs

6 different plastic part designs are considered here. As mentioned earlier, the basic shapes are two, each having three different thicknesses. Hence six different design of experiments sets are created too. Table 4.1 shows the DOE set with the plastic part dimension. The CAD models of these plastic parts are shown in Figure 4.1.

Table 4.1
Plastic part dimensions for DOE 6-11

DOE number	Shape	Thickness (mm)	Height (mm)	Larger diameter (mm)	Smaller diameter (mm)
DOE-6	cylindrical	1	60	80	80
DOE-7	cylindrical	3.5	60	80	80
DOE-8	cylindrical	6	60	80	80
DOE-9	conical	1	60	80	50
DOE-10	conical	3.5	60	80	50
DOE-11	conical	6	60	80	50



Cylindrical, thickness 1mm Cylindrical, thickness3.5mm Cylindrical, thickness 6mm

Conical, thickness 1mm Conical, thickness3.5mm Conical, thickness 6mm

Fig. 4.1. CAD models of six different plastic parts.

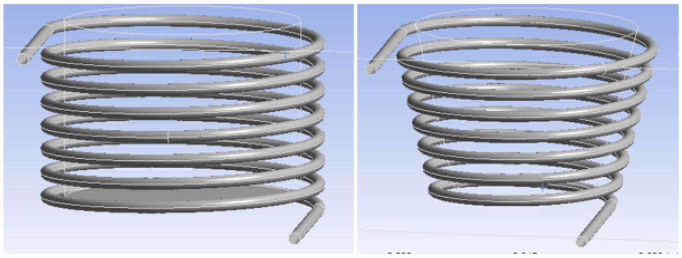
4.3 Design of Experiments Setup (DOE 6-11)

Consider the first case in first row of Table 3.12. The channel cross section is rectangular (3.8mm × 2.5mm), with P = 8mm and L = 6mm. The cross section is converted into circular and square shaped ones keeping the perimeter same. Resulting channel dimensions are circular section channel with diameter 4mm and square section channel of 3.1mm × 3.1mm. The value of P and L are same in all three cases. In this manner, one row of Table 3.12 gives rise to 3 different configurations of conformal cooling channel designs. As a result, the 9 rows of Table 14 provides 9 × 3 = 27 types of channel designs. First 9 of them are for 1mm thick plastic part, next 9 for 3.5mm thick plastic part and the last 9 are for 6mm thick plastic part design.

Table 4.2, 4.3, 4.4 show the channel dimensions of these 27conformal channel designs. These tables are for three different part thicknesses as mentioned earlier. These are for DOE 6, 7 and 8 respectively, which are the cylindrical plastic parts. These 27 designs can be repeated in injection molds for conical shape plastic part. The only difference between these cases would be the profile of channels. For the first case (cylindrical), the channel spiral shape is cylindrical while conical shape plastic part will have conical shape spirals. Hence, the channel dimensions for DOE-6 are exactly same for the channel dimensions for DOE-9. Similarly DOE-7 matches with DOE-10 and DOE-8 matches with DOE-11. Figure 4.2 shows generic channel design for cylindrical and conical shape for better understanding of the reader.

Table 4.2
Channel dimensions for DOE-6

Case number	Section size (mm)	P(mm)	L(mm)
6.1	D = 4	8	6
6.2	3.8 × 2.5	8	6
6.3	3.1 × 3.1	8	6
6.4	D = 4	16	6
6.5	3.8 × 2.5	8	6
6.6	3.1 × 3.1	16	6
6.7	D = 6	16	6
6.8	5.6 × 3.8	16	6
6.9	4.7 × 4.7	16	6



Cylindrical shape spiral channel

Conical shape spiral channel

Fig. 4.2. Cylindrical and conical conformal channels.

Applying the above mentioned technique of channel design, 6 design of experiment sets (DOE6-11) are created and analyzed for their thermal performance. As

Table 4.3
Channel dimensions for DOE-7

Case number	Section size (mm)	P(mm)	L(mm)
7.1	D = 8	16	12
7.2	7.5 × 5	16	12
7.3	6.3 × 6.3	16	12
7.4	D = 10	26	6
7.5	9.4 × 6.3	26	12
7.6	7.9 × 7.9	26	12
7.7	D = 12	36	12
7.8	11.3 × 7.5	36	12
7.9	9.4 × 9.4	36	12

Table 4.4
Channel dimensions for DOE-8

Case number	Section size (mm)	P(mm)	L(mm)
8.1	D = 12	24	18
8.2	11.3 × 7.5	24	18
8.3	9.4 × 9.4	24	18
8.4	D = 13	28	28
8.5	12.3 × 8.2	28	28
8.6	10.2 × 10.2	28	28
8.7	D = 14	24	18
8.8	13.2 × 8.8	24	18
8.9	10.9 × 10.9	24	18

the structural stability has already been tested and the designs are chosen based on the thermal and structural performance earlier, structural analysis has not been conducted here for the DOE-6-11. The results are discussed in the following section.

