



# **VALIDATION OF HEAT TRANSFER SIMULATION MODELS FOR INJECTION MOULDING OF ABS IN ALUMIDE® TOOLING**

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## DECLARATION

I, KGOMOTSO DAVID MOSIMANYANE [REDACTED] (ID number), [REDACTED] (Student number), do hereby declare that this research project submitted to Central University of Technology, Free State for the degree MAGISTER TECHNOLOGIAE: ENGINEERING: MECHANICAL, is my own independent work that has not been submitted before to any institution by me or any other person, in fulfilment of the requirements for the attainment of any qualification.

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## ABSTRACT

In this research, a nylon/aluminium composite (Alumide<sup>®</sup>) material was investigated for its suitability to produce moulds for injection moulding through an additive manufacturing process. Literature shows that Alumide<sup>®</sup> has a low melting point, even lower than most polymer materials used in injection moulding. It also has a low thermal conductivity of 0.8 W/mK compared to 51.9 W/mK of steel, making it poor in heat transfer. In order for Alumide<sup>®</sup> to be used successfully for injection moulding tooling, effective cooling of the moulds need to be applied. This project aimed to validate Moldex3D and Sigmasoft injection moulding simulation software to predict the amount of heat that is transferred from the mould cavity to the mould thereby determining the effectiveness of a given water conformal cooling layout. Two case studies were conducted where Alumide<sup>®</sup> was used as a tooling material for injection moulding of Acrylonitrile Butadiene Styrene (ABS). The case studies addressed the cooling channel design, moulding parameters and mould temperature for Alumide<sup>®</sup>. Simulations were conducted using the mentioned software packages in order to design and analyse cooling for Alumide<sup>®</sup> moulds. Simulation mould temperature results were compared with the actual field test results in order to validate the simulation packages used. Recommendations were made in terms of cooling channel design for Alumide<sup>®</sup> moulds in order to prevent defects that appear on the inserts along the cooling channels.

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## ABBREVIATIONS

3D	Three Dimensional – Height (Z), Width (X), Length (Y)
ABS	Acrylonitrile Butadiene Styrene
ACES	Accurate Clear Epoxy Solid
AIM	ACES Injection Moulding
AM	Additive Manufacturing
ASTM	American Society for Testing and Materials
CAD	Computer-Aided Design
CAE	Computer-Aided Engineering
CAM	Computer-Aided Manufacturing
CUT	Central University of Technology, Free State
CSIR	Council for Scientific and Industrial Research
DAQ	Data Acquisition
DTM	American Manufacturer of Selective Laser Sintering Systems
DMLS	Direct Metal Laser Sintering
EBM	Electron Beam Melting
EOS	Electro Optical Systems – German manufacturer of Laser Sintering Systems
EOS P385	Polymer-series Laser Sintering Machine from EOS
EOSINT P	Polymer-series Laser Sintering Technology from EOS

FDM	Fused Deposition Modelling
FEA	Finite Element Analysis
HDT	Heat Deflection Temperature
HDPE	High-Density Polyethylene
IM	Injection Moulding
LDPE	Low-Density Polyethylene
LS	Laser Sintering
LOM	Laminated Object Manufacturing
MLSHM	Metal Laser Sintering Hybrid Milling
PIM	Polymer Injection Moulding
PMMA	Polymethyl Methacrylate
POM	Polyoxymethylene
RIM	Reaction Injection Moulding
RM	Rapid Manufacturing
RP	Rapid Prototyping
RT	Rapid Tooling
RTV	Room Temperature Vulcanizing
SABS	South African Bureau of Standards
SLM	Selective Laser Melting
SLS	Selective Laser Sintering

STL	Standard Triangulation Language - file format that derived its name from Stereolithography
SN	Sensor Nodes, used for measuring temperature
SLA	Stereolithography
UV	Ultraviolet

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## CHAPTER 1: INTRODUCTION

### 1.1 INTRODUCTION

New product development is a complex exercise as it involves various phases such as design, prototyping and production. As metal products are increasingly being replaced by polymer products, this development makes the polymer industry a major manufacturing sector [1]. Products developed in this sector may be produced by various methods such as Injection Moulding (IM), roto-moulding, blow-moulding, extrusion, etc. Polymer Injection Moulding (PIM) remains the major manufacturing technology used in the production of polymer goods such as toys, consumer goods, medical devices, etc. [2] More than one third of all thermoplastic materials and over half of all polymer-processing equipment is based on PIM processes [5]. This process consists of the following steps: heating the polymer materials to a liquid state, injection of the melt inside the mould cavity, solidifying of the melt by cooling and ejection of the product from the mould.

Tool production or mould production for PIM constitutes a large portion of the costs in the entire product development process [2]. The conventional way of producing moulds for PIM is expensive due to the production processes which result in longer lead times [2]. As a result, this method of producing moulds is not economical when low-production runs of less than 500 components are required [2]. Research has shown that PIM tools produced by means of Additive Manufacturing (AM) are less expensive [2]. AM technologies build components layer-by-layer using data from a Three Dimensional (3D) Computer Aided Design (CAD) model. Compared to conventional methods, there is less material wastages, less machining and less intensive work [3]. For example, there is no machining of electrodes for the spark erosion process which is commonly used in the manufacturing of conventional steel moulds.

The process of producing tools by using AM is called Rapid Tooling (RT). Rapid tools are used to test new products before going into large-scale production. These tools can be produced using indirect and direct methods. The indirect method uses AM patterns to produce moulds by casting; the direct method uses the AM machine to directly manufacture the core and cavity of the mould. For this study, the direct method will be used to produce Alumide<sup>®</sup> cavities through Laser Sintering (LS).

This research investigates PIM tools of Alumide<sup>®</sup> manufactured by means of the AM process through LS. Alumide<sup>®</sup> is an aluminium-filled nylon material developed by Electro Optical Systems (EOS) GmbH. Generally, injection moulds are made of high-strength metals, primarily using steel [4]. Steel has a higher thermal conductivity compared to Alumide<sup>®</sup>; therefore, heat transfer in steel will be better compared to Alumide<sup>®</sup>. Cooling of Alumide<sup>®</sup> inserts has to be effective to achieve the desired heat transfer. LS of Alumide<sup>®</sup> is performed at a temperature of 180°C which is close to the melting point of most polymer materials. Using these inserts for IM of polymer, which is typically performed at a temperature of 210°C, adequate cooling of the inserts is crucial. Furthermore, cooling of moulds is important in improving the quality of the product and increasing productivity.

Generally, mould-cooling is carried out by incorporating cooling channels in the mould core and cavity. There are two types of cooling channels: conventional and conformal cooling channels. Conventional cooling channels are made by drilling straight channels in the cavity and core of the mould, whereas conformal cooling channels follows the profile of the geometry and can be made by the AM process. Due to the nature of the AM process, conformal cooling channels are not limited to geometry; therefore, more efficient cooling channel designs can be achieved.

## **1.2 PROBLEM STATEMENT**

In product development nowadays it is often necessary to manufacture small quantities of functional polymer parts to validate design functionality before mass production. It is during this stage of development where RT is considered, as it is quick to manufacture and less expensive compared to conventional tools. In this study rapid tools are produced using Alumide® as a tooling material. Alumide® can be processed on an AM machine such as the EOS P385 machine. Alumide® melts at 170 to 180°C making it problematic to withstand injection temperatures of polymers during IM.

An injection mould is expected to perform well both mechanically and thermally but no research has been performed on the cooling of Alumide® to ascertain if the material is suitable for producing injection moulds. An optimized cooling strategy is necessary in order to qualify Alumide® as a feasible PIM tooling material.

## **1.3 HYPOTHETICAL RESOLUTION**

Alumide® can be used as a tooling material for PIM on the basis that effective cooling of moulds during injection can be perfected. In order to achieve this goal, dedicated PIM software can be used to simulate and optimize a given cooling channel layout.

## **1.4 PURPOSE OF THE STUDY**

The purpose of the study is to investigate if Alumide® tooling produced through AM can be sufficiently cooled through conformal water cooling for it to be successfully used for injection moulding of ABS polymer. The study furthermore aim to validate commercially available PIM simulation software for this to be used to optimize cooling in Alumide® tooling.

## **1.5 IMPORTANCE OF THE STUDY**

Initial tests on laser sintered Alumide® inserts have shown positive results which indicate that this material may be used for PIM, provided that suitable cooling is provided. It is therefore important to conduct a study on the cooling of Alumide® in order to show that the

material can be used for injection moulding tools if effective cooling is used. Using this material instead of steel will result in significant cost saving due to the lower price of producing Alumide® tooling for limited run IM compared to traditional steel tooling.

## **1.6 LIMITATIONS OF THE STUDY**

This masters study feeds into a larger doctorate study where all aspects related to IM of different polymers into Alumide® tooling is investigated. The focus of this study is on cooling of Alumide® tooling. It therefore does not include other aspects normally associated with tooling for IM such as mould cavity surface roughness and dimensional accuracy. Only one polymer namely ABS was investigated for suitability for IM in Alumide® tooling since this is a thermoplastic polymer that is commonly used for producing consumer products through IM. Thermoset polymers were not included in the study since the low Heat Deflection Temperature (HDT) of Alumide® does not allow for this kind of moulding which requires heat for the material to set.

## **1.7 METHODOLOGY**

The method used was as follows:

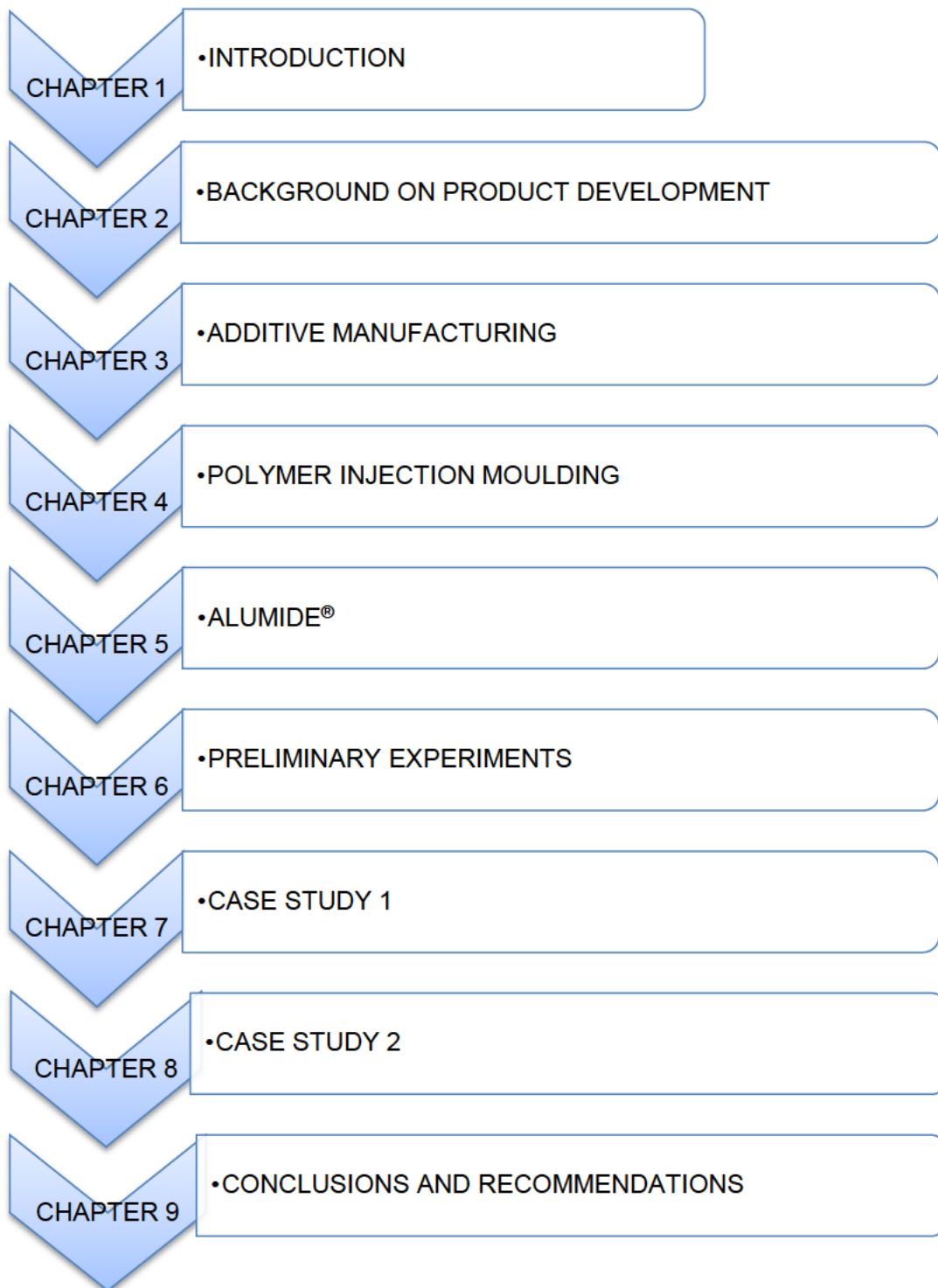
- a) Determine which software packages are available to design and simulate cooling for IM and acquire the package that is most appropriate for this research. An alternative strategy will be to make use of this type of software from Central University of Technology's (CUT) partners in industry if commercially available software is found to be too expensive. This research may be mutually beneficial to them and CUT.
- b) Complete initial tests to be used as input parameters for the design of cooling channels.
- c) Design conformal cooling channels for an Alumide® insert using the acquired software. Use the software's Computer-Aided Engineering (CAE) functions to

optimize the cooling so as to limit the mould's temperatures to remain within the temperature span of the polymer being processed while IM is taking place.

- d) Develop a temperature monitoring device and program to validate simulation model.
- e) Manufacture the Alumide<sup>®</sup> inserts through LS.
- f) Perform an IM production run with the Alumide<sup>®</sup> inserts while monitoring:
  - both the internal and surface temperature rise of the moulds at different ambient temperatures,
  - water flow rates through cooling channels,
  - IM pressures and
  - cycle time.

## 1.8 OVERVIEW OF THE THESIS

Figure 1.1 shows the overview of the chapters for the study.



*Figure 1.1: Schematic overview of the thesis*

## 1.9 CHAPTER SUMMARY

This chapter outlined the overview of the research. The composition of Alumide<sup>®</sup> material has been briefly discussed. The cost of Alumide<sup>®</sup> tooling has been indicated to be lower when compared with steel tooling due to the lower cost of producing the Alumide<sup>®</sup> tools through LS compared with steel tools manufactured through traditional processes. The emphasis on cooling of Alumide<sup>®</sup> has been highlighted to be important due to its low thermal conductivity. The other important factor discussed was the low melting point of Alumide<sup>®</sup> compared with polymer materials used in IM. These two factors promote the need for efficient cooling of Alumide<sup>®</sup> inserts in PIM. The methodology discussed how cooling of Alumide<sup>®</sup> moulds will be investigated to achieve the objective of the research.

## **CHAPTER 2: BACKGROUND ON PRODUCT DEVELOPMENT**

### **2.1 INTRODUCTION**

Developing a new product from an idea to an end product is a complex process as it requires engineers, industrial designers, marketing teams, manufacturers, intellectual property attorneys, etc. Product development is critical if a company wishes to expand and grow [1]. It is therefore important that time and cost of developing a product be minimized without compromising quality. In some cases, a series of products will need to be developed for testing, therefore it is important to use manufacturing processes which are faster and cost effective. There should be flexibility in the product development process, giving the developer a number of different design options, in order to find the best design [8]. It should also be noted that during product development, a client's requirements can change completely from the initial brief. Over the years it has become obvious that product technologies are changing faster than before and this has called for faster product development cycles.

### **2.2 PRODUCT DEVELOPMENT CYCLE**

Research, analysis, designs, prototyping, testing and production are key elements in product development. A good new product results from well-defined product specifications and methods of development [9]. These methods are nothing but a product development cycle. Figure 2.1 illustrates a simplified product development cycle.

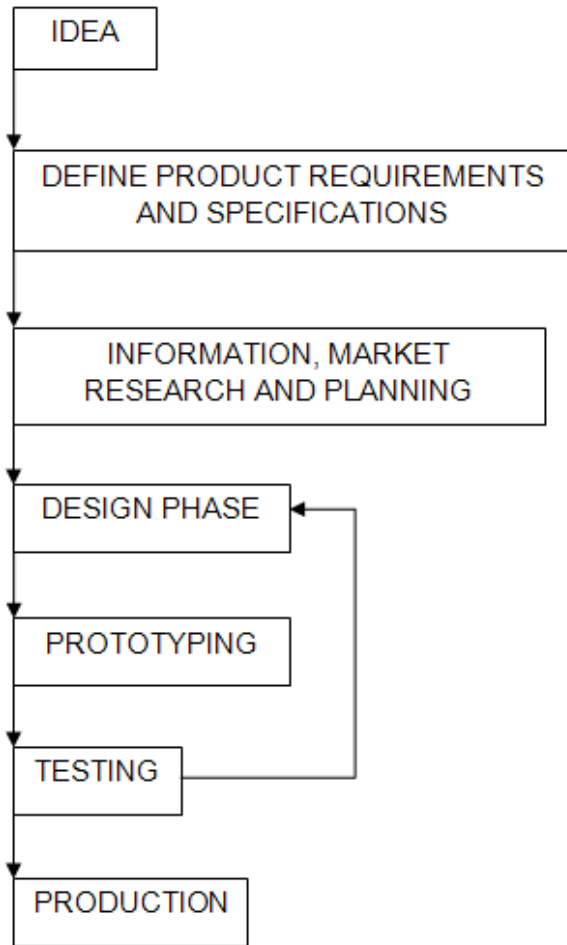


Figure 2.1: Product development cycle [10]

### 2.2.1 Project Idea

Most of the products seen today have begun with an idea or a number of ideas. It is important that an idea be realistic in terms of its functionality and whether it is manufacturable. Good ideas have the potential to be developed into business opportunities if the market is viable [11].

### 2.2.2 Definition of product requirements and specifications

This stage is important as it defines how the end product should operate; it may include environmental requirements, product material, size, shape, etc. [10]. The initial requirements may change as a result of information gathered during the research phase. Understanding the end user of the product will help to define the relevant requirements.

Specifications will outline product strength, performance, look and feel. The number of products to be produced should also be defined in order to select a cost-efficient manufacturing process. Skipping this stage may result in longer product lead times due to time spent revisiting the design to double check the work, whereas if the specifications are given at the beginning, it would reduce this time-consuming process. It is important to define the specifications early in the product development stage before starting on any designs.

### **2.2.3 Information, market research and planning**

Gathering of information will help in advancing the product requirements and alter some of the specifications. At this stage, market research must be carried out to see if there are similar products. This step is essential if the client wants to file a patent. Searching the market will also identify the need for such a product, which really drives the whole reason for developing it [12]. A developer needs to be assured that the product will work or sell. This will be confirmed if proper market- and information searches are done.

### **2.2.4 Design phase**

Design involves a great deal of engineering analysis, such as Finite Element Analysis (FEA). A good design does not result from a single design but a number of concepts. Each concept is evaluated on feasibility, strength, ease of manufacturing, cost, etc. The one that scores the highest points is considered for a final design that will be prototyped. The final design is modelled on CAD software and thereafter FEA is done to check the performance of the product. A design might change after FEA or after prototyping to improve various aspects of the product which were found to be problematic.

### **2.2.5 Prototyping and testing**

A prototype is a physical object which is manufactured from a design that can actually be tested to prove certain areas of the design. Some prototypes are made by conventional methods of machining which take longer and are costly. AM creates physical parts directly from CAD, helping companies reduce the cycle time of product development [13]. AM is also used to develop injection moulding tools for the production of polymer parts. In some

cases a product needs to be tested in the final polymer material and to do this a mould needs to be manufactured. The less expensive way to do this is to manufacture the mould by means of RT using AM [14].

### **2.2.6 Production phase**

At this stage, most of the problems have been ironed out as all the tests, analyses, market research and business plans have been completed. All the technical drawings are handed to the various sections of the manufacturing shop to begin production. Choosing the correct manufacturing process is important as it differs for each product and the number of products to be produced.

## **2.3 THE RISKS OF NEW PRODUCT DEVELOPMENT**

Risks can be defined as circumstances that cause extreme expenses, delays and product uncertainties. During product development ideas can be changed many times, making the process difficult. Furthermore, studies have shown that products have failed in the market due to the lack of understanding of the customers' needs. Sometimes the product may have new features and these may require a change in customer behaviour as well as legal requirements which may have to be complied with, such as the South African Bureau of Standards (SABS).

There is also the risk of confidential information being leaked should the necessary measures not be in place such as a none disclosure agreement.

## **2.4 ADDITIVE MANUFACTURING IN PRODUCT DEVELOPMENT**

The use of AM has reduced the time-to-market and manufacturing costs during the testing phase, and improved the design of new products. The use of this technology will eliminate a lot of expensive changes which might occur on the tooling if the product is not satisfactory [15]. AM technologies build products layer-by-layer directly from CAD data as opposed to expensive and time consuming subtractive processes such as milling, turning, spark erosion etc. Various materials can be used to manufacture prototypes such as polymers,

metal and even composites [16]. There is also a high level of design and manufacturing freedom because there are no traditional manufacturing processes. AM can produce components with functional abilities to be used as end products. This is an advantage because products can be tested and modified before advancing to production [13].

It can be argued that nowadays there are CAE packages which can be used to predict the performance of the product, but many product development processes show that a physical evaluation of the real component is important [13]. Tools and dies can also be produced by means of AM, it is important whenever a product is to be developed by injection moulding.

## **2.5 RAPID TOOLING IN PRODUCT DEVELOPMENT**

The term Rapid Tooling (RT) is typically used to describe a process which either uses an AM model as a pattern to create a mould or uses an AM process directly to produce a tool. RT differs from conventional tooling by its shorter tooling time and its lower tooling cost [13].

In comparison with conventional machining methods, the majority of AM systems tend to produce parts using a process of addition rather than subtraction or removal of material. Therefore there is lower waste compared to conventional methods of manufacturing [7]. AM and RT continue to have a huge impact on how products are designed and tested.

RT methods can be divided into two categories:

- Indirect methods
- Direct methods

### 2.5.1 Indirect Rapid Tooling Methods

The indirect method uses RP patterns to produce moulds by means of casting. Indirect methods can be used to validate the product design during the product development cycle [22]. The product accuracy is controlled by the accuracy of the pattern produced.

#### a) Spray Metal Tooling

This method is divided into two types: Gas Metal Spraying and Arc Metal Spraying [22]. Gas Metal Spraying uses a low melting point alloy passing through the nozzle. The material used is a metal wire usually lead or tin and is melted by a conical jet of burning gas [22].

Arc Metal Spraying creates the surface of the mould by using an arc spray technique to coat a thin layer of metal usually a low melting point alloy on the pattern [22]. A thin shell of about 2 mm thickness is sprayed over the pattern to create a mould and epoxy is used to backfill it, which makes the insert rigid [15].

Spray metal tooling can produce more than 1000 parts depending on the care given to the mould and the material formed [15]. Spray metal tools are used in many processes such as sheet metal forming, injection moulding, compression moulding, blow moulding and vacuum forming [15].

#### b) Electroforming tools

During electroforming a thin shell is electroplated onto a master pattern, therefore it is essential that the surface of the pattern is electrically conductive. Nickel is the common material used for electroplating in this process because it has good thermal conductivity and strength [15].

Once the plating is completed, the shell is removed and backfilled with epoxy resin to improve the strength of the mould.

Plating into deep narrow slots and holes can be a problem for this technique of making moulds. This method is also not a quick process, it can take weeks for a 5 mm thick tool surface [6].

c) Epoxy tooling

The epoxy tooling starts with an AM pattern or model as a master. A frame is placed around the pattern and epoxy is poured over one half of the pattern. The casting process is repeated to manufacture the other half of the mould.

Epoxy tools have a limited tool life and poor thermal transfer [22]. Epoxy tools can produce polymer injection moulded parts out of thermopolymers [22]. Up to 5000 polypropylene parts and 200 glass filled nylon parts can be injection moulded using epoxy tools [22].

d) 3D Keltool

The process starts by fabricating a master pattern of the core and cavity by means of stereolithography (SLA). Silicone rubber is then poured into the pattern which is placed inside a frame. A mixture of metal powder and a binder is next poured into the cavity created in silicone. The green part created is then placed into a furnace in order to remove the binder and fuse the metal particles together [22]. The part is then infiltrated with copper to produce a fully dense mould.

Stellite or A-6 composite tool steel can be used to produce these moulds which are capable of producing more than 1000 000 parts [22].

e) Aluminium and Zinc Kirksite tooling

The process starts with a pattern which should be capable of withstanding the casting temperatures of aluminium and zinc which is around 450°C [6]. A silicone mould is produced by using a SLA pattern and thereafter the mould is used to cast ceramic in order to have a prototype able to withstand casting temperatures. After drying the ceramic pattern is placed in the mould frame to cast aluminium/zinc over it [15]. Each tool half is made separately in

this manner. The technique may be used for products that require low dimensional accuracy [15].

### **2.5.2 Direct Rapid Tooling Methods**

Direct RT methods produce the moulds or tools directly from a 3D CAD model by using AM technology. Direct RT can be divided into two main groups namely bridge tooling and hard tooling. Bridge tooling is less expensive and useful for tool validation. It is used for short production runs.

Hard tooling can produce tools which are used for pre-production and production. In this method laser sintered metal powder is used to produce the mould inserts.

Direct RT does not only involve AM processes but also a subtractive process such as high speed cutting [22].

#### **i. Direct Metal Laser Sintering, Selective Laser Melting and LaserCusing**

Direct Metal Laser Sintering (DMLS) from EOS, Selective Laser Melting (SLM) from Renishaw and LaserCusing from CONCEPT Laser are powder bed fusion based technologies which use laser as energy source [68]. These technologies produce products layer by layer from powder materials by using laser to melt the particles of the powder.

Metal components and tool inserts can be produced by the DMLS process. DMLS tools can be used for IM having undergone secondary processes such as polishing or shot peening to improve surface finish. For tooling purposes, bronze- and steel-based materials can be used. Direct Metal 20, which is bronze-nickel based, can be processed with a 20 $\mu$ m layer thickness [17]. EOS MaragingSteel MS1 is considered to be a high performance steel which can be used for production in IM [17].

The SLM process is an AM technique developed to produce components which are nearly fully dense with mechanical properties close to the bulk materials [59]. The power of the

laser used is higher than the one used in SLS and the component produced is similar to the series production requiring less post process techniques [60]. The high heat input causes material vapourisation and spatter during processing. Furthermore too high energy causes excessive melting of the layers resulting in the balling effect. Balling decreases the part density and increases the surface roughness [61].

LaserCUSING machines use stochastic exposure strategy to produce islands in the layer that are build together [58]. These islands help in reducing the stresses within the part. Mould inserts with conformal cooling can be manufactured using this AM processes [57].

LaserCUSING allows for a range of materials to be used such as high-grade steels, hot-work steels, stainless hot-work steels, aluminum alloys, nickel-base alloys, titanium alloys, pure titanium, cobalt-chromium alloys, bronze alloys and precious-metal alloys [57].

## ii. Laminated Tooling

Layers of sheet metal are cut to duplicate the CAD model using laser cutting or water jet technologies. To produce a tool, the slices being cut are clamped and bonded, creating a cavity. Larger tools can be produced using this technique. A variety of tools can be produced, such as press tools, blow moulds, injection moulds and thermal forming tools [15].

## iii. Electron Beam Melting

Electron Beam Melting (EBM) was developed by Arcam in order to manufacture metal parts which are fully dense [62]. The technology builds parts by melting metal powder layer-by-layer. EBM has high efficiency due to the electron beam gun as opposed to laser used in LS and laser melting processes [62]. The process occurs in a vacuum environment providing a clean workspace, therefore minimizing contamination [63]. Furthermore the

vacuum environment prevents loss of energy that can be caused by fast moving electrons colliding with air or gas particles [64].

EBM uses a number of materials such as H13 steel, titanium-6aluminium-4vanadium (Ti6Al4V), titanium-48aluminium-2chrome-2niobium (Ti-48Al-2Cr-2Nb) and CoCr alloys [65].

#### iv. Metal Laser Sintering Hybrid Milling

DMLS is capable of producing complex geometries but unfortunately many of these components cannot be used as build because of the rough surfaces. Secondary operations such as milling have to be carried out in order to finish the component [66].

Metal Laser Sintering Hybrid Milling (MLSHM) combines DMLS process with high speed precision milling to finish the laser sintered part and end with a fully machined component.

## 2.6 BENEFITS OF RAPID TOOLING IN PRODUCT DEVELOPMENT

The various RT techniques covered in this chapter have certain characteristics and all have the advantage of producing a prototype faster [18]. The other advantage of RT techniques is that they are less expensive than the traditional tool production techniques. It has to be realized that expensive tooling can only be justified when mass-producing a product [19]. For product development, an intermediate tool is sometimes required for small quantities of parts; therefore, for this purpose RT is highly suitable. RT allows for design refinement and modification because the product can be tested early in the development process. RT also addresses the limitations caused by the declining number of skilled toolmakers as it is labour and time-saving [20]. The ability of RT tooling techniques to produce conformal cooling channels offers an advantage to the tool giving it a better thermal performance.

Complex geometries required in IM can be produced in the form of separate inserts using AM techniques [21]. During the last few years, there has been much focus on developing AM for RT, which has opened new opportunities for RT to produce not only bridge tooling but also production tools [22]. RT tooling can be summed up by saying that it offers strategic-, production- and decision-making advantages [8].

## **2.7 CHAPTER SUMMARY**

This chapter has provided an overview of the product development cycle; it also highlighted the risks of product development. It has been proved that AM can reduce the risks in product development. Furthermore, RT has shown to be a critical technique in reducing the risk during product development of polymer products. Indirect methods has been discussed as methods that can be used to validate the product design during the product development cycle. Furthermore the accuracy of these products depend on the accuracy of the pattern used to manufacture the mould. Direct RT methods produce tools directly from 3D CAD data. These tools can be used as pre-production or production tools.

## CHAPTER 3: ADDITIVE MANUFACTURING

### 3.1 INTRODUCTION

AM technologies create products directly from 3D CAD. The terminology standard for AM was developed by the ASTM F-42 committee and according to the committee's first standard, ASTM F2792-10, AM is defined as "the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing technologies" [23]. AM technologies present the following benefits [24]:

- Reduced lead-times to produce prototype products
- Product visualization in its physical state
- Early detection and reduction of design error
- Waste elimination and costly late design changes
- Ability to plan for assemblies

The other advantage of AM technology, apart from producing prototype parts, is its ability to produce tooling known as RT for the PIM industry.

AM technology developed from various technologies such as CAD or Computer Aided Manufacturing (CAM) which have been there before. Table 3.1 shows the historic development of the AM technology.

Table 3.1: Historical development of AM and other related technologies [25 & 68]

Year of Introduction	Technology
1770	Mechanization
1946	First computer
1952	First numerical control (CNC) machine tool
1960	First commercial laser
1961	First commercial robot
1963	First interactive graphics system (early version of Computer Aided Design)
1988	First commercial prototyping system
1992	First commercialised AM machine by Desktop Technology Manufacturing (DTM) Corporation
1994	EOS Released the EOSINT machine

By 1994 there were only three AM systems in South Africa [27]. However, South African academics, researchers and industry saw the need to explore AM technology for the benefit of new product development. Figure 3.1 shows the positive growth in the investment made in acquiring AM systems in South Africa.

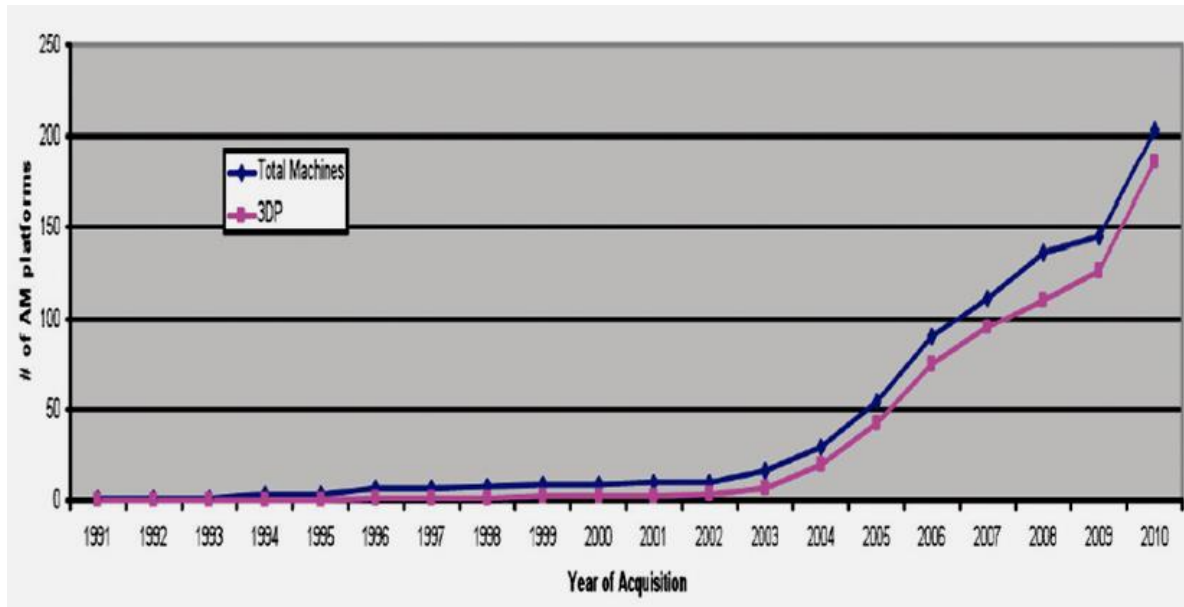


Figure 3.1: South Africa AM evolution 1991-2010 [27]

There have been many developments in AM technologies in the past 30 years. One of the processes developed during this period is Rapid Manufacturing (RM) which means that the technology can be used to produce end-user products [26].

