DESIGN AND COMPARITIVE THERMAL ANALYSIS OF CONSTRUCTAL COOLING CHANNEL

by

Mohamad Haiqal Bin Mazlan

Dissertation submitted in partial fulfillment of
The requirements for the
Bachelor of Engineering (Hons)
(Mechanical Engineering)

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
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Approved by,

____

(Dr. Majdi Abdul Rani)

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK
September 2013

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

MOHAMAD HAIQAL BIN MAZLAN

ABSTRACT

Injection Mould Thermal Management is a critical issue in plastic injection molding process and has major effects on production cycle time that is directly linked with the cost and also has great significance on part quality. For this reason, cooling system design has great significant for plastic products industry by injection molding. It is crucial not only to reduce molding cycle time but also is considerably affects the productivity and quality of the product. The cooling channels in injection molding have circular cross section and straight line due to the conventional manufacturing technique of drilling. In Rapid Prototyping and Tooling techniques of fabricating conformal cooling channel, the cross section is also circular but the problem lies with the design of the conformal cooling channel. There are many designs but which design will allow the performance of the injection mold cooling time to decrease? A study has been made by Dr. Andrian Bejan (2002) in his paper "Optimal Tree-shaped Networks for Fluid Flow in a Disc-shaped Body" and he modeled a tree shape cooling channel for a disk to solve the flow resistance problem so that the cooling time will decrease. In this paper, the new design of cooling channel will be introduced to improve the performance of cooling channel. The research start by analyzing the literature review by Dr. Andrian Bejan who introduce the constructal concept which state that for a finite-size system to persist in time (to live), it must evolve in such a way that it provides easier access to the imposed currents that flow through it. The result is expected to be different from the existed profiled cooling channel and conformal cooling channel but it is strongly believed that the performance will be better than the existed cooling channel.

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TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 Background of Study

The design of the cooling channel is made based on Constructal Theory. Constructal law design in nature is flow. There are two side of constructal law which are we predict the occurrence of design in nature and we design the devices for human use. It puts forth the idea of generating the idea (configuration, pattern, geometry) in nature is a physics phenomenon that unites all animates and inanimate systems. Andrian Bejan state that "for a finite-size system to persist in time (to live), it must evolve in such a way that it provides easier access to the imposed currents that flow through it". The meaning of the sentence is the configuration and function of flow systems change over time in a predictable way that improves function, distributes imperfection, and creates geometries that best arrange high and low resistance areas or volume.

Rapid prototyping is used to make the cooling channel of the mold for injection molding. Rapid Prototyping refer to a class of technologies that can automatically build physical models from Computer-Aided Design (CAD) data. These "three dimensional printers" allow designer to quickly create tangible prototypes of their designs, rather than just two-dimensional pictures. Such models have numerous uses. They make excellent visual aids for communicating ideas with co-workers or customers. In addition, prototypes can be used for design testing. Designers have always utilized prototypes; RP allows them to be made faster and less expensive.

In addition to prototypes, RP techniques can also be used to make tooling (referred to as rapid tooling) and even production-quality parts (rapid manufacturing). For small production runs and complicated objects, rapid prototyping is often the best manufacturing process available. Most prototypes require from three to seventy-two hours to build, depending on the size and complexity of the object. This may seem slow, but it is much faster than the weeks or months required to make a prototype by traditional means such as machining.

1.2 Problem Statement

Longer cooling time in injection molding is a serious problem and can lead to decrease rate of production process. In industry, cooling time takes about 52% of the entire injection molding process. In order to improve the cooling system, this problem is worth to be investigated and to come out with a solution. One of the solutions is the conformal cooling channel which performance is greater than conventional cooling channel. In the recent year, new study has been done and conformal cooling channel is invented. It performance also exceed the conventional cooling channel.

For big company that mass produce the products using injection molding, the reduction of cooling time will increase the profit. There are many designs for the conformal cooling channel but to find or create a design with high effectiveness, the study must be done first and test must be done to prove the design performance.

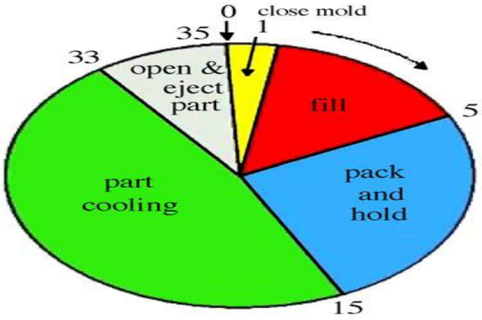


Figure 1.1: Cycle Time in Injection Molding Process

1.3 Objectives

The main objective of the present study is too design a new design of conformal cooling channel that will be used for injection molding process. This requires the study about the constructal law and also the recent study about the previous cooling channel. The prototype for the injection molding which is the constructal cooling channel needs to be made using rapid prototyping machine.

1.4 Scope of Study

To study the heat flow for the conformal cooling channel, a design need to be made by using Solid Work and the design will be imported to ANSYS software. This requires the utilization of CATIA software and ANSYS software to do the simulation and to prove the result of the study. Besides, an overall study of heat dissipation and cooling channel need to be done in order to understand the relationship between the heat flow and the cooling channel design.

1.5 Relevancy of Project

As the industry nowadays are growing rapidly, the invention of new design for conformal cooling channel for injection molding will greatly help the manufacturing company to produce the product faster. The purpose of this research which is to design for new conformal cooling channel is very important to the industry development.

1.6 Feasibility of Project

The project can be done but it requires more efforts from the author as it involves using rapid prototyping machine and making mold by using epoxy. Other than that, the author must finished the simulation by using ANSYS to determine whether the design of the constructal cooling channel is better or not compared to conventional cooling channel. Lastly, this project requires the author to use the vertical injection molding machine to test for the heat distribution for both cooling channel. This project needs a lot of time to be completed but it is predicted to be achievable within the time frame according to Gantt chart.

CHAPTER 2

LITERATURE REVIEW AND THEORY

2.1 Rapid Prototyping

Rapid prototyping additive processes have been existed since 1986. According to Meckley and Edwards (2009)[2], 3D systems were the first manufacturer to create a commercially available machine. These processes create a part out of liquid, molten, or powdered polymer or metal. Parts are created by using lasers or ink-jet technology. In the CAD software, solid models are represented by their outside surfaces. In order for the CAD model to be used in an additive process, it has to be converted to a format that the rapid prototyping machine can understand. Based on the statement above, the CAD software that will be used for my project will be CATIA for modeling purposes.

Meckley and Edwards (2009)[2] also pointed that the files that represent the outside surfaces are called STL files. In this format, triangles represent the surface. To import the STL file into the repid prototyping machine, it has to be processed by converting the triangles, called slicing, into a set of 2D cross sections. This slicing of the STL triangles creates the paths that a laser will travel or that ink-jet machine will use as a boundary for printing. The slicing thickness is determined by machine capability and accuracy requirements for the parts. In most machines, this is done from the bottom of the part to the top, because the equipment to manufacture the prototypes is mounted on the top of the machine. Solid Work software has the function to save the file or the design into STL format. By using this feature, I can save my design in STL format so that the rapid prototyping machine can read the data and fabricate the new design of profiled cooling channel.

Many researchers have been done using RP techniques. One of the researches has been done for the purpose of investment casting of hollow turbine blade. According to H. Wu, D. Li, and N. Guo (2009)[3], an integral ceramic mold is successfully fabricated by combining stereo lithography (SL) and gel casting process, cores and shell are connected with each other and thus high relative position accuracy is guaranteed. This method enhanced the versatility of using SL prototype in the fabrication of integral ceramic mold for investment casting. As for SL technique and ink-jet technique, both have their own advantages and disadvantages but, the technique will be chosen based on the availability of the machine and the type of product that will be fabricated. As for my project, ink-jet technique is chosen for its availability at rapid prototyping and designing room in my university.

For the ink-jet printing technique, a research has been done by W.Y. Yeong, C.K.Chua, and K. F. Leong (2006)[4] about the indirect fabrication of collagen scaffold. It is stated that previous research showed that the availability of biomaterial that can be processed on a commercial RP system is very limited. By hamessing the ability of RP techniques to control the internal morphology of the scaffold, it is possible to couple the design of the scaffold with controlled cell-culture condition. It is proven that rapid prototyping machine is very suitable to be used to fabricate complicated shape and thus, it can be concluded that RP machine is suitable to be used for my project as it can fabricate the complicated form of cooling channel.

2.2 Conformal Cooling Channel

A study has been done by Y. P. Qian (2012)[5] to introduce the process of heat transfer for plastic injection mold with conformal cooling channels and its features. He said that conformal cooling channel has some advantages such as high cooling efficiency and high cooling uniformity. In his paper, response surface methodology combined with mixed regression was used to study the relationship of the layout of conformal cooling channels to the thermal responding efficiency and temperature uniformity. The result obtained is when the cooling channels locate near the mould cavity surface and/or the pitch of cooling channels is small, the cooling time decrease because the time required for solidifying of product decrease.

Based on the application of the conformal cooling channel, a research done by B. Lubos and D. Jozef (2013)[7] use the method of direct metal laser sintering (DMLS) to produce the cooling channel. The comparison between conformal cooling channel and conventional cooling channel is done. The result indicates that conformal cooling channel revealed higher rate of heat removal intensity from the mould and higher temperature uniformity in the area of punch. Conformal cooling channel is also designed for many purposes. One of the purposes is to be used as cooling channel in a rapid blow mould. A research by K. M. Au and K. M. Yu (2012)[10] shows that conformal cooling channel is used to shorten the cooling period which take up approximately two third of the complete blow molding cycle. A comparison has been made between conformal cooling channel and straight line-drilled cooling channel (SLDCC). The result indicated that the cooling time and temperature uniformity of the blow-molded part can be effectively improved. The proposed conformal cooling channel design has a shorter cooling time and a lower part temperature that the SLDCC.

Research topic that has closed connection with my project is “The Design and Optimization of Conformal Cooling Channels in The Injection Molding Tools” by D. E. Dimla, M. Camilotto, and F. Miani (2005)[12]. The research objective is to determine an optimum and efficient design for conformal cooling/heating channels in the configuration of an injection molding tools using FEA and thermal heat transfer analysis. There are four elements that need to be controlled during the process which are temperature, pressure, time, and thermal properties. For obtaining good design, the Author used I-DEAS^{TM} software for prototyping and simulation. As for the result, if the cooling channels can be made to comfort to the shape of the part as much as possible, the cooling system cycle time can be significantly reduced with cooling taking place uniformly in all zones.

2.3 Constructal Law

Constructal law is a broad concept and it can be proved with a lot of examples. One of the examples is the tree-shaped flows. The design in nature is the tree-shaped networks with and without loops, which dominate practically everything that flows, from lungs and vascularized tissues to river basin. A better example is given by A. Bejan and J. H. Marden (2009)[21] in their research paper “The Constructal Unification of Biological and Geophysical Design”. Tree-shaped water flow (streams) along channels and high-resistivity flow (diffusion) across the interstices between channels. One flow mechanism sustains the other, diffusion at the smallest (interstitial) scale, and channel flow at scales larger than the diffusion scale. Not the other way around. Both mechanisms are necessary when the flow system is large enough. On the other hand, when the system is small enough, one mechanism (diffusion) is more effective than two. From the sentences, the meaning can be related to small injection molding mould size. One cooling channel is better than two for small size mould.

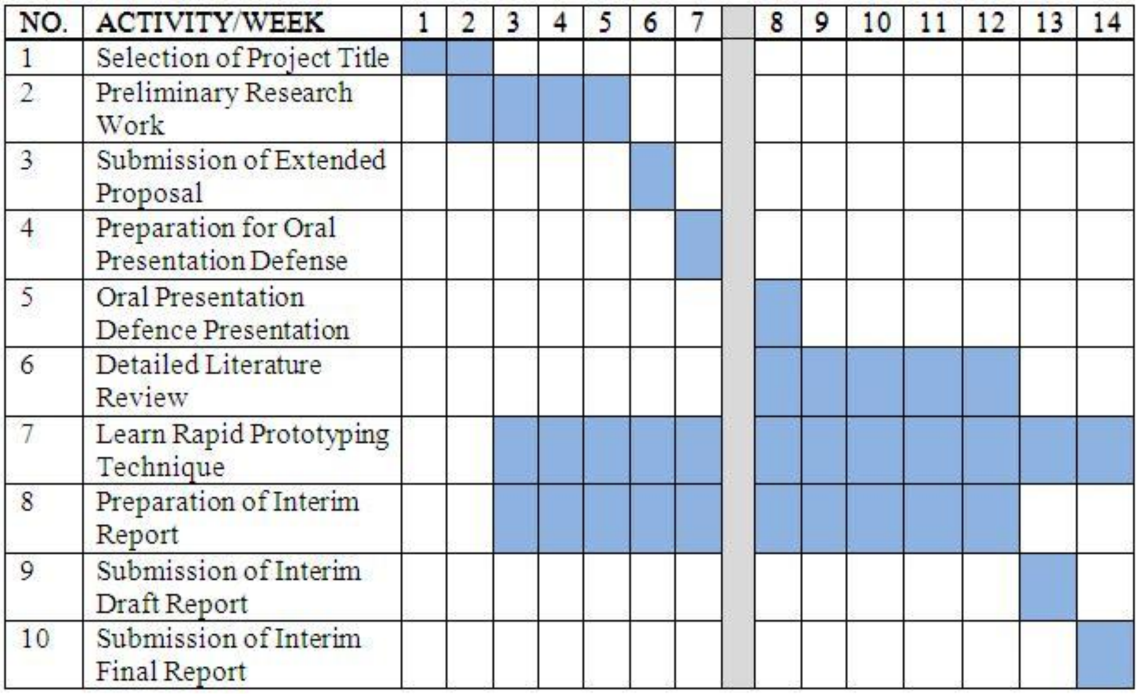
Constructal law has been used in many research papers for optimization purpose. One of the papers titled "Optimal Tree-Shaped Networks for Fluid Flow in a Disc-Shaped Body" which is written by W. Wechsatol (2002)[18] used the tree-shaped network system for the design of the cooling channel for the disc. In this paper, the author stated that the transition from one level of complexity to the next, higher one is abrupt. This means the use of fewer channel is better for example; the usage of two branches at one point is better than using three branches. In the design, the optimize structure for flow between one point and an area or volume (an infinity of points) is shaped as a tree in which every geometric detail is deducible from the minimization of global resistance to flow. Point-circle flows are already recognized as useful design for electronic cooling, so, the author adapted the concept and designed the optimal flow structure which is shaped as tree that covers the disc.

Other research which has connection with my project is "Constructal Flow Orientation in Conjugate Cooling Channels with Internal Heat Generation" by T. Bello-Ochende and A. Bejan (2012)[20]. This research is about the development of the three-dimensional flow architecture of conjugate cooling channels in forced convection with internal heat generation within the solid for an array or circular cooling channels with different flow orientation. The application of this evolution design approach to the discovery of external heat exchanger started with Bejan and Sciubba. Three flows of studies are used. They are array of channels with parallel flow, array of channels in which the flow in every second row is in a counter direction with its neighbor, and lastly the flows in all arrays of channels are in counter flow relative to each other. The purpose of this test is to improve thermal performance by minimizing thermal resistance for a wide range of dimensionless pressure difference. As for the result, the minimized thermal resistance decreases as the applied dimensionless pressure difference and porosity increase.