4.4 Results and Findings of DOE 6-11

All the six design of experiment sets DOE-6 to DOE11 has 9 design cases each. The thermal results of these are shown in Table 4.5 and Table 4.6. The first one is for cylindrical cases and the second one is for conical cases.

Table 4.5
Cooling times in case studies for cylindrical part

Case number	Cooling time (s)	Case number	Cooling time (s)	Case number	Cooling time (s)
6.1	13.51	7.1	28.82	8.1	27.65
6.2	14.32	7.7	24.01	8.2	28.48
6.3	13.87	7.3	23.73	8.3	28.72
6.4	20.03	7.4	27.50	8.4	30.35
6.5	14.68	7.5	26.55	8.5	30.78
6.6	20.39	7.6	27.45	8.6	30.16
6.7	17.46	7.7	29.3	8.7	26.89
6.8	17.53	7.8	29.98	8.8	27.47
6.9	17.86	7.9	30.27	8.9	27.16

From the Table 4.5 and 4.6, it is prominent that though all the other design variables including the perimeter of the channels are kept unchanged, the cooling time does vary if the cross section changes. This means effect of cross section is very important while designing conformal cooling channels for injection molds. An important thing to be noted here is for similar cases (e.g., same pitch, same wall to channel

Table 4.6
Cooling times in case studies for conical part

Case number	Cooling time (s)	Case number	Cooling time (s)	Case number	Cooling time (s)
9.1	12.7	10.1	22.63	11.1	17.63
9.2	12.84	10.7	19.84	11.2	17.87
9.3	12.75	10.3	19.65	11.3	20.05
9.4	18.03	10.4	21.48	11.4	18.13
9.5	18.27	10.5	21.39	11.5	17.74
9.6	18.25	10.6	20.85	11.6	17.5
9.7	15.94	10.7	21.02	11.7	15.96
9.8	16.21	10.8	22.63	11.8	16.51
9.9	16.04	10.9	22.36	11.9	16.37

distance), sometimes the circular channel provides better result than the rectangular ones, and sometimes the opposite happens. Moreover, the often the square channels even provide better result than the corresponding circular or rectangular one. Hence, no single cross section can be designated as better than the other for all sorts of mold design scenario.

For DOE-6, the minimum cooling time obtained is13.51s, which occurs at case 6.1. This is a circular shape conformal channel with D = 4mm, P = 8mm and L = 6mm. The design cases 6.2 and 6.3 which have the exact same P and L values, but rectangular and square section of channel provides slightly higher cooling time 14.32s and 13.87s respectively. The other design cases in DOE-6 provides cooling time in the range of 14s-20s. It is reasonable to mention here that this DOE-6 is only for cylindrical shapes 1mm thick plastic parts only, whereas DOE-7 and DOE-8 are for 3.5mm and 6mm plastic parts respectively. As mentioned earlier, a cylindrical shaped plastic part with 1mm thickness is cooled down to its ejection temperature at around 28s. Hence, all the design cases in DOE-6 (6.1-6.9) are acceptable design solutions while a mold designer needs to do design one. It is possible for a mold designer to choose and even mix and match from any of these cases if there are some design constraints does not permit him to choose the most effective one (case 6.1 in this scenario).

On the other hand, for DOE-7, the best result 23.73s is achieved at case 7.3, which is a square section cooling channel (6.3mm × 6.3mm), with P = 16mm and L = 12mm. The similar design cases (same P and L as case 7.3) provides higher cooling time. Also the other design cases in DOE-7 provides cooling time of 25s-30s. Again for DOE-8 (6mm thickness plastic part) the best solution comes in case 8.7, which is 26.89s. The channel dimension is D = 14mm, P = 24mm and L = 18mm.The overall range of cooling time in DOE-8 is 27s-30s. So it is clear that longer time is required to cool the thick plastic parts compared to the thinner ones. All these design cases provide significant improvement from the traditional straight drilled designs of injection molds. These also provide insight to a range of variables in which the mold designers can work on while creating their own CAD model, if the specific design obtained in this study cannot be created due to other design constraints.

It is notable here that starting from DOE-6, the variation of cooling time decreases in DOE-7 and then again in DOE-8. This indicates that to design a conformal cooling channel configuration for a thick plastic part, it is highly critical and a very little change can cause improvement in cooling time. While designing such channels, mold designers need to concentrate more and may need to conduct detailed design of experiments in a wide range of design variables and with a small gap between levels to find out the most effective design for their purpose. On the other hand, designing for comparatively thin plastic parts, it is easier to find the most effective configuration, as a small change causes noteworthy difference in cooling time, and designers can work on a specific range of design variables.