### 3.2 ADDITIVE MANUFACTURING PROCESS CHAIN

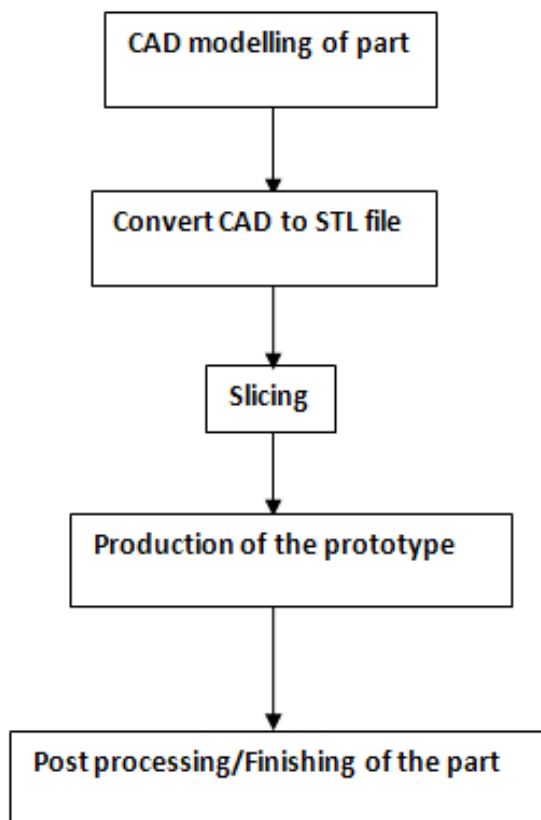
AM differs from other manufacturing processes such as turning, milling, grinding, etc., which are subtractive, meaning that material is removed in the form of shavings from the stock material. Today, every commercial AM machine works in a similar fashion. In the AM process, the part is produced by deposition of material in the (X-Y) plane to create a layer. In the Z-plane the layers are stacked on top of one another which results in stair steps on the surface of the product, but if the settings are adjusted to a finer layer thickness, the

product surface can be improved. The layer thickness depends on the material deposited as well as the machine used and cannot always be adjusted.

The AM process uses the following basic steps to make a prototype or product:

- CAD design
- Convert the CAD model to Standard Triangulation Language (STL) file format
- Slice the STL file into 2D cross-sectional layers
- Production of the prototype part
- Post processing

A typical process chain is illustrated in Figure 3.2.



*Figure 3.2: AM process steps [25]*

### **3.2.1 CAD modelling**

Some AM systems require an STL file as an input to be able to produce a product [28]. A CAD drawing is prepared by producing good surfaces of the part before manufacturing. A solid model can also be prepared from reverse engineering by joining surfaces together. Reverse engineering refers to converting an available physical part to a CAD model. Furthermore parts can be designed in any CAD software as long as the design can be exported in STL format.

### **3.2.2 Conversion of CAD model into STL format**

The STL format is used in AM technologies in order to process or read the CAD model. Supports may be created for STL file, if needed. Support structures are required to support overhanging parts in order to prevent such parts from not being fully formed or manufactured. Processes such as Fused Deposition Modelling (FDM) and SLA use support structures on overhanging parts. The STL files are not exact copies but rather approximate copies, because the surface of the CAD model is generated by ordering a series of triangular facets over the surface [6].

### **3.2.3 Slicing of the STL file into 2D cross-sectional layers**

The STL file is sliced layer-by- layer. Slicing is carried out after the CAD model is being converted to STL format. When an object is sliced, horizontal slice planes are intersected with the sides of the triangular facets at each particular slice height. The collective intersecting points are then adjacently joined by straight lines to form contours at each height. During building of the prototype, the material is added in the Z-axis.

### **3.2.4 Production of the physical part**

The slice file is sent to the AM machine for production of the part. Once the machine is running there is very little intervention by the operator because the system is fully automated. The build time depends on the size of the part and the number of parts needed.

### **3.2.5 Post processing phase**

This is considered as the last step in the AM process which is:

- Part removal
- Cleaning
- Post-curing in stereolithography (SLA)
- Finishing

During part removal and cleaning, the part is taken out of the machine and excess material is removed, including the supports depending on the AM process being used. Post-curing is needed to completely solidify SLA parts and also to improve its mechanical properties. An apparatus using ultraviolet radiation is used for this process which is quicker than the time taken to build the prototype.

Surface-finishing of the part may involve sanding and machining of the part to remove some material to improve surface quality.

## **3.3 ADDITIVE MANUFACTURING TECHNOLOGIES**

In this chapter, only a few important AM technologies are covered namely SLA, LS, Fused Deposition Modeling (FDM) and layer-laminated manufacturing, called Laminated Object Manufacturing (LOM).

### **3.3.1 Stereolithography process**

In this process liquid resin forms a solid product when exposed to ultraviolet (UV) laser light, which scans across the surface of the resin. A layer-by-layer process is carried out by an elevation mechanism which lowers at the end of each layer. A stereolithography machine consists of a build platform containing liquid resin and an argon ion laser [25]. A typical apparatus is shown in Figure 3.3. The process within the machine occurs in the following sequence:

- At first the polymer is maintained in a liquid state
- A platform is located one layer thickness below the surface of the liquid polymer

- The UV laser scans the polymer layer above the platform. The polymer solidifies and takes the shape of the cross-section
- The platform is lowered one layer thickness, and then the next scan begins
- This process is repeated until the entire part is formed
- To completely solidify the part, a process called post-curing is necessary. The green part is cured in a UV oven

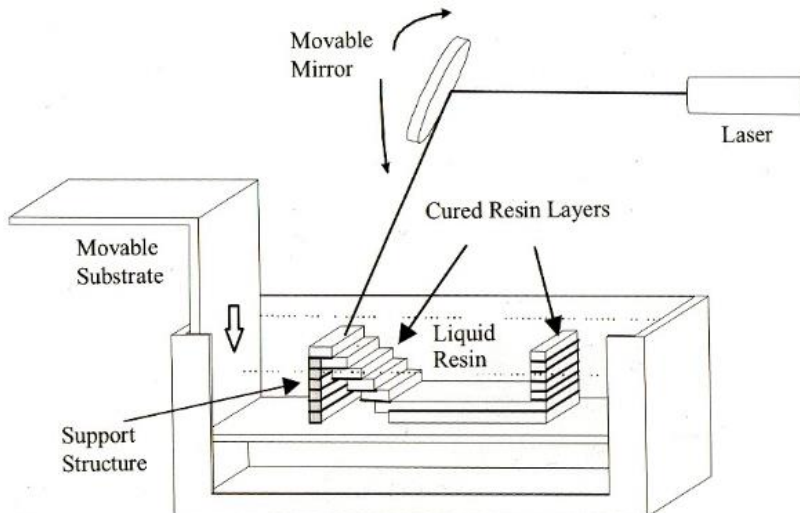


Figure 3.3: Schematic diagram of a typical stereolithography machine [25]

The green part is low in strength and supports are provided for stability. Solid supports are not recommended as they are difficult to remove and may damage the part.

### 3.3.2 Laser Sintering process

In the LS process, fine polymer powder is spread on a build platform by a recoating blade; thereafter a laser beam is projected on the powder tracing the cross-section of the part which is being built. The next layer is spread on top of the previously fabricated layer by the recoating mechanism [25]. The layer of powder is then sintered onto the previous layer by the laser. A schematic diagram of the EOS LS process is shown in Figure 3.4. During fabrication it is important to note that exposure parameters and scan patterns will affect the

mechanical properties of a part. A nitrogen environment is required in the build chamber in order to prevent oxidation.

At the completion of the part fabrication, the part is removed from the build platform and loose powder is removed. The part can be used as is or it can be finished by other means such as sanding, coating or painting. In this process there are no supports as the powder acts as the support.

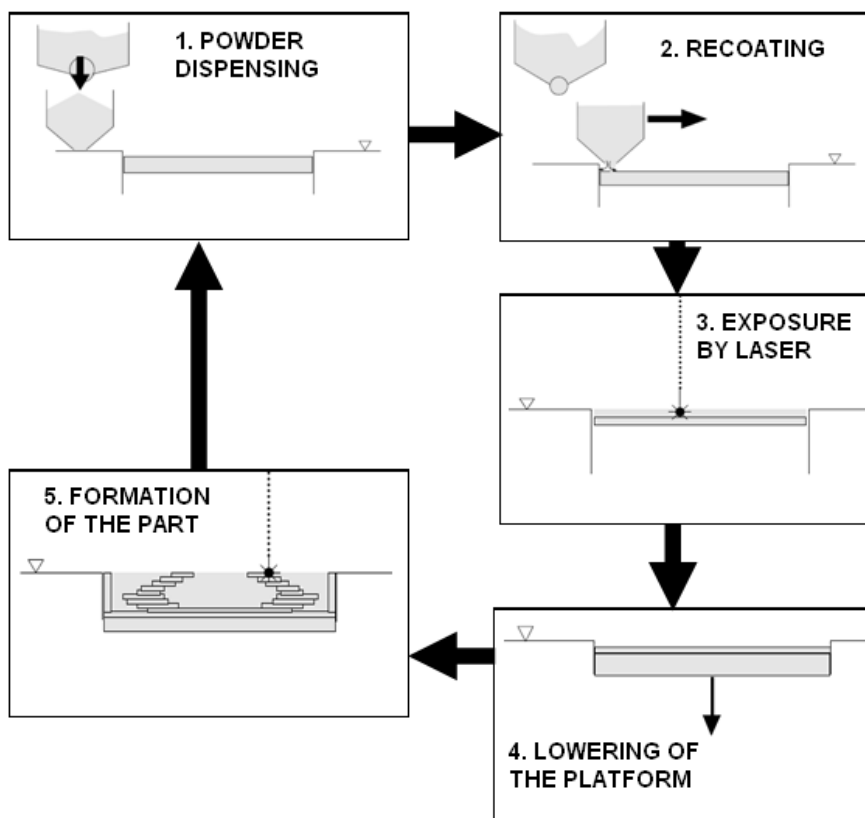


Figure 3.4: Laser Sintering process cycle by EOS [70]

### 3.3.3 Fused Deposition Modelling (FDM) process

In this process a nozzle deposits a thread of molten polymer material (Figure 3.5). During processing it is necessary to maintain a steady nozzle and a constant material extrusion rate. Supports are required to support overhanging structures. The newer FDM machines

are provided with two nozzles, one for part manufacturing and one for support generation. The advantage is that the support material is of poorer quality and weaker and therefore it is easy to remove during the cleaning process.

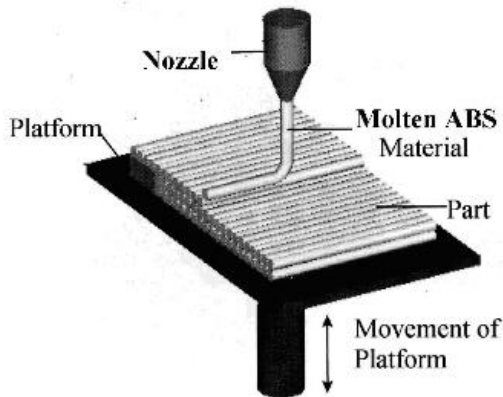


Figure 3.5: Fused Deposition Modelling System [25]

### 3.3.4 Laminated Object Manufacturing (LOM) process

In LOM, slices are cut in the required contour to form layers of the product being manufactured. A hot roller is used to activate a heat sensitive adhesive which joins the slices together. A finished part is covered with urethane, silicone fluid or epoxy resin to prevent distortion. The limitation of the process is found in the manufacturing of hollow parts and parts with undercuts. The process is shown in Figure 3.6.

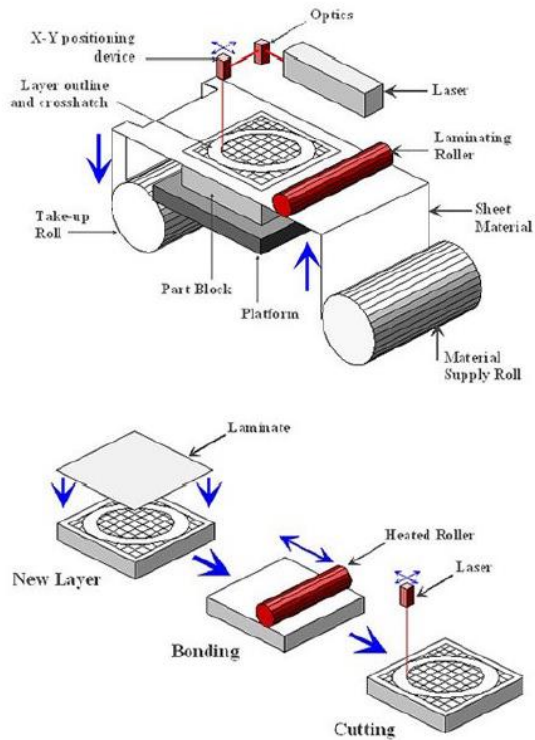


Figure 3.6: Laminated Object Manufacturing process [25]

### 3.4 APPLICATIONS OF ADDITIVE MANUFACTURING

AM has a variety of processes with different characteristics, strengths and weaknesses. The number of AM applications has grown over the years mainly due to the improvement and development of the materials used. Other factors which have increased the application of AM technology are process control; accuracy of the parts; speed of the process; cost and reliability of the process and parts. These factors dictate how AM can be applied and in this chapter the following applications of AM are discussed:

- Casting and pattern-making
- Rapid tooling
- Medical applications
- Rapid manufacturing
- Product development

### **3.4.1 Casting and pattern-making**

Patterns and cores for casting can be produced by AM. Investment casting is one of the processes used to create complex and detailed components such as jewellery, dental fixtures as well as mechanical and industrial components [24].

### **3.4.2 Rapid tooling**

Rapid tooling refers to techniques used for making tools in a short time [24]. Today, many RT methods are developed and used by industry to cut costs and also meet the short lead-times on products. In chapter two, methods of producing RT were discussed, namely direct and indirect methods. In AM, RT may be achieved by direct methods, where dies, cores and cavities are directly manufactured by AM machines. Rapid tooling by indirect methods can also be used, where a master model needs to be fabricated first and thereafter used to produce a tool, such as in casting. In this study, a direct method of manufacturing tools for IM is investigated using LS.

### **3.4.3 Medical applications**

It is projected that the global medical market will continue to grow, requiring various medical devices to assist patients with cancer and other diseases, disabilities and trauma [29]. Medical components produced by means of AM techniques allow various advantages such as short lead-times, the ability to make complex components and to make customized implants for specific patients. Prosthetics, which match the surrounding areas, can be produced with high strength and light weight. The other advantage is that materials deposited by DMLS are as good as or have better mechanical properties and physical properties compared to wrought or cast material.

### **3.4.4 Rapid manufacturing**

Companies around the world have successfully used AM to produce finished components. The aerospace industry is the biggest user of AM. The Wohlers' Report states that the production of AM parts has increased and this is due to improved material quality and

decreasing cost [30]. This technology may also be helpful in the maintenance and repair process where a certain machine component is no longer available.

### **3.5 CHAPTER SUMMARY**

In this chapter AM was described as a process that produces a product directly from a CAD model, layer-by-layer as opposed to subtractive manufacturing techniques. The technology provides many benefits in product development, as it allows designers to investigate the product in its physical state.

AM can be used for various applications such as RT, casting and pattern-making, rapid manufacturing, medical applications and product development. In all these applications, time and costs are reduced compared to conventional ways of manufacturing.

## CHAPTER 4: POLYMER INJECTION MOULDING

### 4.1 INTRODUCTION

PIM is used to produce large quantities of identical polymer items. It caters for a variety of polymer materials, both thermosets and thermoplastics. PIM is a process of injecting melted resin (melted “polymer”) into a mould. The process starts with a steel mould which is clamped under pressure to accommodate the force at which the polymer injection will take place. The injected polymer inside the cavity cools, solidifies and is then removed as a finished product. The cavity is the inverse shape of the desired product being produced. This process of producing polymer products has to meet the increasing demand of high quality products; therefore injection moulds have to be manufactured with the highest precision [30]. An IM tool is a complex system which should meet many demands or functions. Three primary functions of an IM tool are to contain the melt, to transfer the heat and to eject the part [33]. Figure 4.1a shows the typical layout of an injection mould as installed in the IM machine. It mainly consists of a mould unit (Figure 4.1b) with a core, cavity, runners, gates and cooling channels.

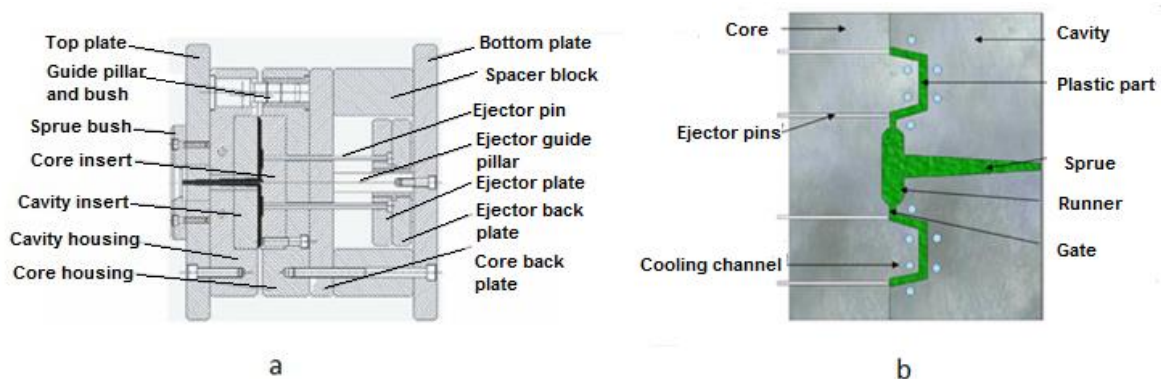


Figure 4.1 Typical construction of an injection mould (a) and basic injection mould unit (b) [34 & 35]

IM provides the following benefits [46]:

- High production output rates
- The use of inserts in the product
- Close tolerance on small complex parts
- More than one material may be used in co-injection moulding
- There is little post production work required
- Scrap of thermoplastics can be reground and reused
- Production may be fully automated

## 4.2 POLYMER INJECTION MOULDING CYCLE

A cycle of an IM process consists of five steps which are plastification, injection, holding, cooling and lastly ejection as shown in Figure 4.2 [31]. Plastification is the melting of polymer pellets through the heating chamber situated in the IM machine – see Figure 4.3.

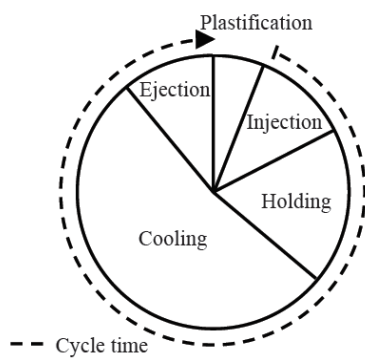


Figure 4.2: Injection moulding cycle [31]

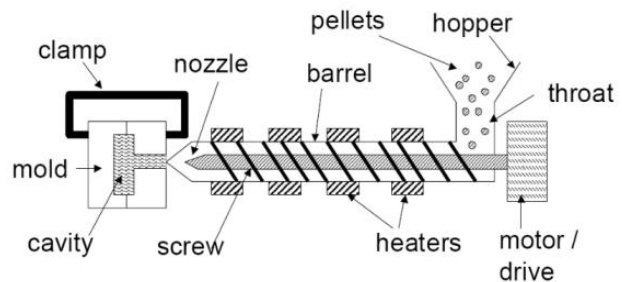


Figure 4.3: Schematic of an injection moulding machine [32]

#### **4.2.1 Injection stage**

In the injection stage the mould is closed and the nozzle is moved towards the sprue bush of the tool. Molten polymer is then injected into the mould by the screw [32].

#### **4.2.2 Holding pressure stage**

At this stage the mould is completely filled. The screw remains stationary for some time to keep the polymer in the mould under pressure. The time taken to keep the polymer under pressure is called holding time. Due to cooling there will be some contraction. Holding time compensates for this by injecting additional melt into the mould. The pressure should be high enough to avoid sink marks and low enough to release the product with ease [32].

#### **4.2.3 Cooling stage**

It is important to understand that the melt starts cooling as soon as it touches the cavity surface. During the moulding process a certain cooling time is set before the mould ejects the product and by that time the product is fully solidified. The cooling time will depend on the wall thickness of the product. Section 4.3 will discuss cooling in detail.

#### **4.2.4 Ejection stage**

When the molten material has cooled sufficiently to retain its shape, the mould opens and the product is ejected from the mould. After ejection the mould closes and the cycle starts again [32].

### **4.3 COOLING IN POLYMER INJECTION MOULDING**

Cooling time occupies 70% to 80% of the moulding process; therefore, the design of cooling systems is very important in IM [38]. An injection mould is expected to perform well both mechanically and thermally. A constant temperature during the moulding process is of high importance in order to increase productivity and produce quality products [36]. The rate of heat exchange between the injected polymer and the mould is an important factor in the

performance of the injection mould [37]. Uniform cooling in a mould will minimize defects such as sink marks; differential shrinkage; thermal residual stress and part warpage [36]. Proper cooling channel design is vital as shown in Figure 4.4.

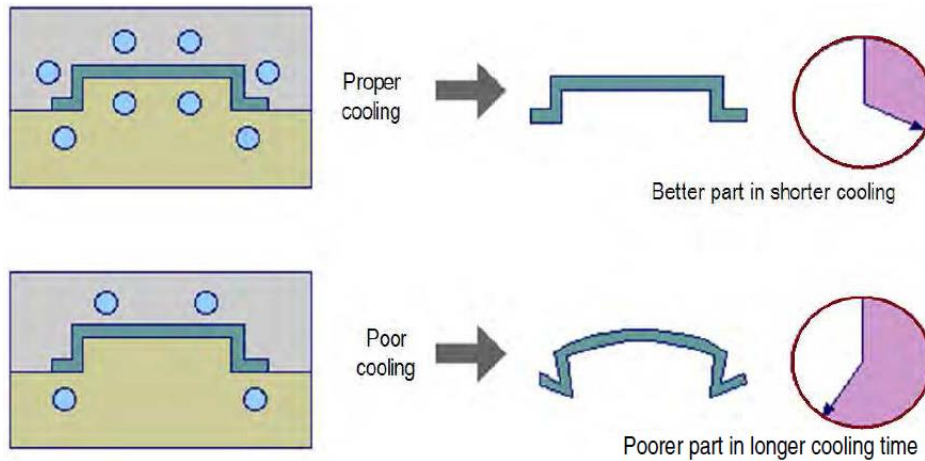


Figure 4.4: Proper cooling design vs poor cooling design [38]

Water is the most common medium of cooling because of its excellent thermal transfer properties, its low cost and its availability [39].

Water is fed from a chiller into the channels provided in the mould inserts. Traditionally, the cooling channels have been made conventionally by drilling straight holes in the core or cavity of the mould as shown in Figure 4.5. This method of making cooling channels is limited as it requires machining and only certain areas can be reached by a drill. In some cases, areas which need cooling may not be reached. Heat dissipation in this instance is not uniform in the cavity or core. Drilling holes traditionally may cause the following effects [40]:

- Uneven temperature levels on the cavity surface
- Uneven cooling resulting in internal stress which causes warpage
- Effective cooling of the polymer part cannot be achieved

- Drilling operation poses a risk of hitting the ejector holes or even breaking the drill inside the hole. This can make the mould unusable.

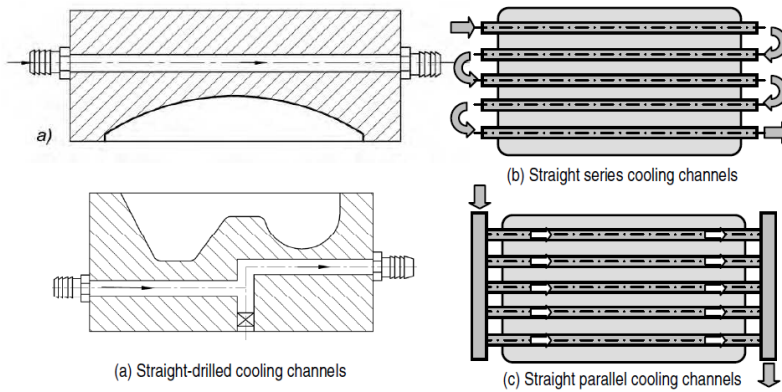


Figure 4.5: Conventional cooling channel [38]

These problems are solved nowadays by the use of AM which allows designers to design cooling channels of any possible shape. These channels are called conformal cooling channels because they are designed based on the contour of the product – see Figure 4.6. This means that the conformal cooling channels follow the shape of the product thereby improving the cooling efficiency [38].

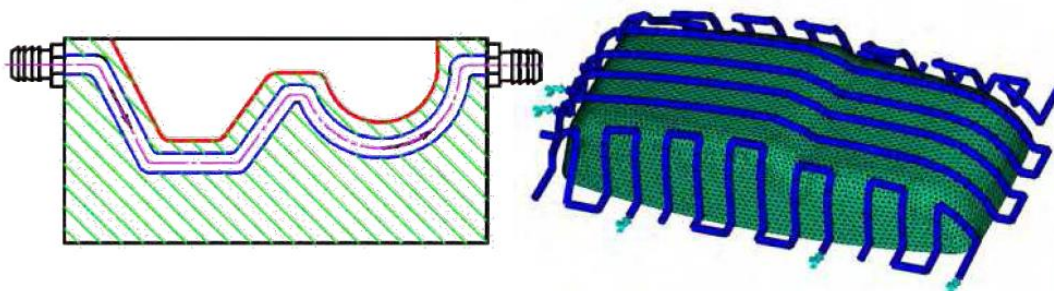


Figure 4.6: Conformal cooling channels [38]

With conformal cooling, the cooling rate difference is minimized throughout the entire product, ensuring a uniform heat transfer. To clearly understand cooling in the mould it is important to have background on how heat transfer occurs in the mould.

#### 4.3.1 Heat transfer in the mould

Heat transfer determines the rate of energy transfer between objects as a result of temperature differences [42]. There are three modes of heat transfer: conduction, convection and radiation [41]. Conduction is the transfer of heat through a material by direct contact; in IM this is between the polymer and the cavity, then between the cavity and the cooling channels [5]. Convection is the transfer of heat in a fluid as a result of its flow; this would be through the water pumped into the cooling channels [54]. Radiation is heat transfer to the environment [5].

In Figure 4.7 it can be seen that heat flows from a high temperature to a low temperature; this relationship is governed by Fourier's law [42].

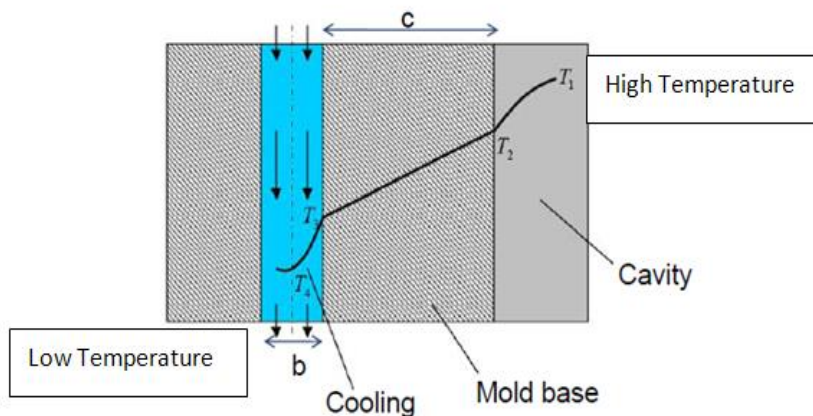


Figure 4.7: Heat transfer in the mould [41]

The following heat transfers are considered in IM:

- Heat removed from cavity to mould base
- Heat removed from mould base to cooling channels
- Mould surface radiation
- Mould surface convection
- Heat removed at ejection [41].

#### **4.3.2 Factors affecting cooling rate in the mould**

##### **(a) Polymer part design: Part thickness**

The polymer part affects the cooling rate by its thickness; a thicker part requires a longer cooling time [31].

##### **(b) Mould Material**

A mould material with a high thermal conductivity will transfer heat faster [43]. Alumide<sup>®</sup>, which is the focus of this study, has a low thermal conductivity of 0.5-0.8 W/m; making the material poor in heat transfer.

##### **(c) Lay-out of the cooling channels**

These factors will result in faster heat transfer [31]:

- A shorter distance from the cooling channel to the cavity
- A bigger diameter of the cooling channel
- A broad area covered by the cooling channels

##### **(d) Coolant Flow**

Turbulent flow is preferred in order to remove heat, as it transfers heat efficiently [38]. Uniform cooling channels ensures that the coolant maintains turbulence throughout the entire length of the channel [38]. When the Reynolds number for a given pipe is less than

2100, the flow is regular and is called laminar flow. When the Reynolds number is above 2100, the flow is called turbulent flow [42]. In this instance the flow is chaotic and irregular. From the formula in E.1 it can be observed that to achieve turbulent flow the velocity of the water has to increase or the diameter of the cooling channel has to be increased. The Reynolds number is given by:

$$\text{Re} = \frac{\rho v D}{\mu} \quad (1)$$

Where:

$\rho$  - the density of the fluid (kg/m<sup>3</sup>)

$v$  - velocity of the fluid through the pipe (m/s)

$D$  - diameter of the pipe or the diameter of the cooling channel

$\mu$  - the viscosity of the fluid (Pa.s)

### **(e) Coolant properties**

Coolant with lower viscosity, higher thermal capacity and lower temperature would provide a better cooling effect and shorter cooling time [44].

### **(f) Polymer material**

Polymers with high thermal diffusivity have an excellent heat transfer effect [45]. Appendix A shows Table 1 highlighting the thermal diffusivity of polymer materials and mould bases, and this gives an indication of materials that will provide good heat transfer. The thermal diffusivity  $\alpha$  is given by the following relationship [45]:

$$\alpha = \frac{k}{\rho C_p} \quad (2)$$

Where:

$k$  - the thermal conductivity (W/(m.K))

$\rho$  - the density of the polymer (kg/m<sup>3</sup>)

$C_p$  - the specific heat capacity

It can also be noted from the formula that materials with higher thermal conductivity will have higher thermal diffusivity.

#### **4.4 CHAPTER SUMMARY**

PIM is explained as a process which is complex as it has to meet all the functions to produce a successful polymer product. However, there are numerous benefits of using PIM as it delivers a high production rate and moulded products can be used as final products. Through the stages of the IM cycle, cooling is one of the critical phases as it occupies 70% to 80% of the cycle time. Furthermore, it will impact on the product quality if proper cooling channel design is implemented. Conventional cooling channels do not provide a uniform cooling effect as some areas of the cavity cannot be reached by conventional drilling operations. However, a uniform cooling effect is achieved by using conformal cooling channels as there is no limit to the design using AM technology.

Heat transfer in a mould is affected by various factors such as polymer part thickness, mould material, cooling channel design, coolant flow, coolant properties and the polymer material used in producing the part.

## CHAPTER 5: GENERAL OVERVIEW OF ALUMIDE®

### 5.1 INTRODUCTION

Alumide® is an aluminium-filled nylon material developed by EOS GmbH. Parts produced with Alumide® material through AM have a metallic look with high dimensional accuracy [47]. The laser sintered material can be ground, polished, tapped and machined by milling, turning, drilling or reaming [48]. There is less wear on the tools during machining of Alumide® compared to metals [48].

### 5.2 APPLICATIONS OF ALUMIDE®

Alumide® is typically used for manufacturing of rigid prototypes used in the automotive industry to perform tests on components [49]. In some instances Alumide® is also used as the end product [47]. It is used for the manufacturing of jigs as well as moulds for IM of small production runs, as shown in Figure 5.1 [49].



*Figure 5.1: Alumide® material as a direct tool for rubber injection moulding [47]*

### 5.3 PROCESSING OF ALUMIDE®

Alumide® is suitable for AM processing on the following EOSINT P systems [50]:

- P700 with or without conveyor system
- P380
- P360 with upgrade S & P
- P350/2 + upgrade 99 + upgrade S & P

Mechanical exposure parameters or surface exposure parameters may be used during processing of Alumide® through LS. Mechanical exposure parameters provide optimal mechanical part properties at slow exposure speeds [50]. In setting surface exposure parameters, there is a compromise between quicker layer times and the mechanical properties of the part. In this instance there will be minor reduction in mechanical characteristics [50].

The recommended layer thickness is 0.15 mm in the AM process and it is recommended that only new powder be used in order to get quality parts [50]. Furthermore the use of new powder will ensure consistency in the quality of produced parts, making them comparable.

### 5.4 PROPERTIES OF ALUMIDE®

The general properties of Alumide® are summarized in Table 5.1.

Table 5.1: General powder properties of Alumide® [50]

Property	Amount	Used standard or method
Average particle size (µm)	60	Laser diffraction
Bulk density (g/cm <sup>3</sup> )	0.64 ± 0.04	DIN 53466
Laser sintered density of Alumide® using mechanical exposure. (g/cm <sup>3</sup> )	1.36 ± 0.05	EOS Method

The thermal properties of Alumide® laser sintered parts are summarized in Table 5.2.