CHAPTER 3

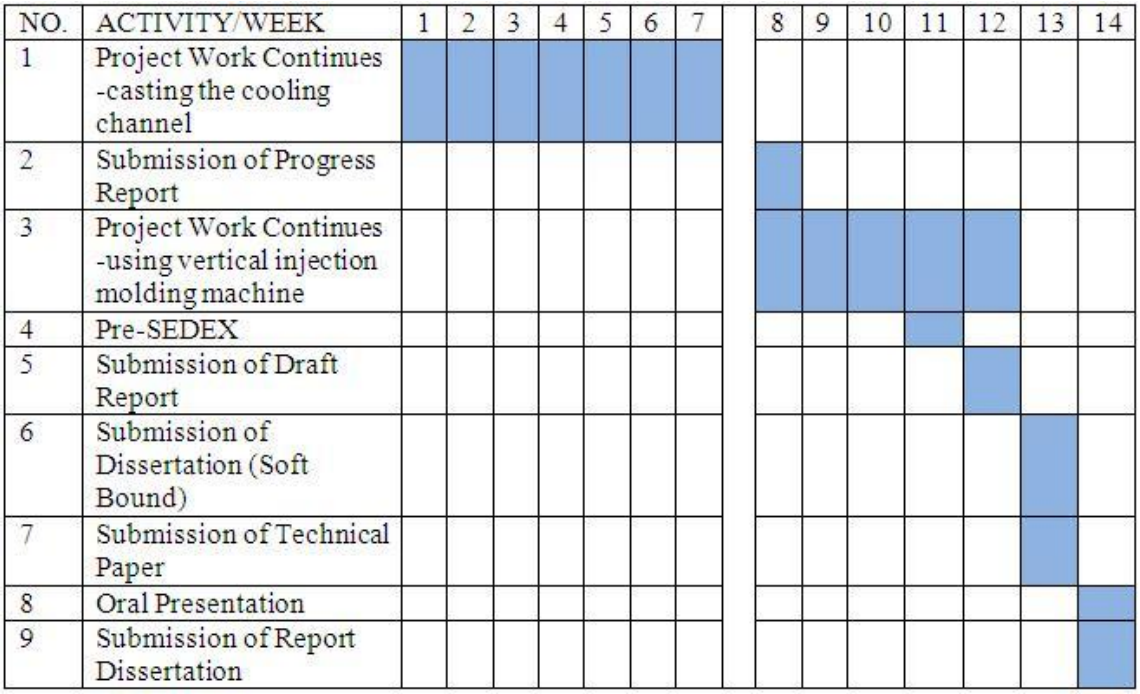
METHODOLOGY

This chapter is divided into several sections to discuss in details of the methodology used in this project. Section 3.1 elaborates the method on how to choose the design for the cooling channel for injection molding. Section3.2 shows how the author designs the constructal cooling channel and conventional cooling channel. This section also will give more detail on how the author designs a complete mold for injection molding. Section 3.3 gives the explanation on how the author uses the ANSYS software to stimulate a comparison between constructal and conventional cooling channel. Section 3.4 consists of the methodology on how the author make the prototype and section 3.5 gives illustration of the experiment set-up and the equipments or tools used. To ensure that the project could be done within the time period given, Gantt Charts shown in Table 3.1 and Table 3.2 were followed.



NO.	ACTIVITY/WEEK	1	2	3	4	5	6	7		8	9	10	11	12	13	14
1	Selection of Project Title	■	■													
2	Preliminary Research Work		■	■	■	■										
3	Submission of Extended Proposal						■									
4	Preparation for Oral Presentation Defense							■								
5	Oral Presentation Defence Presentation									■						
6	Detailed Literature Review									■	■	■	■	■		
7	Learn Rapid Prototyping Technique			■	■	■	■	■		■	■	■	■	■	■	■
8	Preparation of Interim Report			■	■	■	■	■		■	■	■	■	■		
9	Submission of Interim Draft Report														■	
10	Submission of Interim Final Report															■

Table 3.1: Project time line for final year project 1



NO.	ACTIVITY/WEEK	1	2	3	4	5	6	7		8	9	10	11	12	13	14
1	Project Work Continues -casting the cooling channel	■	■	■	■	■	■	■								
2	Submission of Progress Report									■						
3	Project Work Continues -using vertical injection molding machine									■	■	■	■	■		
4	Pre-SEDEX												■			
5	Submission of Draft Report													■		
6	Submission of Dissertation (Soft Bound)														■	
7	Submission of Technical Paper														■	
8	Oral Presentation															■
9	Submission of Report Dissertation															■

Table 3.2: Project time line for final year project 2

This project will follow the methodology flow chart shown in figure 3.1 below. Study was done to choose the suitable design for constructal cooling channel in order to test the performance and the cooling time for the mold. It is followed by the design generation by using CATIA and simulation by using ANSYS. Prototype is made by using rapid prototyping machine and also epoxy. The prototype is tested by using the vertical injection molding and the cooling time will be compared.

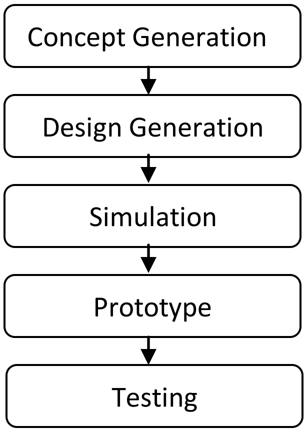


Figure 3.1: Methodology flow chart

3.1 Concept Generation

Constructal theory is analyzed and accepted to be used for the project. The dendrite pattern which is proposed by Dr. Andrian Bejan is selected as it is proven to allow the flow easier for the system. Dr. Andrian states that this pattern has minimum resistance flow structure when there is only one level of pairing.

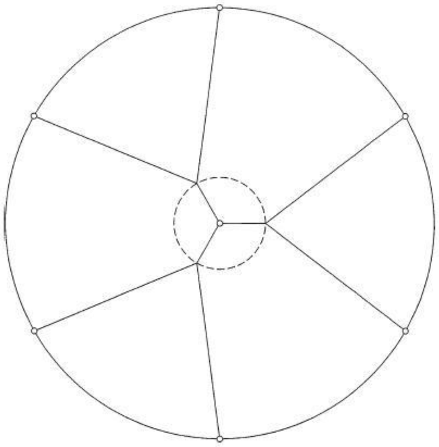


Figure 3.2: Dendritic pattern

3.2 Design Generation

The design is done by using CATIA software. For every mold in the design, there are three parts which are closer, container, and base. Closer is the place where it will receive the injection molding shot from the vertical injection molding machine. Other than that, it covers the container so that the injection molding material will not leak. It has the dimension of 140 mm width, 125 length, and 20 mm height. Container is the place where the melted material will be placed inside the mold. The melted material will follow the shape of the inside container in which the shape is cylinder with the diameter of 100 mm and the height of 10 mm. The container outer shape has the following dimension which is the same as closer. Base is where cooling channels are placed. For the constructal cooling channel, the cooling channel will follow the dendritic pattern. The diameter for the cooling channel is 10 mm. The outer shape of the base has the parameters which is the same as closer.

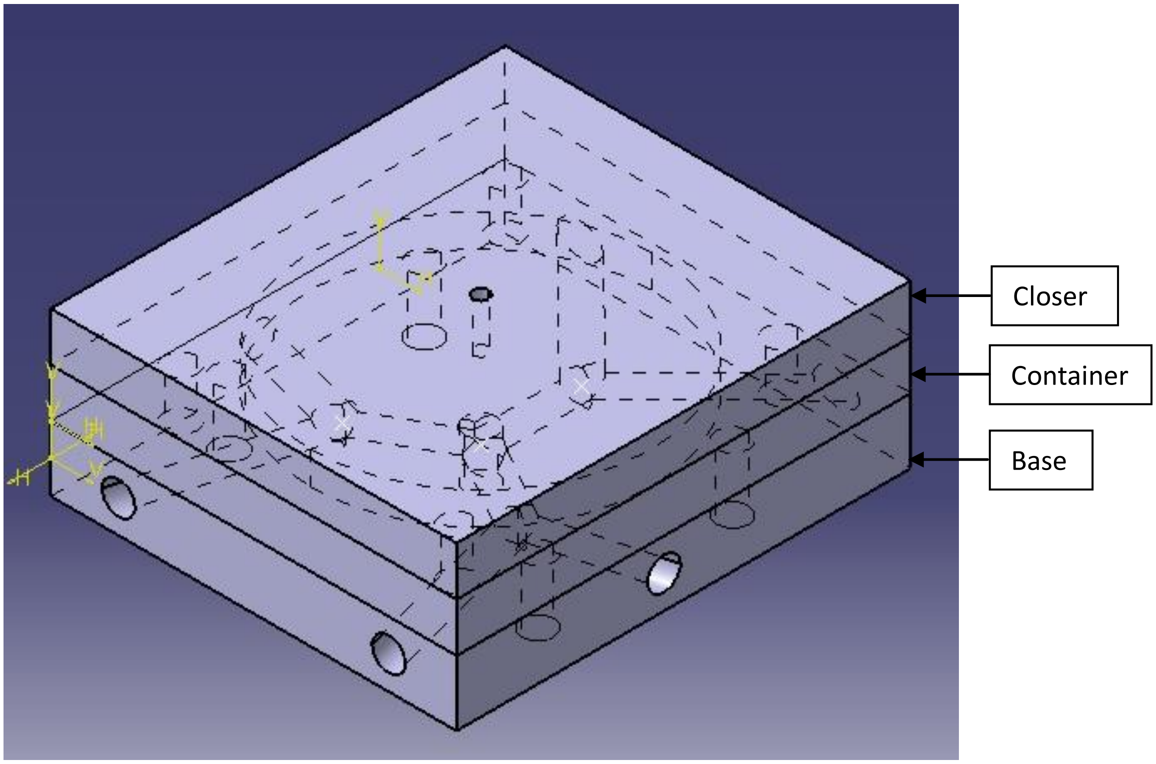


Figure 3.3: Part assembly for the constructal cooling channel mold

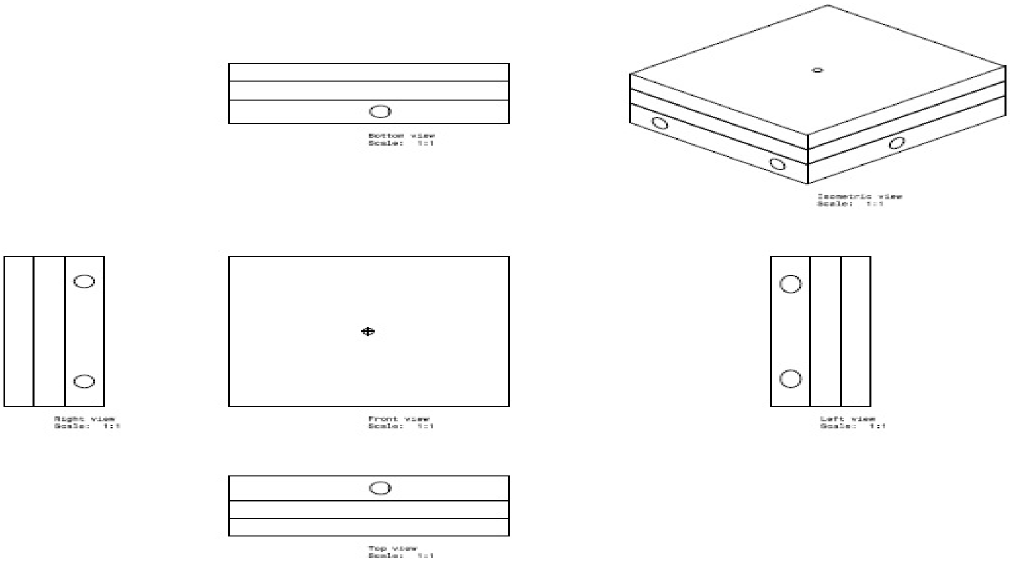


Figure 3.4: Drafting view for conformal cooling channel

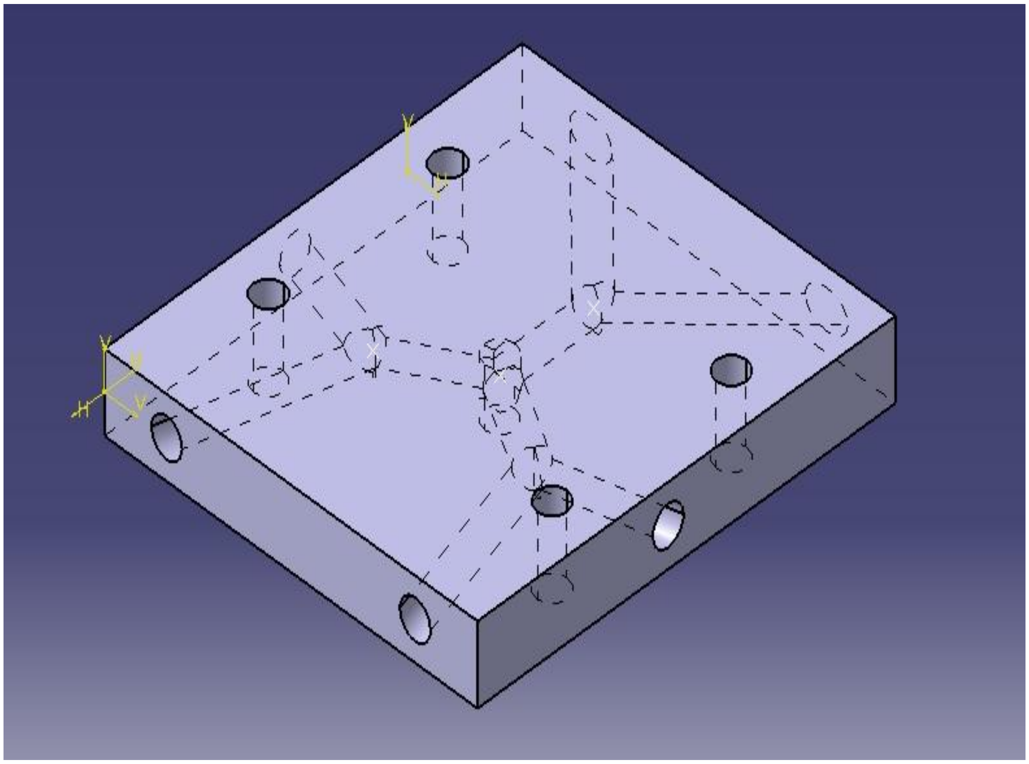


Figure 3.5: Base for conformal cooling channel

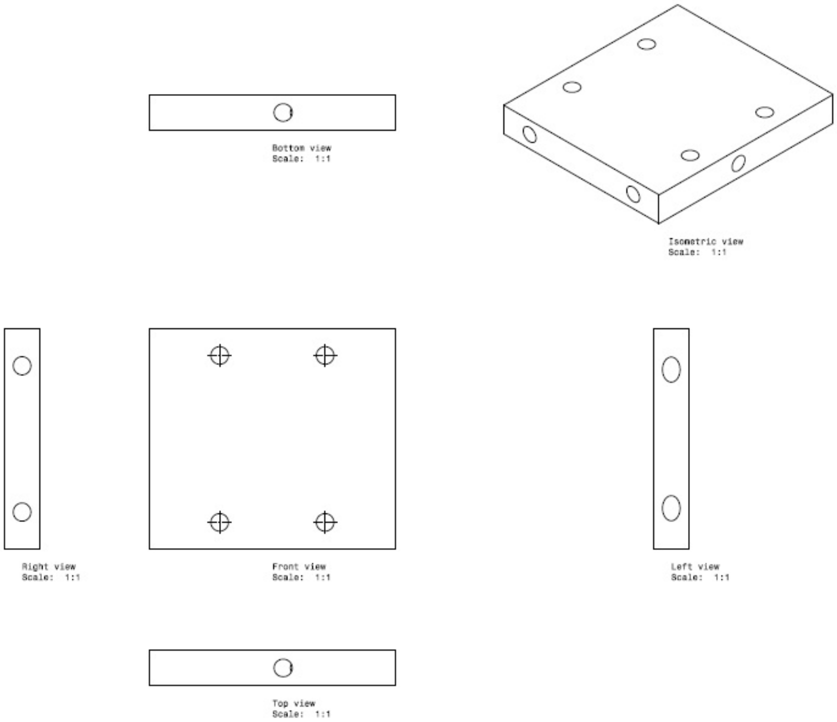


Figure 3.6: Drafting view for conformal cooling channel base

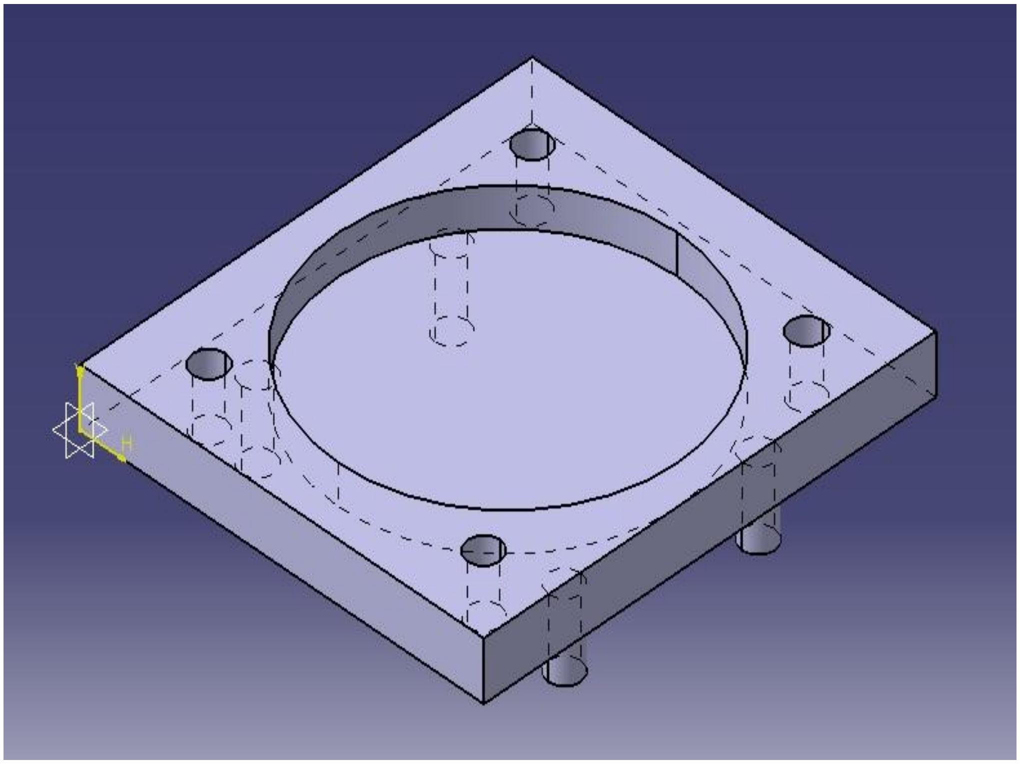


Figure 3.7: Container for conformal cooling channel and conventional cooling channel