Now, the DOE-9, 10 and 11 are designed for conical shaped plastic parts. The best results are 12.70s, 19.65s and 15.96s obtained in case 9.1, 10.3 and 11.7 respectively. It is notable here that these cooling times are quite shorter than the ones for cylindrical shape plastic parts. It is an important idea for the plastic industry. As conical shape is easier to produce and provides benefit to industry by taking shorter cooling time, the designers may consider replacing cylindrical bodies, such as bottle cap, bowls, plastic containers etc. with conical shaped ones, if possible. Moreover, using draft angle in the part design can also help in reducing the cooling times too.

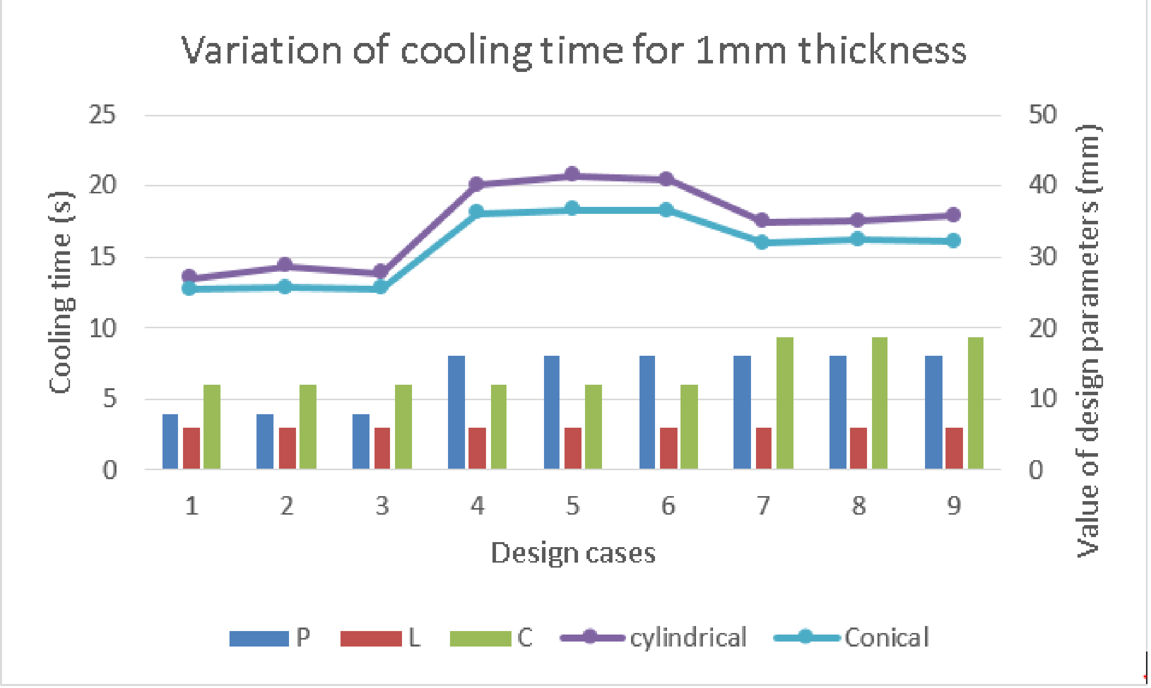


Fig. 4.3. Cooling time variation for 1mm thickness.

Yet, for the cases that have been discussed and analyzed in this study, design solutions are only in terms of channel design, size and shape, design variables have been obtained by analysis. Moreover, it is very important to note that, the channel design configuration that provides the minimum cooling time for a 1mm thick cylindrical plastic part, is exactly the same for the 1mm thick conical shape part too. This happens again for the 3.5mm and 6mm thick parts also, indicating the results are quite reliable and can be adopted for other shapes of plastic part bodies as a rectangular