Table 5.2: Thermal properties of Alumide® [50]

Property	Amount	Used standard or method
Melting point (°C)	172-180	DIN 53736
Heat distortion temperature (°C)	177.1	ASTMD 648 (0.45 MPa)
Vicat softening temperature B/50 (°C)	169	DIN EN ISO 306
Thermal conductivity at 170°C (W/(mK))	0.5-0.8	Heated wire

The EOS specification document for Alumide® does not mention the specific heat capacity ( $C_p$ ) of that material. Hence the tests to determine the heat capacity of Alumide® were conducted at the Council for Scientific and Industrial Research (CSIR) laboratories. Alumide® was heated at a rate of 10°C/min from 30 to 120°C. The results the results are as shown in Table 5.3.

Table 5.3: Specific heat capacity of Alumide® tested by CSIR

Temperature (°C)	Specific heat capacity J/(g.°C)
60	0.5191
80	0.7521
100	0.9102

From the data in Table 5.2 it can be seen that Alumide® melts at around 172°C-180°C which is lower than most polymer IM materials for example, ABS melts at around 200°C -270°C, Polypropelene melts at around 250°C-270°C and Nylon 6 melts at around 230°C-260°C. These melting temperatures pose a risk of damaging the Alumide® mould if cooling is not efficient should the material be used to produce IM moulds.

Thermal conductivity is another important property in heat transfer, compared to the traditional tooling material (steel), Alumide® has a low thermal conductivity. Mechanical

properties of Alumide® processed on an EOS P380 machine for mechanical exposure and surface exposure parameters are shown in Tables 5.4 and 5.5 respectively.

Table 5.4: Mechanical properties of Alumide® in P380 for mechanical exposure parameters [50]

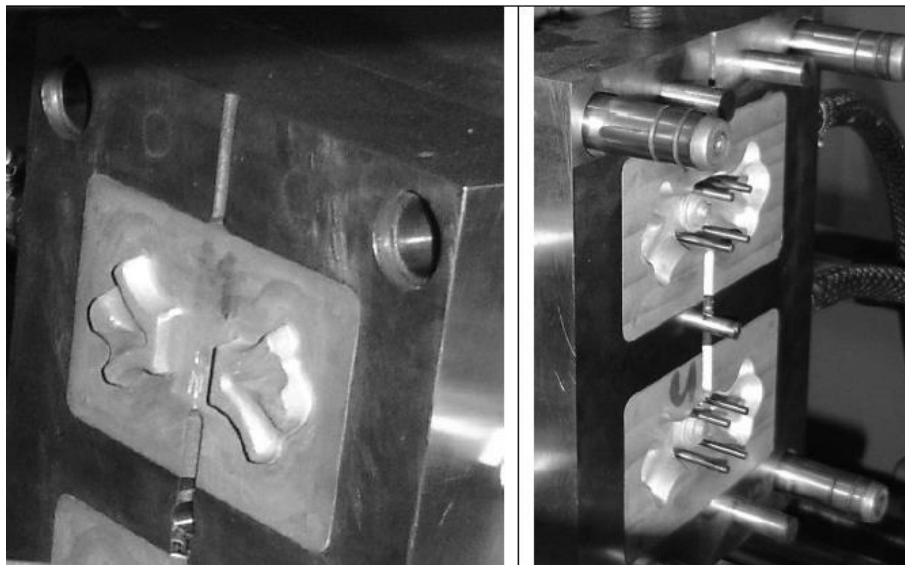
Property	Amount	Standard used
Tensile modulus of elasticity (N/mm <sup>2</sup> )	3800 ± 150	DIN EN ISO 527
Tensile strength (N/mm <sup>2</sup> )	46 ± 3	DIN EN ISO 527
Elongation at tear (%)	4 ± 0.5	DIN EN ISO 527
Bending modulus of elasticity (N/mm <sup>2</sup> )	2900 ± 200	DIN EN ISO 178
Bending strength (N/mm <sup>2</sup> )	71 ± 1.5	DIN EN ISO 178
Charpy impact strength (KJ/m <sup>2</sup> )	29 ± 2	DIN EN ISO 179
Charpy notch impact strength (KJ/m <sup>2</sup> )	4.6 ± 0.3	DIN EN ISO 179
Shore D hardness	76 ± 2	DIN 53505

Table 5.5: Mechanical properties of Alumide® in P380 for surface exposure parameters [50]

Property	Amount	Standard used
Tensile modulus of elasticity (N/mm <sup>2</sup> )	3600 ± 150	DIN EN ISO 527
Tensile strength (N/mm <sup>2</sup> )	45 ± 3	DIN EN ISO 527
Elongation at tear (%)	3 ± 0.5	DIN EN ISO 527
Bending modulus of elasticity (N/mm <sup>2</sup> )	2800 ± 130	DIN EN ISO 178
Bending strength (N/mm <sup>2</sup> )	70 ± 1.5	DIN EN ISO 178
Charpy impact strength (KJ/m <sup>2</sup> )	29 ± 2	DIN EN ISO 179
Charpy notch impact strength (KJ/m <sup>2</sup> )	4.6 ± 0.3	DIN EN ISO 179
Shore D hardness	76 ± 2	DIN 53505

## 5.5 ALUMIDE® IN TOOLING OF POLYMER INJECTION MOULDING

According to the study conducted by Booyesen et.al. (2006), the viability of using Alumide® as material for producing inserts for IM was shown [6]. Alumide® inserts as shown in Figure 5.2 were manufactured and a production run of 1000 shots were performed without any visible mould degradation [6].

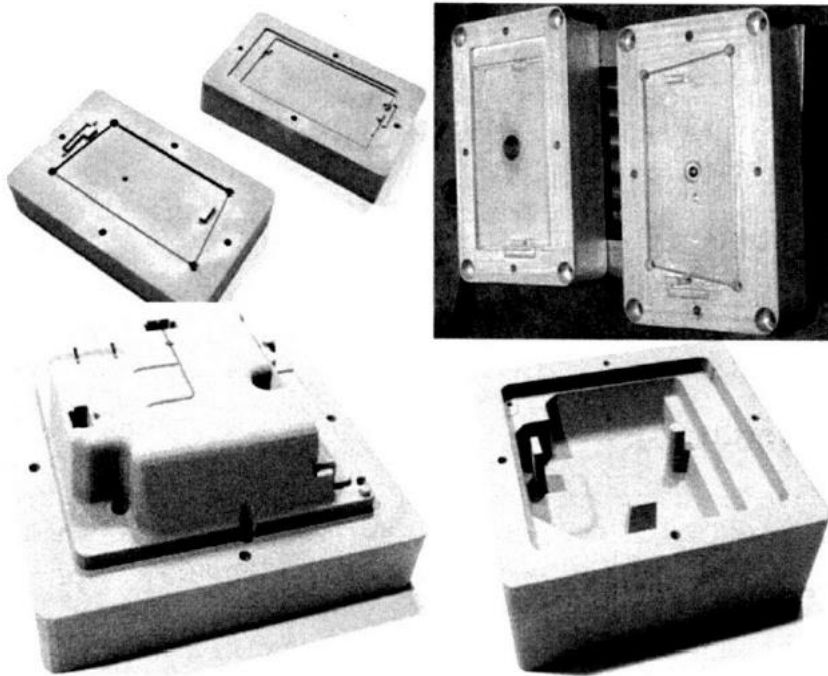


*Figure 5.2: Alumide® inserts in an IM tool [6]*

IM was performed at a temperature of 205°C. The only cooling performed on the moulds was by blowing compressed air onto the faces of the opened mould-halves after ejection of the part [6]. Air cooling was reduced from 60 seconds to 30 seconds and still the parts were moulded without any difficulties. Moulding parts without any cooling resulted in parts adhering to the mould-halves after only nine shots, clearly demonstrating the importance of cooling. To evenly cool the mould surfaces as well as to effectively cool deep thin slots in cores may prove to be difficult using the air cooling technique.

Further proof of the Alumide® IM tooling concept came from a case study performed for Technimark, one of the CUT's industry partners. CUT was approached with a request for IM moulds, where development time and available funding were very limited. Since only a

limited IM production run was required, CUT's advice was to develop mould inserts manufactured in Alumide®. The moulds were developed without any internal cooling channel, Figure 5.3 shows Alumide® tools manufactured.



*Figure 5.3: Mould tools manufactured in Alumide® [6]*

Manufacturing time for two sets of tools was one week. The cost was R23000 in comparison to an estimated R90000 if conventional methods of manufacturing were used [51]. Acrylonitrile Butadiene Styrene (ABS), a flame-retardant material was used to produce the products. Two hundred and thirty samples were produced with the tools, with no visible damage to the moulds. The case studies paved the way for this research to explore cooling in Alumide® moulds. To increase the performance of the IM tool, it is important to have a tool which performs well in all stages of the IM cycle, cooling being one of the critical phases as it influences the production time and part quality.

## **5.6 BENEFITS OF ALUMIDE® IN POLYMER INJECTION MOULDING**

Alumide® inserts can be built much bigger in size due to the available building envelope compared to DMLS inserts, and this gives an added advantage of building bigger cores and cavities. The cost of Alumide® material is four times cheaper than that of DMLS material [55]. The manufacturing time of Alumide® inserts is also quicker compared with DMLS inserts: this advantage improves the cost effectiveness of producing the Alumide® inserts. Machining of Alumide® laser sintered parts is easy due to the cut-breaking effect of the aluminium filling. There will be less wear on the tool used for machining Alumide® laser sintered parts. Like DMLS tooling inserts, Alumide® inserts can also incorporate conformal cooling channels.

## **5.7 CHAPTER SUMMARY**

This chapter provided background on Alumide® which is the tooling material being investigated in this research. A list of Alumide® properties were tabled and discussed as some of these properties are relevant to the study in influencing the cooling analysis of the Alumide® moulds. Furthermore, this chapter has also presented previous IM cases where Alumide® was the tooling material. These cases have shown promising results with Alumide® as a tooling material: however, there were no cooling channels provided in the moulds which in turn caused problems. The cost and time benefits of Alumide® tools proved to be superior when compared with the conventional methods.

## **CHAPTER 6: PRELIMINARY EXPERIMENTS**

### **6.1 INTRODUCTION**

Alumide<sup>®</sup> is a unique tooling material for IM as opposed to DMLS materials. This statement is made simply because there have been very few injection moulds developed using Alumide<sup>®</sup>. Given this uniqueness, it is important to understand the post processes that needs to be performed on Alumide<sup>®</sup> inserts. In this part of the research study, powder removal was investigated on the cooling channels of Alumide<sup>®</sup> inserts. The other area investigated is the safe wall thickness between the cavity/core and the cooling channels. It is equally important to have an IM tool which performs well with no physical damage because of blow holes or leaks.

### **6.2 INVESTIGATION INTO POWDER REMOVAL FROM STRAIGHT CHANNELS AND CONFORMAL COOLING CHANNELS**

A powder removal test was performed in order to evaluate the the minimum cooling channel diameter from which the unsintered Alumide<sup>®</sup> can be successfully removed from complex channels as well as straight channels.

#### **6.2.1 Powder removal on straight cooling channels**

A U-shaped geometry was used to test the removal of powder on straight cooling channels with bends. Figures 6.1 and 6.2 show drawings of U-shaped channels of 2 mm; 4 mm; 6 mm; 8 mm; 10 mm and 12 mm diameters. A 6 mm radius was used on the turns of the channel inside the test geometry. Figure 6.3 shows a picture of a laser sintered product.

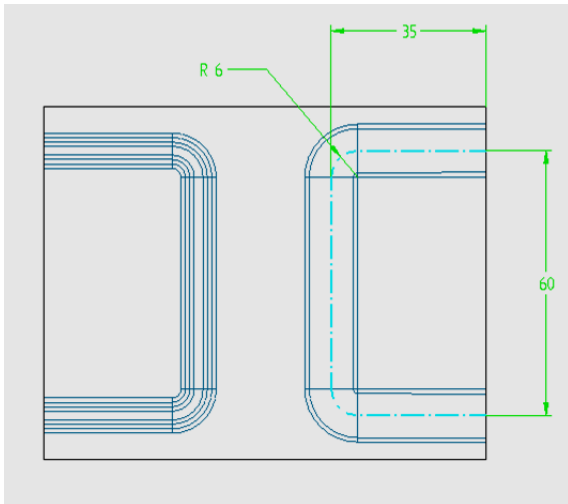


Figure 6.1: Test sample CAD in top view for U-shaped channels

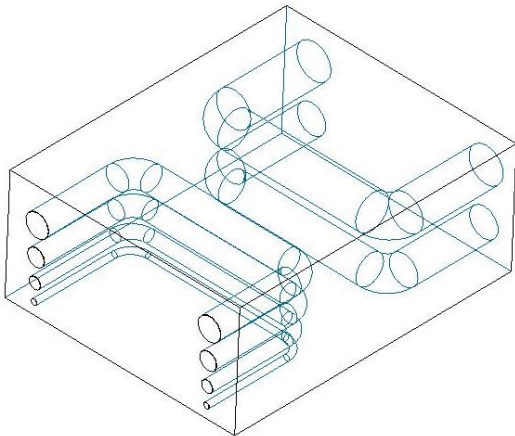


Figure 6.2: Test sample CAD in isometric view for U-shaped channels

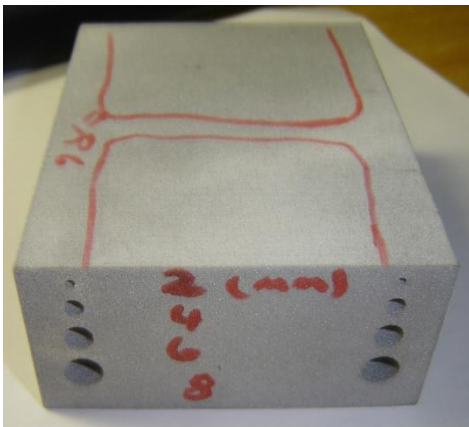


Figure 6.3: Alumide<sup>®</sup> test sample for U-shaped channels

Only one method of powder removal was used. A thin wire of 1 mm thickness was used to loosen the powder and compressed air of 0.6 MPa was used to blow the loose powder out of the channels. Channels of 4 mm; 6mm; 8 mm; 10 mm and 12 mm diameters were cleared without any problem. A channel with a 2 mm diameter could not be cleared using this method.

### 6.2.2 Conformal cooling channels

A spiral geometry was used to test powder removal on conformal cooling channels. Channels with diameters of different sizes were used, namely 4 mm; 6 mm and 8 mm. The spirals had a pitch of 11.4 mm, five turns and a nominal diameter of 33.13 mm. Figures 6.4 and 6.5 show schematic drawings of spiral channels developed for testing. Figure 6.6 shows the actual product after LS.

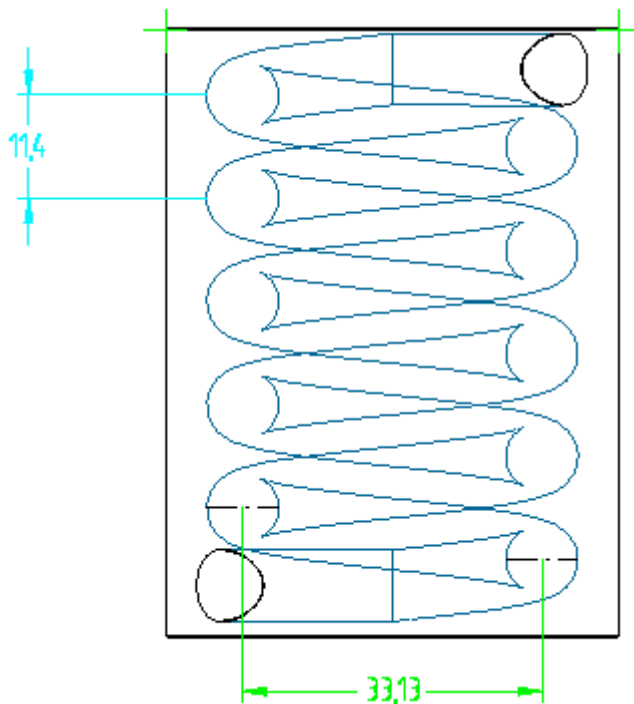
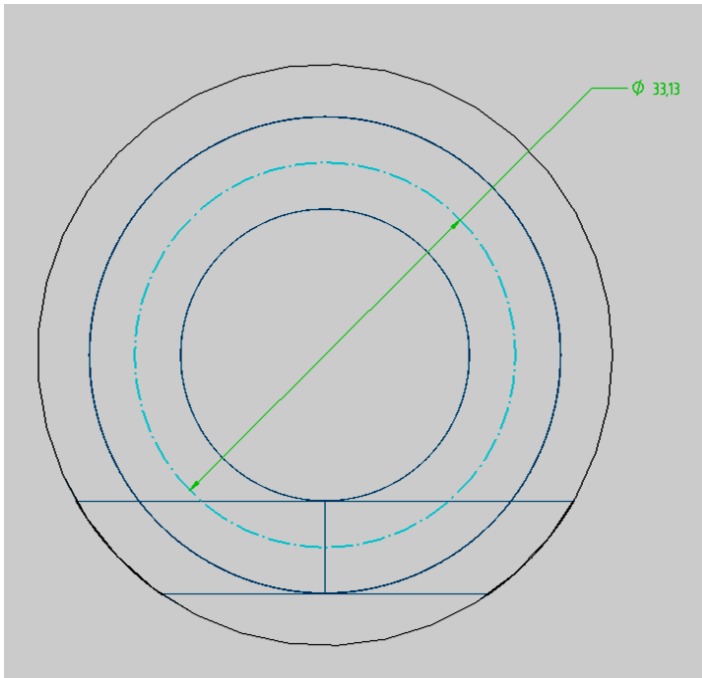


Figure 6.4: CAD in front view for spiral channels test samples



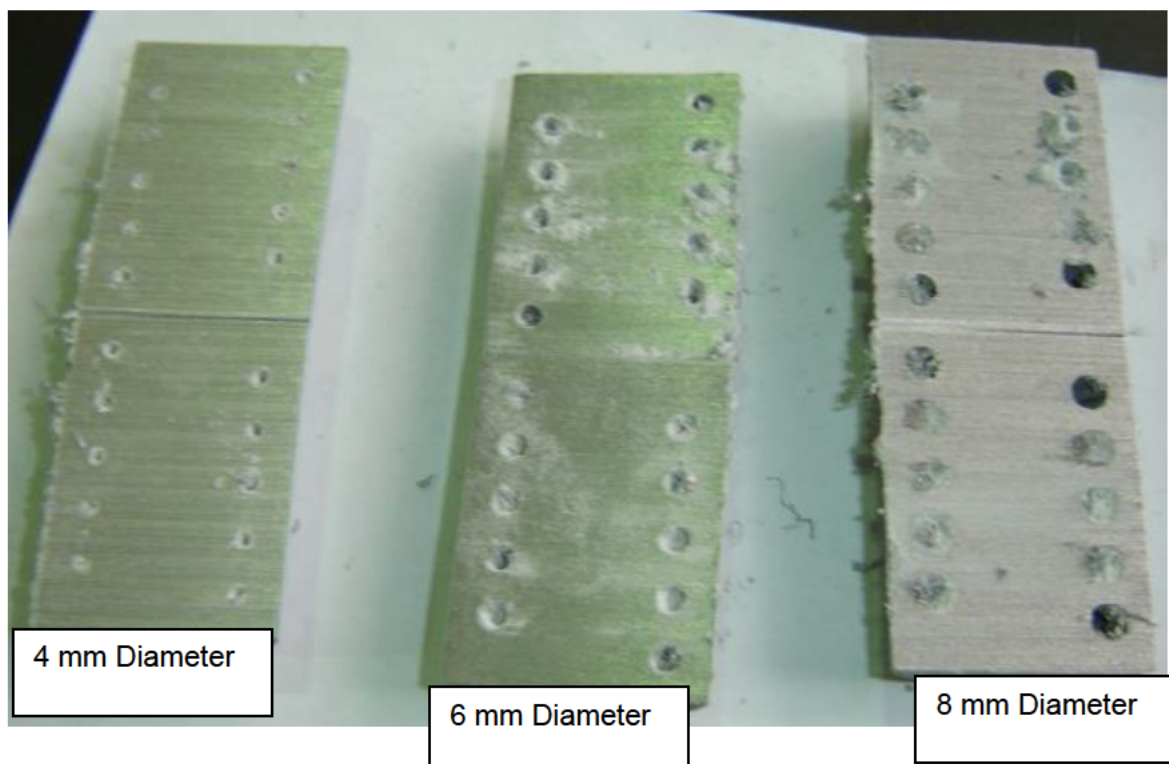
*Figure 6.5: CAD in top view for spiral channels test samples*



*Figure 6.6: Alumide® test samples for spiral channels*

The same method of powder removal was followed for these samples. It was a challenge to get a thin wire through the entire channels. A wire could only reach the first turn of the spiral. Shaking the test samples did help in removing the powder, but it was not enough.

There were degrees of difficulty experienced in removing the powder from the samples of different diameters. The smaller the diameter, the more difficult it became to remove the powder. About 80% of the powder was removed from an 8 mm diameter cooling channel. About 30% and 50% of the powder was removed from the 4 mm and 6 mm diameter channels respectively. Figure 6.7 shows the actual sectional view of the laser sintered samples. From this it is clear to see the amount of powder left inside the channels.



*Figure 6.7: Spiral test samples cut in half*

### 6.2.3 Discussion on powder removal

Channels with smaller diameters are challenging in removing powder. Whenever possible they should be avoided. Conformal cooling channels are the most effective, yet they can be challenging in removing powder. In this investigation only one method was followed. Powder within the straight channels was removed within a time span of one hour, excluding the

2 mm diameter channel. As for the spiral cooling channels, more powder was removed from the 8 mm diameter cooling channel than 4 mm and 6 mm channels. The design can be changed by increasing the pitch of the spiral, and this will ease the removal of powder. It is also important to keep the loose powder as dry as possible to avoid powder from being trapped in the corners. Shallow curves also help in easing powder removal and sharp curves should be avoided. Access holes to the channels can also be included in the design and used to remove excess powder. These holes can then be plugged later. If the spirals have many turns, a hole can be provided after each turn to ease the removal of powder.

The area of conformal cooling design needs to compliment the challenge of powder removal. Designers need to work around this challenge without compromising the advantage of conformal cooling channels.

### **6.3 INVESTIGATION OF A SAFE WALL THICKNESS BETWEEN A MOULD CAVITY AND COOLING CHANNELS FOR ALUMIDE® INSERTS PRODUCED BY LASER SINTERING**

#### **6.3.1 Purpose of investigation**

The aim of this investigation was to identify safe wall thicknesses between cooling channels and the mould cavity which is suitable to resist leakage of water in Alumide® inserts. This will give guidelines in the design of cooling channels. It is important that cooling channels are free of leaks to give effective cooling and result in quality products. For that purpose, the following setup was arranged as shown in Figure 6.8.

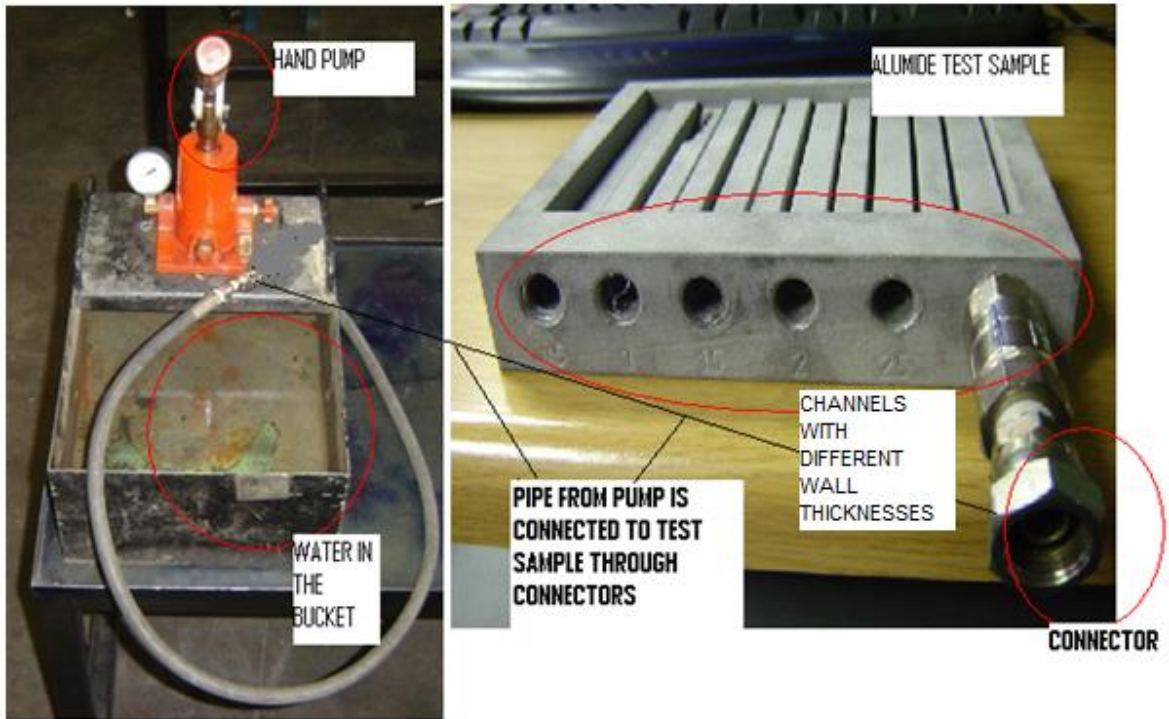


Figure 6.8: Experimental setup for investigating a safe wall thickness for water flowing through channels

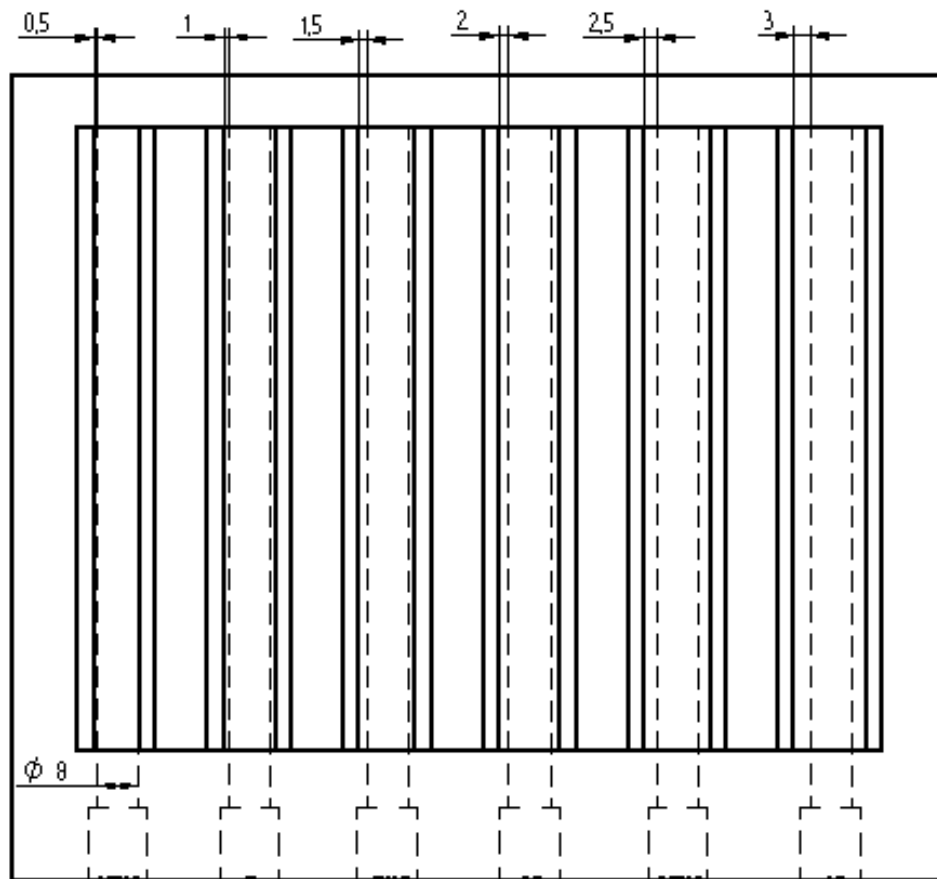


Figure 6.9: CAD showing different wall thicknesses

### 6.3.2 Experimental procedure

- (a) A test piece with six straight channels was designed as shown in Figure 6.9. The test piece had six channels of 8 mm diameter with a length of 145 mm. Around each channel there was a wall thickness provided and the thicknesses were designed to be 0.5 mm; 1 mm; 1.5 mm; 2 mm; 2.5 mm and 3 mm. The thicknesses are indicated in Figure 6.9. Each channel was designed such that a thread could be cut on its open end to allow a water connector to be fitted. The other ends of the channels were designed to be closed.
- (b) The test piece was then manufactured through the LS process using Alumide<sup>®</sup> powder as shown in Figure 6.8.

- (c) After LS, the sample was cleaned and freed of all loose powder.
- (d) The open end of the test piece was then threaded for fitting water connectors.
- (e) Tests were performed by applying pressure to water in each channel. A hand pump shown in Figure 6.8 was used for this purpose.
- (f) The aim was to pressurize water until the walls around the channels cracked or burst. This would give an indication of the highest pressure that a specific wall thickness could handle before it would fail.
- (g) Results were recorded for each test.

### 6.3.3 Results

Highest operating pressure achieved by the pump = 6000 KPa

Table 6.1: Results for wall thickness tests

Wall Thickness (mm)	Pressure (KPa)	Observations
0.5	3000	Crack
1	6000	Crack
1.5	6000	Leaks
2	6000	No defects
2.5	6000	No defects
3	6000	No defects

### 6.3.4 Discussion of results

The highest pressure the pump could achieve was 6000 KPa. Wall thicknesses of 0.5 mm and 1 mm cracked at 3000 KPa and 6000 KPa respectively. A wall thickness of 1.5 mm leaked at a pressure of 6000 KPa. Table 6.1 shows that other thicknesses were resistant to the highest pressure achievable by the pump. The aim of pressurizing the channels till its

walls failed as described under point (f) in section 6.3.1 could not be attained due to the limitations of the pump.

Most cooling units of the IM machines would operate at pressures of 500 – 600 KPa compared to 3000 and 6000 KPa used in this experiment [67]. Cooling channels in IM are provided with an inlet and outlet connector, this also would reduce pressure in the system. In this experiment there were no outlets; therefore, the test sample was exposed to high pressure.

#### **6.4 CHAPTER SUMMARY**

Powder removal in the cooling channels of laser sintered Alumide® insert is a challenge as it is governed by size and design of the cooling channels. Powder from straight cooling channels which are on the same plane are easy to remove. The experiments proved that with 4 mm, 6 mm, 8 mm, 10 mm and 12 mm diameter channels, it was easy to clear the excess powder as opposed to a 2 mm diameter where the powder could not be cleared. Only one method of removing the powder was explored, namely a thin wire and compressed air.

Spiral channels were difficult to clear of powder. In channels with diameters of 4 mm and 6 mm, less powder was removed in comparison with the 8 mm diameter channels. The number of turns on the spiral and the pitch played a role in making this exercise difficult. The recommendation would then be to decrease the number of turns on the spiral and increase the diameter of the channel.

The cooling channels in IM are used to circulate water through the insert of the cavity or core, therefore it is important that the water flows in the channel and does not break through to the cavity. Tests were performed to check the safe wall thickness of Alumide® between cooling channels and cavities. The tests were exaggerated as there was no circulation on the test unit. This means that the walls were subjected to more pressure which will not be

the case if there is circulation. There were no defects observed in wall thicknesses of 2 mm and greater at a maximum of 6000 KPa.

## CHAPTER 7: CASE STUDY 1: FLAT POLYMER COMPONENT

### 7.1 INTRODUCTION

The focus of the study was to optimise cooling parameters for Alumide<sup>®</sup> inserts in IM of polymer parts. Case study 1 investigated the performance of Alumide<sup>®</sup> inserts in IM of a flat polymer component.

In order to cool Alumide<sup>®</sup> moulds sufficiently various factors are important such as proper design of cooling channels and proper moulding parameters. Alumide<sup>®</sup> has low thermal conductivity and therefore it must be cooled properly to achieve a successful product.

The experiment sought to address the following:

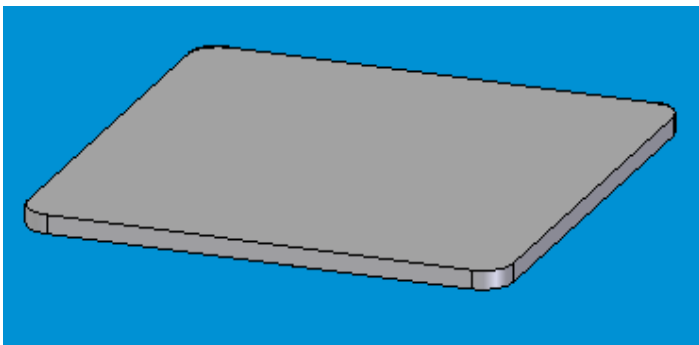
- Cooling channel design for Alumide<sup>®</sup> inserts
- Moulding parameters such as cooling time and coolant flow rate
- Mould temperature of Alumide<sup>®</sup> inserts

The experiments covered both simulations and field tests. Simulation is an important tool in analysing the design of cooling channels. Moldex3D software was used in Case 1 to analyse the cooling design. With the results achieved from simulations, a design of cooling channels can be adjusted to improve the efficiency of the cooling channels. The software also gives guidance on the moulding parameters or condition necessary for moulding the product. A comparison between simulation and field tests are important in this research because the simulation package is used to guide the design and moulding parameters.