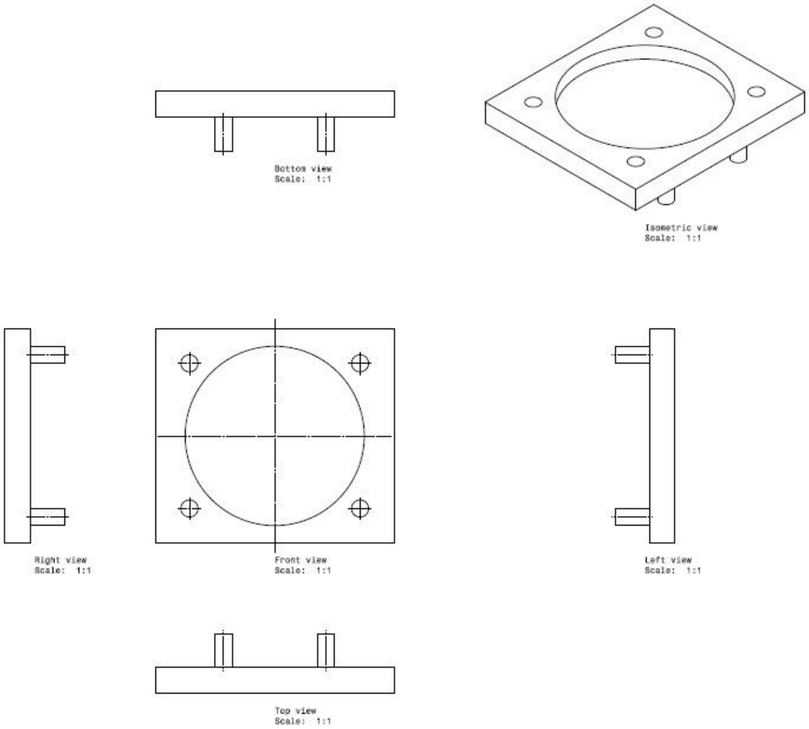


Figure 3.8: Drafting view for container

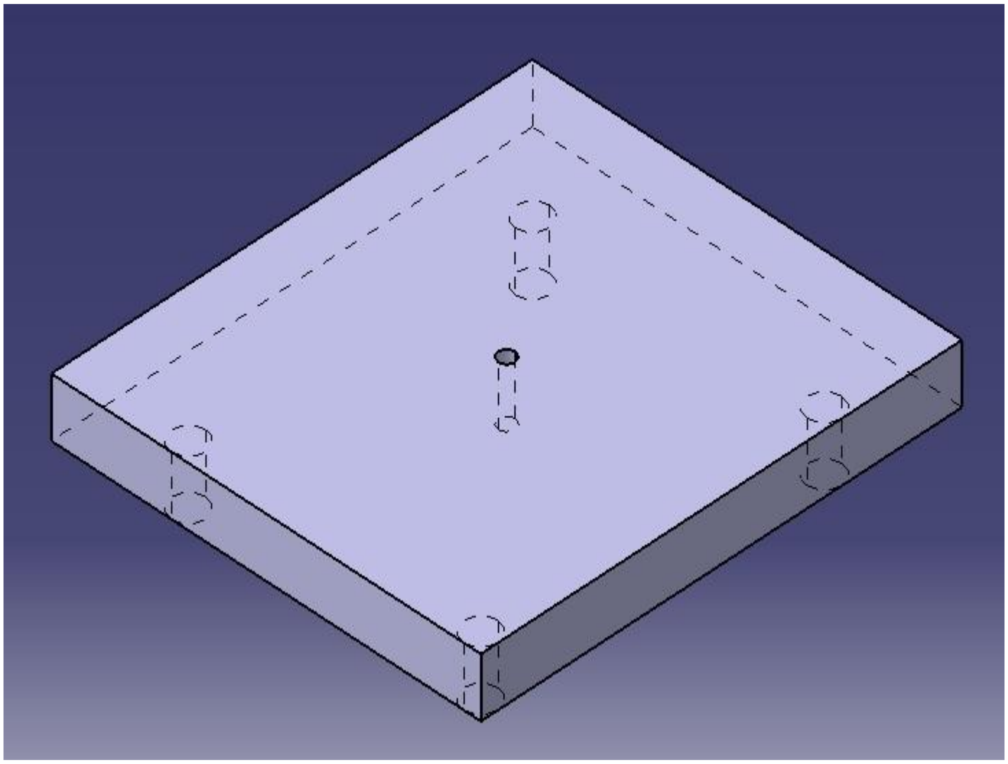


Figure 3.9: Closer for conformal cooling channel and conventional cooling channel