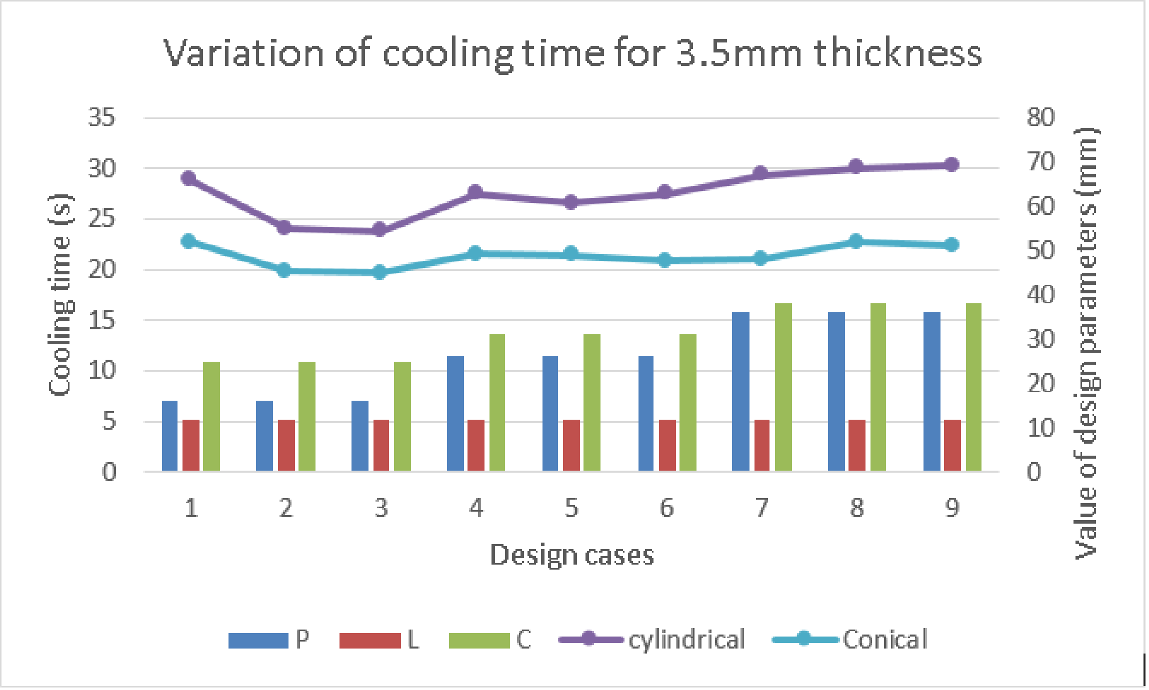


Fig. 4.4. Cooling time variation for 3.5mm thickness.

box or spherical ball etc. Figure 4.3, 4.4 and 4.5 shows the trend of cooling time with different design cases. They provide the comparison of cooling times for similar designs of cylindrical and conical shapes of plastic bodies. For the same thickness, and with the same channel design, the conical parts are cooled down earlier than the cylindrical designs.

This study provides a basis and guideline for the mold designers to adopt a method of designing conformal cooling channels for their injection molds. As it has been already mentioned in the previous chapter that there are some design constraints in injection molds such as the position of inlet and outlet ports, gate, runner, ejector pins etc., one specific design solution may not be feasible to design in a specific industrial case. For this reason, top three design cases are listed in Table 4.7 for each size and shape of plastic parts, so that they can choose and if necessary mix and match the design variables to create the most suitable one for their mold.

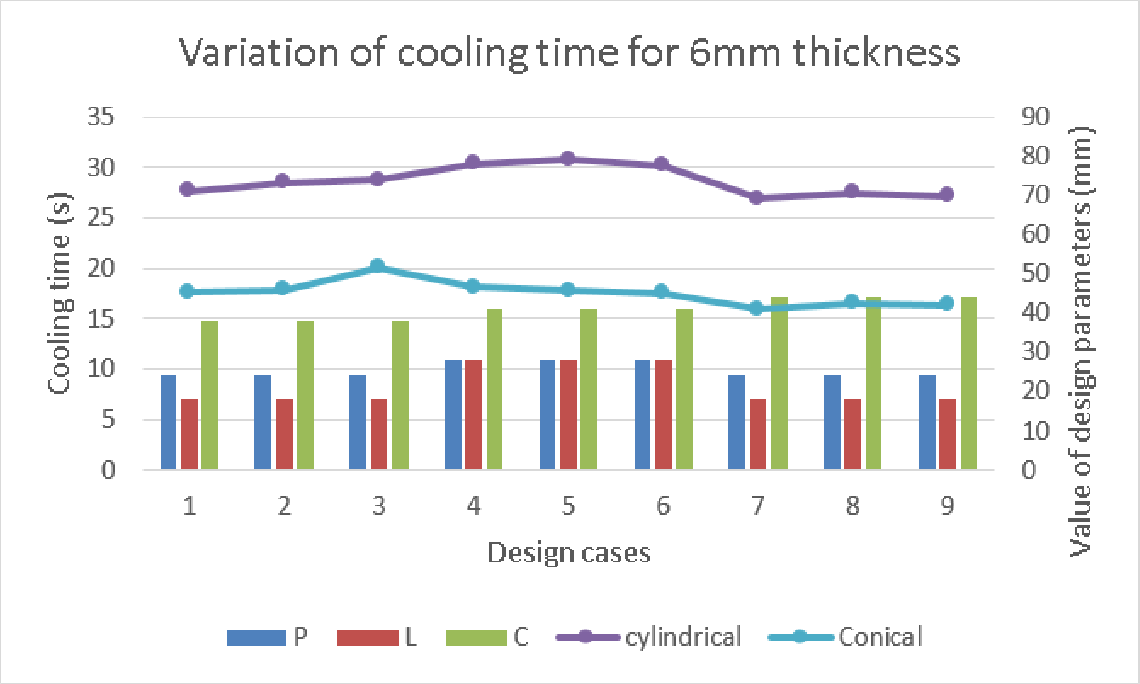


Fig. 4.5. Cooling time variation for 6mm thickness.

In Figure 4.6, the temperature distribution on the plastic parts for the best possible design cases as obtained in DOE-6 to 11 are shown.