## 7.2 CASE STUDY 1: INJECTION MOULD FOR A FLAT POLYMER COMPONENT

### 7.2.1 Introduction

Case 1 focused on a simple flat part with Figure 7.1 showing the component to be moulded. The objective was to investigate the best cooling strategies for Alumide® inserts on a flat component, focusing on the cooling channel design and the operating parameters during IM.



*Figure 7.1: CAD drawing of a flat component*

The component had dimensions of 80 mm x 80 mm x 3 mm with a radius of 3 mm on the edges. The component was moulded in high impact ABS.

## 7.3 DESIGN

### 7.3.1 Mould design

A mould was designed with two Alumide® inserts, one on the fixed half and one on the moving half of the IM machine. Cooling channels were provided on both halves of the mould and they were designed to cover as wide an area of the cavity as possible. The cooling channel layout was restricted by the provision of ejector pins and the sprue bush; as shown in Figures 7.2a and b. The cooling channels were of a simple form due to the simplicity of the product being moulded. A single cavity mould was investigated with sprue injection. The

insert with the cavity was fitted in the moving half to allow for ejection. The fixed half was fitted with a flat insert of Alumide® inside the machined pocket.

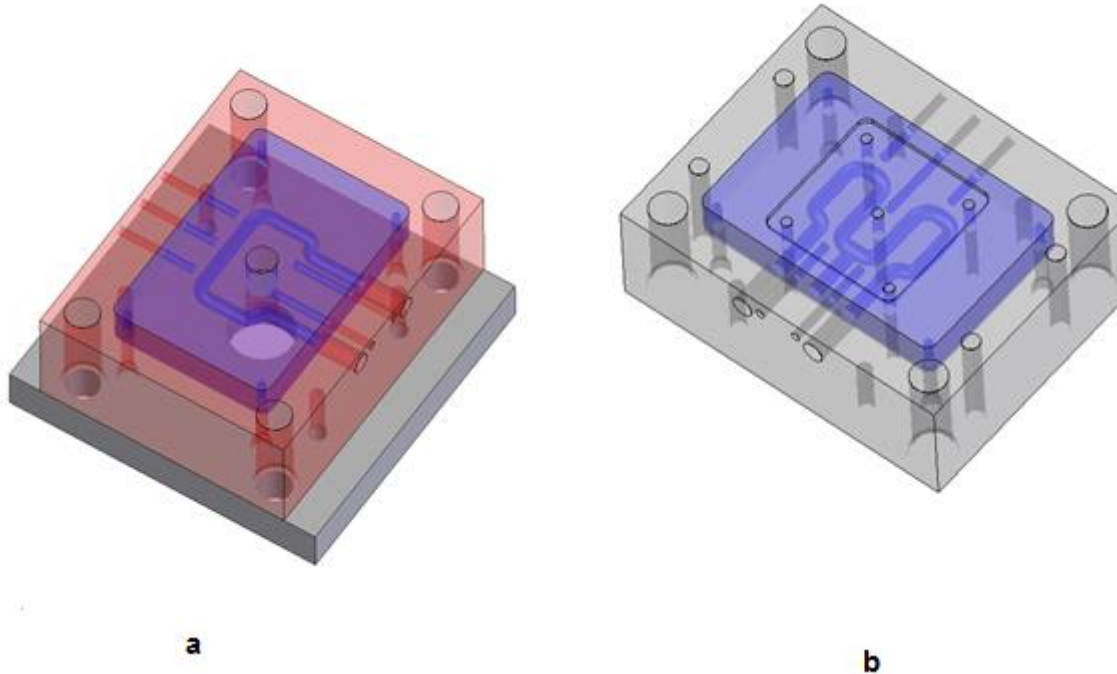


Figure 7.2: CAD of a fixed (a) and moving (b) mould half

### 7.3.2 Cooling channel layout

Only one type of cooling channel layout was used in this investigation, this was influenced by the size and shape of a part being investigated. Cooling channels with a round cross-section and a diameter of 8 mm was used. The reason for this selection is that it is easy to remove the unsintered powder as concluded from experimental work described in Chapter 6. Cooling channels were designed to be on one plane, 6 mm from the surface of the cavity. Care had to be taken not to design the cooling channels too close to the cavity to avoid the walls between the cavity and cooling channels to collapse due to high pressure during injection. Alumide® inserts are porous and it is important that leakages are avoided. The layout of the cooling channels in the moving half and fixed half are shown in Figures 7.3 and 7.4.

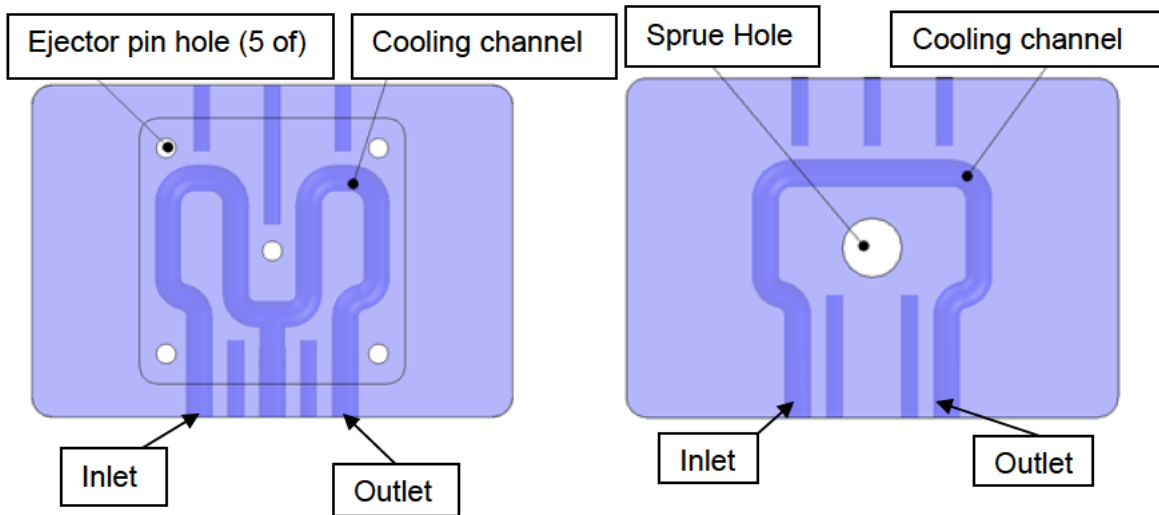


Figure 7.3: Cooling channel layout on the moving half      Figure 7.4: Cooling channel layout on the fixed half

## 7.4 SIMULATION

### 7.4.1 Preparation of simulation model

The model was first prepared in Rhino software to get the preferred mesh for the mould base and cooling channels as shown in Figure 7.5. A mesh is made up of one or more geometric elements. Meshing is a foundation for CAE activities, therefore good quality mesh is essential for accurate and reliable FEA results. A type of mesh called mixed boundary layer mesh was used with the surface mesh of the cavity set to 0.5 mm in size. In this study the mesh created in Rhino was simulated in Moldex3D version R12. Moldex3D is simulation software used to visualise and analyse the IM process in order to validate and optimise the mould design. A full simulation was run to obtain an analysis on melt temperature, mould temperature, injection pressure, clamping pressure and cooling.

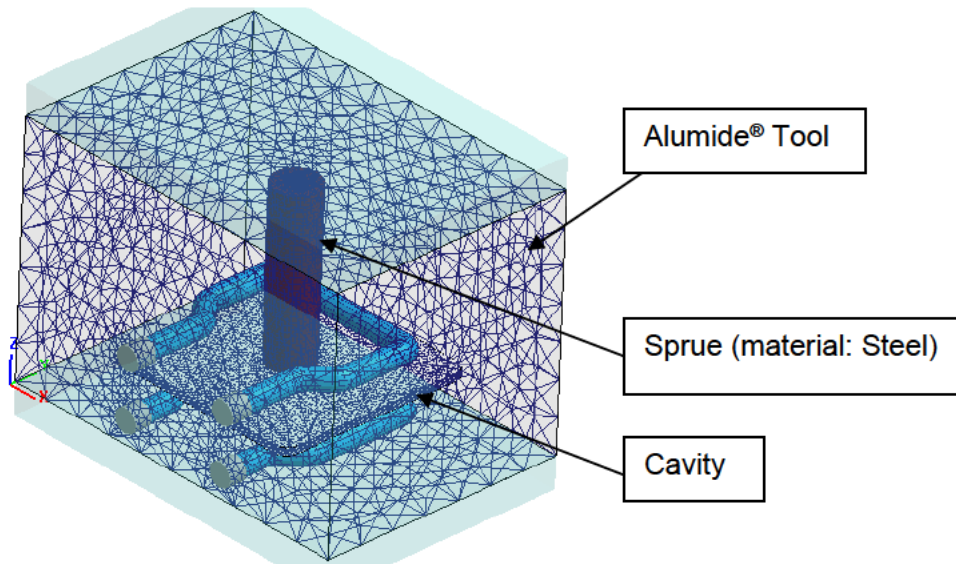


Figure 7.5: Mesh Model

The cavity of the mould was assigned as Alumide® and the sprue was assigned as steel. This configuration is important for the simulation because two tooling materials with different properties form the mould. Steel has a higher thermal conductivity than Alumide® which influences the simulation results compared to simulating only Alumide®.

The meshing also included eight sensor nodes which were used to measure temperature at specific positions in the mould as shown in Figure 7.6.

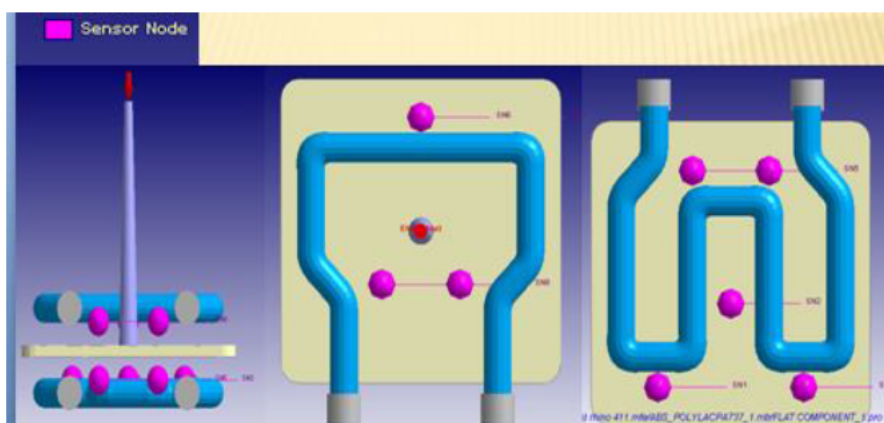


Figure 7.6: Sensor Nodes (SN) on the cavity

**(a) Simulation settings**

The settings were based on the following:

- Cooling channel dimension
- Cooling medium
- Coolant flow rate
- Melt temperature
- Filling time
- Cooling time
- Machine Mode

**(b) Cooling channels**

Two sets of cooling channels were simulated, one set on the moving half and other set on the fixed half. The dimensions of the cooling channel diameter was kept the same on both sets as well as the water flow rate as can be seen in Table 7.1. According to literature a Reynolds (Re) number greater than 2100 is ideal in order to achieve turbulent flow conditions [42]. A flow rate of 33 cm<sup>3</sup>/sec was enough to achieve turbulent flow for the given cooling channel design as can be seen in Table 7.1.

Table 7.1: Simulation of cooling channel settings in Moldex3D

<b>Channel Internal Diameter</b>	<b>Temperature (°C)</b>	<b>Water flow rate (cm<sup>3</sup>/sec)</b>	<b>Coolant</b>	<b>Cooling channel diameter (mm)</b>	<b>Reynolds number</b>
Channel 1	19	33	Water	8	5101.91
Channel 2	19	33	Water	8	5101.91

### (c) Cooling settings

Various parameters used during simulation are listed in Table 7.2.

Table 7.2: Cooling settings in Moldex3D

Parameters	Value	Unit
Mould Temperature	30	°C
Air Temperature	28	°C
Ejection Temperature	58	°C
Cooling Time	50	Seconds
Mould open time	15	Seconds

### (d) Simulation processing summary

Machine mode 1 was used during simulations; the mode makes it possible to input the machine specifications into Moldex3D. The software will then be simulating the exact machine to be used during field trials. Furthermore it can be seen from Table 7.3 that the cycle time to achieve a single product is 73.5 sec. This cycle time was satisfactory, keeping in mind that Alumide® moulds are used for short production runs.

Table 7.3: Simulation process summary in Moldex3D

Stroke/filling time (seconds)	3.5
Max Injection Pressure of machine (MPa)	225
Mould Temperature (°C)	30
Injection Volume (cm <sup>3</sup> )	20.5
Cycle Time (seconds)	73.5
Polymer Material	ABS POLYLAC PA737

Table 7.3 continues

Machine	Shine Well Machinery - SW90 - B
Melt Temperature (°C)	200

#### 7.4.2 Simulation results

##### (a) Filling results

A filling centre temperature of 209°C was achieved which is ideal for ABS in order to prevent short shot, as shown in Figure 7.7. A clamping force of 2.5 tons was the required force to clamp the mould, as shown in Figure 7.8. The shear stress level in the part was not high; therefore, the part produced will not experience warpage as shown in Figure 7.9. The part also had an evenly distributed shear stress. This outcome was good as it produced a part with dimensional stability.

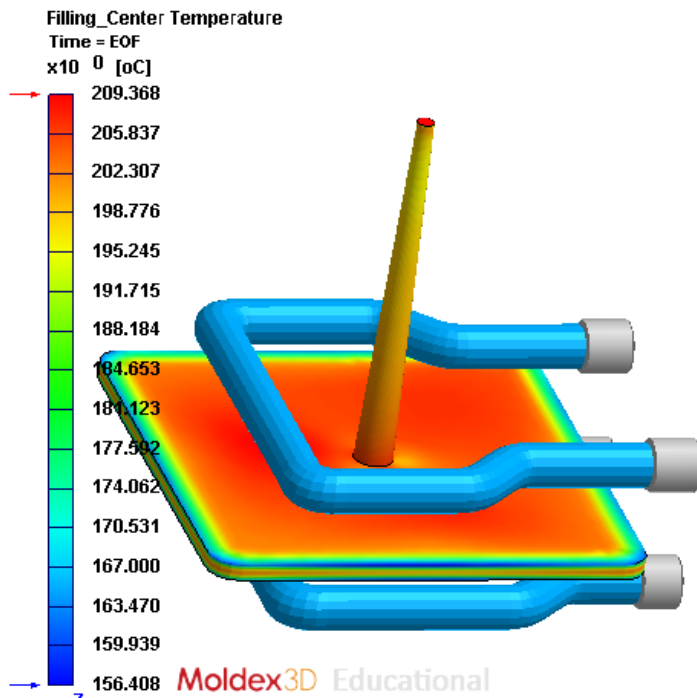


Figure 7.7: Filling centre temperature

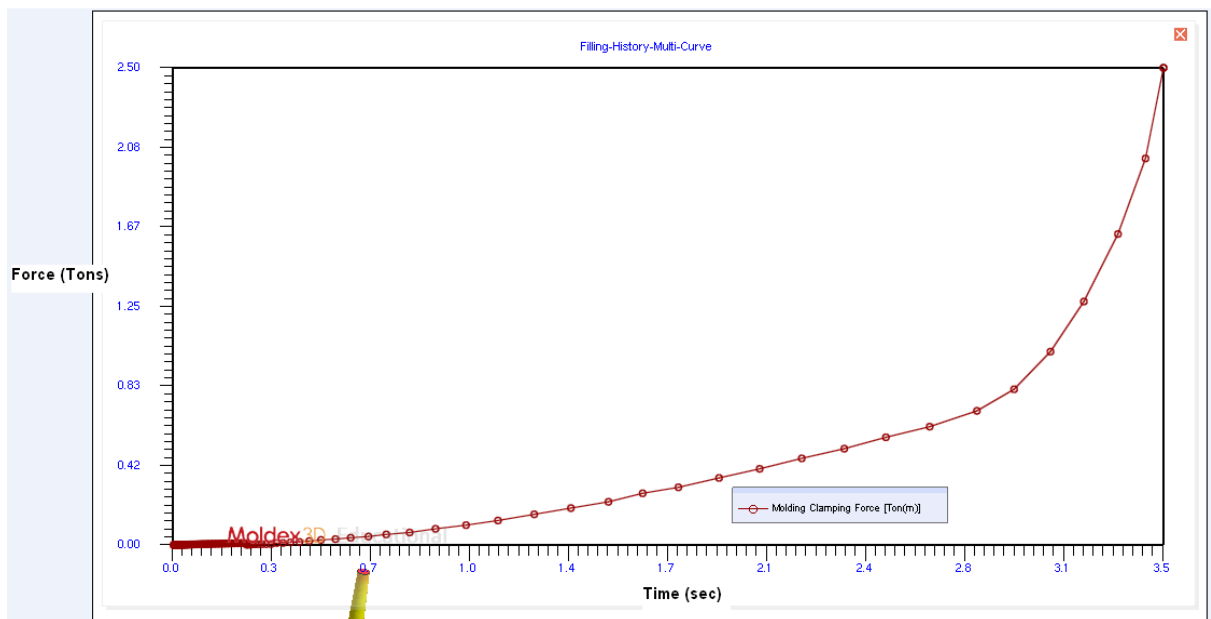


Figure 7.8: Graph representing clamping force (Force vs Time)

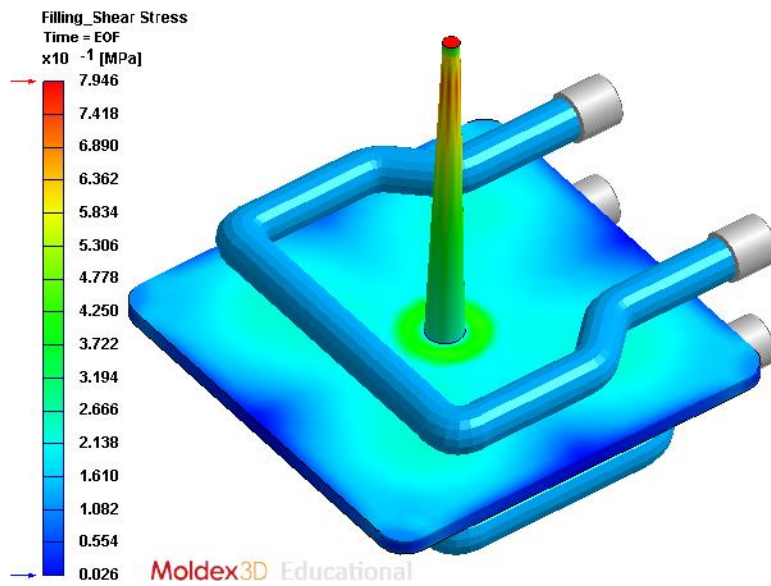


Figure 7.9: Filling shear stress

#### (b) Cooling results

The focus for this research was based on the effective cooling of Alumide®. The following factors were important to this investigation:

- Cooling channel efficiency
- Cooling time
- Temperature of the Sensor Nodes (SN)

#### (c) Cooling efficiency

A positive cooling efficiency was achieved in both cooling channels, and this means that heat was effectively conducted away from the surface of the cavity. The cooling channel in the moving half of the mould released 51% of the heat and the cooling channel in the fixed half released 44.4% of the heat as shown in Figure 7.10. This indicates the percentage of the heat withdrawn separately by each cooling channel from the total heat absorbed by the mould surface. The cooling channel in the moving half covers a length of 279.21 mm as opposed to a length of 209.23 mm covered by the cooling channel in the fixed half.

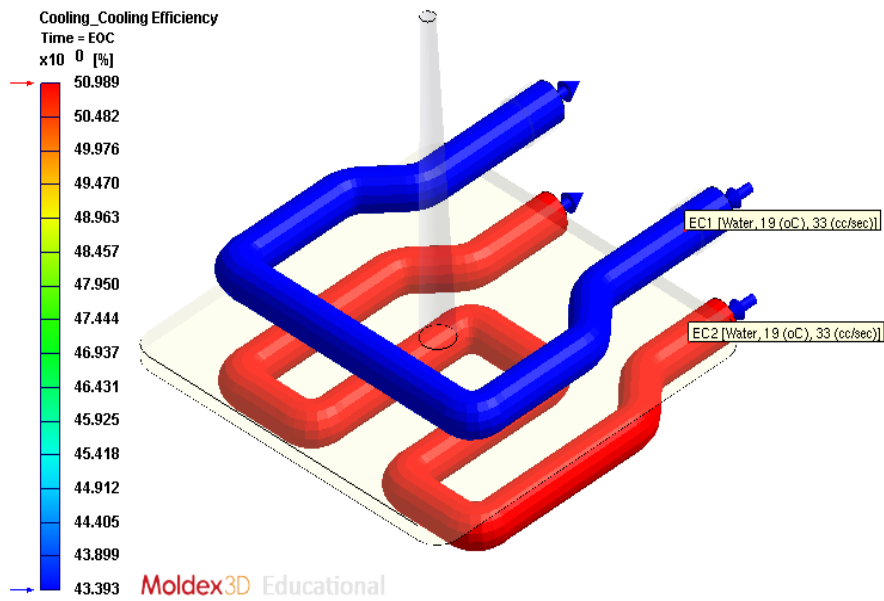


Figure 7.10: Cooling efficiencies of the cooling channels

(d) Cooling time

Figure 7.11 shows that 50 seconds cooling time would be enough to cool most of the part; however, there are some red spots which need longer cooling time. A cooling time of 50 seconds was used for the experiments.

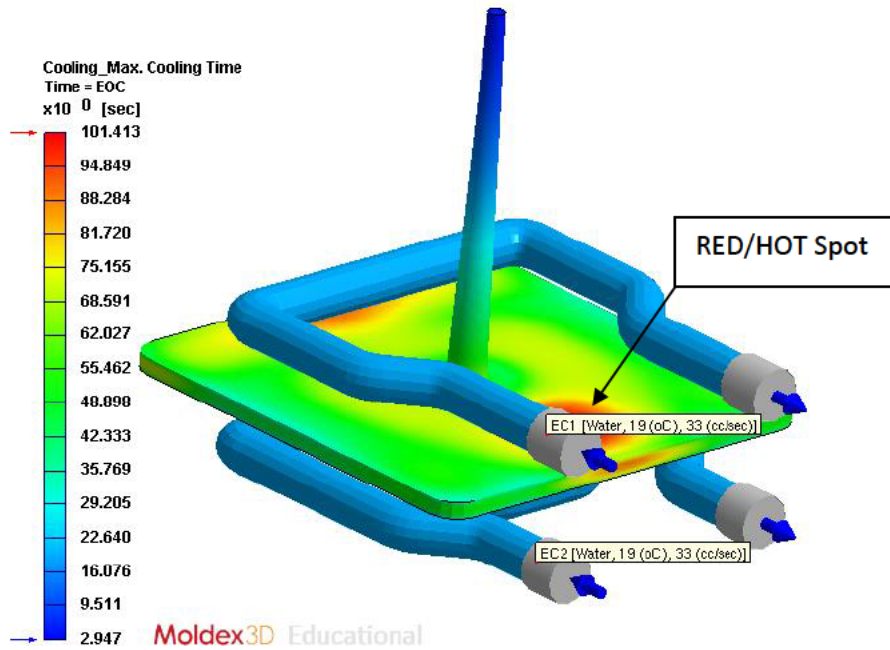


Figure 7.11: Maximum cooling time

(e) Temperature of the sensor nodes

Eight sensor nodes were positioned inside the moulds to measure temperature at specific points during the moulding cycle as shown in Figure 7.6. The sensor nodes were placed 3 mm from the surface of the cavity. Five sensor nodes were placed in the moving cavity and three were placed in the fixed cavity as shown in figures 7.12 and 7.13. Moldex3D gives results for the sensor nodes at a steady condition which means these are the results when the temperature in the moulding process has stabilised. Table 2 in Appendix D shows cooling multi-curve history for four cycles as captured in Moldex3D. These cycles were captured after 30 cycles.

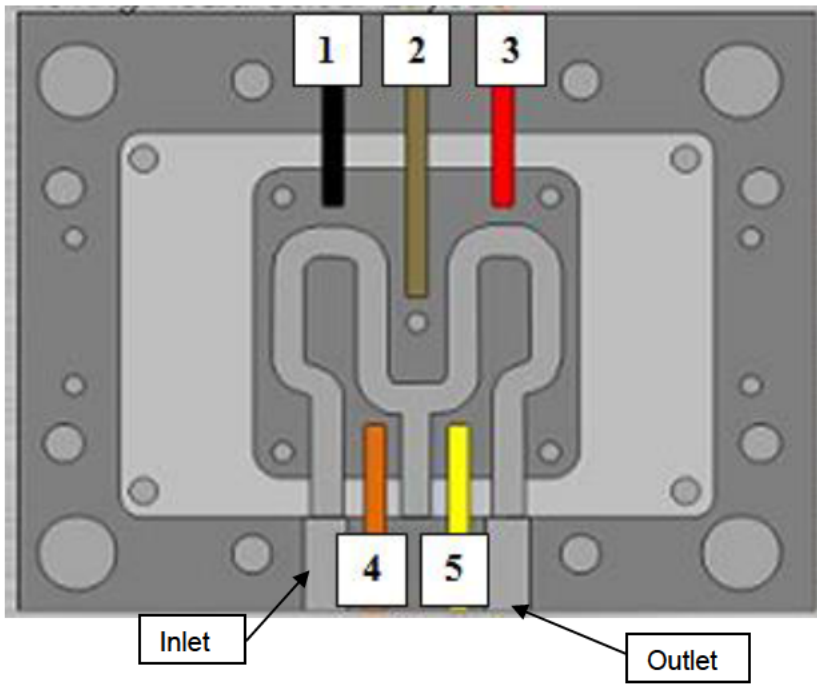


Figure 7.12: SN arrangement in the moving half

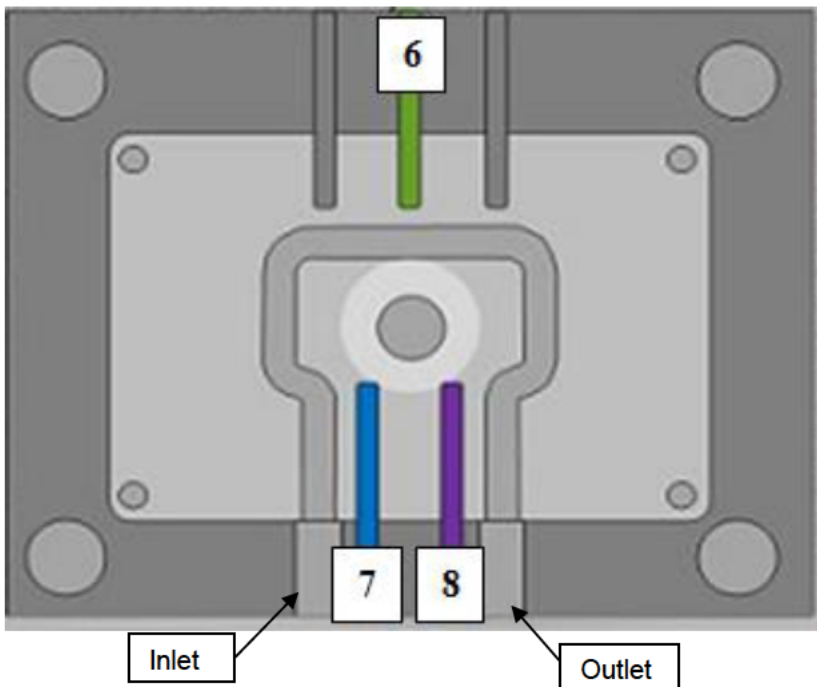


Figure 7.13: SN arrangement in the fixed half

### **7.4.3 Graphical representation of the simulation results on the sensor nodes/probes**

The graphs shown in Figures 7.14 to 7.21 represent realistic conditions during a moulding cycle. The temperature in the mould rose during the injection stage and dropped during the packing and cooling stages. The data was captured in Moldex3D from the 30<sup>th</sup> cycles. It can be observed that after 30 cycles the moulding temperature had reached a steady state as a uniform trend can be seen as shown in Figures 7.14 to 7.21. The average high temperatures of 56.7, 59, 52.9, 53.6, 54.4, 57.5, 66.3 and 67.8°C were recorded at SN 1, 2, 3, 4, 5, 6, 7 and 8 respectively. The average low temperatures of 43.6, 45, 38.2, 39.9, 40.3, 44.8, 55.3 and 56.1°C were recorded at SN 1, 2, 3, 4, 5, 6, 7 and 8 respectively. The average high temperatures are achieved during filling stage whereas average low temperatures are achieved at the end of cooling. The average low temperatures were calculated by using the four points in the low limit whereas the average high temperatures were calculated using the four points in the high limit.