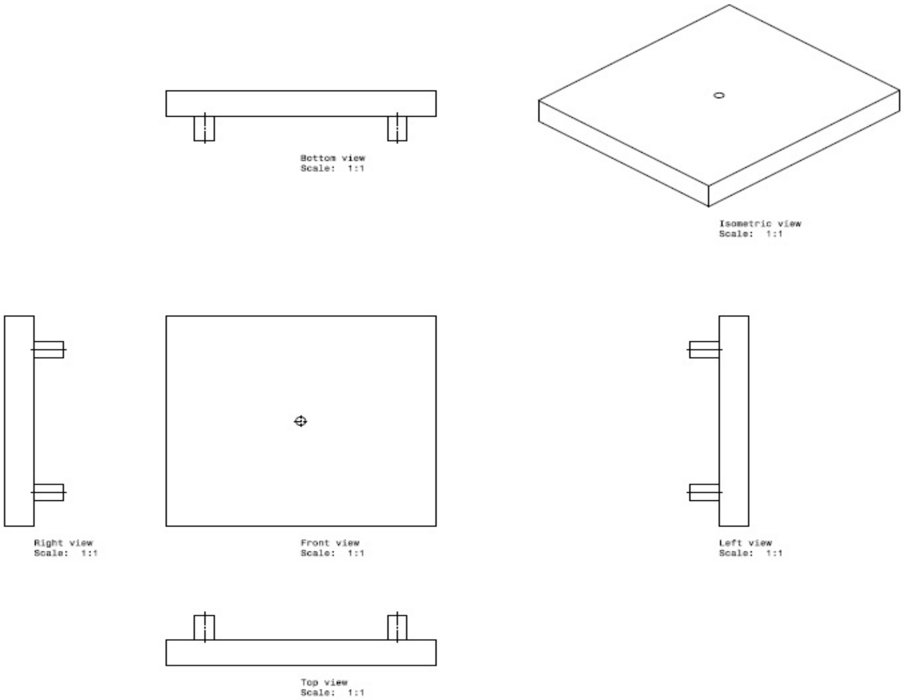


Figure 3.10: Drafting view for closer

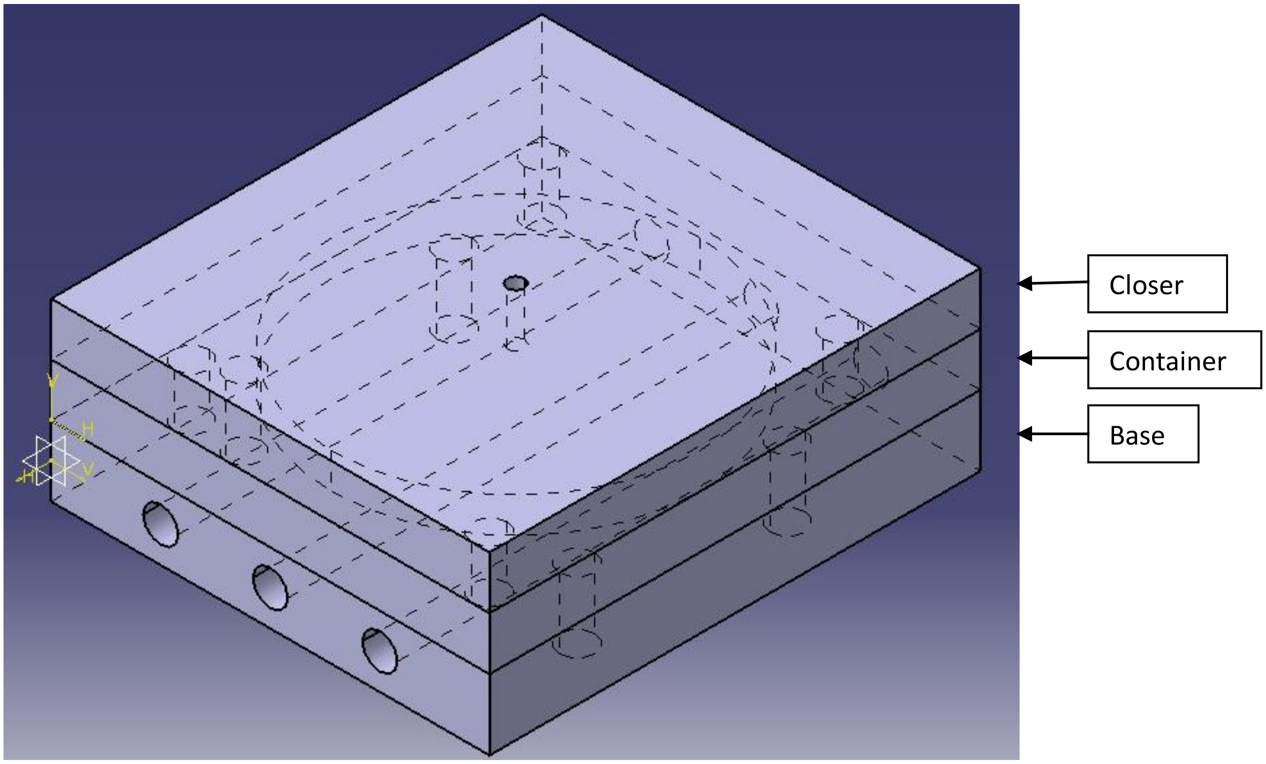


Figure 3.11: Part assembly for conventional cooling channel

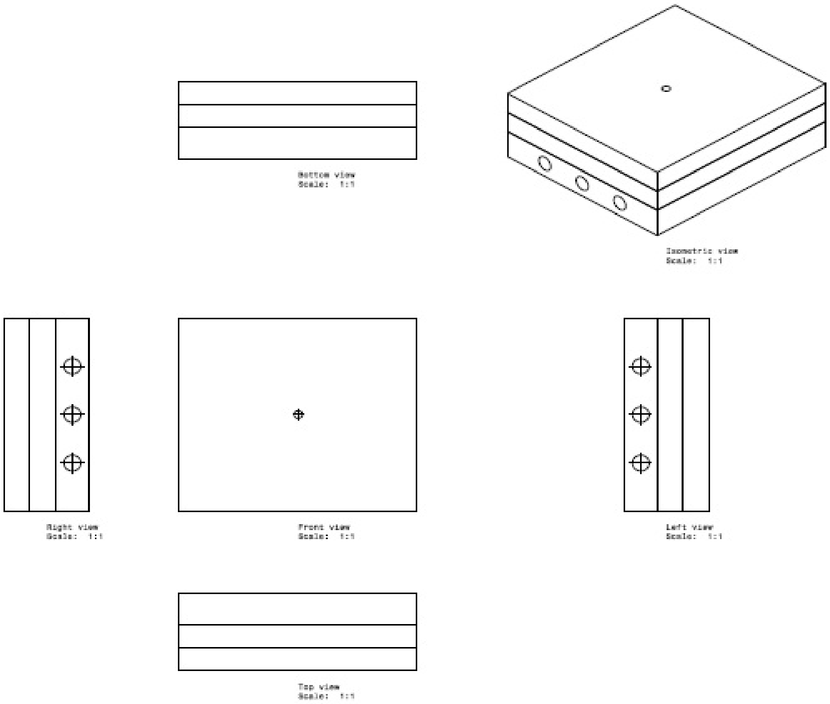


Figure 3.12: Drafting view for conventional cooling channel

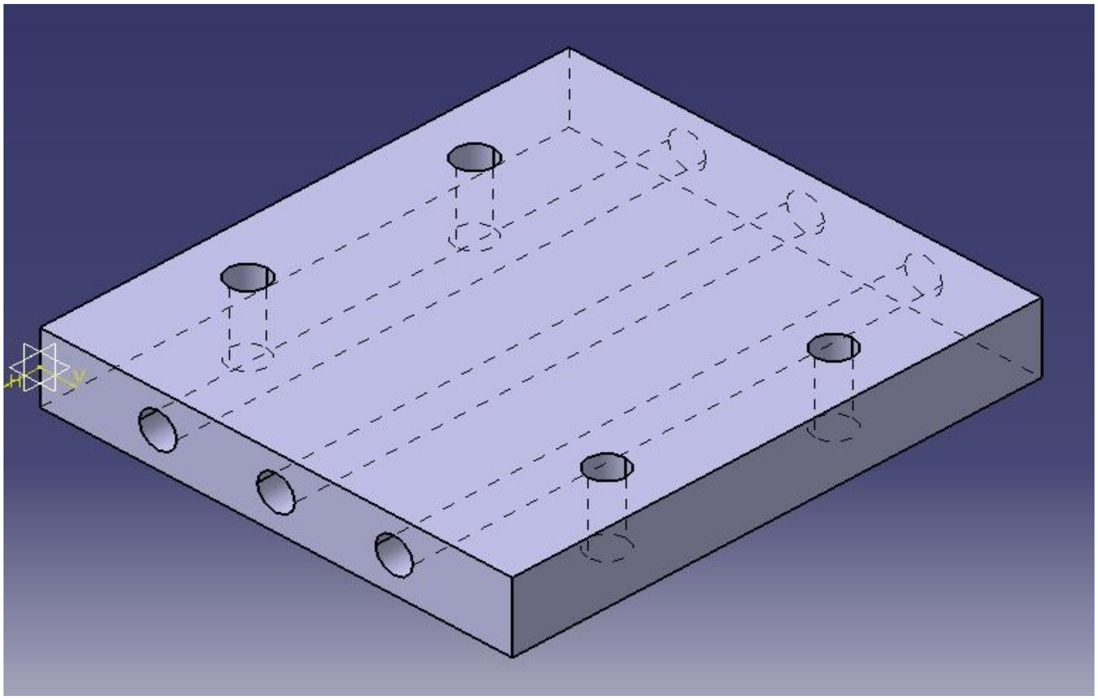


Figure 3.13: Base for conventional cooling channel

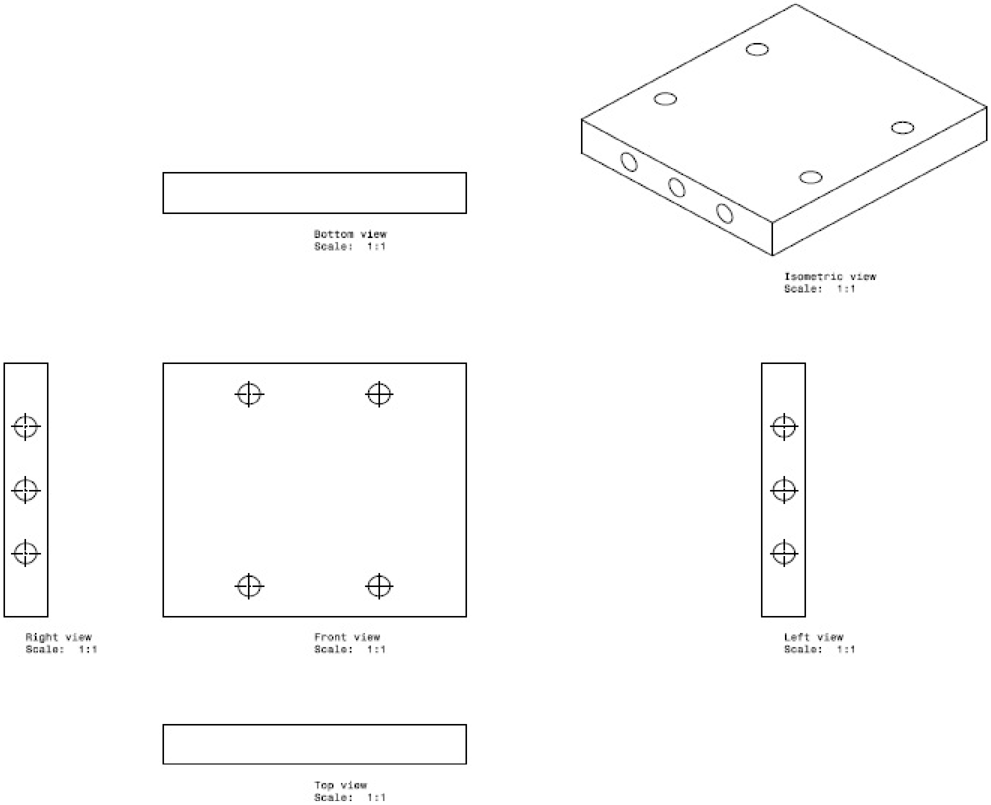


Figure 3.14: Drafting view for base of conventional cooling channel

The conventional cooling channel is designed based on the conventional design used in industry. It is a straight line cooling channel which is made by drilling method. The diameter for the hole is 10 mm and the length for the cooling channel follow the length of the mold which is 140 mm. There are three cooling channel for the conventional and the reason why three cooling channel is chosen is because constructal cooling channel also has three main cooling channel after the main cooling channel where water coming in first.

3.3 Simulation

The simulation is done by using ANSYS Thermal Transient Analysis. The designs from the CATIA will be imported to Solid Work software first and then the file will be saved in parasolid format so that ANSYS can read the file later. In ANSYS, the first step is to choose the material for the mold and the material is epoxy. After defining the material, meshing will be done before defining other parameters. Initial temperature for the mold is defined as 77°C and the reason why this temperature is chosen is because the author wants to use lower temperature to test for the cooling rate so that the results can be obtained faster. In the analysis setting, the time for the simulation must be set. Convection is chosen as the method for cooling and it is applied to every cooling channel.

For the convection parameters, the temperature of water is set to 27°C and the velocity of water is set to 0.85 m/s. To see the temperature distribution, temperature probe is chosen and placed at the inside container. Below is the calculation to find the heat transfer coefficient (h) which will be used in the convection command.

Kinematic viscosity of water, $\nu = 0.801 \times 10^{-6}\ m^2/s$

Pradtl number for water,Pr = 5.43

Thermal conductivity of water, K = 0.615 W/m°C

Density of water, $\rho = 995.6\ kg/m^3$

Raynold number, $Re = VD/\nu = (0.85)\ (0.01) / (0.801 \times 10^{-6}) = 10611$

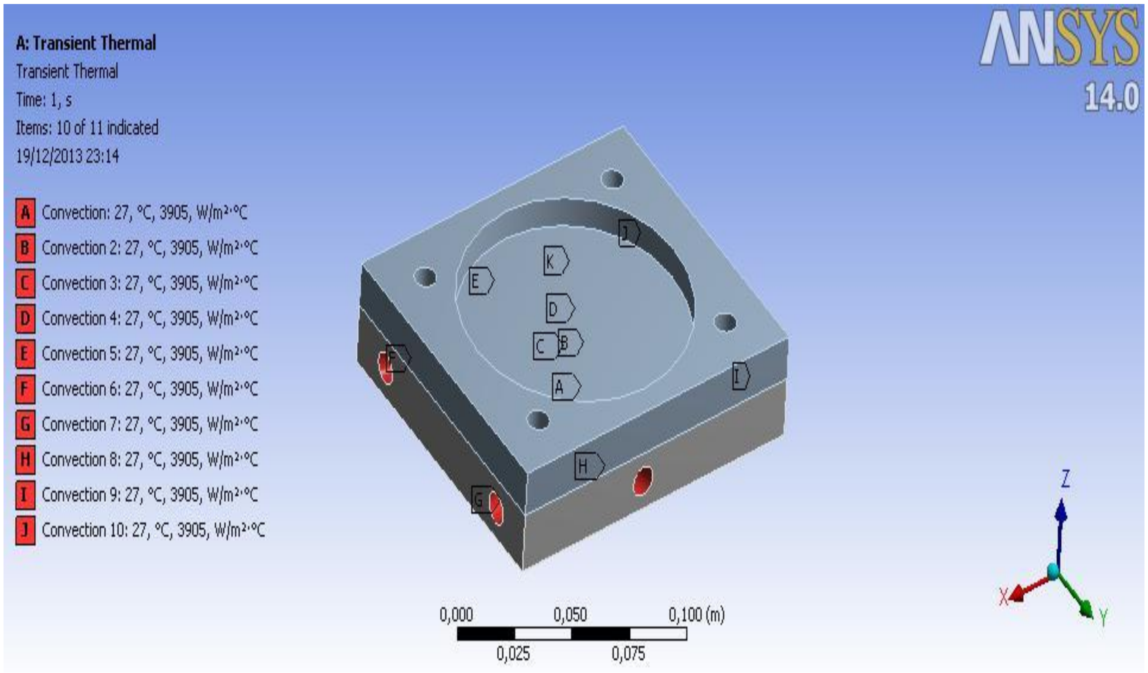
Since 10611 > 10000, it is considered as fully turbulent flow

For turbulent flow;

Nusselt number, $Nu = 0.023Re^{0.8}Pr^{0.3} = (0.023)\ (10611)^{0.8}\ (5.43)^{0.3} = 63.5$

Heat transfer coefficient, $h = NuK/D = (63.5)\ (0.6150 / (0.01) = 3905.25\ W/m^2.^{o}C$

*Heat thermal coefficient is the same for constructal and conventional because it has the same diameter of cooling channel.



A: Transient Thermal

Transient Thermal

Time: 1, s

Items: 10 of 11 indicated

19/12/2013 23:14

- A Convection: 27, °C, 3905, W/m²·°C
- B Convection 2: 27, °C, 3905, W/m²·°C
- C Convection 3: 27, °C, 3905, W/m²·°C
- D Convection 4: 27, °C, 3905, W/m²·°C
- E Convection 5: 27, °C, 3905, W/m²·°C
- F Convection 6: 27, °C, 3905, W/m²·°C
- G Convection 7: 27, °C, 3905, W/m²·°C
- H Convection 8: 27, °C, 3905, W/m²·°C
- I Convection 9: 27, °C, 3905, W/m²·°C
- J Convection 10: 27, °C, 3905, W/m²·°C

Figure 3.15: ANSYS transient thermal analysis

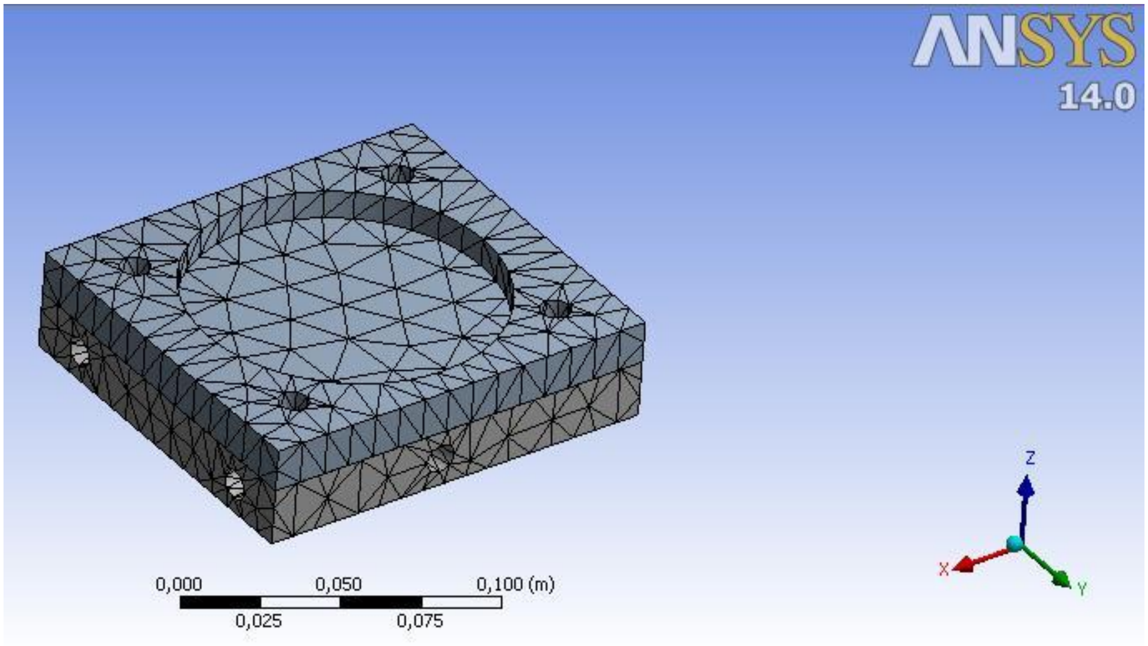


Figure 3.16: Meshing the mold in ANSYS

3.4 Prototype

The prototype is built by using rapid prototyping machine. Below are the steps for doing the prototype:

1. Print the cooling channel by using rapid prototyping machine

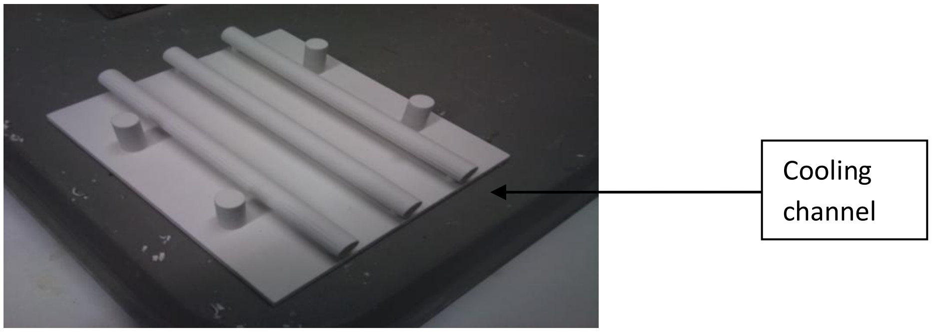


Figure 3.17: The base for conventional cooling channel which is made by using rapid prototyping machine

2. Prepare the epoxy and mix with the hardener at 1:10 ratio

Figure 3.18: Epoxy and hardener

3. Put the mix epoxy into vacuum chamber for 12-15 minutes

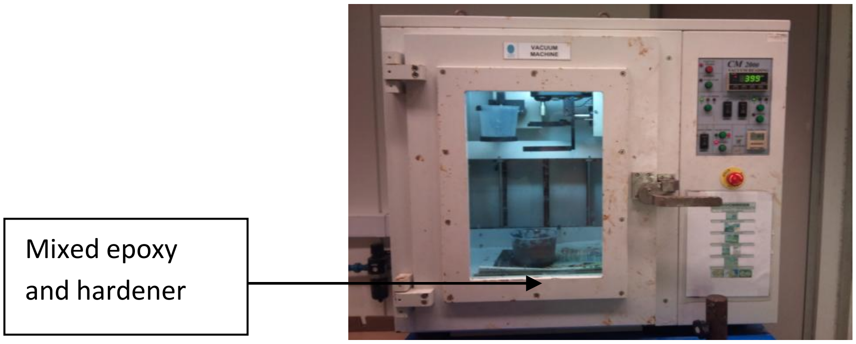


Figure 3.19: Vacuum chamber

4. Pour the epoxy into the container that hold the cooling channel

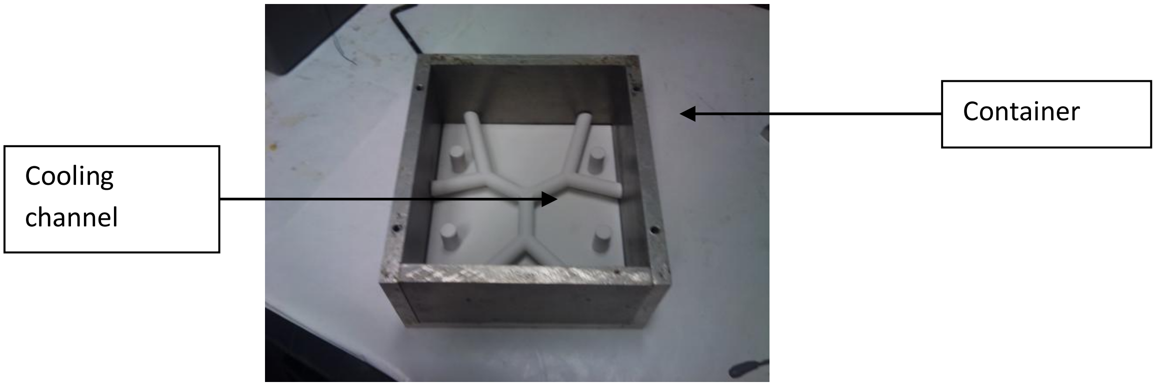


Figure 3.20: The base for holding cooling channel before epoxy is poured

5. Leave the cooling channel for 24 hours to be cured.

6. For the surface finishing purpose, milling machine is used to cut down uneven and bubbling surface.

Figure 3.21: Milling machine

7. Final product (prototype)

Figure 3.22: Prototype for conventional cooling channel, container, and closer

3.5 Testing the cooling channel

To test the cooling channel, thermocouple must be attached to the inside of container during fabrication process. Data logger which is WinDaq equipment for testing temperature distribution will be used during the experiment. Thermocouple head will be connected to the data logger device and the data logger device will be connected to the laptop via cable wire. During the injection, the thermocouple will detect the temperature of the melted material which is high density polypropylene and the graph for the temperature distribution over time during cooling will be recorded. The melting point for polypropylene is 170^{o}C and it takes about five minutes for the vertical injection molding machine to melt the material.