4.5 Results of Moldflow Analysis

Moldflow analysis result provides insight into the injection process parameters. Analyzing the results, the designer can change the control parameters, hence improve the process efficiency.The optimal design solution as obtained in the previous sections are analyzed in the moldflow process model. Figure 4.7shows the moldflow results on the conical part with 1mm thickness. The channel is circular with D = 4mm, P = 8mm and L = 6mm.The results indicate the filling time injection pressure, gate location, warpage percentage etc. Based on these predictions, the mold designer

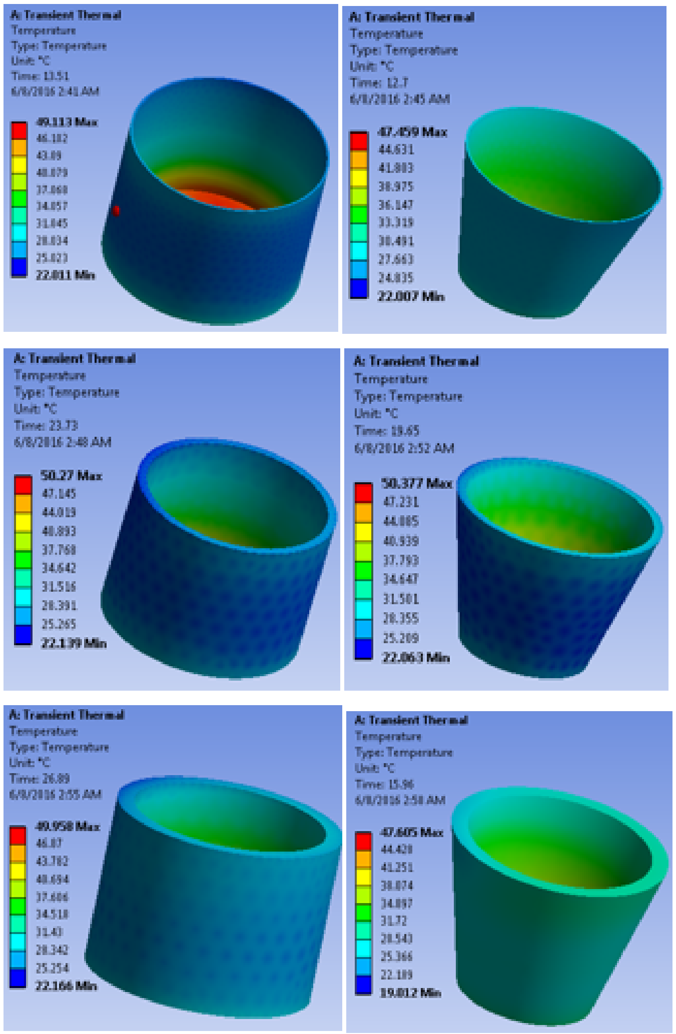
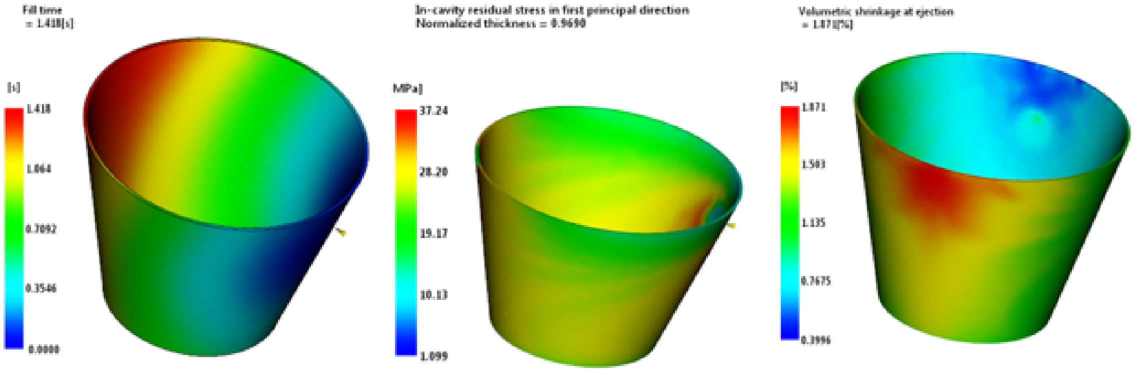


Fig. 4.6. Temperature distribution on plastic part for best design cases

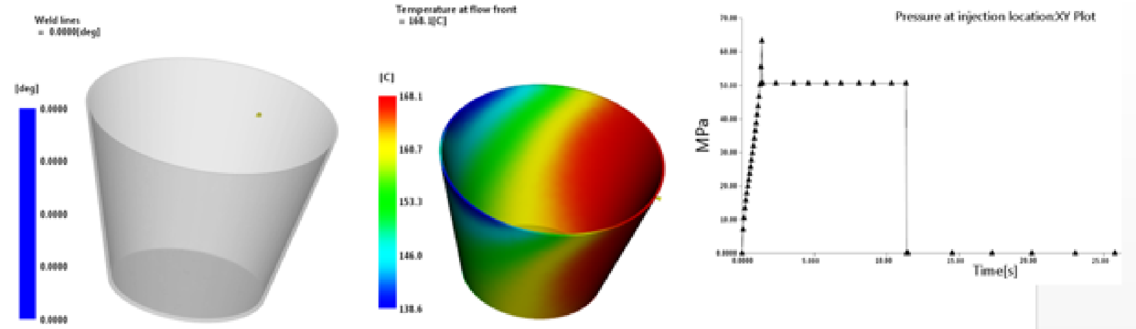
and process control personnel in injection molding process can identify the optimum process parameters.