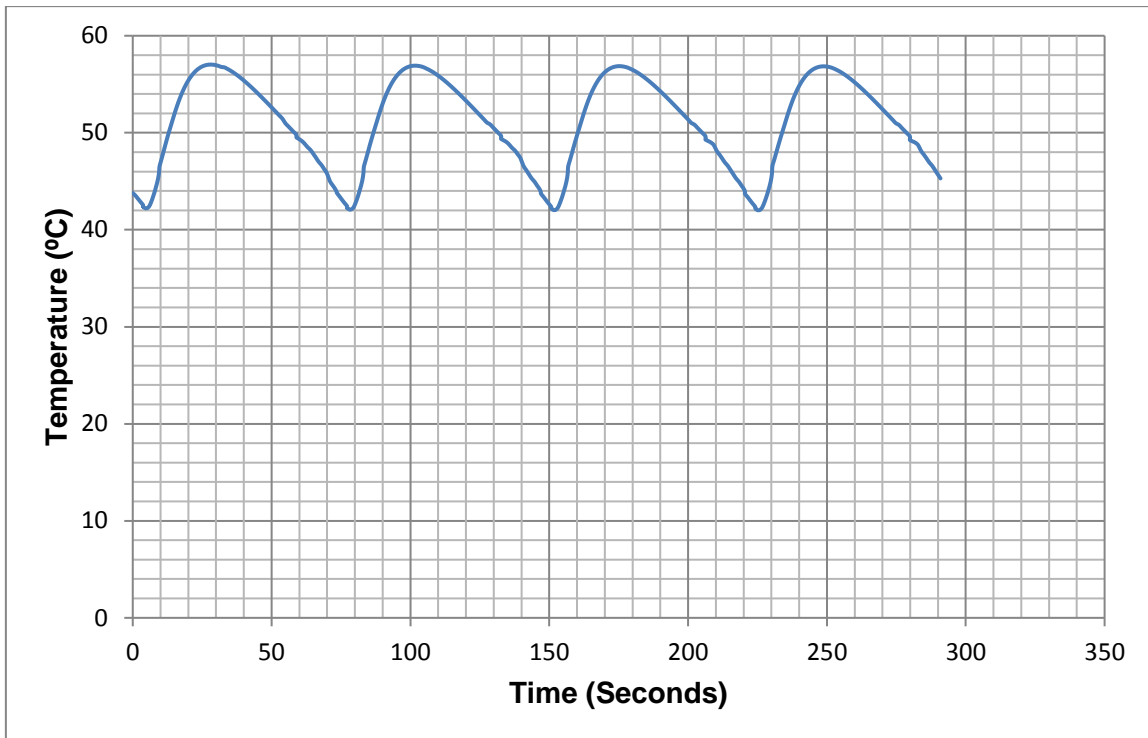


Figure 7.14: SN 1 graph, temperature vs time (captured after 30 cycles)

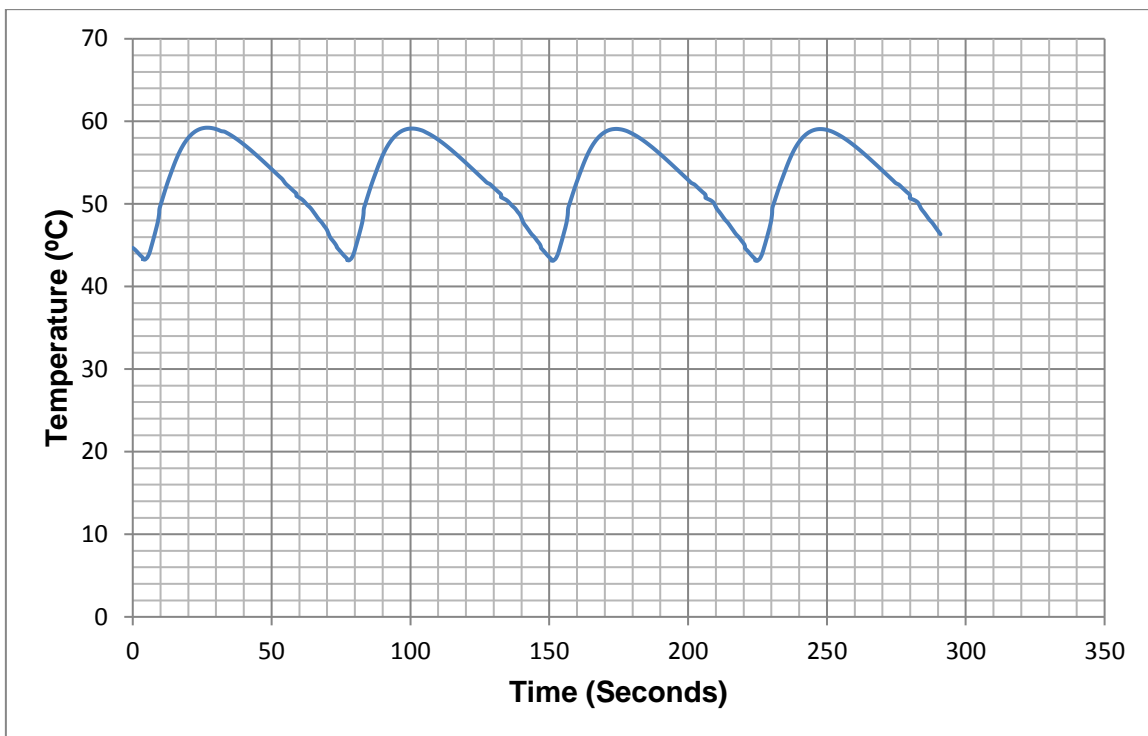


Figure 7.15: SN 2 graph, temperature vs time (captured after 30 cycles)

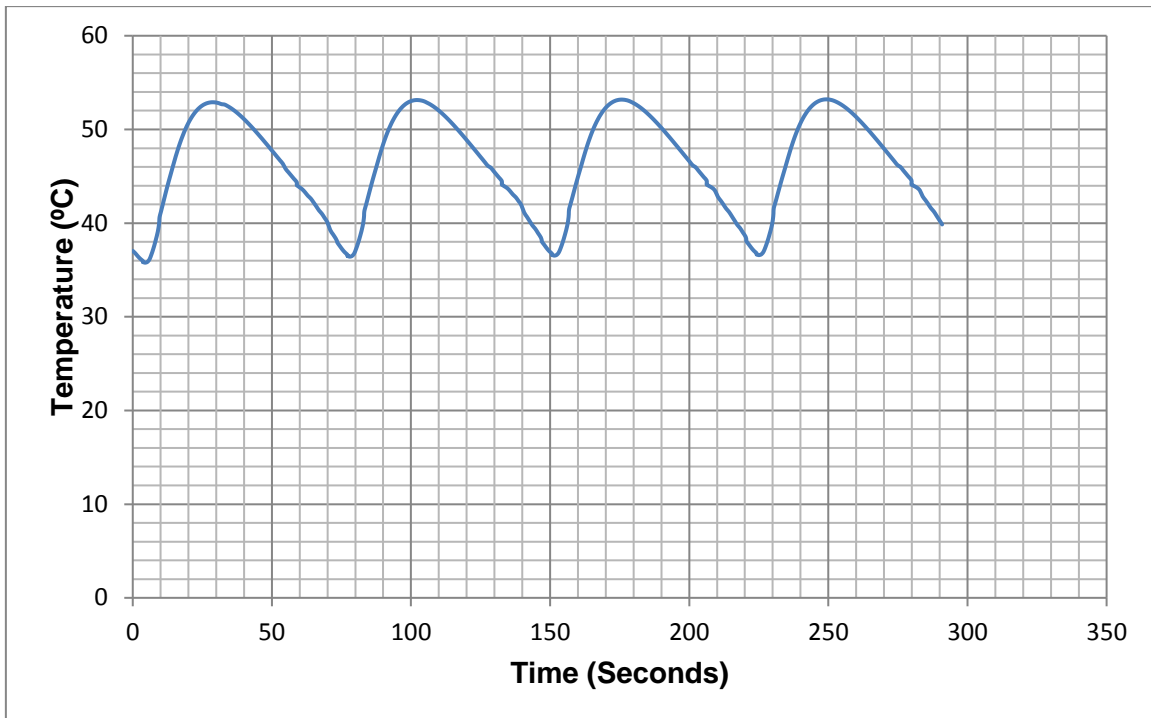


Figure 7.16: SN 3 graph, temperature vs time (captured after 30 cycles)

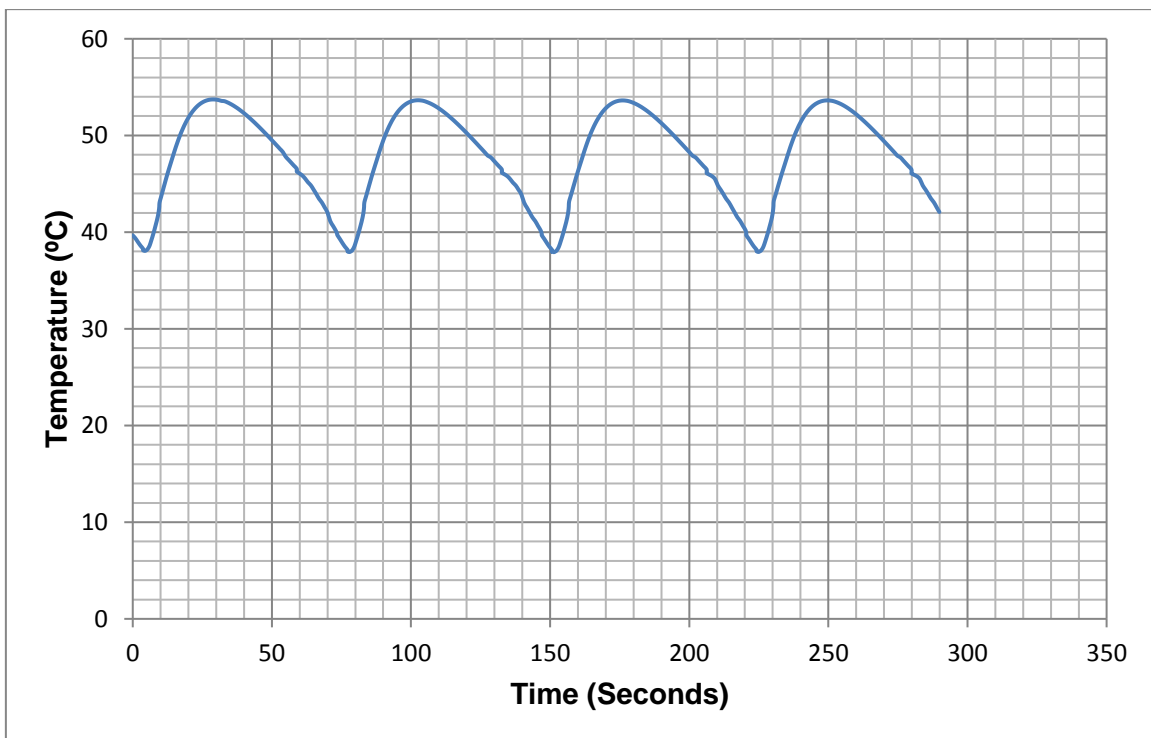


Figure 7.17: SN 4 graph, temperature vs time (captured after 30 cycles)

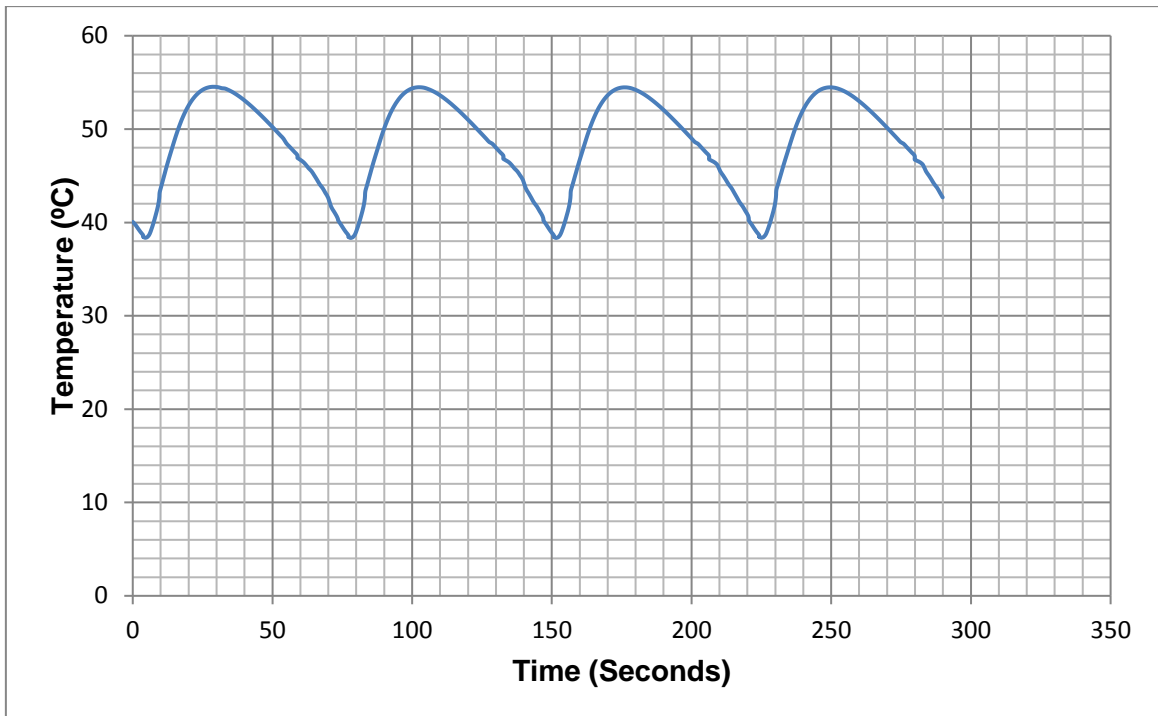


Figure 7.18: SN 5 graph, temperature vs time (captured after 30 cycles)

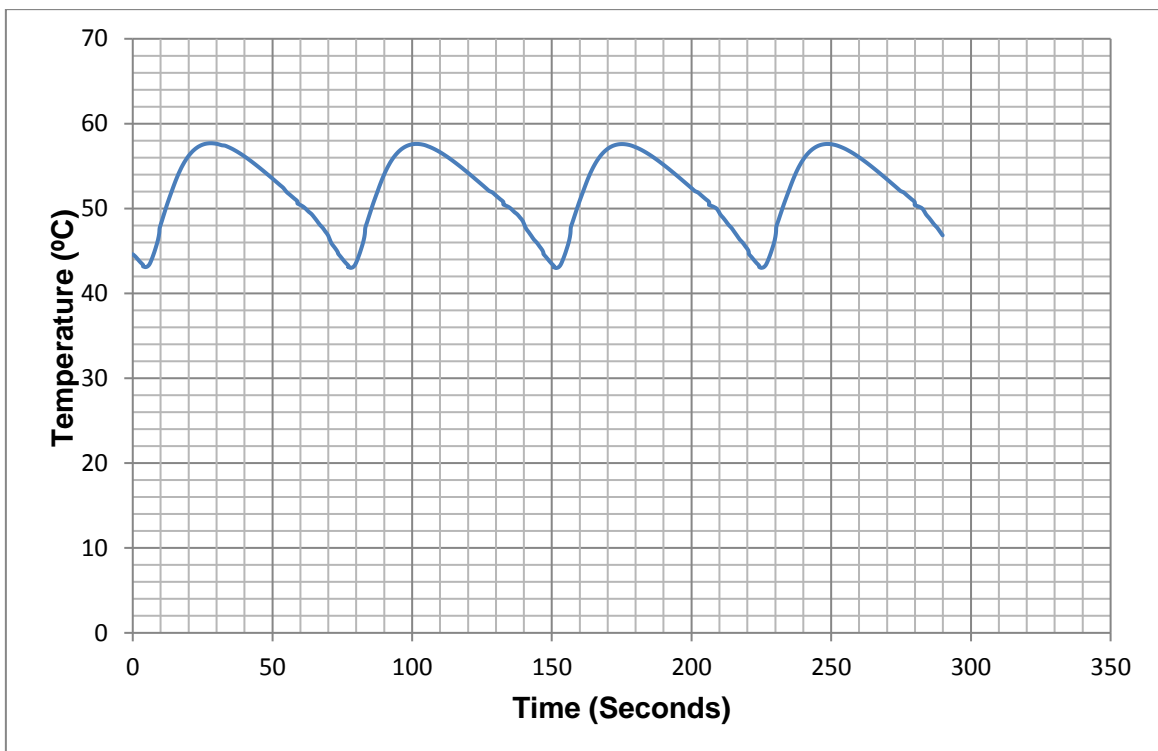


Figure 7.19: SN 6 graph, temperature vs time (captured after 30 cycles)

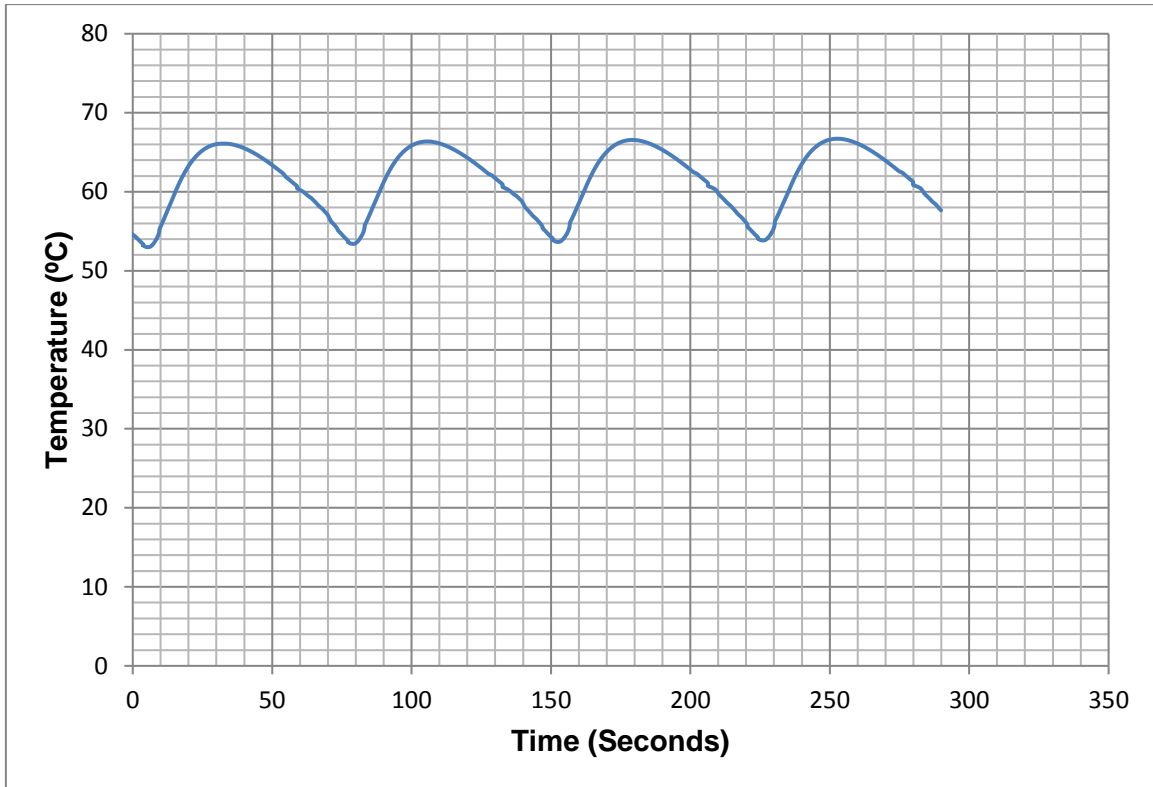


Figure 7.20: SN 7 graph, temperature vs time (captured after 30 cycles)

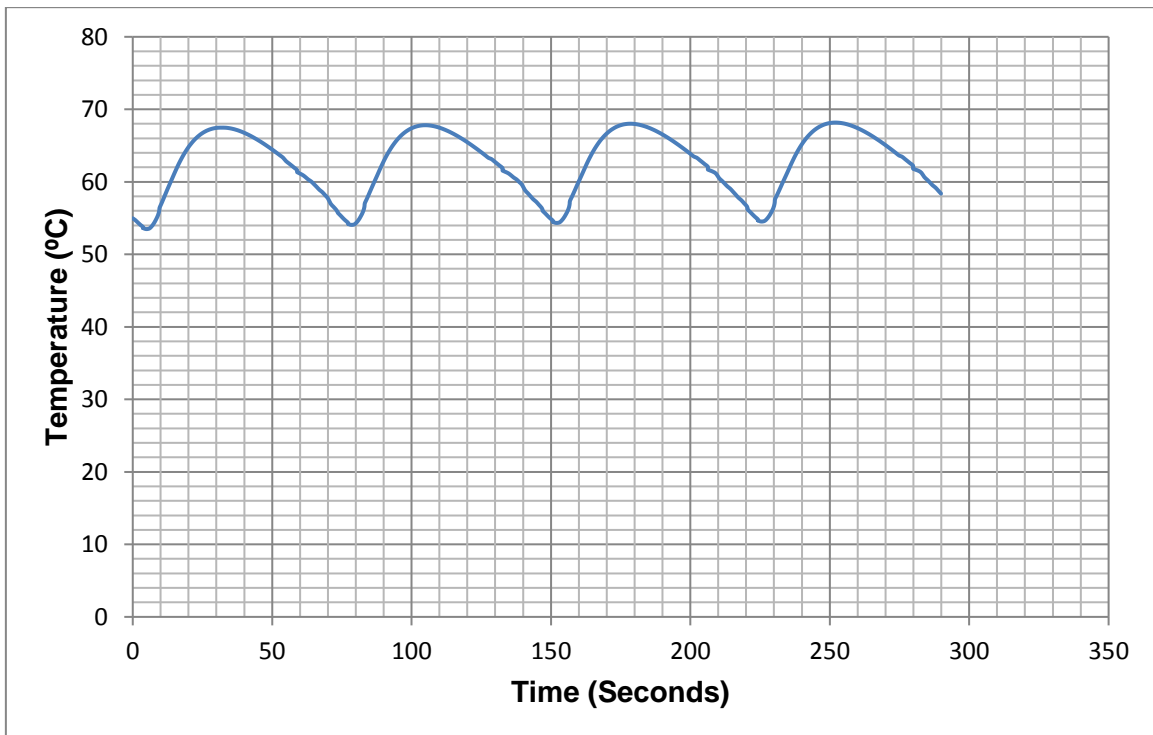


Figure 7.21: SN 8 graph, temperature vs time (captured after 30 cycles)

Figure 7.22 displays the simulated temperature history curves for sensor nodes 1 to 8. It can clearly be seen that the mould temperature at the location of the nodes is between 30 and 70°C.

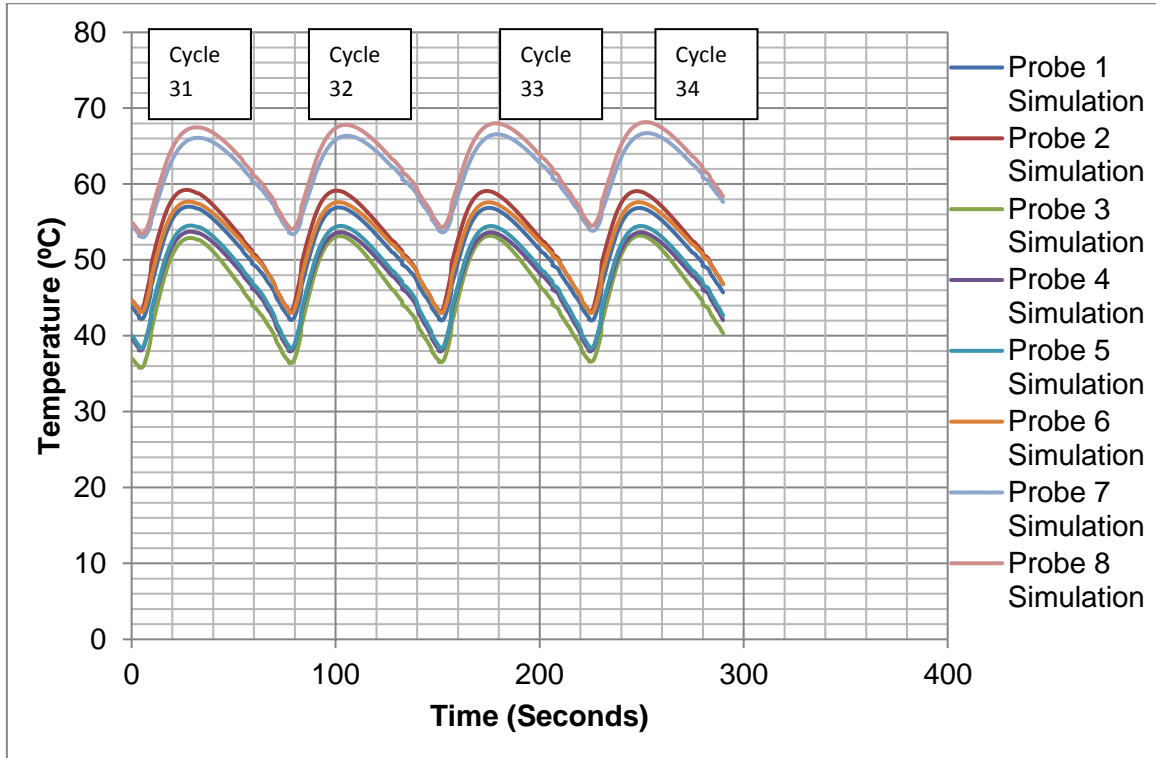


Figure 7.22: SN 1 - SN 8 graphs, temperature vs time (captured after 30 cycles)

## 7.5 FIELD TEST

The Alumide<sup>®</sup> inserts were manufactured on the LS machine as per design, as shown in Figures 7.3 and 7.4. The unsintered powder was then removed from the cooling channels, and the inserts were cleaned and fitted in the steel bolster, see figures 7.23 and 7.24. The moulds were used as manufactured with no polishing operation performed on the Alumide<sup>®</sup> inserts. Thermocouples were fitted to measure temperature on eight points, see Figure 7.24. The manufactured tool was a simple two plate mould as shown in Figure 7.25.

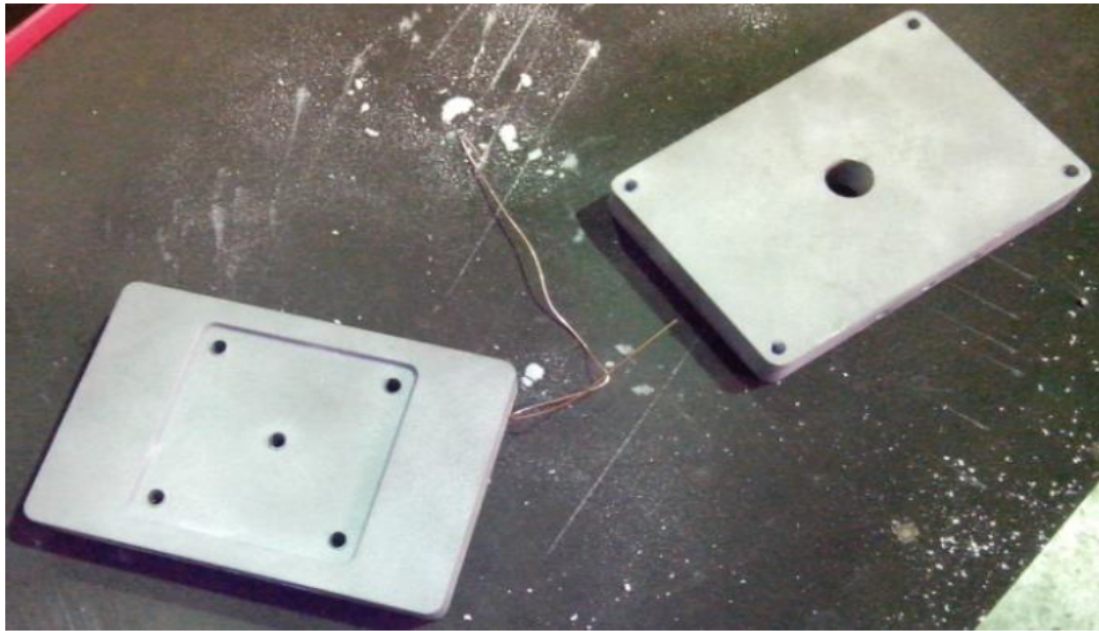


Figure 7.23: Alumide® inserts for a flat component

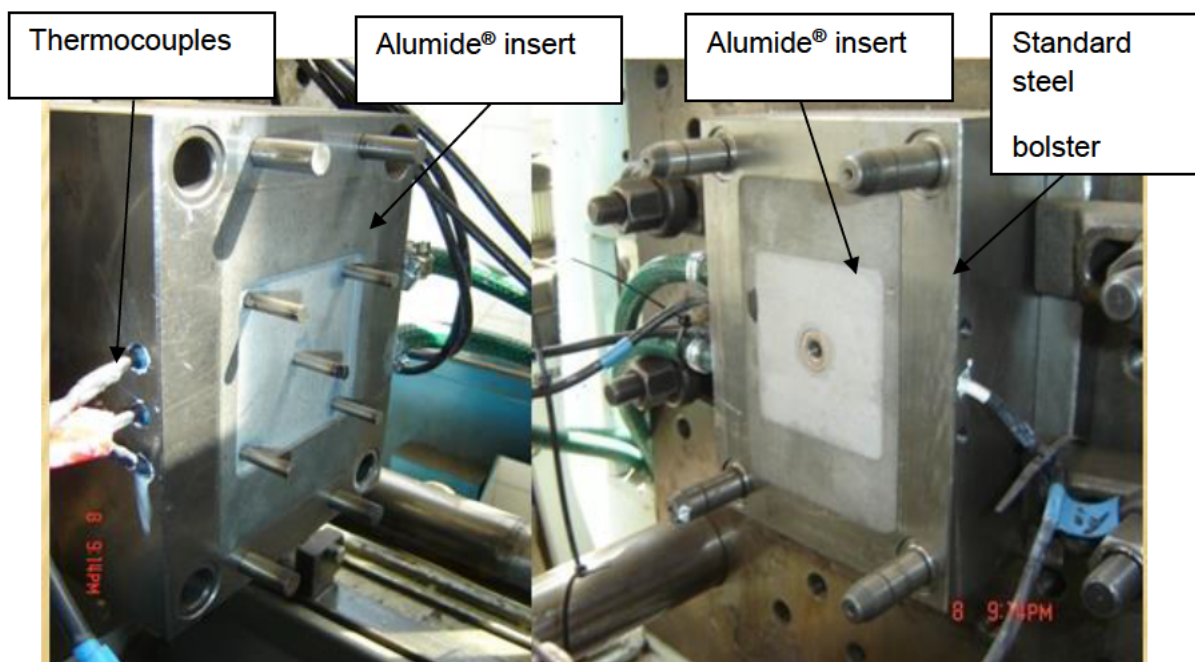
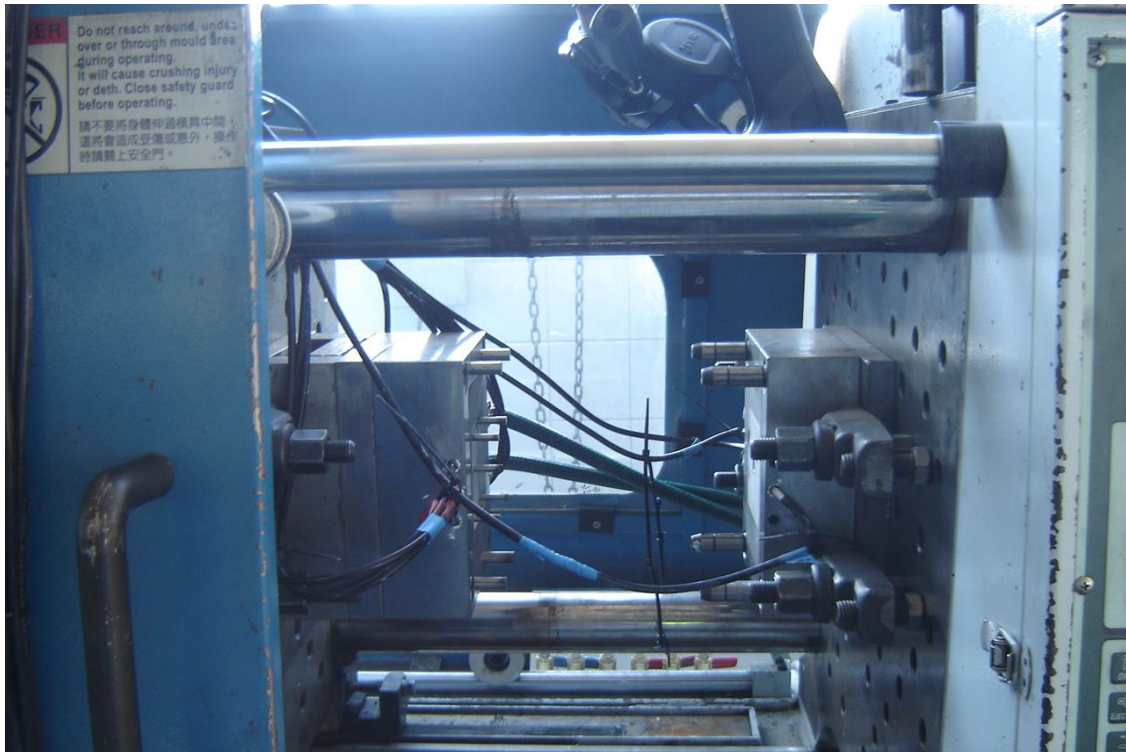


Figure 7.24 : An assembled mould for producing a flat component



*Figure 7.25: A tool during moulding, mounted on a machine*

### **7.5.1 Moulding parameters and experimental procedure**

Experiments were performed on an Shine Well - 90B 90 ton IM machine with a screw diameter of 32 mm. Appendix B shows the specifications of the machine. Water was used as a cooling medium through the cooling channels. LabView was used to capture the temperature of the probes through a Data acquisition (DAQ) medium. The DAQ used was the NI-USB 6009 from National Instruments as shown in Figure 7.26 . Thermistors with a resistance of 10K $\Omega$  were used as probes as shown in Figure 7.26.

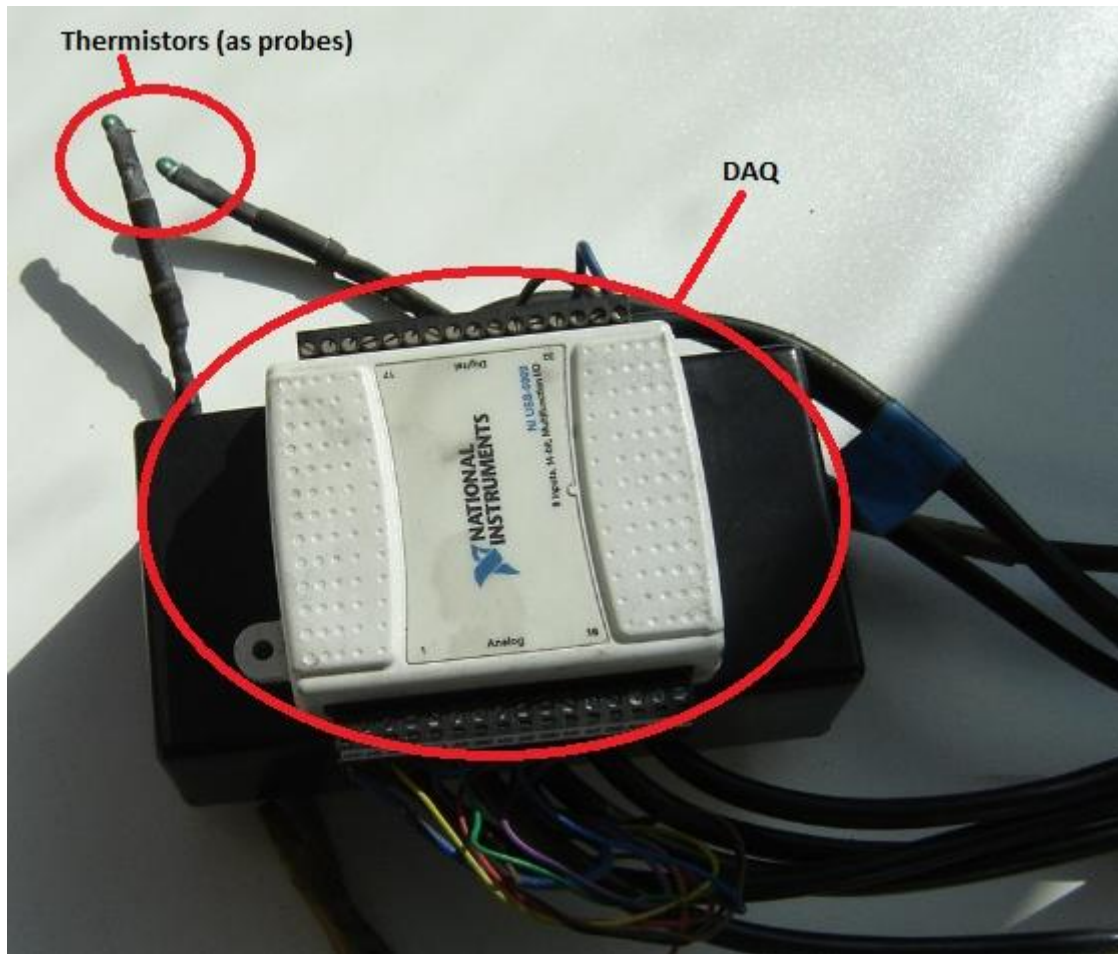


Figure 7.26: DAQ, NI USB 6009 with thermistors connected

### (a) Experiment procedure

1. The IM tool was securely installed in the IM machine.
2. ABS (POLYLAC<sup>®</sup> PA-737) material was poured in the hopper and dried at a temperature of 80<sup>0</sup>C for a duration of two hours. The material data sheet is provided in Appendix C.
3. Thermocouples were inserted in the mould using the holes provided.
4. Cooling channels of the mould were connected to a water flow regulator using hose pipes.
5. IM machine barrel temperatures were set as specified on the material datasheet.
6. Other moulding parameters like injection pressure, holding pressure, cooling time and clamping pressure were set.