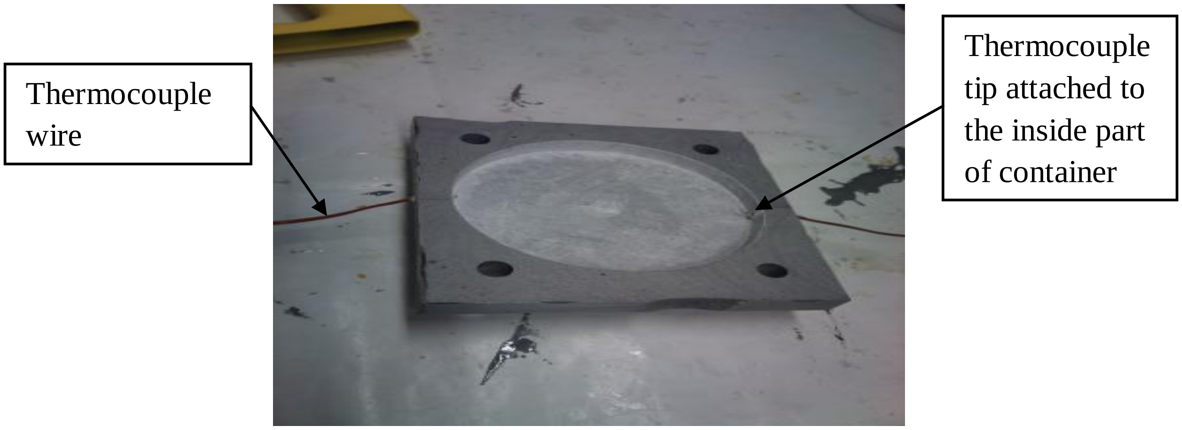


Figure 3.23: Thermocouple connected to container

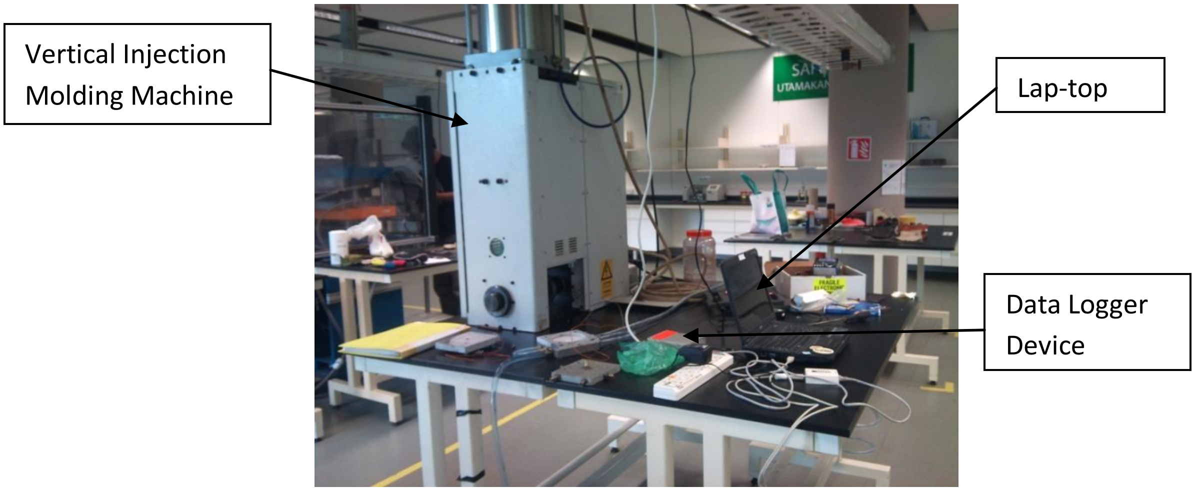


Figure 3.24: Set-up for experiment

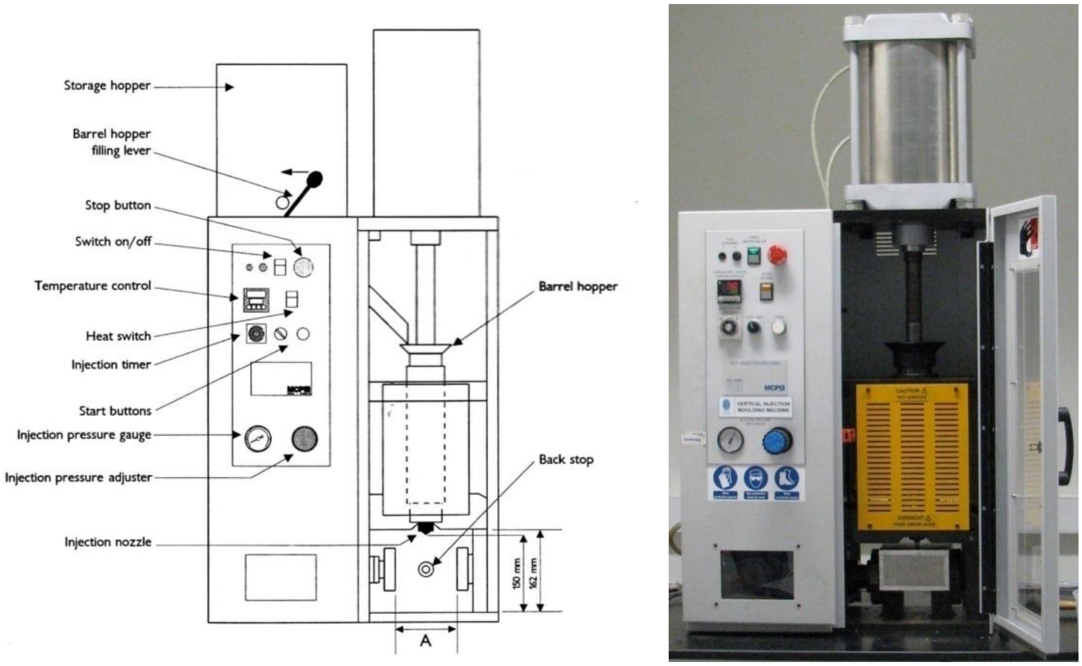


Figure 3.25: Vertical Injection Molding Machine MTT Model 100KSA

<u>Technical Specifications of 100KSA</u>

Injection volume / shot weight		100 ml / 100 gm
Heating capacity		1.8 kW
Temperature range		20 – 350^{o}C
Plasticising		7.0 kg/hr
Air line pressure		8 bar max.
Air consumption per cycle		96 litres
Effective stroke of plunger		195 mm
Standard plunger	diameter	35 mm
	Injection pressure air supply	4 bar
Locking force at 8 bar		20 tonnes
Locking clamp movement		5 mm

CHAPTER 4
RESULT AND DISCUSSION

4.1 Data gathering from ANSYS simulation

Two simulations have been done for ANSYS simulation which is for constructal cooling channel and also conventional cooling channel. The first simulation is done by using the epoxy as the material for the mould. Epoxy has low thermal conductivity which is 0.72 Wm^{-1}C^{-1}. Since epoxy has low thermal conductivity, the period for simulation is made longer so that the temperature distribution can be observed clearly.

Time (s)	Temp. ^{o}C	Time (s)	Temp. ^{o}C
0	77.0	260	75.9
10	77.0	270	75.8
20	77.0	280	75.6
30	77.0	290	75.5
40	77.0	300	75.3
50	77.0	310	75.1
60	77.0	320	75.0
70	76.9	330	74.8
80	76.9	340	74.6
90	76.9	350	74.4
100	76.9	360	74.2
110	76.9	370	73.9
120	76.9	380	73.7
130	76.9	390	73.5
140	76.9	400	73.3
150	76.9	410	73.0
160	76.8	420	72.8
170	76.8	430	72.5
180	76.7	440	72.3
190	76.7	450	72,0
200	76.6	460	71.8
210	76.5	470	71.5
220	76.4	480	71.3
230	76.3	490	71.0
240	76.2	500	70.7
250	76.1		

Table 4.1: Constructal (epoxy)

Time (s)	Temp. ^{o}C	Time (s)	Temp. ^{o}C
0	77.0	260	75.9
10	77.0	270	75.8
20	77.0	280	75.6
30	77.0	290	75.4
40	77.0	300	75.3
50	77.0	310	75.1
60	77.0	320	74.9
70	77.0	330	74.7
80	76.9	340	74.6
90	76.9	350	74.4
100	76.9	360	74.2
110	76.9	370	74.0
120	76.9	380	73.7
130	76.9	390	73.5
140	76.9	400	73.3
150	76.8	410	73.1
160	76.8	420	72.8
170	76.8	430	72.6
180	76.7	440	72.4
190	76.6	450	72.1
200	76.5	460	71.9
210	76.5	470	71.7
220	76.4	480	71.4
230	76.3	490	71.2
240	76.1	500	70.9
250	76.0		

Table 4.2: Conventional (epoxy)

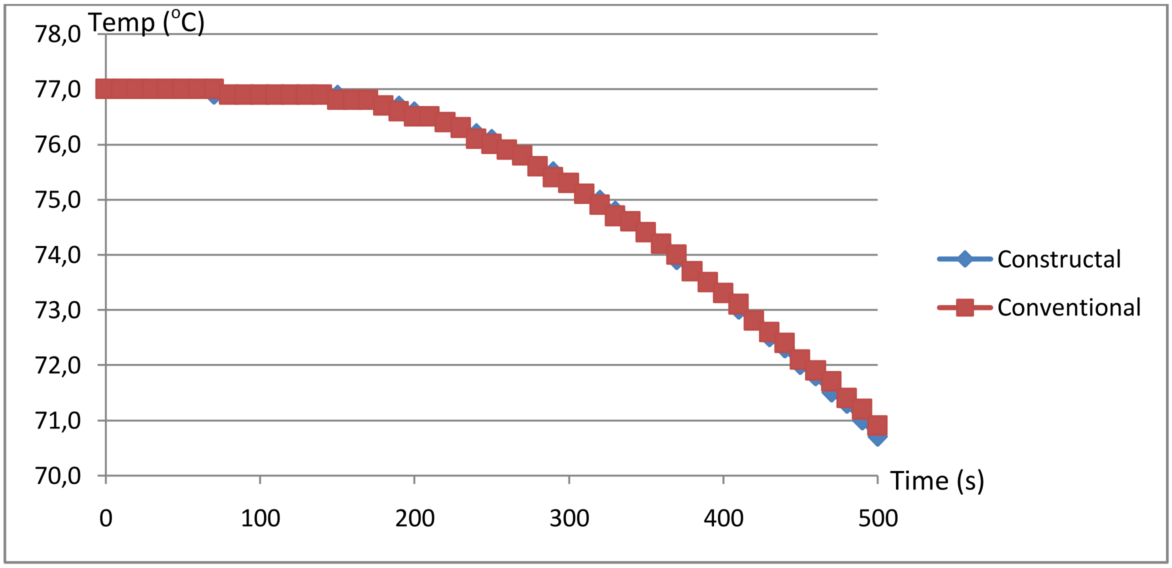


Figure 4.1: Constructal versus conventional cooling channel (epoxy mold)

From the graph above, the differences between constructal and conventional are very small that is 0.2 seconds at the end of the simulation time which is 500 seconds. Even though the difference is small, it is proven that constructal can reach 500 seconds faster than conventional. To verify this data, another simulation is done by using different material which is mild steel which has higher thermal conductivity, h = 60.5 $Wm^{-1}C^{-1}$.

Time (s)	**Temp. °C**	**Time (s)**	**Temp. °C**
0	77,0	110	36,7
10	75,8	120	35,1
20	71,0	130	33,8
30	65,2	140	32,7
40	59,7	150	31,7
50	54,7	160	31,0
60	50,4	170	30,3
70	46,7	180	29,7
80	42,5	190	29,3
90	40,8	200	28,9
100	38,6		

Table 4.3: Constructal (mild steel)

Time (s)	**Temp. °C**	**Time (s)**	**Temp. °C**
0	77,0	110	38,6
10	75,8	120	36,9
20	71,3	130	35,5
30	66,0	140	34,2
40	60,7	150	33,2
50	56,1	160	32,3
60	52,0	170	31,5
70	48,5	180	30,9
80	45,4	190	30,3
90	42,8	200	29,8
100	40,5		

Table 4.4: Conventional (mild steel)

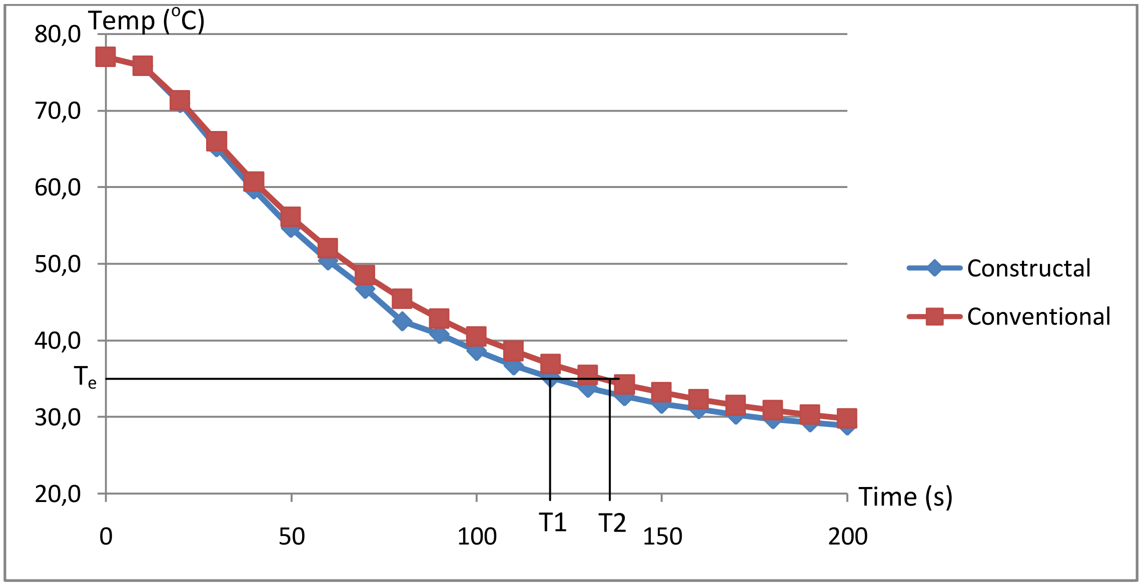


Figure 4.2: Constructal versus conventional cooling channel (mild steel mold)

Based on the graph above, the temperature differences over times can be seen clearly. The time taken for constructal cooling channel to reach 35 °C which is the ejection temperature for the solidified polypropylene is 120 seconds but for conventional cooling channel to reach the ejection temperature (T_e) is 133 seconds. Based on the results, there are two things which can be verified which are constructal cooling channel is better than conventional cooling channel and thermal conductivity of material greatly affected the cooling rate.

4.2 Simulation with different materials used for mold

Based on the previous discussion, it is stated that thermal conductivity affects the cooling rate for the mold. Three different materials are selected so that the cooling time for every material can be compared; the materials chosen are copper alloy, titanium alloy, and gray cast iron. Copper alloy has the thermal conductivity of 401 $Wm^{-1}C^{-1,}$ titanium alloy is 21.9 $Wm^{-1}C^{-1}$, and lastly gray cast iron is 52 $Wm^{-1}C^{-1}$. Simulation is done for 200 seconds for every material for constructal cooling channel and conventional cooling channel. Data are recorded in table form and graph is constructed so that the comparison can be observed clearly.