Fill time

Residual stress

Volumetric shrinkage



Weld lines on plastic

Temperature at flow front

Injection point pressure

Fig. 4.7. Moldflow-insight results.

Table 4.7
Conformal cooling channel design guideline

Plastic part design	Design solution 1(optimum)	Design solution 2 (less optimum than 1)	Design solution 3 (less optimum than 2)
Cylindrical 1 mm	circular D = 4, P = 8, L = 6	square 3.1 × 3.1, P = 8, L = 6	rectangular 3.8 × 2.5, P = 8, L = 6
Cylindrical 1.5mm	rectangular 5.6 × 3.8 P = 8 L = 7	circular D = 6 P = 8 L = 7	square 4.7 × 4.7 P = 8 L = 7
Cylindrical 3.5mm	square 6.3 × 6.3 P = 16 L = 12	circular D = 8 P = 16 L = 12	rectangular 7.5 × 5 P = 16 L = 12
Cylindrical 6mm	circular D = 14 P = 24 L = 18	rectangular 13.2 × 8.8 P = 24 L = 18	circular D = 12 P = 24 L = 18
Conical 1mm	circular D = 4 P = 8 L = 6	square 3.1 × 3.1 P = 8 L = 6	rectangular 3.8 × 2.5 P = 8 L = 6
Conical 3.5mm	square 6.3 ×6.3 P = 16 L = 12	rectangular 7.5 × 5 P = 16 L = 12	square 7.9 × 7.9 P = 26 L = 12
Conical 6mm	circular D = 14 P = 24 L = 18	square 10.9 × 10.9 P = 24 L = 18	rectangular 13.2 × 8.8 P = 24 L = 18

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In this study, a design methodology has been adopted to obtain optimum design of conformal cooling channels in injection molding tools. There is a wide variety of plastic parts that are being used in our everyday life, hence the worldwide plastic injection molding industry is also vast. With the increase of competition in business, mold designers require efficient tools to serve their purpose. The thesis here provides a guideline for them to reach this goal.

Numerical models are developed to analyze the thermal and structural performance of injection molding tools. These model provides a base to compare the performance of various designs of molds and various designs of conformal channel configuration. It needs to be mentioned here that, during the development of numerical models, the coolant temperature was considered to be a bit higher than the room temperature, as well as the mold temperature. This is true for the first shot of a typical injection molding process, when the mold needs to be warm to provide better molding performance, and hot water can serve the purpose. Once the injection molding process reaches a steady state, and the mold body gets warm due to the highly heated molted plastic, the coolant temperature becomes lower than the mold temperature.Considering this phenomena,a benchmark simulation with mold temperature increased to 46.8°C shows that the cooling time is 2-3s higher than that obtained for the case where the mold temperature is assumed at room temperature. Yet, these numbers are very promising in terms of reducing cooling time and correspondingly the total production cycle time.

A number of design of experiments have been undertaken to identify the most suitable design of channel for injection molds. The first two sets of DOE are designed for a single specific part thickness, 1.5mm. Also the effect of channel cross section has been analyzed. For this case, a rectangular section of 5.6 x 3.8mm, with Pitch 8mm and mold wall to channel centerline distance 7mm predicts the minimum cooling time and thus chosen as the optimum solution. Then DOE-3,4,and 5 are conducted to obtain a thermo-mechanically optimized solution of conformal cooling channels for 1mm, 3.5mm and 6mm thick plastic parts.

The results of DOE lead to the setup of DOE6,7,8,9,10 and 11. In these DOEs, the effect of channel cross section is studied with circular, rectangular and square section channels. The study is extended for cylindrical and conical shape plastic parts and various thicknesses.In each case, a specific configuration of channel in terms of section size, pitch and other design parameters offer best results. These results are studied and a final design selection guideline has been proposed in this study. This guideline includes 3 top optimum design solutions for the designers to choose from.It provides very useful insight for the mold designers to choose the design configuration of their respective molds in industry.

Once a design configuration is finalized,it is recommended that mold designers use the moldflow process model to identify the optimum process parameters for their interest. Furthermore, the conformal cooling channels can be incorporated into a porous structure optimized mold body, and thus the benefit of additive manufacturing can be attained to the maximum.