7. The machine was purged and moulding commenced.
8. A laptop was connected to the DAQ. A lab-view program was developed to log temperatures at specific positions as explained in Section 7.5.1. The temperatures of the probes could be observed during the moulding process through the graphic interface as shown in Figure 7.27. At the end of the moulding tests the results were exported into Microsoft Excel in order to generate the graphs.

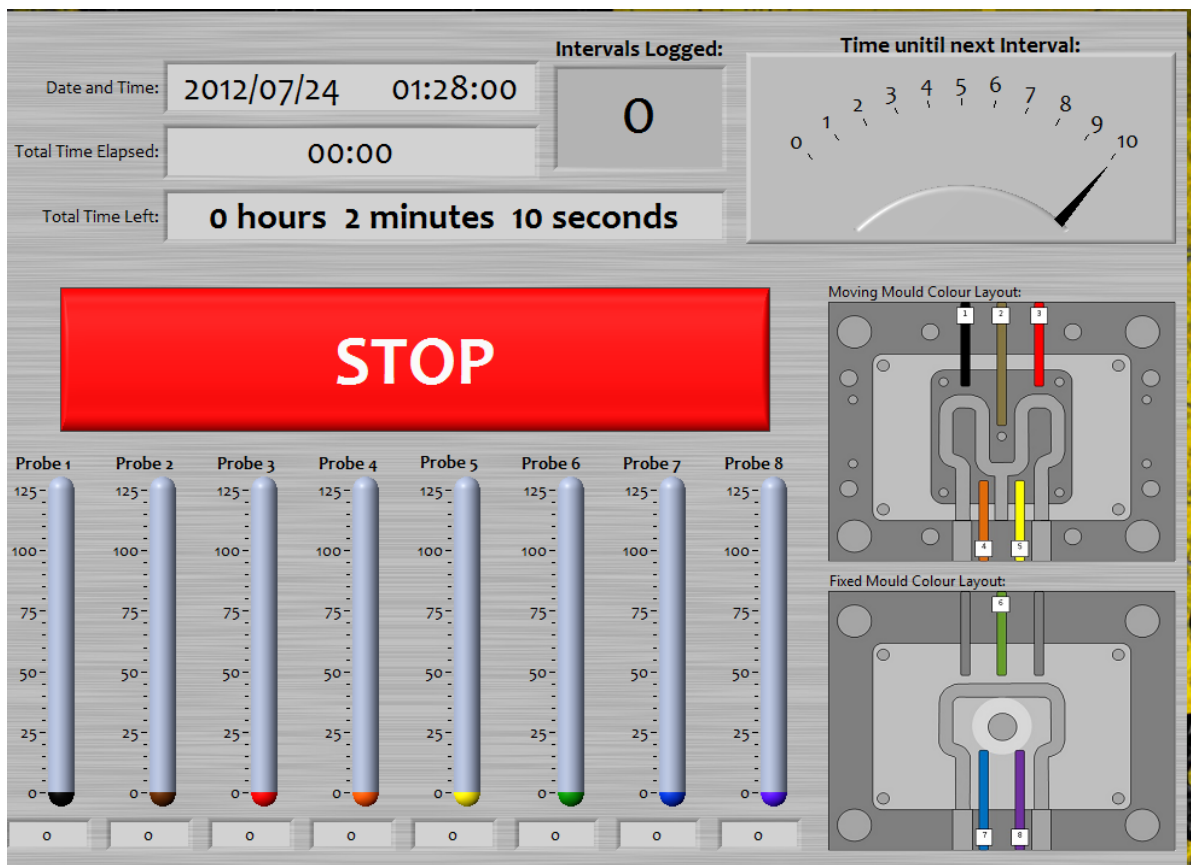


Figure 7.27: Graphic interface for the DAQ as displayed on a laptop

### (b) Machine settings

Table 7.4 shows a summary of the settings used during field tests.

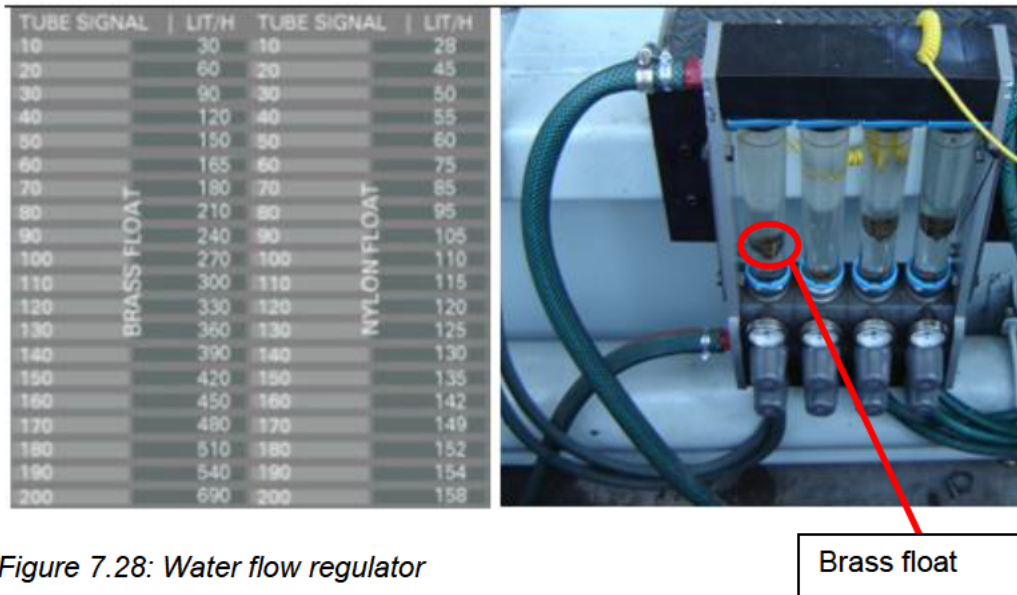
Table 7.4: Machine settings during field test of Case Study 1

<b>Barrel Temperature (°C)</b>	
Rear/Middle/Nozzle	200/210/220
<b>Water flow rate (cm<sup>3</sup>/sec)</b>	33
<b>Cooling Time (seconds)</b>	50
<b>Filling Time (seconds)</b>	3
<b>Injection Pressure (kg/cm<sup>2</sup>)</b>	689

The water temperature entering the mould from the chiller was recorded at a temperature of 20°C.

### (c) Reynolds number

To achieve the same Reynolds number as the one used for simulations, a water flow rate of 33 cm<sup>3</sup>/sec through the mould was used. Since the water flow regulator on the IM machine is calibrated in L/hr the flow rate was converted to this measuring unit thus equalling 118.8 L/hr. The brass float in the flow meter was set to this flow rate as shown in Figure 7.28.



### 7.5.2 Experiment results

From the experiment, the main focus was to check whether a mould temperature of between 30 and 70°C could be achieved in Alumide® with the applied moulding parameters and cooling channel design as stated in the data sheet shown in Appendix C. The secondary focus was to cool the component efficiently without experiencing problems such as an unfilled cavity due to the polymer cooling too fast before 100% filling is achieved. A cycle time of 75 seconds was achieved with 100% filling outcome. The temperatures of the probes are tabulated in Table 3 of Appendix E.

### 7.5.3 Graphical representation of the field test results

Figures 7.29 to 7.36 represent the graphs of the eight probes used to monitor the mould temperature during the field test and it can be clearly observed that the mould temperature at the specified measuring points fell between 30 and 70°C.

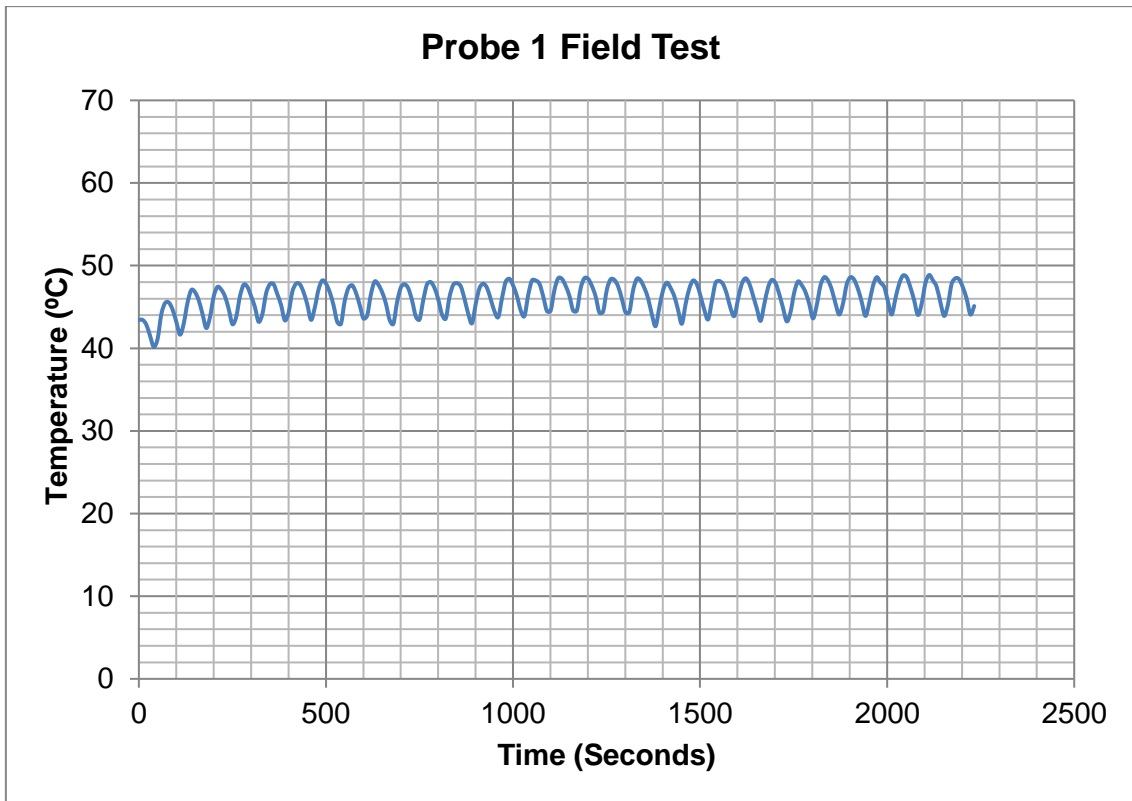


Figure 7.29: Probe 1 graph, temperature vs time (field test, captured after 30 cycles)

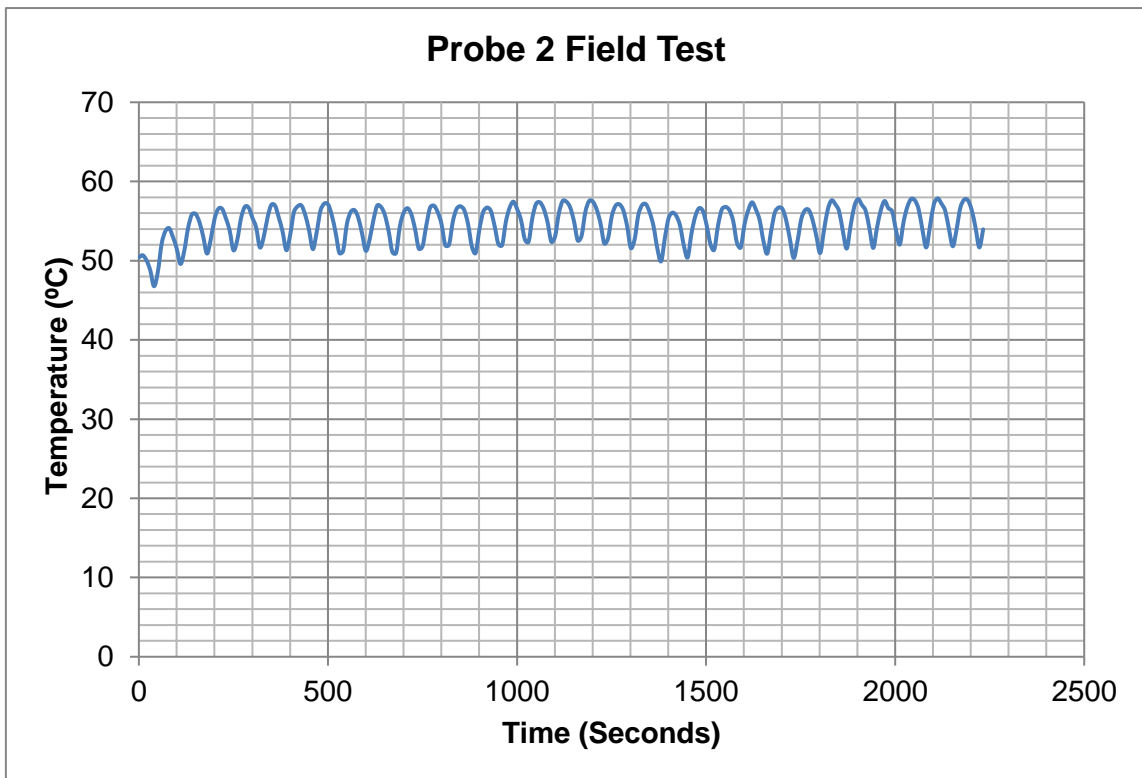


Figure 7.30: Probe 2 graph, temperature vs time (field test, captured after 30 cycles)

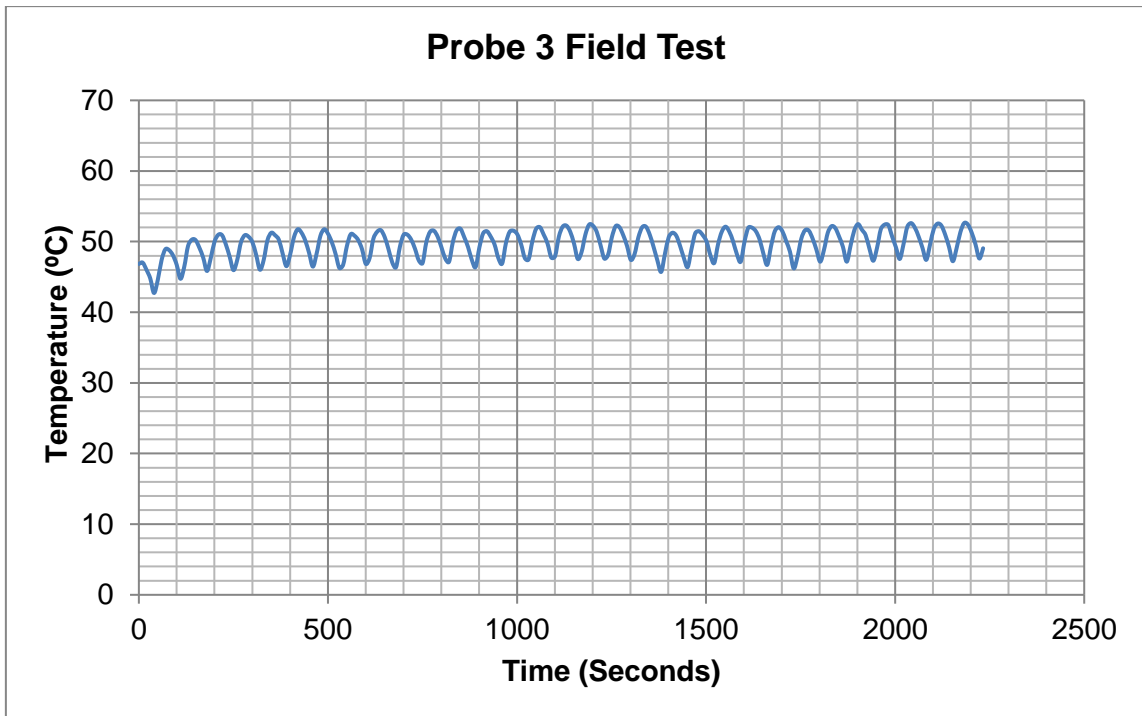


Figure 7.31: Probe 3 graph, temperature vs time (field test, captured after 30 cycles)

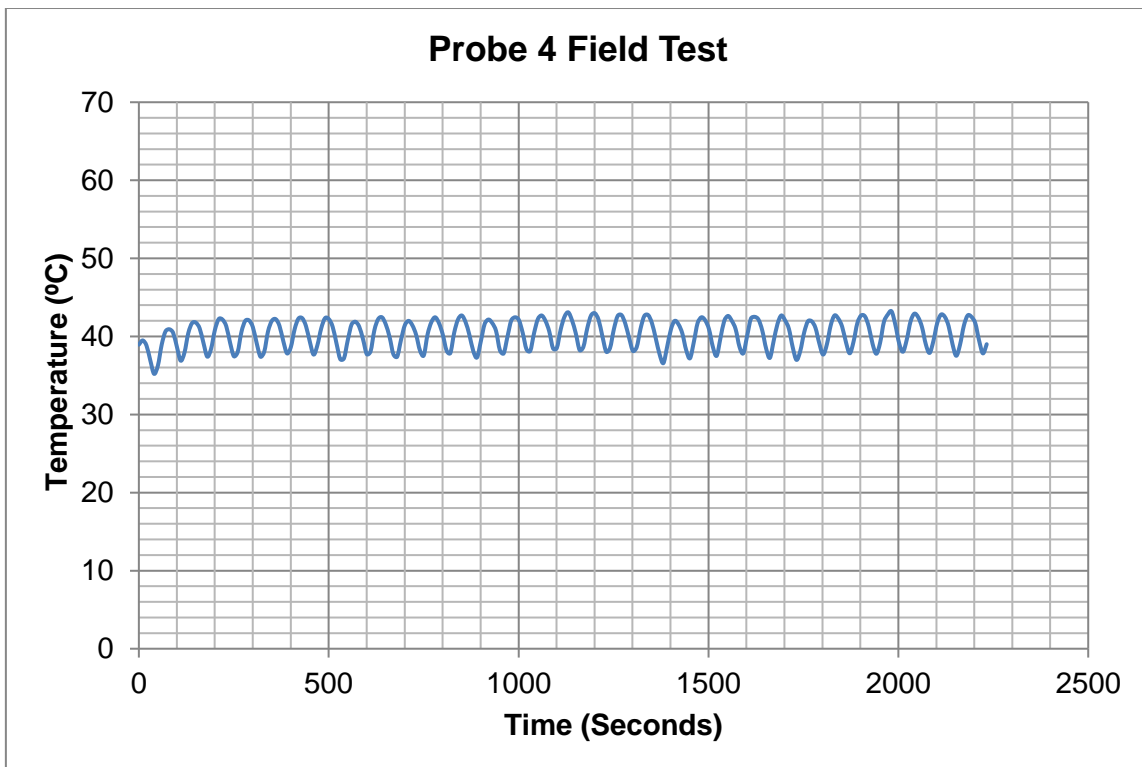


Figure 7.32: Probe 4 graph, temperature vs time (field test, captured after 30 cycles)

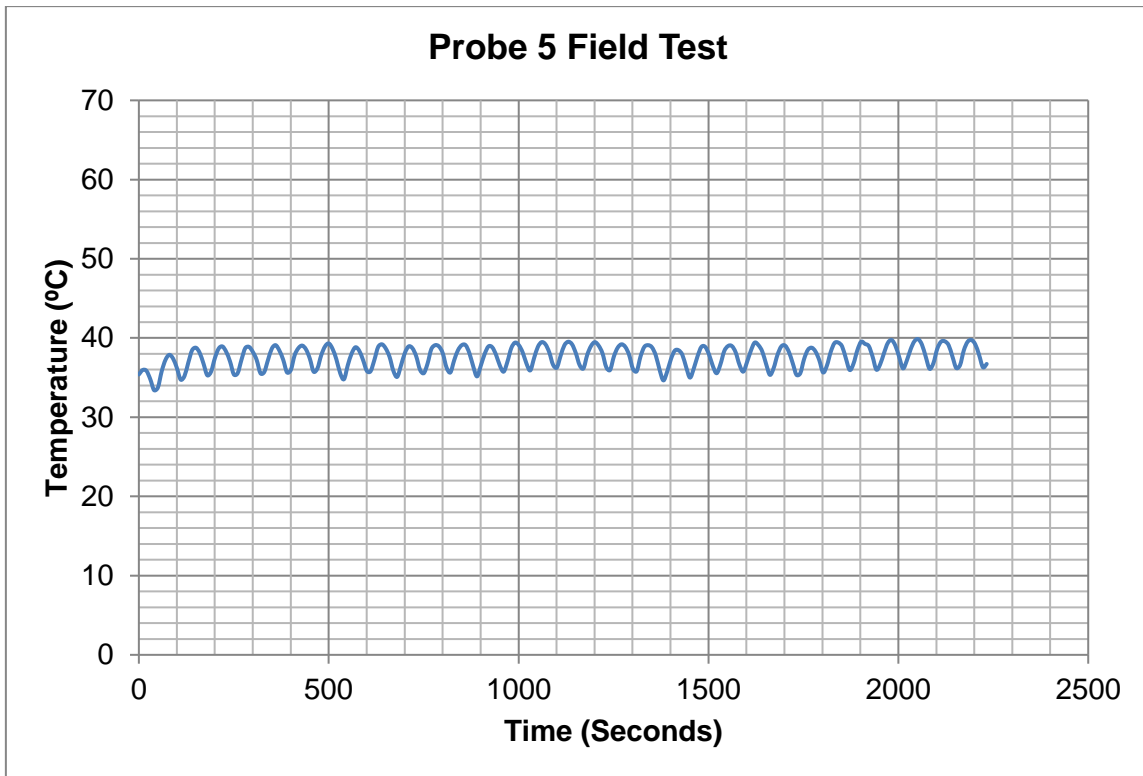


Figure 7.33: Probe 5 graph, temperature vs time (field test, captured after 30 cycles)

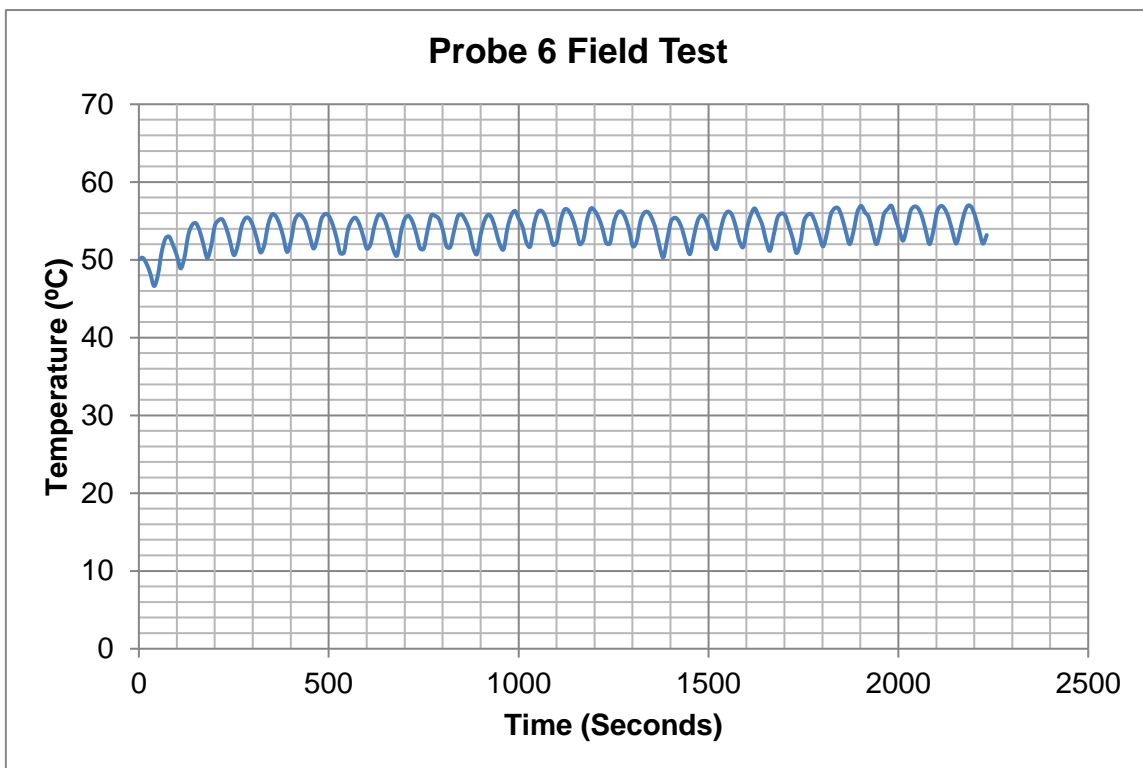


Figure 7.34: Probe 6 graph, temperature vs time (field test, captured after 30 cycles)

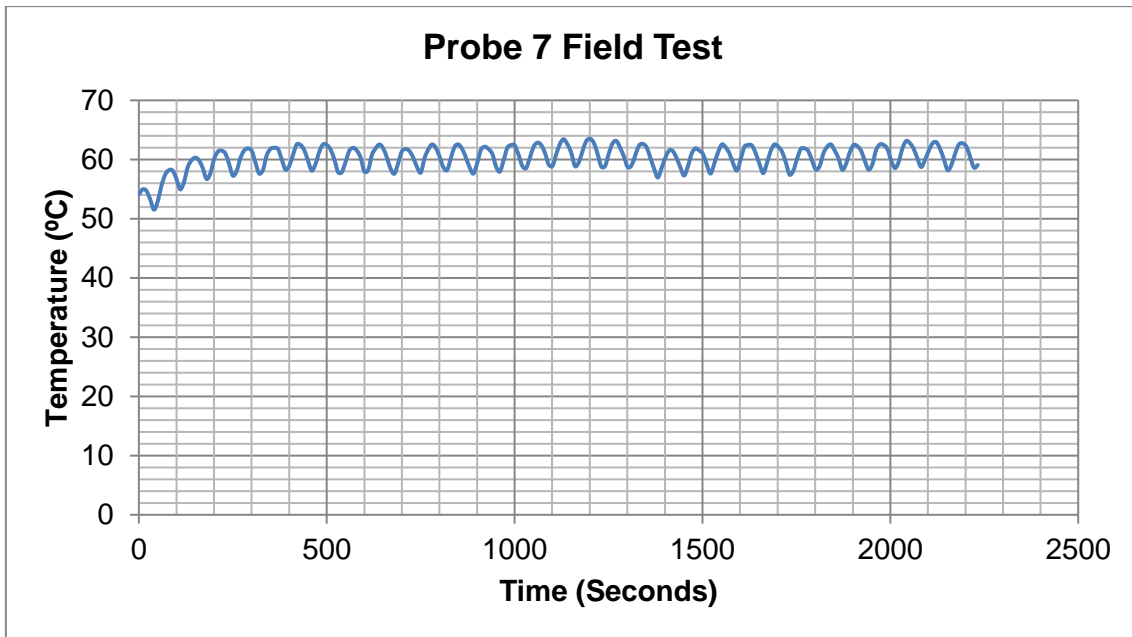


Figure 7.35: Probe 7 graph, temperature vs time (field test, captured after 30 cycles)

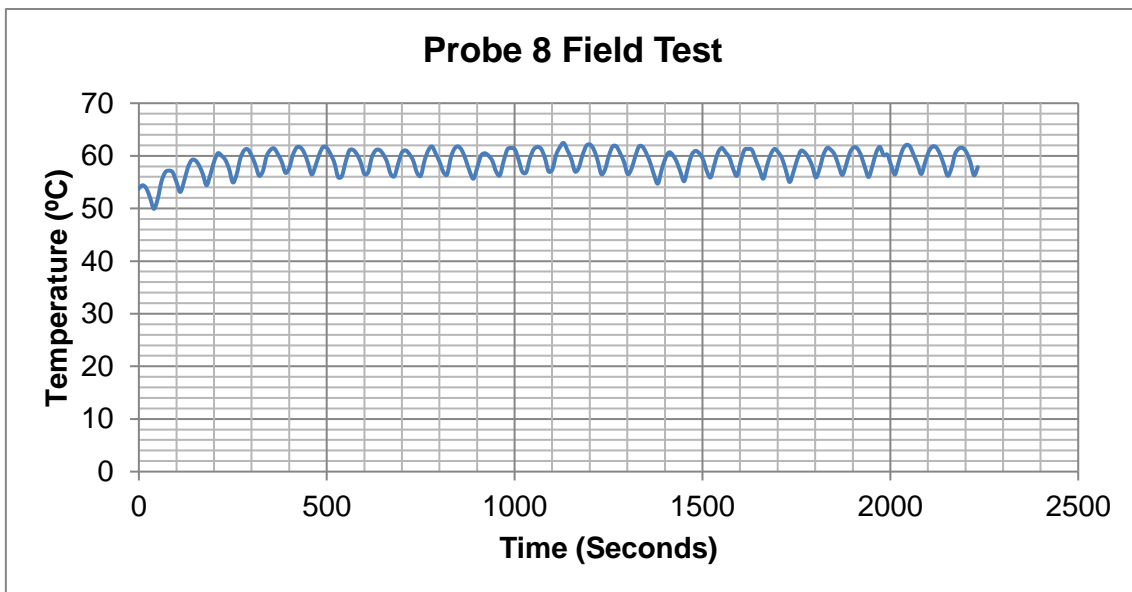


Figure 7.36: Probe 8 graph, temperature vs time (field test, captured after 30 cycles)

It can be seen in Figure 7.37 that the temperature of the probes range between 30 and 70°C.

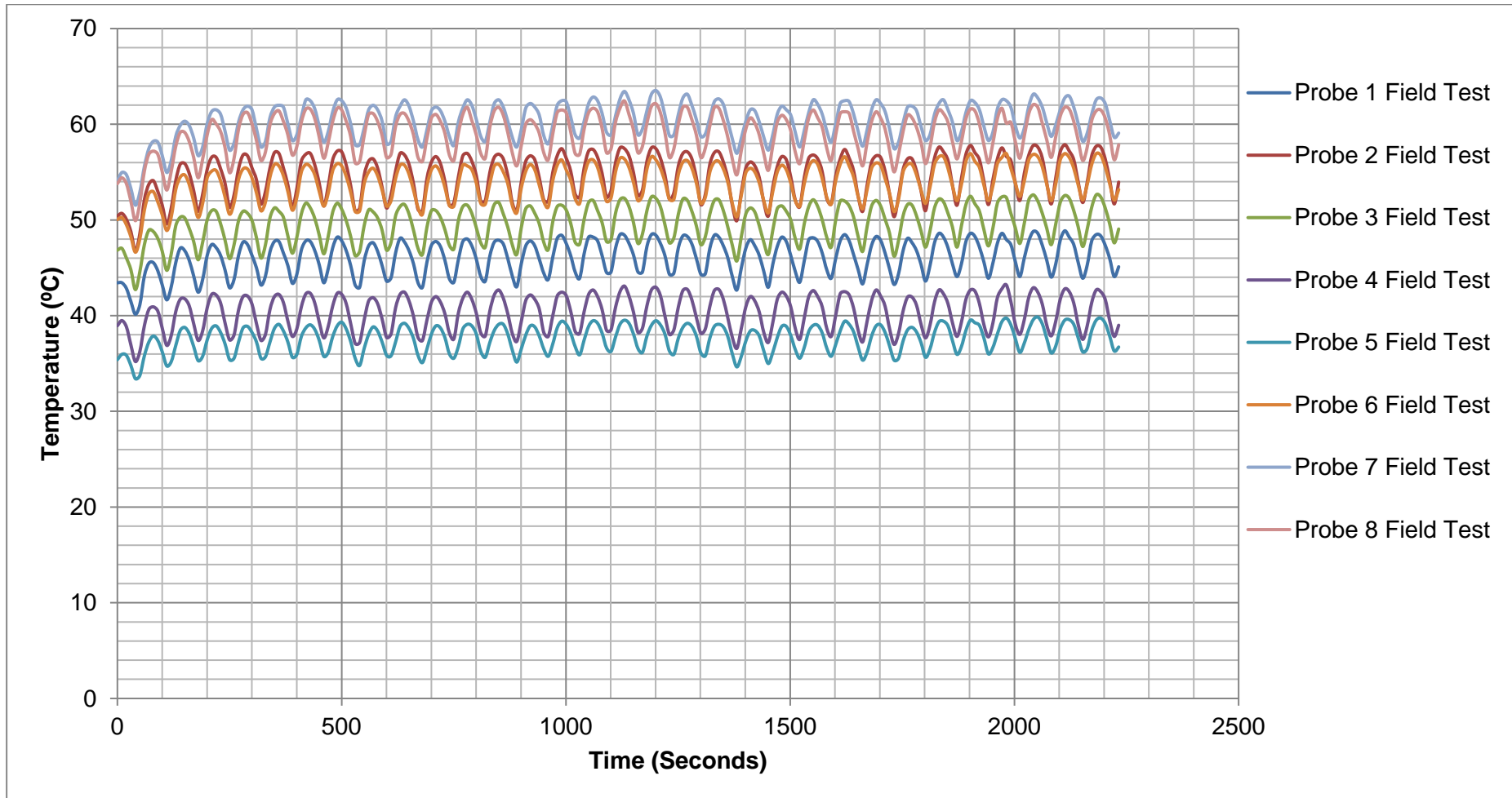


Figure 7.37: Probe 1 - 8 graphs, temperature vs time (field test, captured after 30 cycles)

## 7.6 COMPARISON OF RESULTS: SIMULATION vs FIELD TEST

The temperature outputs provided by Moldex3D were compared with the field test temperatures captured in LabView. The graphs in figures 7.38 to 7.45 demonstrate temperatures of the eight probes used. Probes 1 to 8, both in simulation and field tests, show a realistic rise and drop in temperature demonstrating a typical injection moulding cycle where the mould temperature will rise during filling and start dropping during the packing, cooling and open stages. Simulation shows that after 30 cycles the mould had reached a steady state temperature and field tests reached a steady state temperature after 34 cycles. To compare the results of the field tests, values from 680 seconds were used; at this stage the mould is in a steady state. Simulation in Moldex3D captured four cycles which were in a steady state; therefore, the graphs were drawn for four cycles.