Copper Alloy		**Titanium Alloy**		**Gray Cast Iron**	
Time (s)	**Temp. ^{o}C**	**Time (s)**	**Temp. ^{o}C**	**Time (s)**	**Temp. ^{o}C**
0	77.0	0	77.0	0	77.0
10	67.6	10	76.7	10	75.9
20	57.2	20	74.5	20	71.5
30	49.3	30	70.7	30	65.9
40	43.5	40	66.3	40	60.4
50	39.3	50	61.9	50	55.4
60	36.0	60	57.8	60	51.0
70	33.7	70	54.1	70	47.3
80	31.9	80	50.8	80	44.1
90	30.7	90	47.8	90	41.4
100	29.7	100	45.2	100	39.1
110	29.0	110	42.9	110	37.2
120	28.5	120	40.9	120	35.5
130	28.1	130	39.1	130	34.1
140	27.8	140	37.6	140	33.0
150	27.6	150	36.3	150	32.0
160	27.4	160	35.1	160	31.2
170	27.3	170	34.0	170	30.5
180	27.2	180	33.1	180	29.9
190	27.2	190	32.3	190	29.5
200	27.1	200	31.6	200	29.1

Table 4.5: Comparison for different material used for constructal cooling channel mold

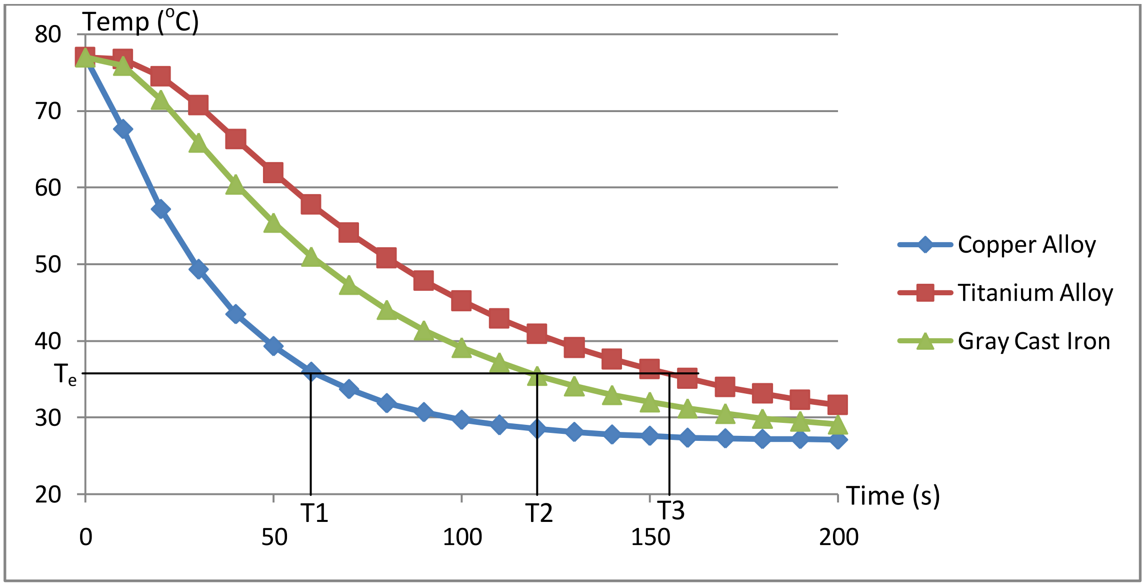


Figure 4.3: Constructal cooling channel (different materials used as mold)

Copper Alloy		Titanium Alloy		Gray Cast Iron	
Time (s)	Temp. ^{o}C	Time (s)	Temp. ^{o}C	Time (s)	Temp. ^{o}C
0	77.0	0	77.0	0	77.0
10	68.3	10	76.7	10	75.9
20	58.9	20	74.6	20	71.7
30	51.6	30	70.9	30	66.5
40	45.9	40	66.9	40	61.4
50	41.6	50	62.9	50	56.8
60	38.2	60	59.1	60	52.7
70	35.6	70	55.6	70	49.1
80	33.6	80	52.4	80	46.0
90	32.1	90	49.6	90	43.3
100	30.9	100	47.0	100	41.0
110	30.0	110	44.8	110	39.0
120	29.3	120	42.7	120	37.3
130	28.8	130	40.9	130	35.9
140	28.4	140	39.4	140	34.6
150	28.1	150	37.9	150	33.5
160	27.8	160	36.7	160	32.6
170	27.6	170	35.6	170	31.8
180	27.5	180	34.6	180	31.1
190	27.4	190	33.7	190	30.5
200	27.3	200	32.9	200	30.0

Table 4.6: Comparison for different material used for conventional cooling channel mold

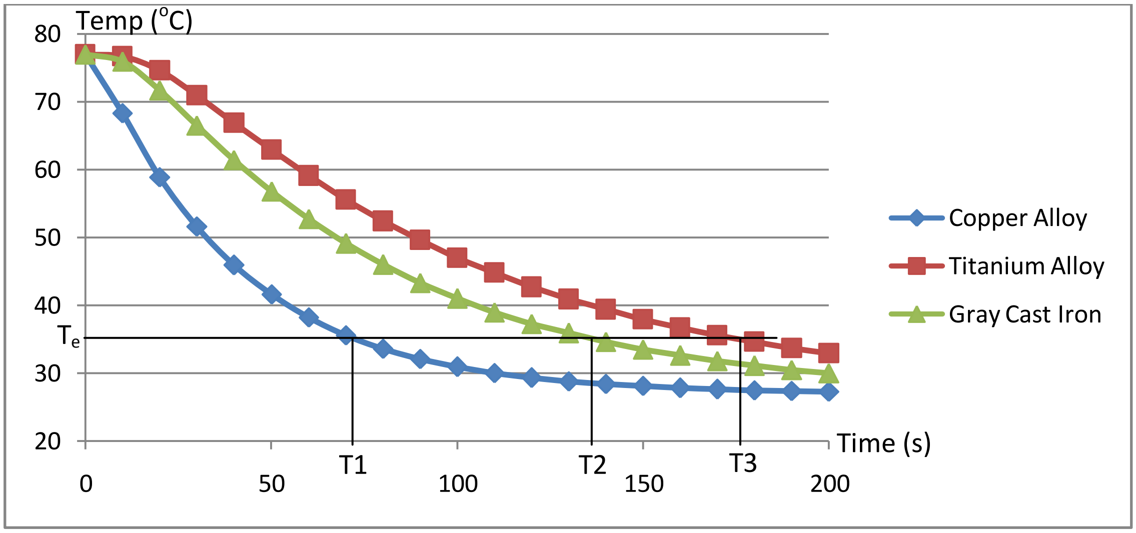


Figure 4.4: Conventional cooling channel (different materials used as mold)

From figure 4.4, copper alloy reach the ejection temperature at 35 °C earlier than titanium alloy and gray cast iron. The times taken for all the materials for constructal cooling channel are 65 seconds, 161 seconds, and 125 seconds. For conventional cooling channel, the times taken are 72 seconds, 175 seconds, and 136 seconds. From the data obtained, the higher the thermal conductivity, the shorter the cooling time to reach ejection temperature. Graphs below are provided to show the differences between constructal cooling channel and conventional cooling channel when using the same materials (copper alloy, titanium alloy, and gray cast iron).

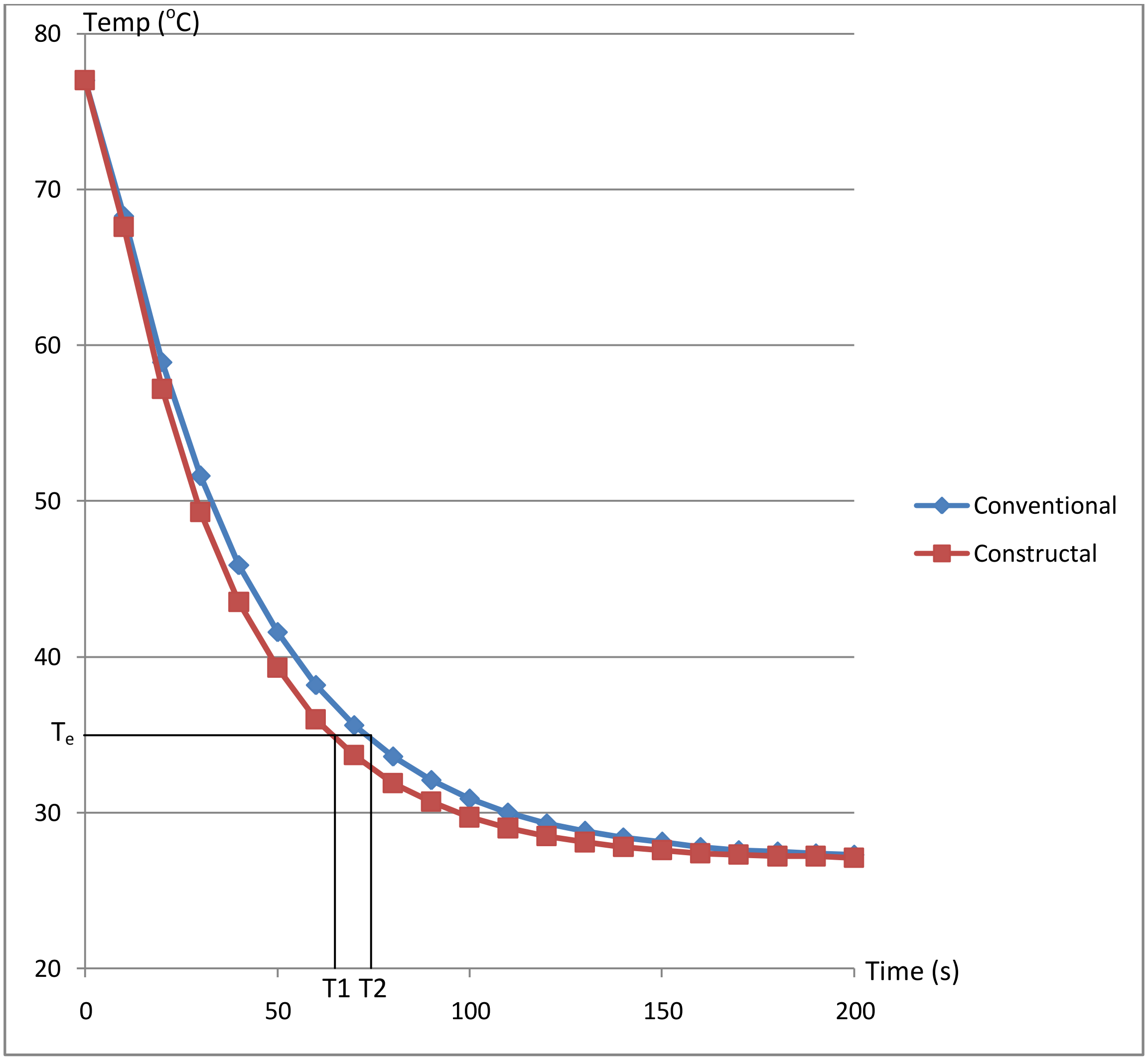


Figure 4.5: Constructal versus convention cooling channel (use copper alloy as mold)

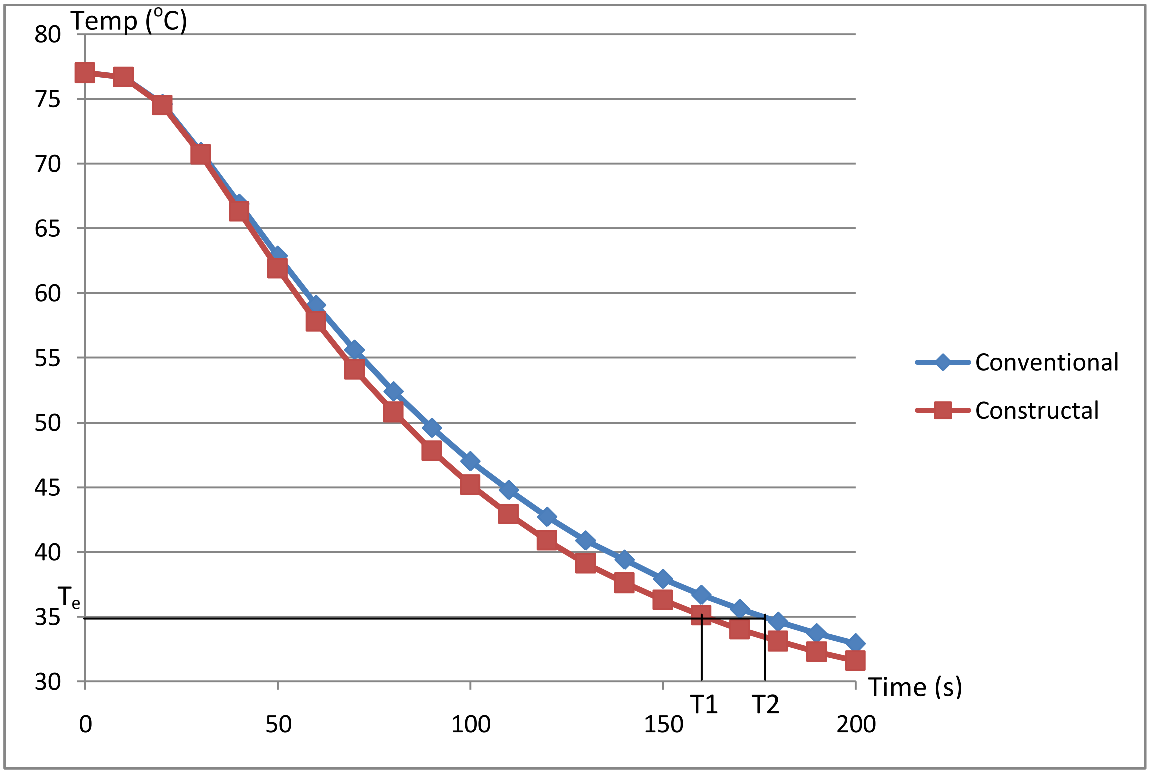


Figure 4.6: Constructal versus convention cooling channel (use titanium alloy as mold)

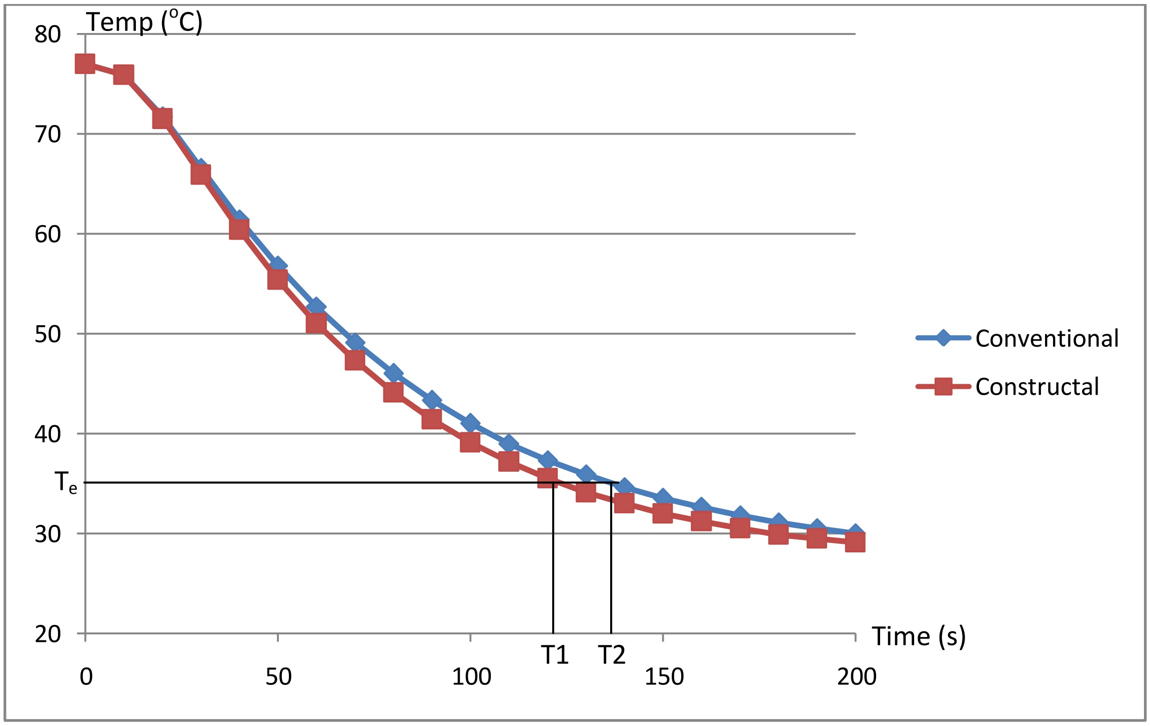


Figure 4.7: Constructal versus convention cooling channel (use gray cast iron as mold)

4.3 Experiment using vertical injection molding machine

Five experiments are done for every cooling channel which are constructal cooling channel and conventional cooling channel. The average range for the data is calculated and tabulated in table. The comparison for the time for ejection can be seen in table 4.7, table 4.8 and figure 4.8. From the graph, the distance between the lines is very close to each other. The reason for this is because epoxy has lower thermal conductivity but the reason why we choose epoxy as the material for making mold is because it is easier to use epoxy during casting process of the mold. Other than that, if we use melted metal as the mold, the printed section from the rapid prototyping machine will be damaged heavily and the mold will be a failure. As UTP has only powder 3D printer rapid prototyping machine that is still working, I have no other option but to use the available machine to cast the mold for the complicated cooling channel. From the graph, the time taken for the constructal cooling channel to reach ejection temperature at 35 ^{o}C is 1476 seconds and 1488 seconds for conventional cooling channel. The difference is only 12 seconds but it indicates that constructal cooling channel is better than conventional cooling channel.