5.2 Recommendations

The following section provides some improvement possibilities for design and analysis of conformal cooling channels:

1. Mold designers need to follow the guideline that is provided by this study while designing conformal cooling channels for their cavity and core.

2. The results provide design recommendations for cylindrical and conical designs only and for specific thicknesses. Yet, the techniques are applicable for other part shapes too.

3. Uniform thickness of plastic part is very important to achieve better cooling, less warping and minimum molding defects.

4. Designing for thicker plastic parts needs detailed attention compared to the thinner ones.

5. Once the channel design is finalized, the use of Moldflow to identify suitable process parameters as well as Position of gates, runner, inlet outlet locations, flow rate, coolant temperature, injection Pressure etc.

6.Further studies can be conducted to adapt the variable distance of cooling channels from mold wall to obtain more uniformity of cooling.

7.The study can provide guideline towards creating empirical formulae for the design parameters of CCC.

8. Finally, further study need to be conducted with the combination of all techniques, it is advisable to create a user-friendly interface to create the CAD model of injection mold with conformal cooling channels automatically.The .stl file thus created can be used to 3D print the mold easily.

LIST OF REFERENCES

LIST OF REFERENCES

[1] D. V. Rosato and M. G. Rosato, *Injection Molding Handbook*. Springer Science & Business Media, 2012.

[2] R. Zheng, R. I. Tanner, and X.-J. Fan, *Injection molding: integration of theory and modeling methods*. Springer Science & Business Media, 2011.

[3] D. Dimla, M. Camilotto, and F. Miani, "Design and optimisation of conformal cooling channels in injection moulding tools," *Journal of Materials Processing Technology*, vol. 164, pp. 1294–1300, 2005.

[4] E. Sachs, E. Wylonis, S. Allen, M. Cima, and H. Guo, "Production of injection molding tooling with conformal cooling channels using the three dimensional printing process," *Polymer Engineering & Science*, vol. 40, no. 5, pp. 1232–1247, 2000.

[5] X. Xu, E. Sachs, S. Allen, and M. Cima, "Designing conformal cooling channels for tooling," in *Solid Freeform Fabrication Proceedings*, pp. 131–146, 1998.

[6] X. Xu, E. Sachs, and S. Allen, "The design of conformal cooling channels in injection molding tooling," *Polymer Engineering & Science*, vol. 41, no. 7, pp. 1265–1279, 2001.

[7] E. Sachs, S. Allen, H. Guo, J. Banos, M. Cima, J. Serdy, and D. Brancazio, "Progress on tooling by 3d printing; conformal cooling, dimensional control, surface finish and hardness," in *Proceedings of Solid Freeform Fabrication Symposium*, pp. 115–123, 1997.

[8] J. Ferreira and A. Mateus, "Studies of rapid soft tooling with conformal cooling channels for plastic injection moulding," *Journal of Materials Processing Technology*, vol. 142, no. 2, pp. 508–516, 2003.

[9] J. Meckley and R. Edwards, "A study on the design and effectiveness of conformal cooling channels in rapid tooling inserts," *The Technology Interface Journal*, vol. 10, no. 1, pp. 1–28, 2009.

[10] N. Hopkinson and P. Dickens, "Conformal cooling and heating channels using laser sintered tools," in *Solid freeform fabrication conference, Texas*, pp. 490–497, 2000.

[11] S. Yoo, "Design of conformal cooling/heating channels for layered tooling," in *Smart Manufacturing Application, 2008. ICSMA 2008. International Conference on*, pp. 126–129, IEEE, 2008.

[12] K. Altaf, A. M. A. Rani, and V. R. Raghavan, "Fabrication of circular and profiled conformal cooling channels in aluminum filled epoxy injection mould tools," in *National Postgraduate Conference (NPC), 2011*, pp. 1–4, IEEE, 2011.

[13] C. Li, C. Li, and A. Mok, “Automatic layout design of plastic injection mould cooling system,” *Computer-Aided Design*, vol. 37, no. 7, pp. 645–662, 2005.

[14] A. Saifullah and S. H. Masood, “Optimum cooling channels design and thermal analysis of an injection moulded plastic part mould,” in *Materials Science Forum*, vol. 561, pp. 1999–2002, Trans Tech Publ, 2007.

[15] A. Saifullah, S. Masood, and I. Sbarski, “New cooling channel design for injection moulding,” in *Proceedings of the World Congress on Engineering*, vol. 1, 2009.

[16] A. Saifullah, S. Masood, and I. Sbarski, “Thermal–structural analysis of bi-metallic conformal cooling for injection moulds,” *The International Journal of Advanced Manufacturing Technology*, vol. 62, no. 1-4, pp. 123–133, 2012.

[17] R. X. Xu and E. Sachs, “Rapid thermal cycling with low thermal inertia tools,” *Polymer Engineering & Science*, vol. 49, no. 2, pp. 305–316, 2009.

[18] Y. Sun, K. Lee, and A. Nee, “Design and fem analysis of the milled groove insert method for cooling of plastic injection moulds,” *The International Journal of Advanced Manufacturing Technology*, vol. 24, no. 9-10, pp. 715–726, 2004.