### a) Probe 1, Figure 7.38

The average high temperatures measured at probe 1 were 56.7 and 48.5°C in simulation and field test respectively, resulting in a deviation of 14.4%. A deviation of 0.5% was achieved for the average low temperatures with simulation and field test recording 43.6 and 43.8°C respectively.

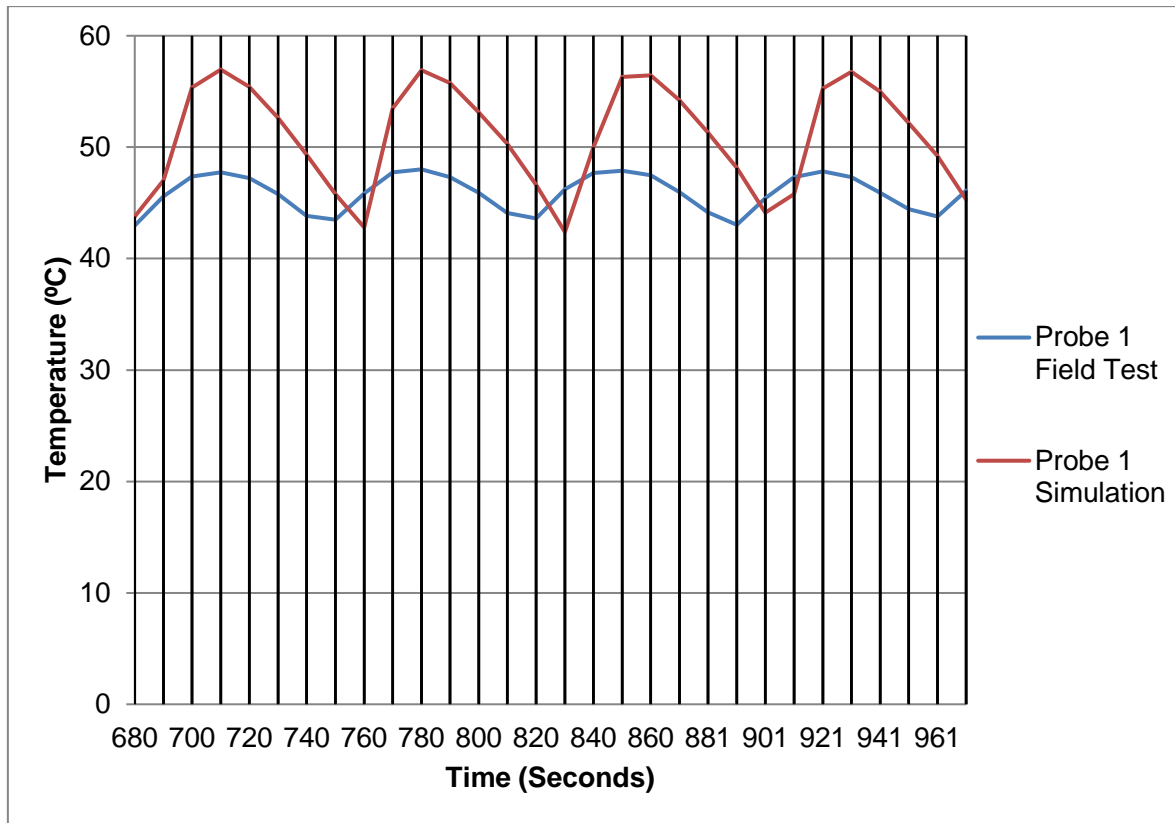
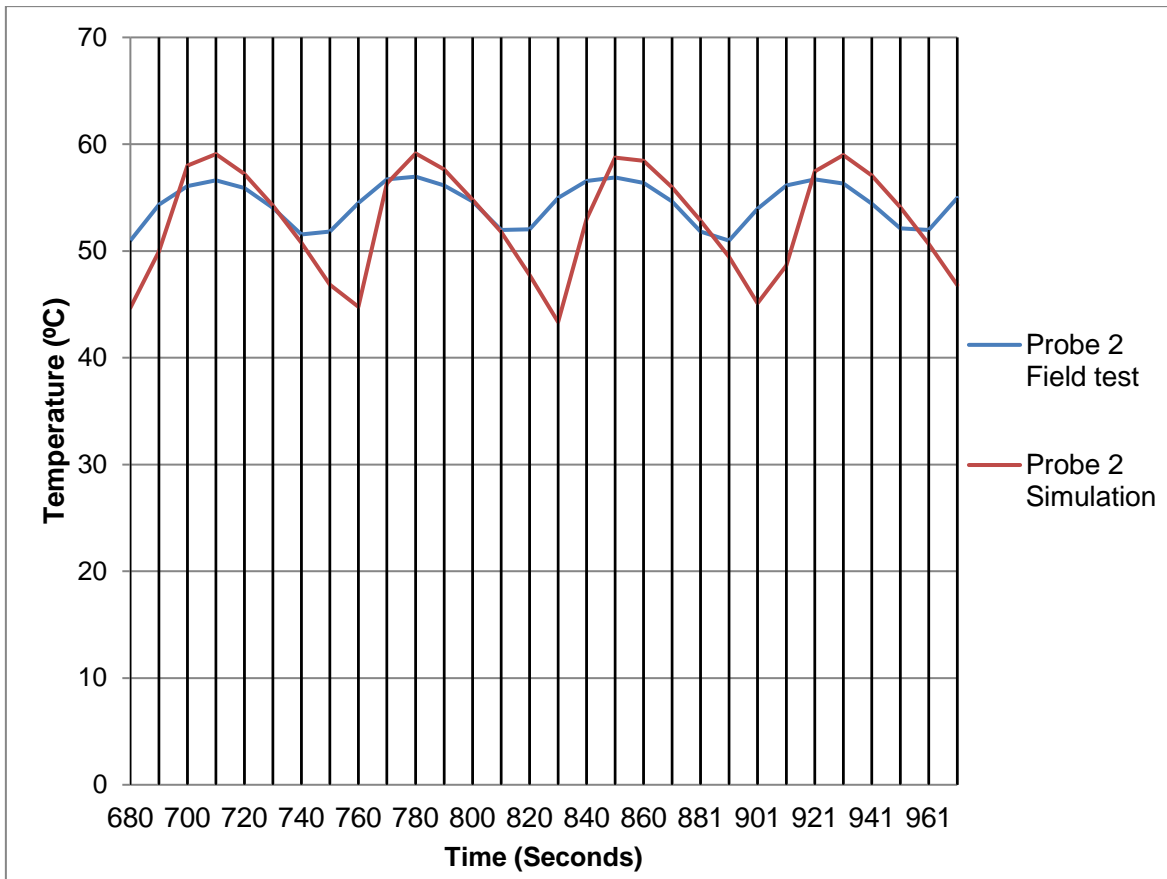


Figure 7.38: Comparison, Probe 1 graphs, temperature vs time (field test vs simulation, from 680 to 970 seconds)

**b) Probe 2, Figure 7.39**

The average high temperatures measured at probe 2 were 59 and 57.4°C in simulation and field test respectively, resulting in a deviation of 2.7%. A deviation of 12.5% was achieved for the average low temperatures with simulation and field test recording 45 and 51.4°C respectively.



*Figure 7.39: Comparison, Probe 2 graphs, temperature vs time (field test vs simulation, from 680 to 970 seconds)*

**c) Probe 3, Figure 7.40**

The average high temperatures measured at probe 3 were 52.9 and 52.3°C in simulation and field test respectively, resulting in a deviation of 1.1%. A deviation of 18.7% was achieved for the average low temperatures with simulation and field test recording 38.2 and 47°C respectively.

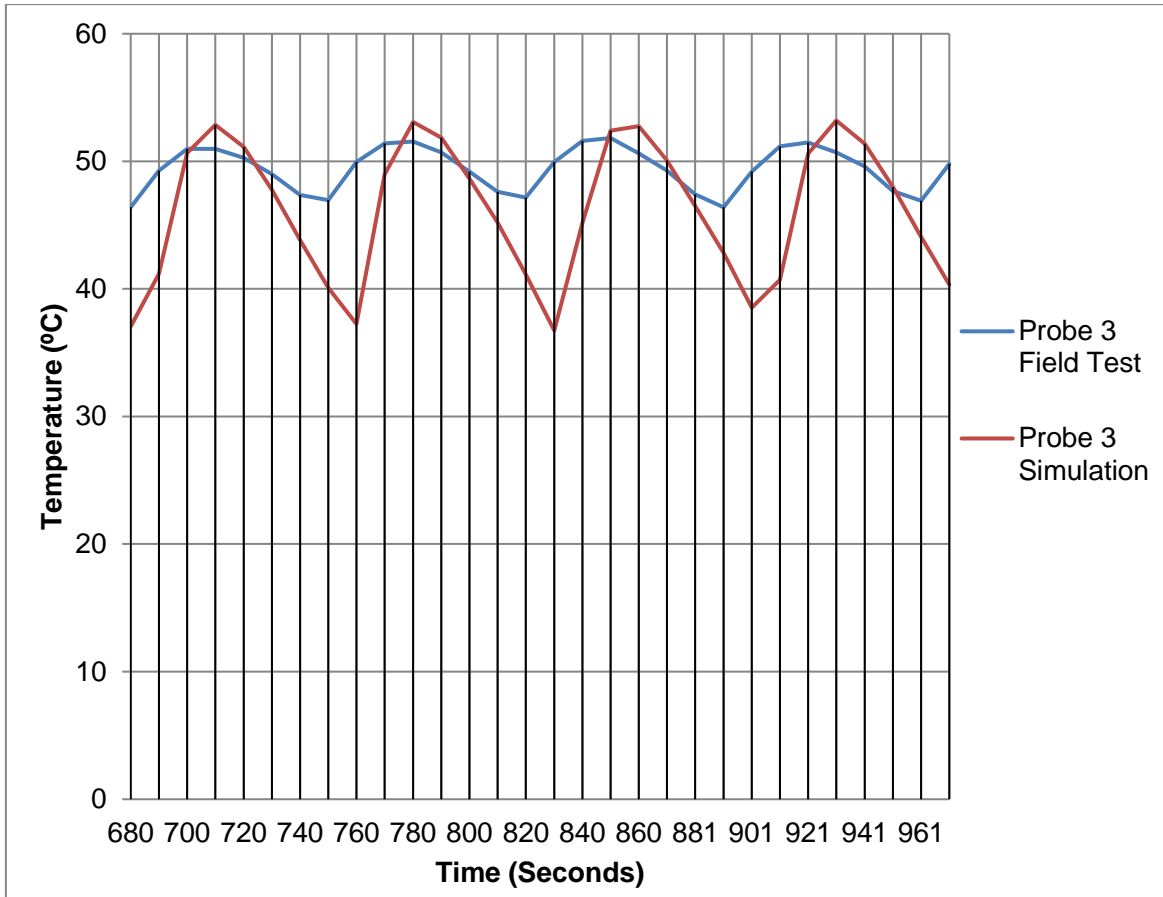


Figure 7.40: Comparison, Probe 3 graphs, temperature vs time (field test vs simulation, from 680 to 970 seconds)

**d) Probe 4, Figure 7.41**

The average high temperatures measured at probe 4 were 53.6 and 42.6°C in simulation and field test respectively, resulting in a deviation of 20.5%. A deviation of 5.8% was achieved for the average low temperatures with simulation and field test recording 39.9 and 37.6°C respectively.

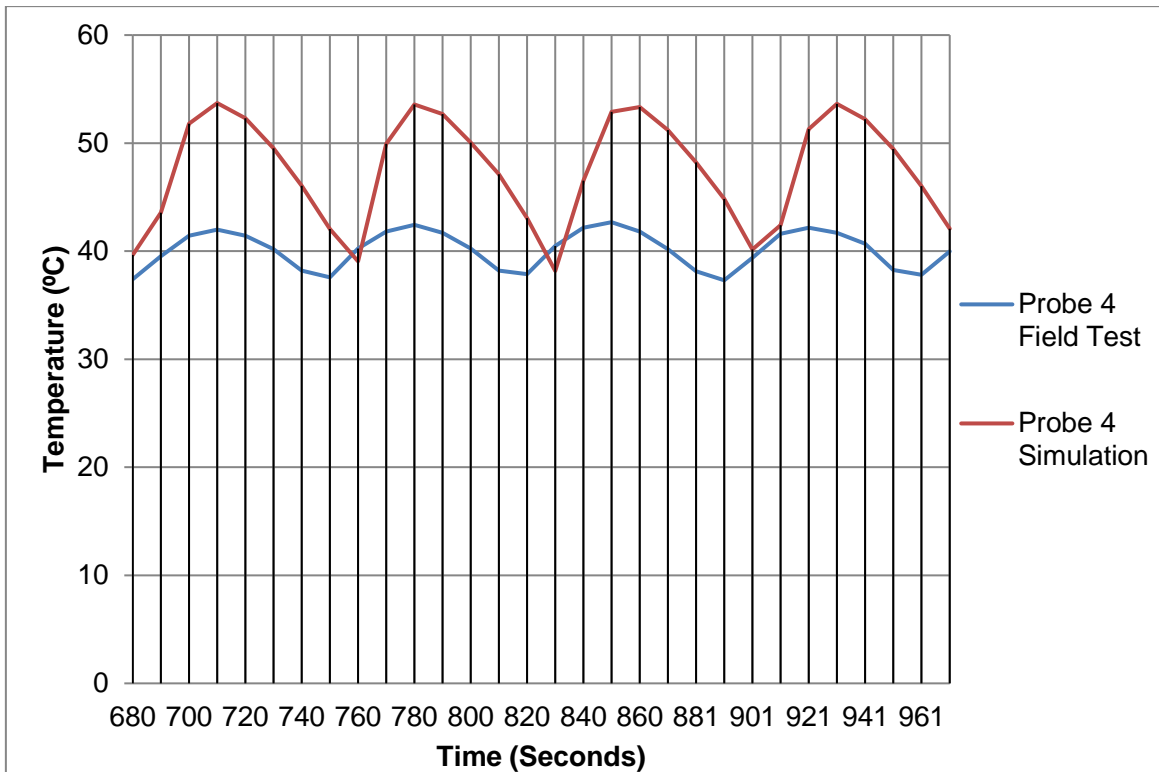


Figure 7.41: Comparison, Probe 4 graphs, temperature vs time (field test vs simulation, from 680 to 970 seconds)

**e) Probe 5, Figure 7.42**

The average high temperatures measured at probe 5 were 54.4 and 39.3°C in simulation and field test respectively, resulting in a deviation of 27.8%. A deviation of 11.2% was achieved for the average low temperatures with simulation and field test recording 40.3 and 35.8°C respectively.

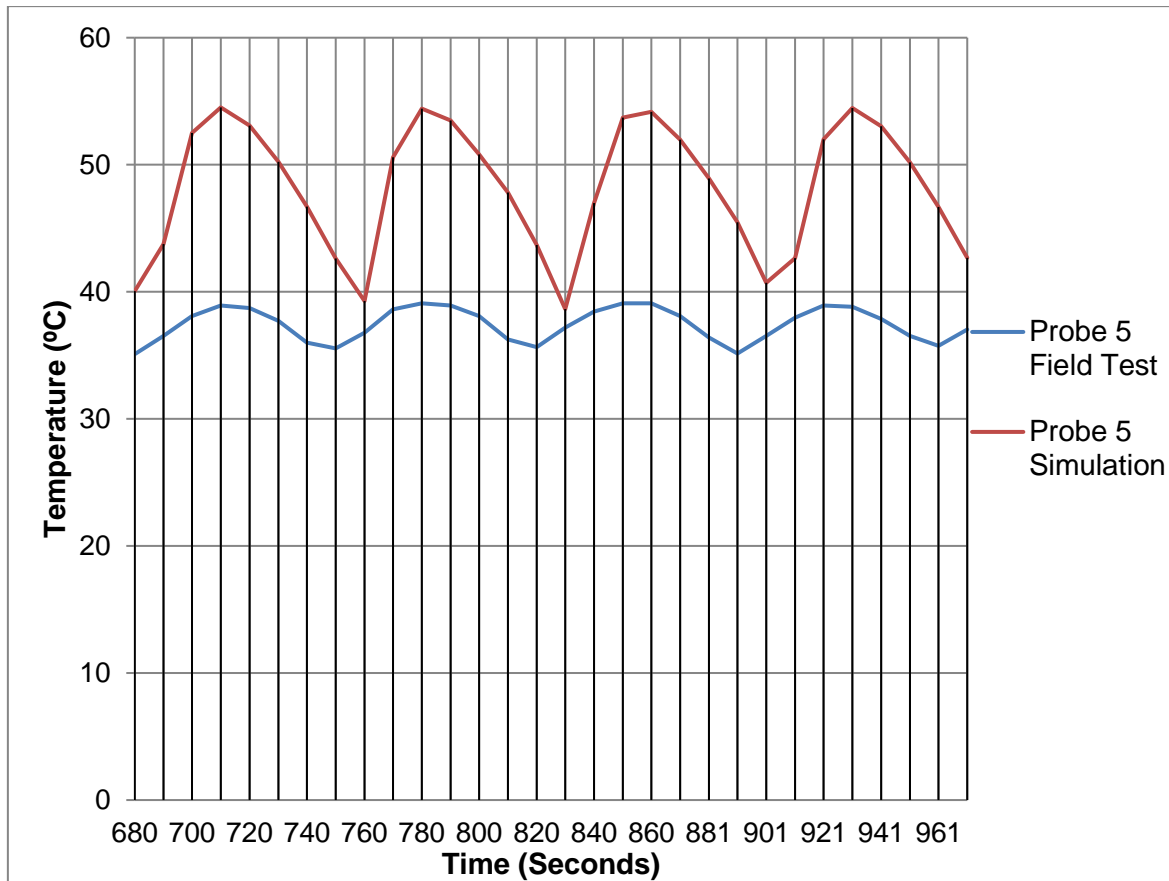
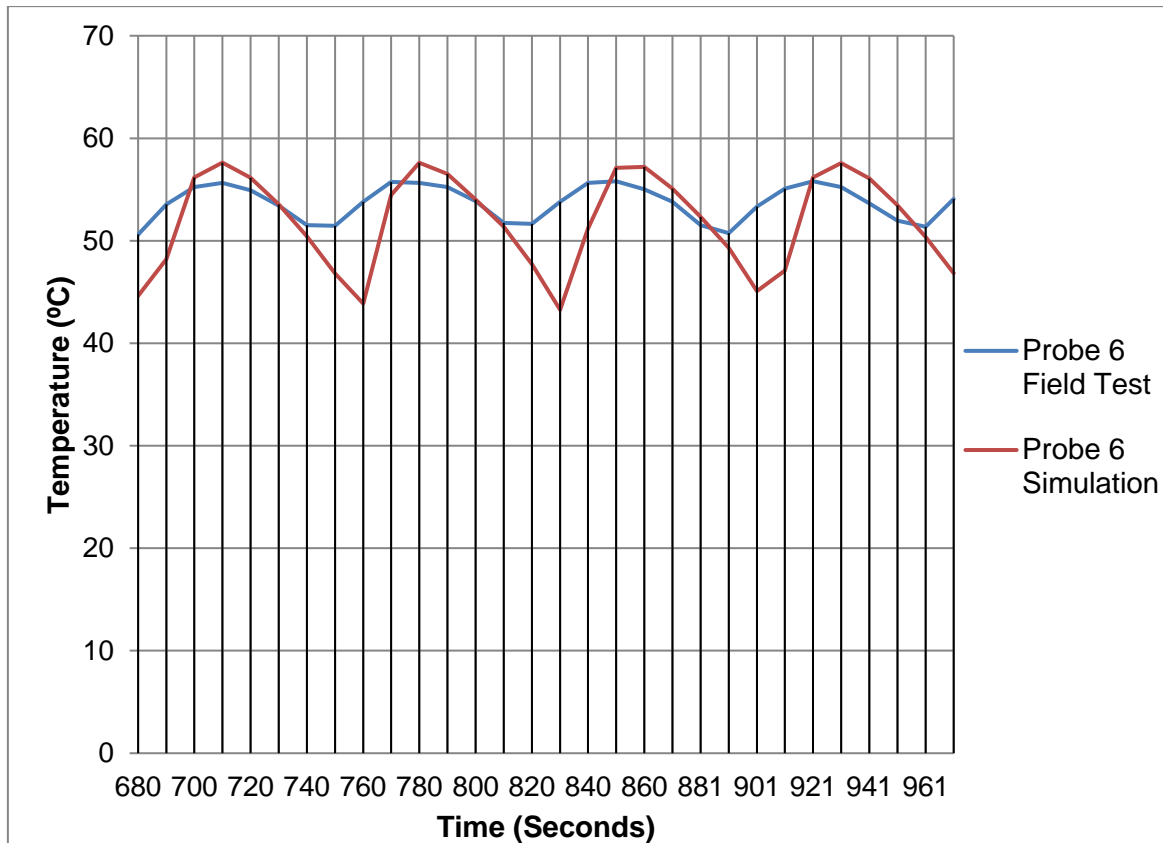


Figure 7.42: Comparison, Probe 5 graphs, temperature vs time (field test vs simulation, from 680 to 970 seconds)

**f) Probe 6, Figure 7.43**

The average high temperatures measured at probe 6 were 57.5 and 56.5°C in simulation and field test respectively, resulting in a deviation of 1.7%. A deviation of 13.3% was achieved for the average low temperatures with simulation and field test recording 44.8 and 51.7°C respectively.



*Figure 7.43: Comparison, Probe 6 graphs, temperature vs time (field test vs simulation, from 680 to 970 seconds)*

**g) Probe 7, Figure 7.44**

The average high temperatures measured at probe 7 were 66.3 and 62.5°C in simulation and field test respectively, resulting in a deviation of 5.7%. A deviation of 4.8% was achieved for the average low temperatures with simulation and field test recording 55.3 and 58.1°C respectively.

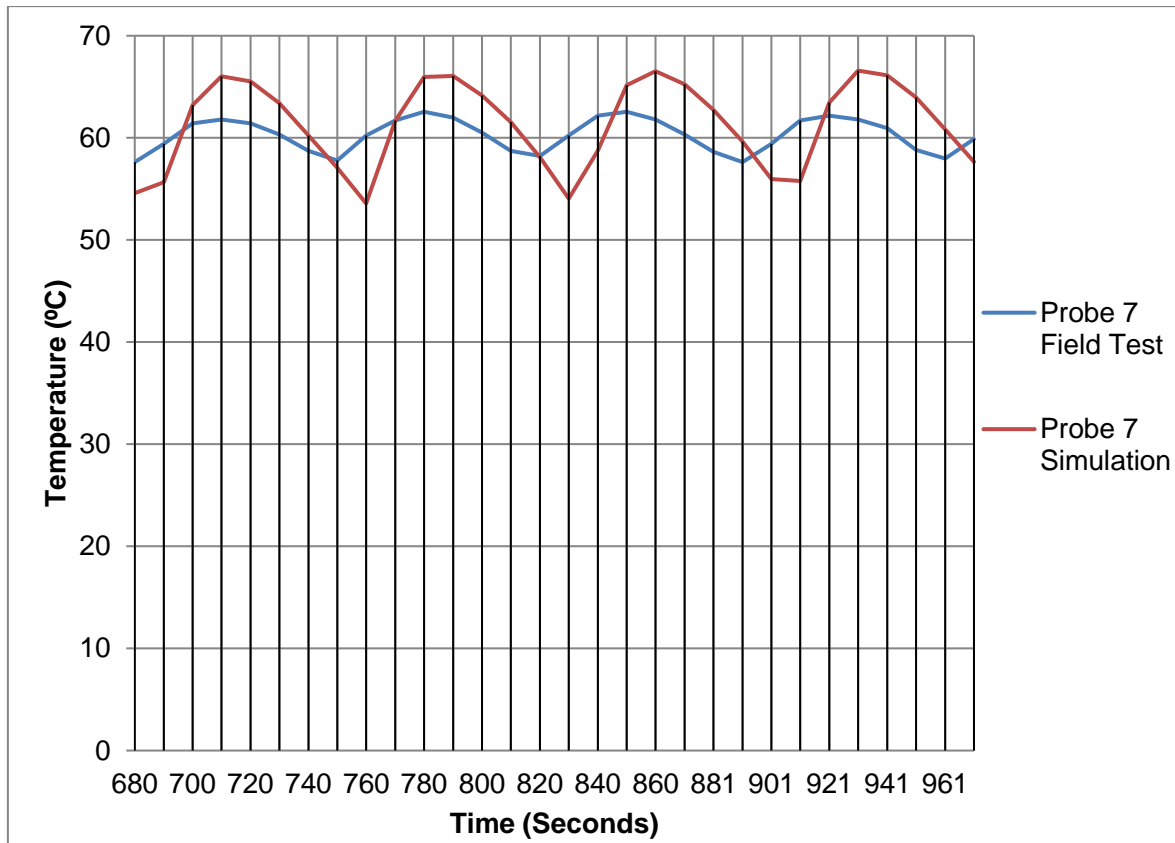
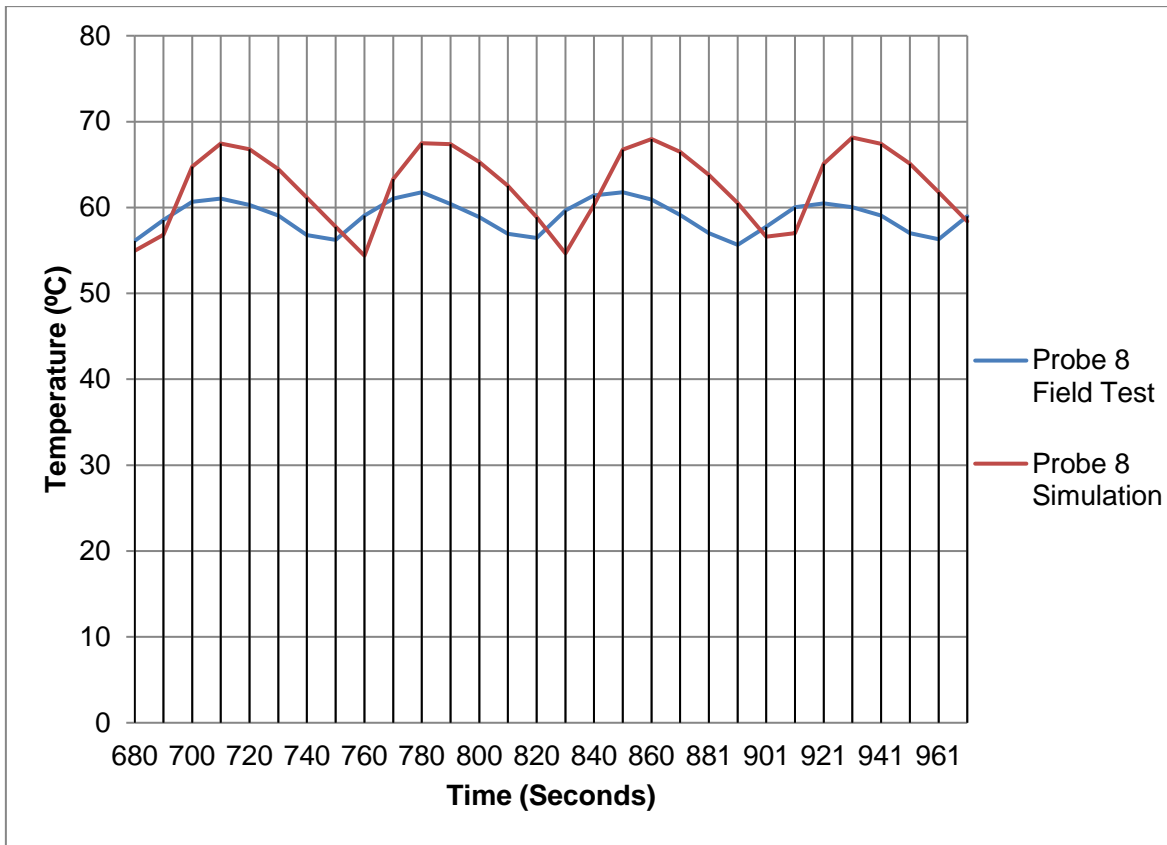


Figure 7.44: Comparison, Probe 7 graphs, temperature vs time (field test vs simulation, from 680 to 970 seconds)

#### h) Probe 8, Figure 7.45

The average high temperatures measured at probe 8 were 67.8 and 61.5°C in simulation and field test respectively, resulting in a deviation of 9.3%. A deviation of 0.2% was achieved for the average low temperatures with simulation and field test recording 56.1 and 56°C respectively.



*Figure 7.45: Comparison, Probe 8 graphs, temperature vs time (field test vs simulation, from 680 to 970 seconds)*

A summary of temperatures captured during simulation and field tests is tabulated in Table 7.5.

Table 7.5: Case study 1, average high and average low probe temperatures during simulation and field tests (Deviations provided)

	<b>Simulation (°C)</b>	<b>Field Test (°C)</b>	<b>Deviation (%)</b>
Probe 1, Average high temperatures	56.7	48.5	14.4
Probe 1, Average low temperatures	43.6	43.8	0.5
Probe 2, Average high temperatures	59	57.4	2.7
Probe 2, Average low temperatures	45	51.4	12.5
Probe 3, Average high temperatures	52.9	52.3	1.1
Probe 3, Average low temperatures	38.2	47.0	18.7
Probe 4, Average high temperatures	53.6	42.6	20.5
Probe 4, Average low temperatures	39.9	37.6	5.8
Probe 5, Average high temperatures	54.4	39.3	27.8
Probe 5, Average low temperatures	40.3	35.8	11.2
Probe 6, Average high temperatures	57.5	56.5	1.7
Probe 6, Average low temperatures	44.8	51.7	13.3

Table 7.5 continues

	<b>Simulation (°C)</b>	<b>Field Test (°C)</b>	<b>Deviation (%)</b>
Probe 7, Average high temperatures	66.3	62.5	5.7
Probe 7, Average low temperatures	55.3	58.1	4.8
Probe 8, Average high temperatures	67.8	61.5	9.3
Probe 8, Average low temperatures	56.1	56.0	0.2

## 7.7 TENSILE STRENGTH TESTING OF THE PRODUCED PRODUCT

Tensile test pieces were machined on a milling machine from the ABS products produced from the Alumide® moulds as shown in figures 7.46 and 7.47. The reason for the test was to compare the tensile strength of the products produced with the information presented in the data-sheet of the ABS material which was used for moulding. During moulding, care had to be taken to use proper processing parameters such as mould temperature, injection speed, injection pressure, holding pressure and cooling time in order to get products with good tensile strength [56].



*Figure 7.46: ABS product*



*Figure 7.47: Machined tensile test pieces  
from the product produced*

The tensile strength tests were performed on a Lloyd instruments LS100 machine, as shown in Figure 7.48. Ten tests were performed and the tensile strength results are tabulated in Table 7.6 with an average of 33.5 MPa.



*Figure 7.48: Lloyd instruments LS100 machine*

Table 7.6: Results of the tensile tests performed on ABS parts produced by the Alumide® mould

Test piece number	Tensile strength (MPa)
1	32.8
2	35.2
3	35.4
4	34.3
5	33.2
6	34.0
7	34.3
8	32.6
9	32.3
10	31.0
<b>Average</b>	<b>33.5</b>

The tensile strength of the ABS (POLYLAC® PA-737) is 36.2 MPa as shown in Appendix C. A deviation of 7.5% was achieved between the manufacturer’s values and the test results, which is an acceptable value.

## 7.8 DISCUSSION OF RESULTS

Effective moulding of ABS in Alumide® moulds could take place at temperatures that ranged from 30 to 70°C during the IM cycle according to the results of the ABS data sheet. These results were achieved during simulation and field test as shown in figures 7.22 and 7.37. The simulation and field test compared fairly good with 63% of the measuring points resulting in a deviation of less than 10% as shown in Table 7.5. On average 9.4% deviation was achieved. The simulation showed that the cooling channel on the moving half absorbed 51% of the heat whereas the cooling channel on the fixed half absorbed 44.4% of the heat

as shown in Figure 7.10. Furthermore, a cooling time of 50 seconds was sufficient to successfully eject the product without any distortions or difficulties.

A product with tensile strength close to that specified by the manufacturer was achieved, proving that the necessary IM parameters were used such as melt temperatures, moulding temperatures and pre-drying of the polymer. The surface finish of the produced product had visible stair steps as no polishing had been done on the moulds.

## **7.9 CHAPTER SUMMARY**

Case study 1 investigated a flat component 80 mm x 80 mm x 3 mm in dimension. ABS (POLYLAC<sup>®</sup> PA-737) was used as component material. Alumide<sup>®</sup> was used as a tooling material. Design of the cooling channels were investigated on Moldex3D before the actual inserts were laser sintered.

The focus was to investigate the cooling efficiency of Alumide<sup>®</sup> inserts during polymer injection moulding cycles. The study showed that the cooling channels dissipate most of the heat at around 95.4% efficiency as a result of cooling channels in the moving half dissipating 51% and cooling channels in the fixed half dissipating 44.4%. However, some hot-spots were experienced around the sprue as expected. A Reynolds number of 5000 was used for this case study, providing a desired turbulent flow in the cooling channel.

When comparing the simulation and field results it was observed that the temperature measured from the probes are within the moulding temperature for the ABS material used in this research, which is between 30 and 70°C.

A tensile test was conducted to check whether products produced by means of Alumide<sup>®</sup> tooling would meet the mechanical properties as supplied by the manufacturers.