Time (s)	Temp. ^{o}C	Time (s)	Temp. ^{o}C
1	170	808	100
100	165	874	95
201	160	939	90
263	155	990	85
326	150	1041	80
373	145	1091	75
421	140	1140	70
464	135	1203	65
506	130	1265	60
557	125	1313	55
608	120	1360	50
659	115	1405	45
710	110	1450	40
759	105	1476	35

Table 4.7: Constructal (epoxy)

Time (s)	Temp. ^{o}C	Time (s)	Temp. ^{o}C
1	170	818	100
130	165	884	95
208	160	949	90
282	155	999	85
335	150	1049	80
383	145	1101	75
431	140	1152	70
472	135	1213	65
513	130	1274	60
565	125	1321	55
617	120	1368	50
670	115	1414	45
722	110	1460	40
770	105	1488	35

Table 4.8: Conventional (epoxy)

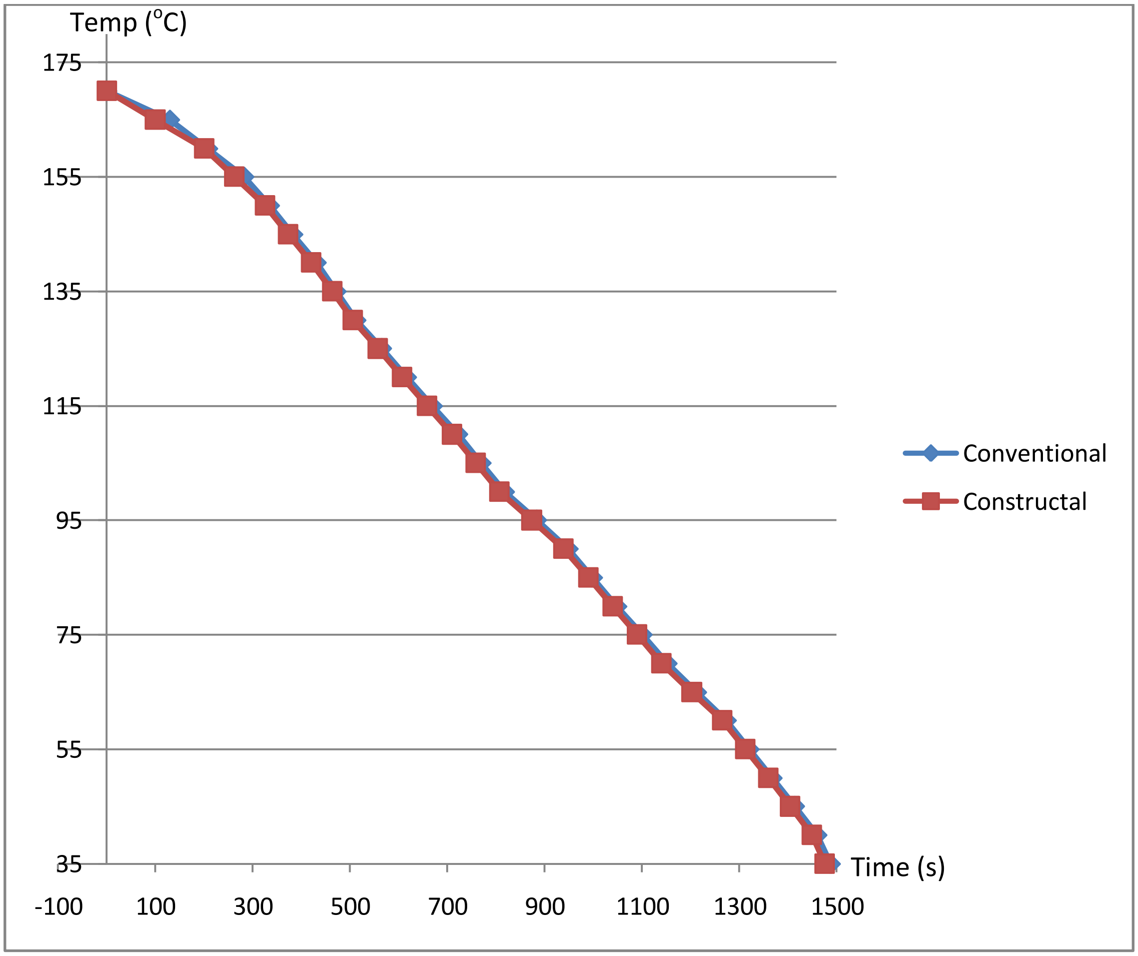


Figure 4.8: Constructal versus conventional cooling channel experiment data

The polypropylene is melted at 170 ^oC and that is the reason why the temperature is recorded as 170 ^oC by the data logger. The cooling rate is very slow and this can be seen by the time required to cool the melted polypropylene which is 24.6 minutes for constructal cooling channel and 24.8 minutes for conventional cooling channel. During the experiment, the temperature of inflow water is range from 23 ^oC to 24^oC and the temperature of outflow range from 27^oC to 29^oC throughout the experiment. The flow rate of water is adjusted by using flow meter in which the flow rate of water is at 4 liters/minutes (0.85 m/s).

CHAPTER 5

CONCLUSION AND RECOMMENDATION

The design of cooling channel for injection molding and thermal conductivity of materials used for making mold affect the cooling time. A design based on constructal theory is made using CATIA and by using ANSYS transient thermal analysis, the comparison between constructal cooling channel and conventional cooling channel are made. The initial parameters for the simulations are obtained from the literature reviews. Experiment is also done to verify the result of the simulation and from the analysis which has been done, following conclusions were obtained:

- The design of constructal cooling channel is verified to have higher cooling rate than conventional cooling channel. By using epoxy as the mold, the difference is very small, but if metal is used as mold, the difference can be seen clearly as indicated by the result from the simulation.
- From simulation, there is only 0.2 seconds different when using epoxy mold at 500 seconds. Other materials are tested for 200 seconds as they have high thermal conductivity. When mild steel is chosen as mold, the time different is 13 seconds, 7 seconds when using copper alloy, 14 seconds when using titanium alloy and 11 seconds when using gray cast iron as mold.
- From experiment, the constructal cooling channel is faster than conventional cooling channel by 12 seconds even though both of the molds took longer time to reach ejection temperature.
- Thermal conductivity is one of the factors that impact heavily the cooling rate of the mold. The higher the thermal conductivity, the faster the cooling rate or the shorter the time required to reach ejection temperature at 35 ^{o}C.

These findings will contribute to the design of the mold in injection molding industry which is rapidly growing especially for mass production. For example, if the production for item takes 60 seconds by using conventional cooling channel, the time can be reduced to 48 seconds by using constructal cooling channel. If the production is for 1000 units, the times that can be saved is 12000 seconds which is equal to8.33 hours.

To improve this project, there are several things that can be done which is to implement the concept of profiled cooling channel which has been introduced by Dr. Khurram[1]. The cross section of the cooling channel is changed so that the contact area will increase and thus increase the rate of heat transfer. Dr. Khurram said that by using profiled cooling channel, the percentage that can be reduced for cooling time is about 15% of the entire cooling process.

Next is to study the behavior the flow of the water. This can be done by using ANSYS fluent. Each state of flow (laminar, transient, and turbulent) can affect the flow of water especially the design with complicated cooling channel. Each design must be made so that it can allow the flow to be easier. The place for water input for constructal cooling channel must also be changed so that it will not oppose the gravity force. Thus, the design can be improved by studying the suitable configuration for making the best cooling channel design.

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APPENDIX A

Process of Making Prototype

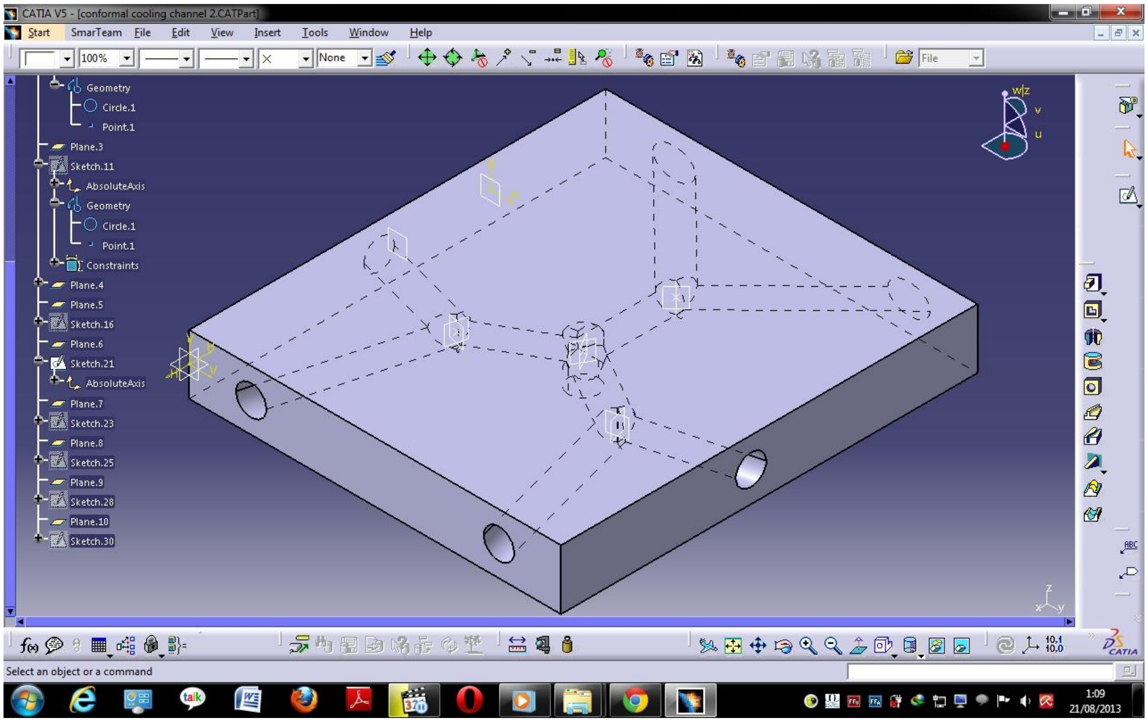

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Figure A-1: Design of constructal cooling channel (base)

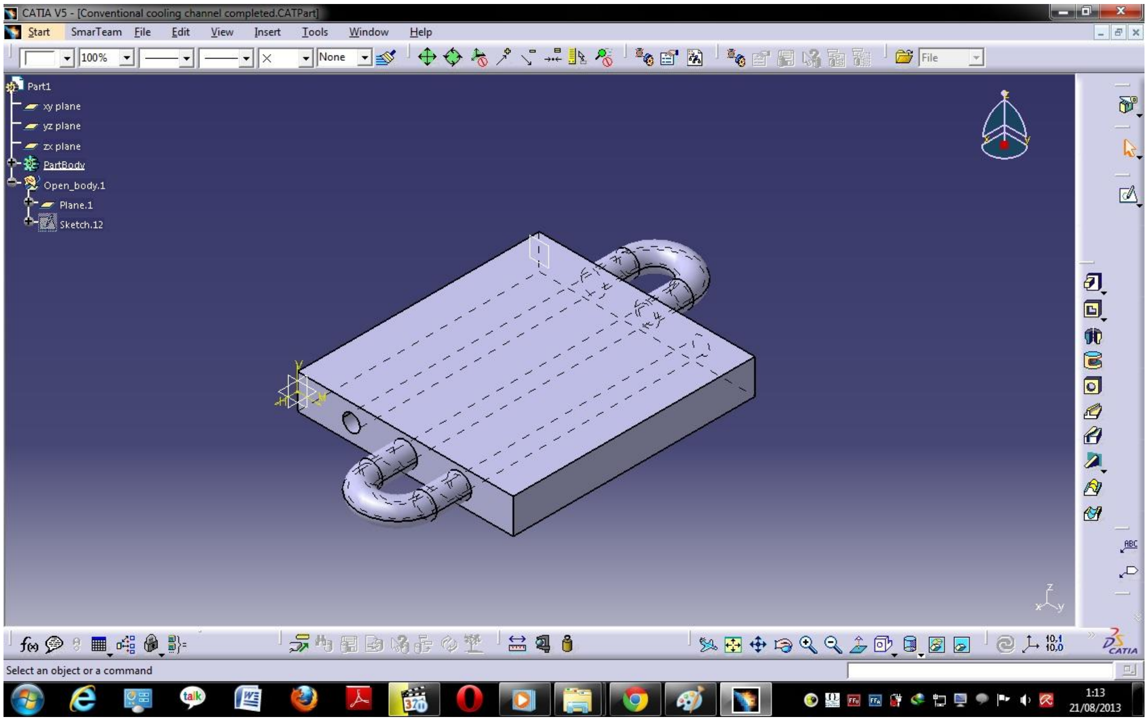

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Figure A-2: Design of conventional cooling channel (base)

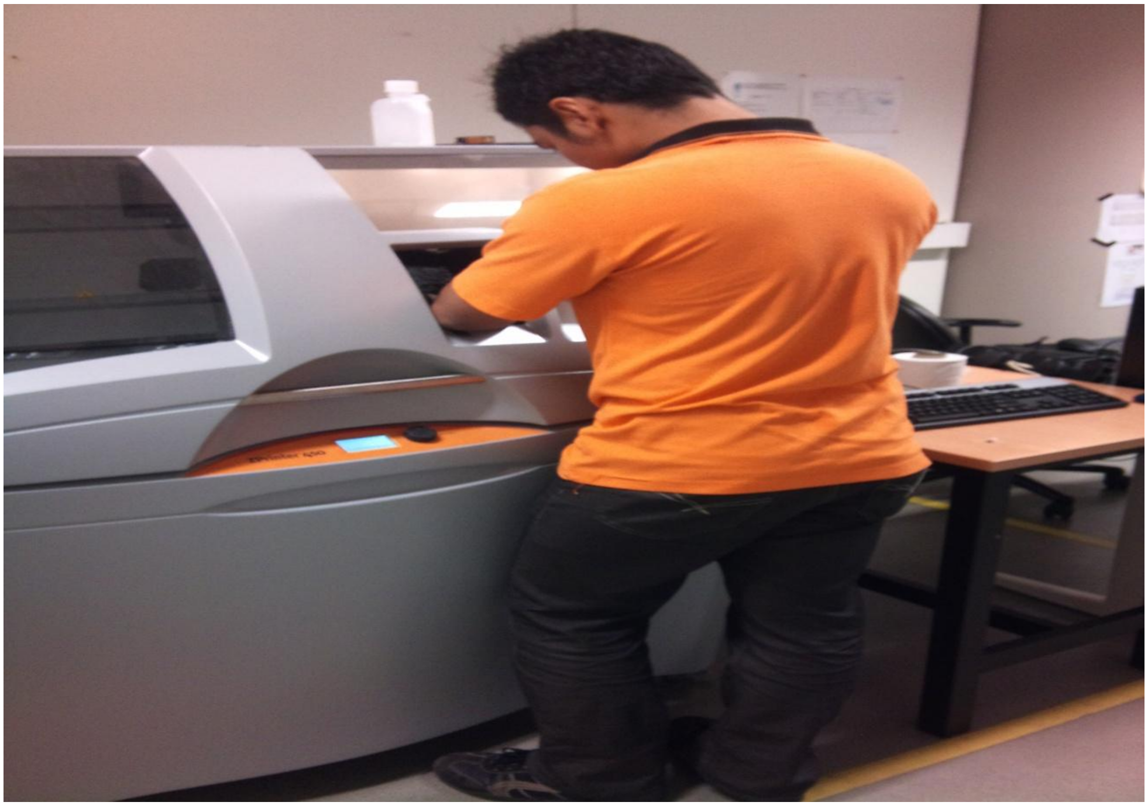

Figure A-3: Using rapid prototyping machine to print designed part for casting the mold