[19] T. ó Gloinn, C. Hayes, P. Hanniffy, and K. Vaugh, “Fea simulation of conformal cooling within injection moulds,” *International Journal of Manufacturing Research*, vol. 2, no. 2, pp. 162–170, 2007.

[20] K. Au and K. Yu, “A scaffolding architecture for conformal cooling design in rapid plastic injection moulding,” *The International Journal of Advanced Manufacturing Technology*, vol. 34, no. 5-6, pp. 496–515, 2007.

[21] F. Hsu, K. Wang, C. Huang, and R. Chang, “Investigation on conformal cooling system design in injection molding,” *Advances in Production Engineering & Management*, vol. 8, no. 2, p. 107, 2013.

[22] H.-S. Park and X.-P. Dang, “Optimization of conformal cooling channels with array of baffles for plastic injection mold,” *International Journal of Precision Engineering and Manufacturing*, vol. 11, no. 6, pp. 879–890, 2010.

[23] X.-P. Dang and H.-S. Park, “Design of u-shape milled groove conformal cooling channels for plastic injection mold,” *International Journal of Precision Engineering and Manufacturing*, vol. 12, no. 1, pp. 73–84, 2011.

[24] M. Khan, S. K. Afaq, N. U. Khan, and S. Ahmad, “Cycle time reduction in injection molding process by selection of robust cooling channel design,” *ISRN Mechanical Engineering*, 2014.

[25] Y. Wang, K.-M. Yu, C. C. Wang, and Y. Zhang, “Automatic design of conformal cooling circuits for rapid tooling,” *Computer-Aided Design*, vol. 43, no. 8, pp. 1001–1010, 2011.

[26] J. H. Choi, J. S. Kim, E. S. Han, H. P. Park, and B. O. Rhee, “Study on an optimized configuration of conformal cooling channel by branching law,” in *ASME 2014 12th Biennial Conference on Engineering Systems Design and Analysis*, American Society of Mechanical Engineers, 2014.

[27] H. S. Park and N. H. Pham, "Automatically generating conformal cooling channel design for plastic injection molding," *Annals of DAAAM & Proceedings*, pp. 539–541, 2007.

[28] H.-S. Park and N. H. Pham, "Design of conformal cooling channels for an automotive part," *International Journal of Automotive Technology*, vol. 10, no. 1, pp. 87–93, 2009.

[29] Y. Wang, K.-M. Yu, and C. C. Wang, "Spiral and conformal cooling in plastic injection molding," *Computer-Aided Design*, vol. 63, pp. 1–11, 2015.

[30] K. Au, K. Yu, and W. Chiu, "Visibility-based conformal cooling channel generation for rapid tooling," *Computer-Aided Design*, vol. 43, no. 4, pp. 356–373, 2011.

[31] K. Au and K. Yu, "Variable distance adjustment for conformal cooling channel design in rapid tool," *Journal of Manufacturing Science and Engineering*, vol. 136, no. 4, p. 044501, 2014.

[32] A. Agazzi, V. Sobotka, R. Le Goff, and Y. Jarny, "Uniform cooling and part warpage reduction in injection molding thanks to the design of an effective cooling system," in *Key Engineering Materials*, vol. 554, pp. 1611–1618, Trans Tech Publ, 2013.

[33] S. Mayer, "Optimised mould temperature control procedure using dmls," *EOS Whitepaper, EOS GmbH Ltd*, pp. 1–10, 2005.

[34] Customerpartnet, "Injection molding," *http://www.custompartnet.com/wu /InjectionMolding*, Last accessed June 2016.

[35] T. Wu, S. A. Jahan, P. Kumaar, A. Tovar, H. El-Mounayri, Y. Zhang, J. Zhang, D. Acheson, K. Brand, and R. Nalim, "A framework for optimizing the design of injection molds with conformal cooling for additive manufacturing," *Procedia Manufacturing*, vol. 1, pp. 404–415, 2015.

[36] B.-O. Rhee, C.-S. Park, H.-K. Chang, H.-W. Jung, and Y.-J. Lee, "Automatic generation of optimum cooling circuit for large injection molded parts," *International Journal of Precision Engineering and Manufacturing*, vol. 11, no. 3, pp. 439–444, 2010.

[37] C. Fetecau, F. Stan, and L. I. Sandu, "In-mold monitoring of temperature and cavity pressure during the injection molding process," in *ASME 2014 International Manufacturing Science and Engineering Conference collocated with the JSME 2014 International Conference on Materials and Processing and the 42nd North American Manufacturing Research Conference*, American Society of Mechanical Engineers, 2014.

[38] S. Young, "Additive manufacturing applications for the tooling industry," *http://files.ctctcdn.com/f4e5fcaa001/8a681c1b-de6b-431c-acf5-888b03ec38b3.pdf*, Last accessed June 2016.