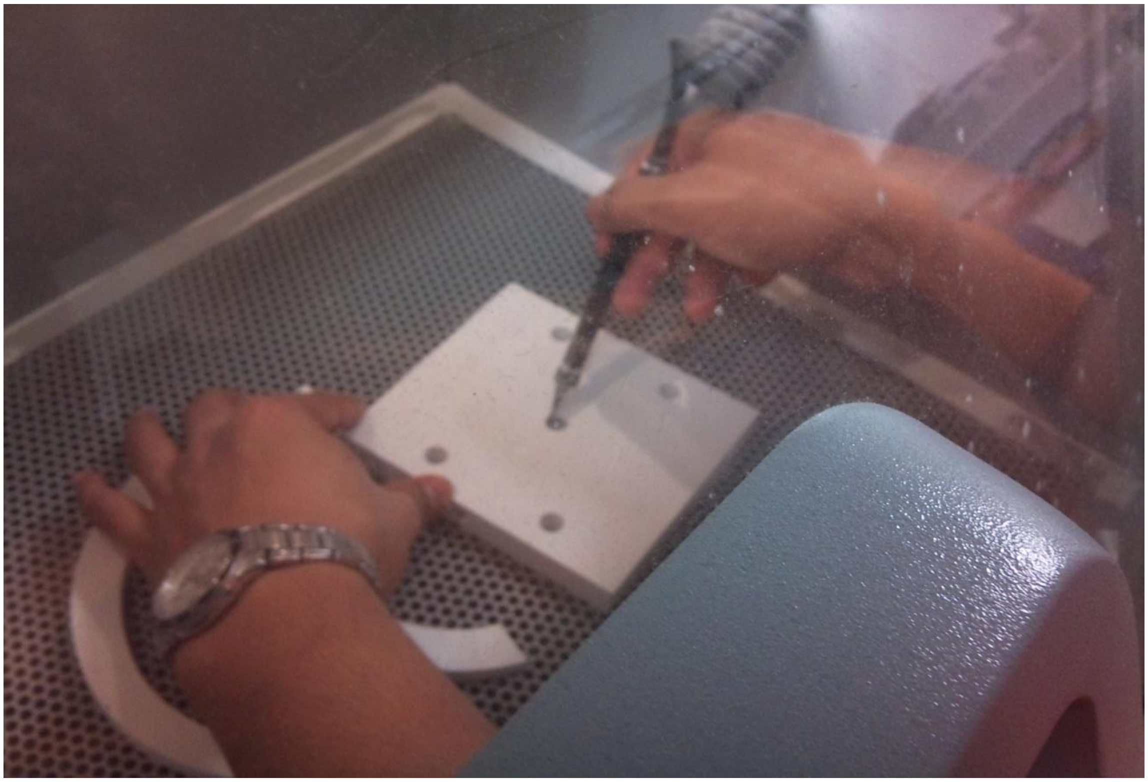

Figure A-4: Using blower to remove the excess powder from the printed part

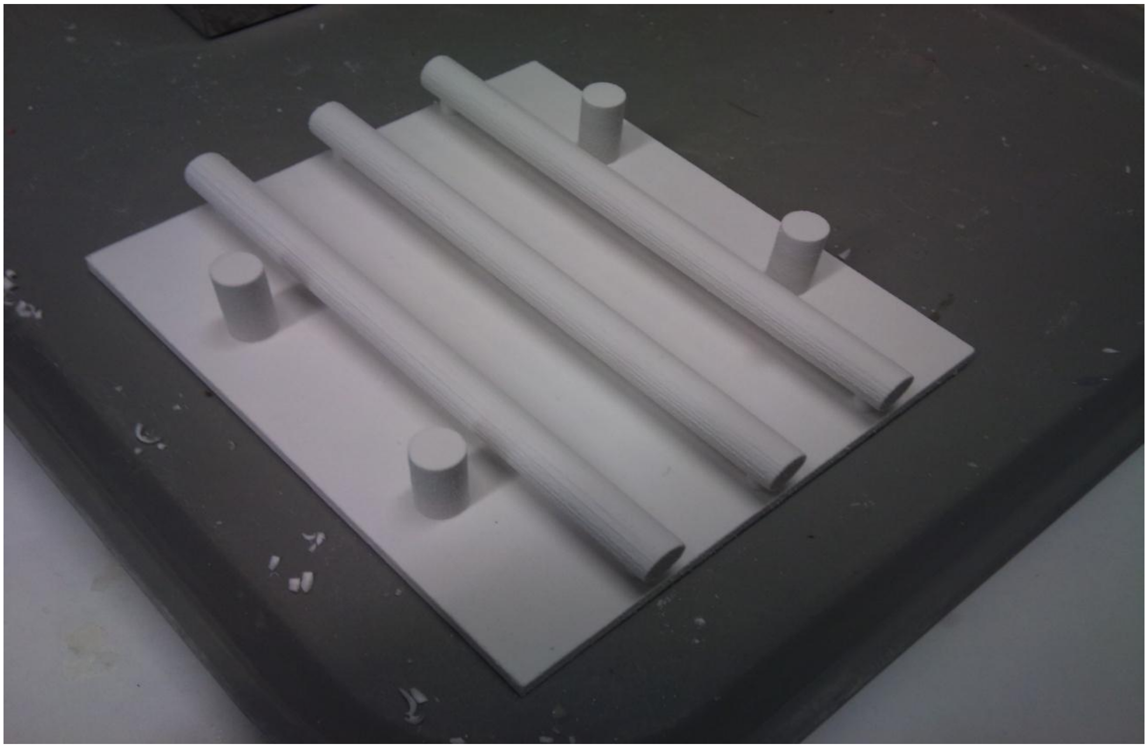

Figure A-5: Internal part of conventional cooling channel after printed with rapid prototyping machine

Figure A-6: Stirring the epoxy with metal stick to soften the epoxy

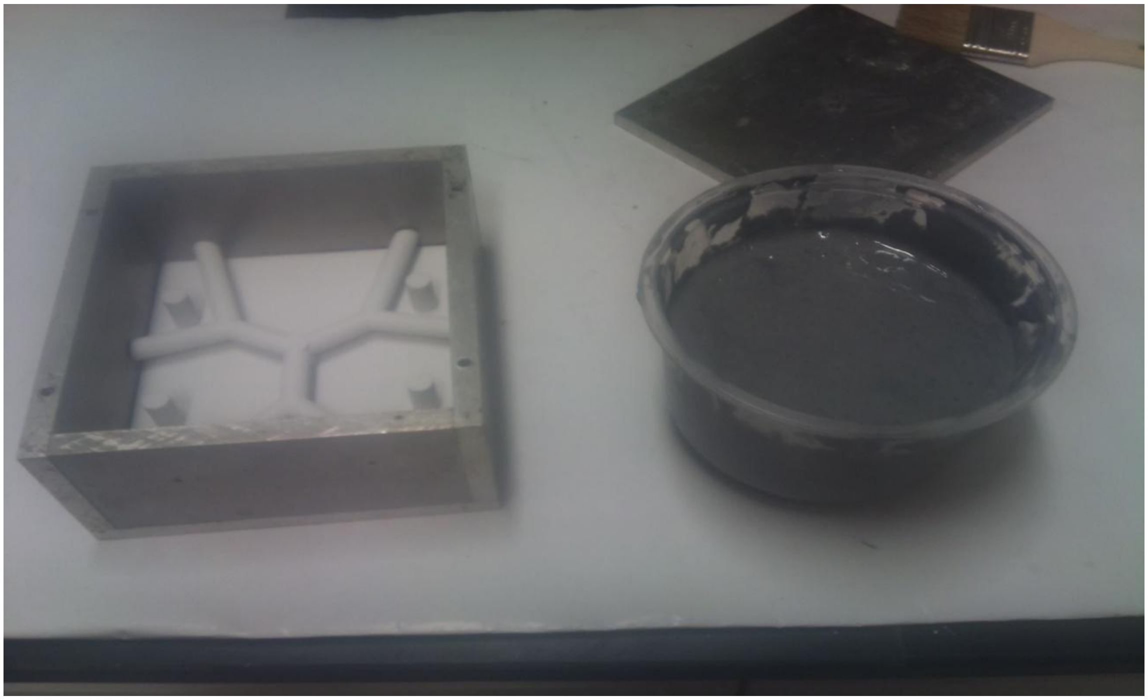

Figure A-7: Epoxy mixture (right) and steel container (left); before epoxy is poured inside the container to cast the mold

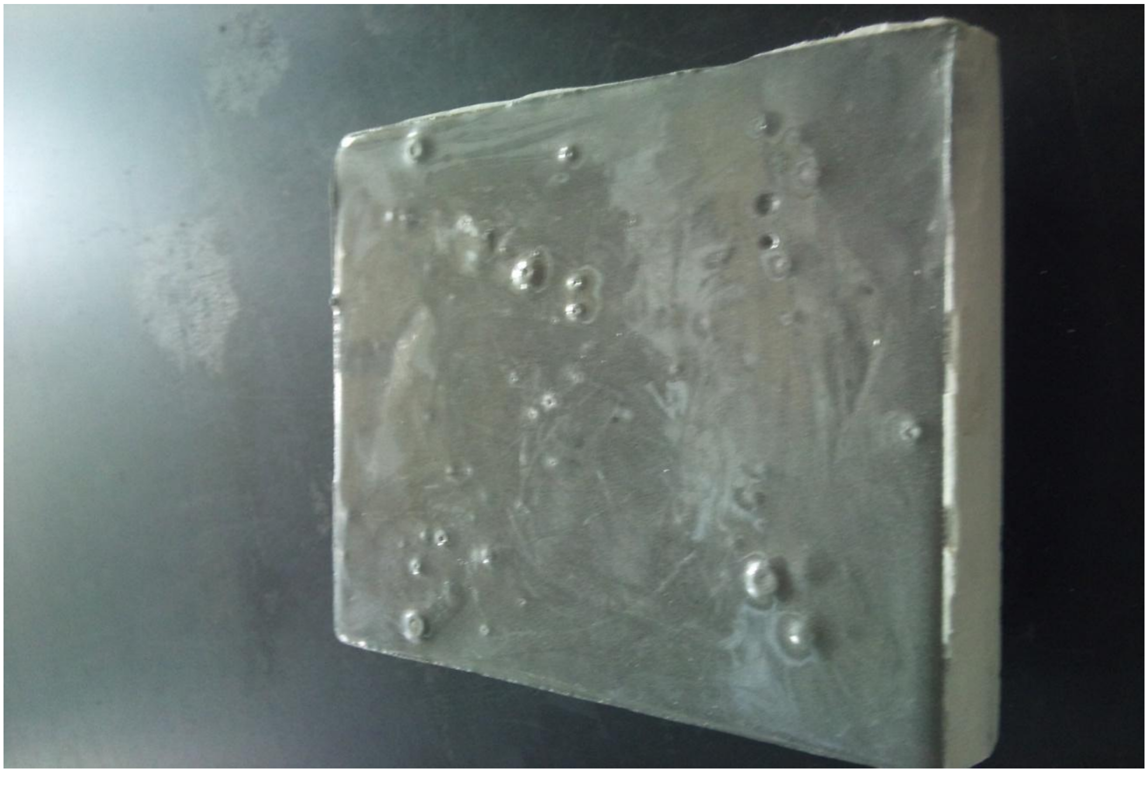

Figure A-8: Bubbling effect on the surface of the mold after epoxy solidified

APPENDIX B

Constructal Law

Figure B-1: Leaf pattern is one of constructal theory stated by Dr. Andrian

Figure B-2: Branches of smaller river combine into Main River also follow constructal theory

Figure B-3: The thunder has many brunches indicated that it makes the flow easier for the thunder to discharge the electric based on constructal theory

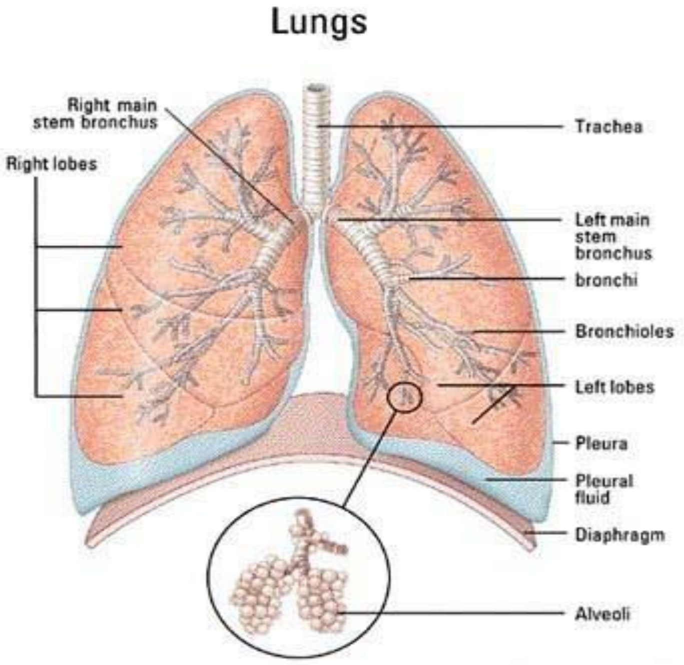

Figure B-4: The design of trachea divided into small section (bronchioles) to allow easier flow of oxygen based on constructal theory

APPENDIX C

Profiled Cooling Channel

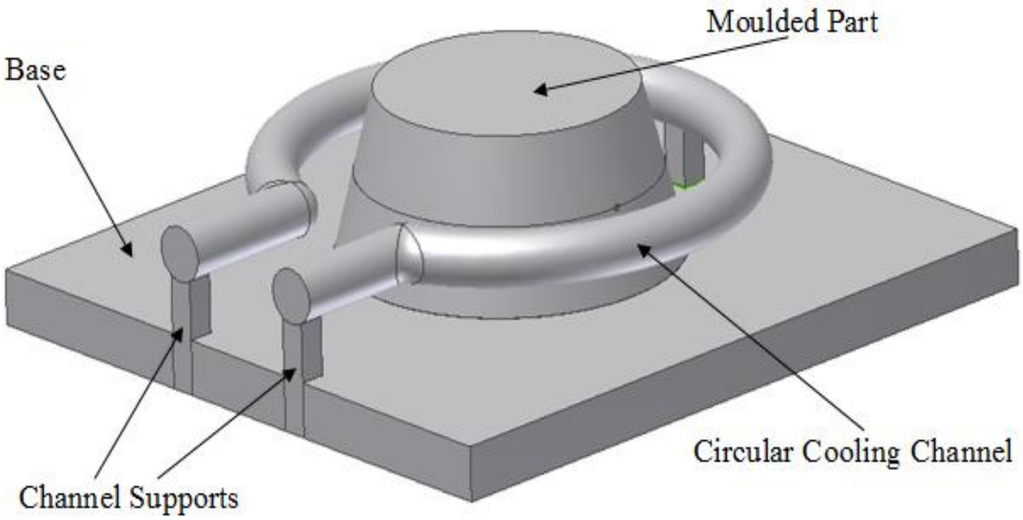

Figure C-1: Design of conformal cooling channel

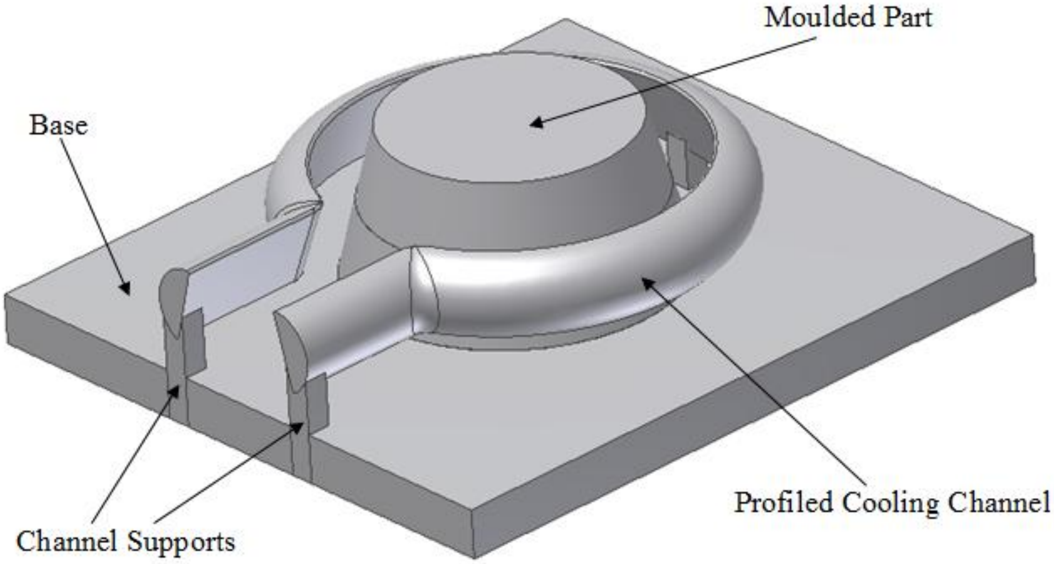

Figure C-2: Profiled cooling channel