## **CHAPTER 8: CASE STUDY 2: POLYMER CUP**

### **8.1 INTRODUCTION**

As opposed to a simple flat geometry used in Case study 1, a deep geometry was used for Case study 2. The idea was to experiment on a component with a deeper cavity that would absorb more heat. Furthermore, the geometry would allow for conformal cooling demonstrating the advantages of RT by AM.

The experiment addressed the following:

- Cooling channel design for Alumide<sup>®</sup> inserts
- Moulding parameters such as cooling time and coolant flow rate
- Mould temperature of Alumide<sup>®</sup> inserts

The experiments covered both simulations and field tests. In Case study 2 a complex conformal cooling channel design was chosen and it was therefore decided to use Sigmasoft<sup>®</sup> software as local support is available to verify simulation results.

### **8.2 CASE STUDY 2: INJECTION MOULD OF A POLYMER CUP**

Case study 2 focused on a polymer cup as a component to be moulded. The cup had dimensions of 72 mm in diameter and 55 mm in height, a thickness of 2 mm and a draft angle of 5°, see figures 8.1 and 8.2. The objective was to investigate the best cooling strategies for Alumide<sup>®</sup> inserts on a cup component, focusing on the cooling channel design and the operating parameters during IM.



Figure 8.1: CAD of the cup

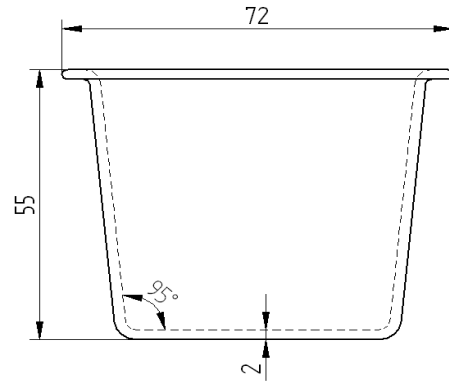


Figure 8.2: CAD showing dimensions of the  
cup

## 8.3 DESIGN

### 8.3.1 Mould design

A mould was designed with two Alumide<sup>®</sup> inserts, one on the fixed half and one on the moving half. Conformal cooling channels were provided on both halves of the mould, forming a spiral. A single cavity mould with sprue injection was investigated. The insert with the cavity was fitted in the fixed half as shown in Figure 8.3. A moving half was fitted with a core and the ejection system as shown in Figure 8.4.

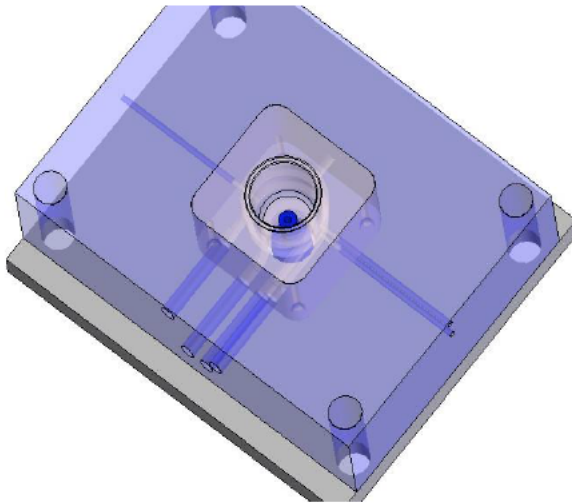


Figure 8.3: CAD of the fixed mould half

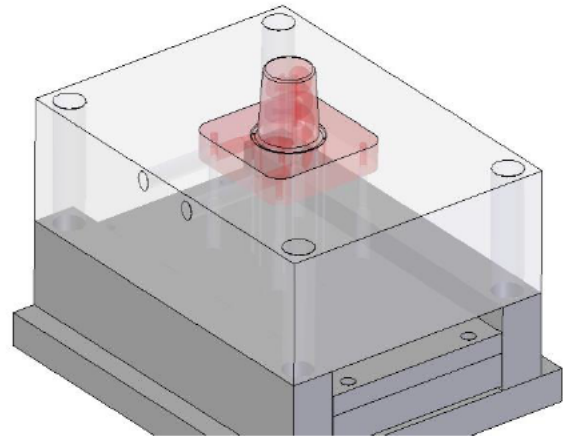


Figure 8.4: CAD of the moving half

### 8.3.2 Cooling channel layout

Conformal cooling channels were used in this design. The cooling channels in the cavity have a helical profile with a pitch of 22 mm and two turns while the channels in the core have a helical profile with a pitch of 18.5 mm and two turns, see figures 8.5 and 8.6. At the bottom of the cup profile of the cavity insert there is an additional cooling channel absorbing heat from the sprue system; therefore, the cavity insert has two inlets and two outlets, see Figure 8.5. The geometry of the cooling channels is rectangular in profile with dimensions of 10 mm x 8 mm with fillets of 2.5 mm in radius as shown in Figure 8.7. This geometry is also referred to as a long hole cross section, and it is known to improve the cooling performance of the mould [69]. Furthermore long holes cover more area compared to round holes. The cooling channels are spaced 4 mm from the surface of the cavity.

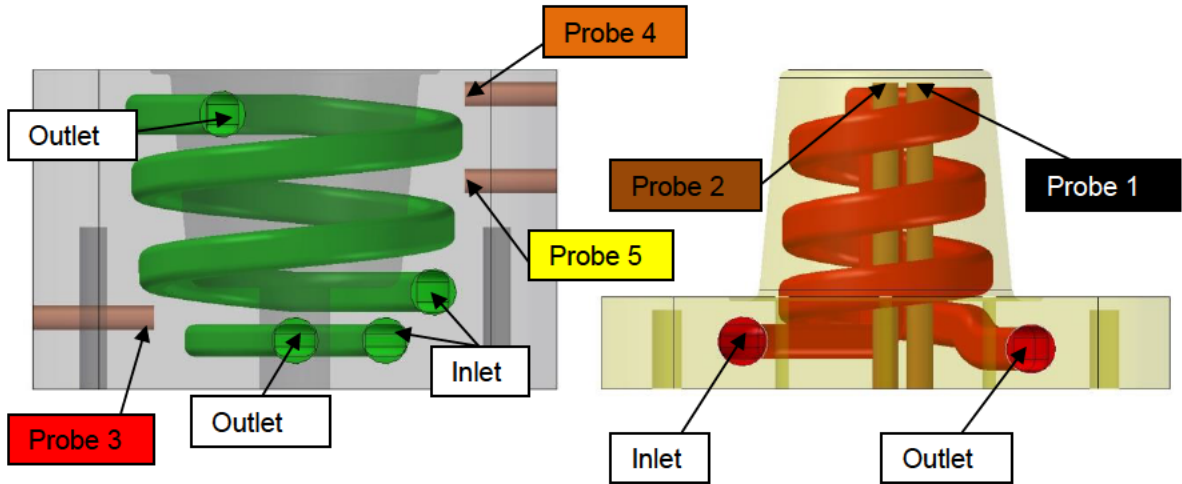


Figure 8.5: CAD of a cavity showing the cooling channel design

Figure 8.6: CAD of a core showing the cooling channel design

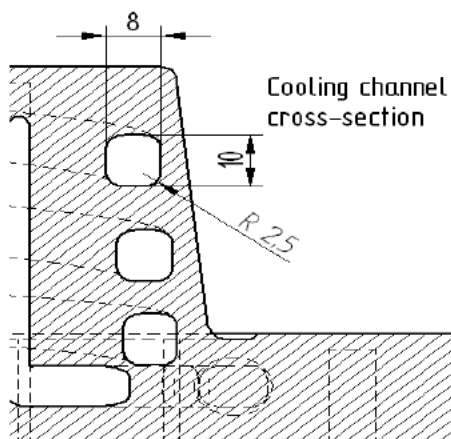


Figure 8.7: Cross-section of the cooling channel design

### 8.3.3 Arrangement of the probes

The design of the mould incorporated five holes which were used to insert the probes for the measurement of temperature within the mould. The objective of this was to monitor the mould temperature ensuring that it remains between 30 and 70°C which is within the range of the mould temperature for the ABS material. The arrangement is shown in figures 8.5, 8.6, 8.8 and 8.9. The probes on the core insert were placed 3 mm from the surface of the core. Probes 3, 4 and 5 were placed 13 mm, 11.5 mm and 13.5 mm further away from the

surface of the cavity respectively. The placement of the probes in the cavity side was restricted by the space between the cooling channels. It can be seen that a better measurement would be made from the core side where the probes are much closer to the surface of the cavity.

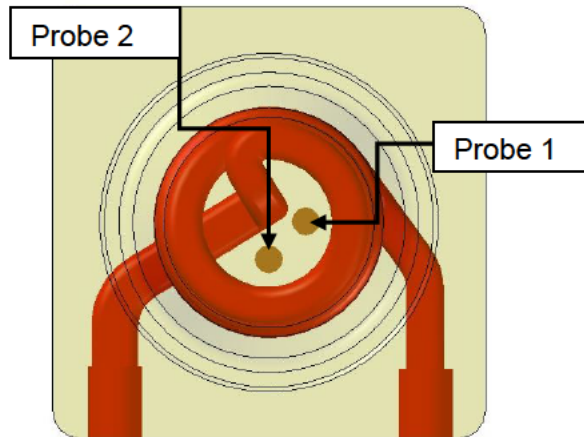


Figure 8.8: Probe arrangement (core top view)

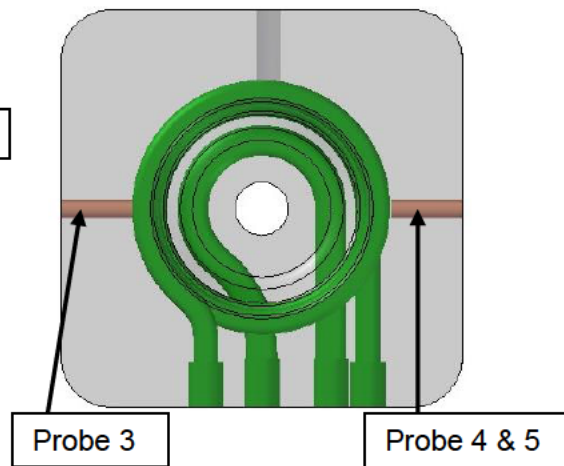


Figure 8.9: Probe arrangement (cavity top view)

## 8.4 SIMULATION

### 8.4.1 Introduction to simulation

During simulation an assumption was made that the total volume of water in the cooling system does not heat up because the water passes quickly through the channels to the chiller.

### 8.4.2 Simulation settings

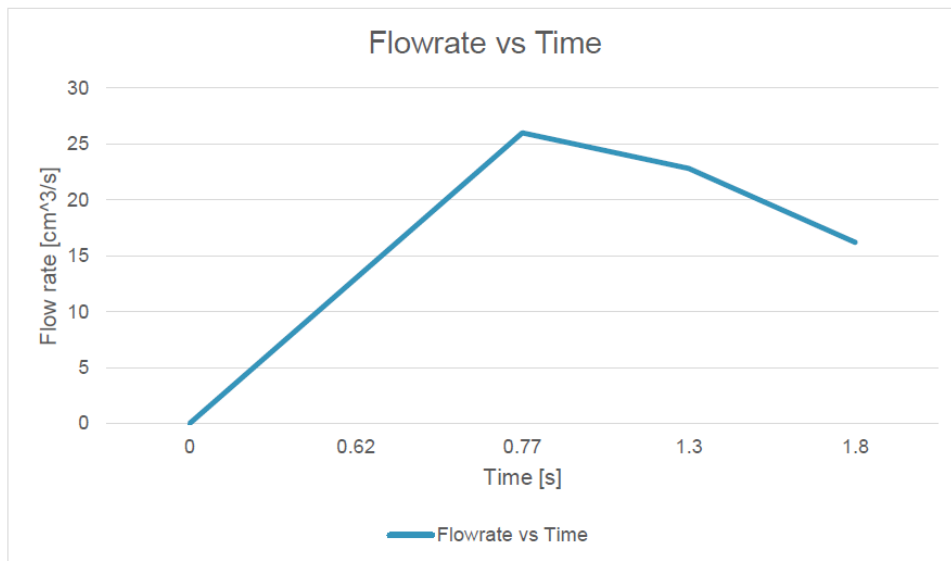
The following settings were used during simulation trials:

- Cooling medium: Water
- Water temperature: 19°C
- Mould close time after injection: 55 seconds
- Mould opening-closing time: 8 seconds
- Number of cycles simulated: 20

- Polymer material used: ABS Terluran GP35
- Melt temperature: 243°C
- Bolster material: Mild Steel
- Insert material: Alumide®

**(a) Filling flow-rate profile**

Filling flow rate reaches a maximum of 26 cm<sup>3</sup>/s as shown in Figure 8.10.



*Figure 8.10: Graph of filling profile: Flow rate vs time*

## (b) Packing profile

Packing pressure remained constant at 10.5 bars, as shown in Figure 8.11.

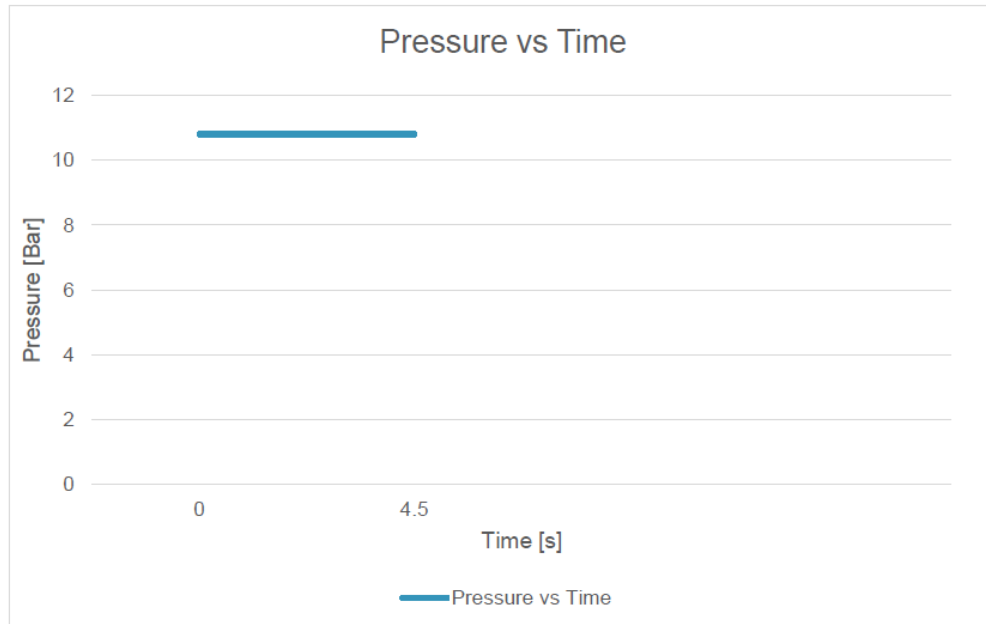


Figure 8.11: Graph of packing profile: Pressure vs Time

### 8.4.3 Simulation results

#### i. Temperature distribution in the mould inserts

The cooling results were based on the twenty cycles which were simulated in Sigmasoft®. In Figure 8.12 it can be seen that the majority of the surface of the cavity cooled down efficiently at around 48.4°C except the area at the sprue side which experienced a temperature of 77.8°C at the end of cooling. The area at the sprue was expected to be a hot spot as it is the feeding system where the molten polymer is injected into the mould.

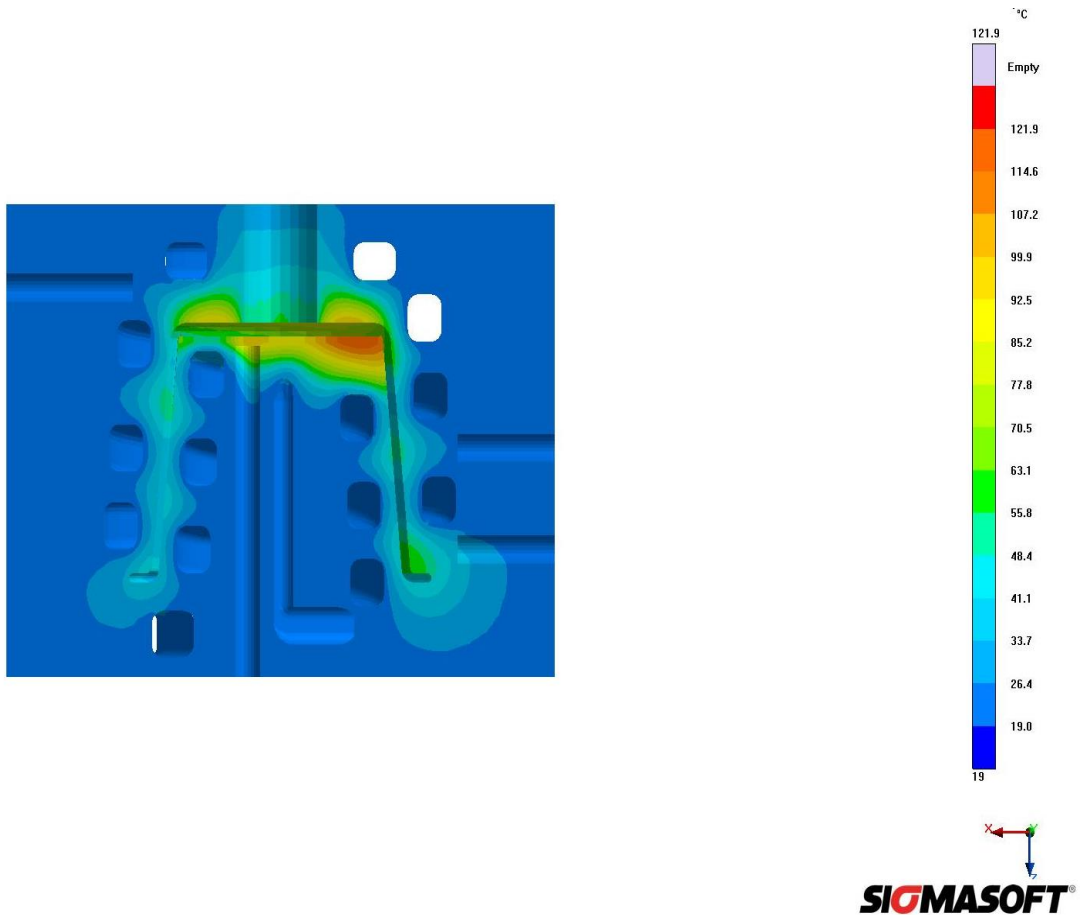


Figure 8.12: Cavity temperature at the end of cooling

ii. Temperature of the probes during simulation

The temperature inside the mould was measured from the beginning of the first cycle up to the 20<sup>th</sup> cycle using the five probes installed inside the moulds. With this condition, the temperature was expected to rise and reach a steady-state. The results are shown in figures 8.13 to 8.17.

The graphs represents ideal conditions during a moulding cycle. During injection, the temperature in the mould rises and drops during the packing and cooling stages. It can be observed that the moulding temperature reached a steady state as a uniform temperature was achieved. At the fourth cycle it can be seen from Figures 8.13 to 8.17 that the mould temperature began to reach steady state conditions. Probes 1 and 2 recorded the average

high temperature of 48.6 and 63.3°C respectively; this is because they were positioned closer to the feed system or the sprue. These temperatures were achieved during the filling stage. Probes 1 and 2 recorded average low temperatures of 39.1 and 51.5°C at the end of cooling respectively as shown in figures 8.13 and 8.14. Probes 3, 4 and 5 were placed away from the cavity surface, as explained in section 8.3.3; these probes recorded the average high temperatures of 23.4, 33 and 23.4°C respectively as shown in figures 8.15 to 8.17. At the end of cooling probes 3, 4 and 5 recorded average low temperatures of 22.8, 29.8 and 22.7°C respectively. The average values were obtained by considering the last four points in the high and low limit. At these points the mould temperature had stabilised significantly.

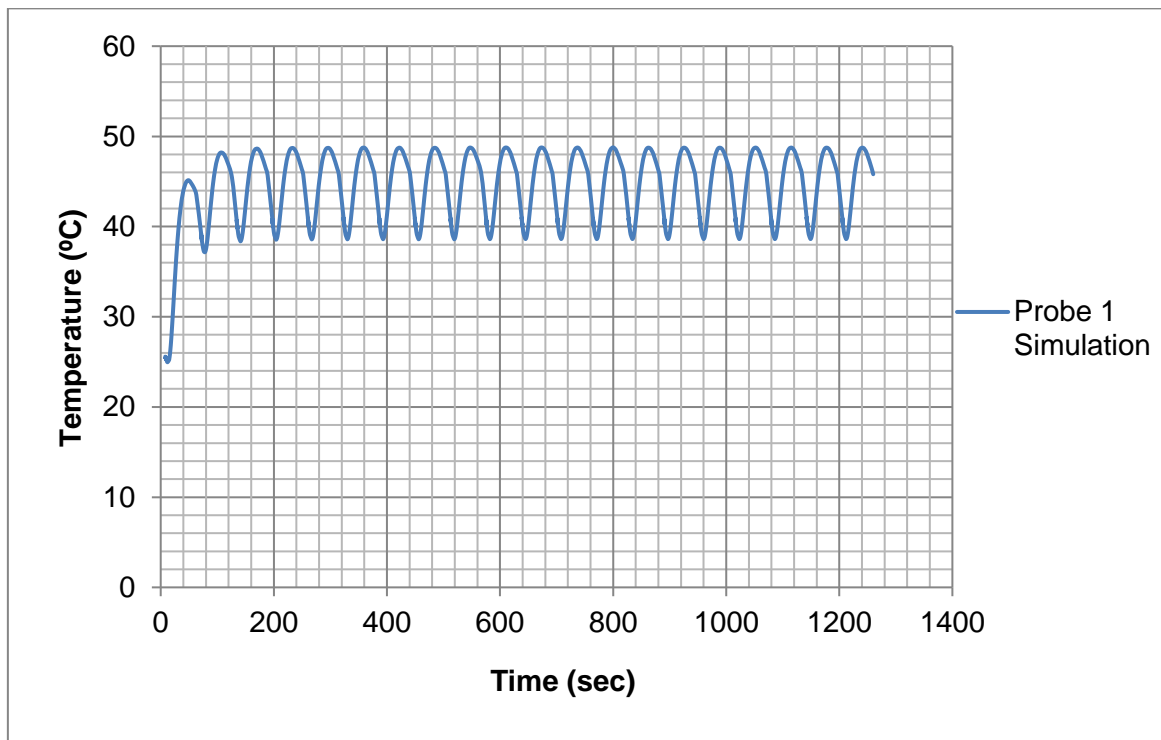


Figure 8.13: Graph of Probe 1 (simulation), temperature vs time (captured from first cycle up to the 20<sup>th</sup> cycle)

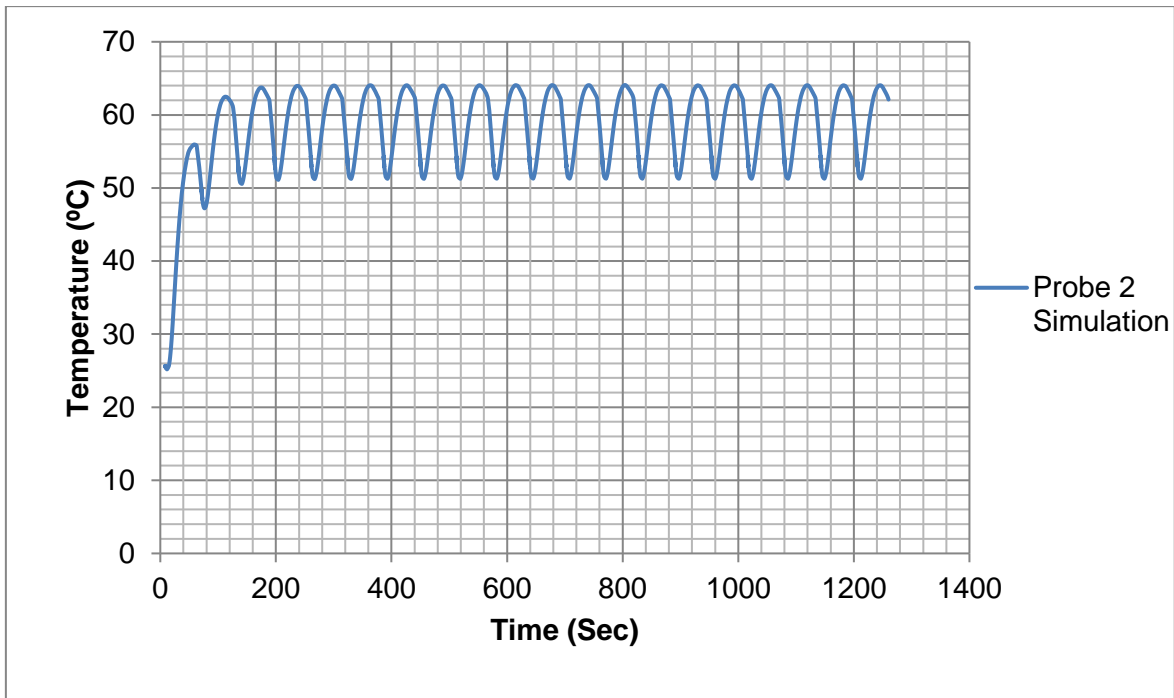


Figure 8.14: Graph of Probe 2 (simulation), temperature vs time (captured from first cycle up to the 20<sup>th</sup> cycle)

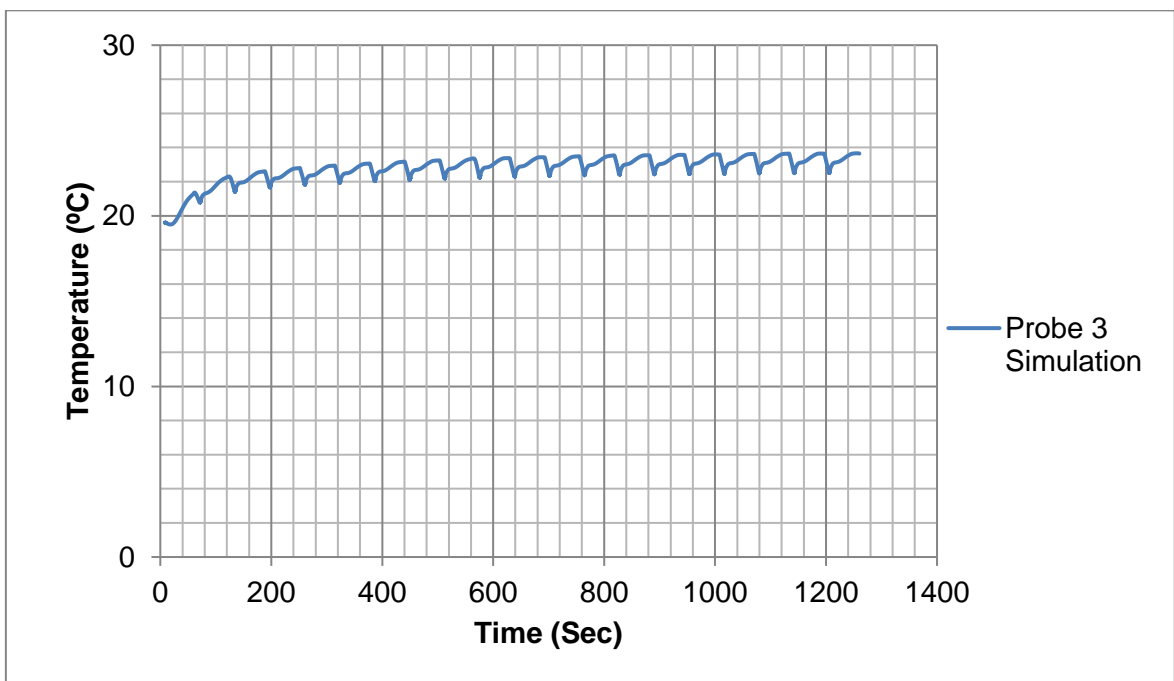


Figure 8.15: Graph of Probe 3 (simulation), temperature vs time (captured from first cycle up to the 20<sup>th</sup> cycle)

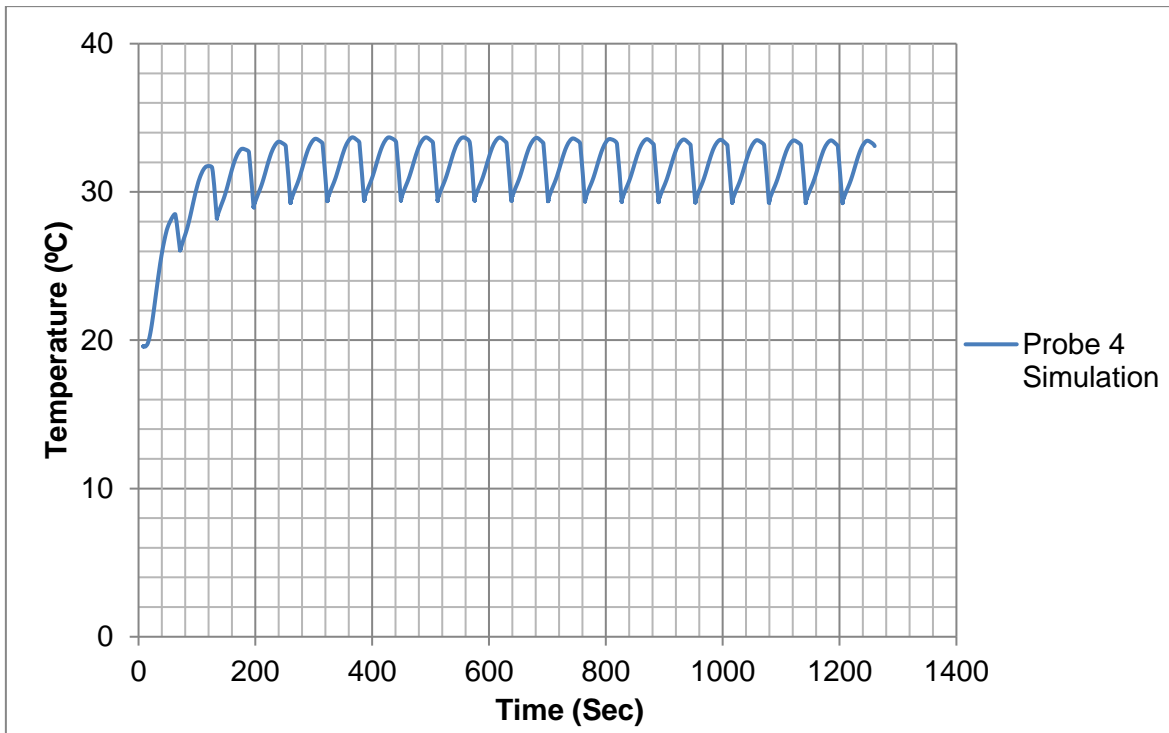


Figure 8.16: Graph of Probe 4 (simulation), temperature vs time (captured from first cycle up to the 20<sup>th</sup> cycle)

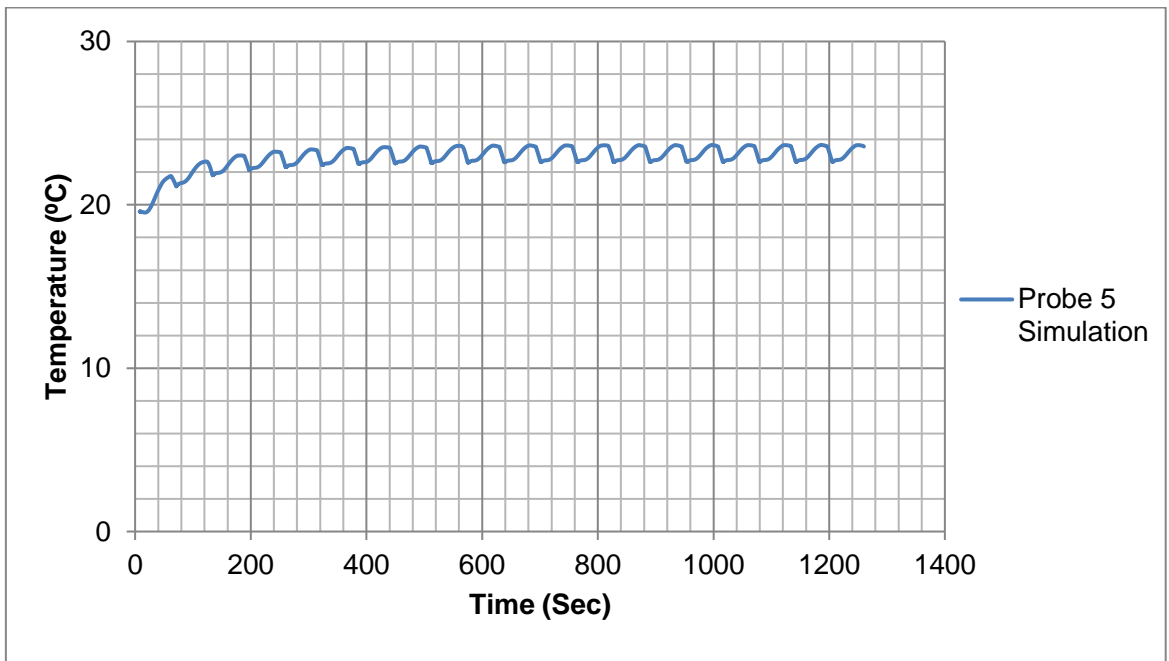


Figure 8.17: Graph of Probe 5 (simulation), temperature vs time (captured from first cycle up to the 20<sup>th</sup> cycle)

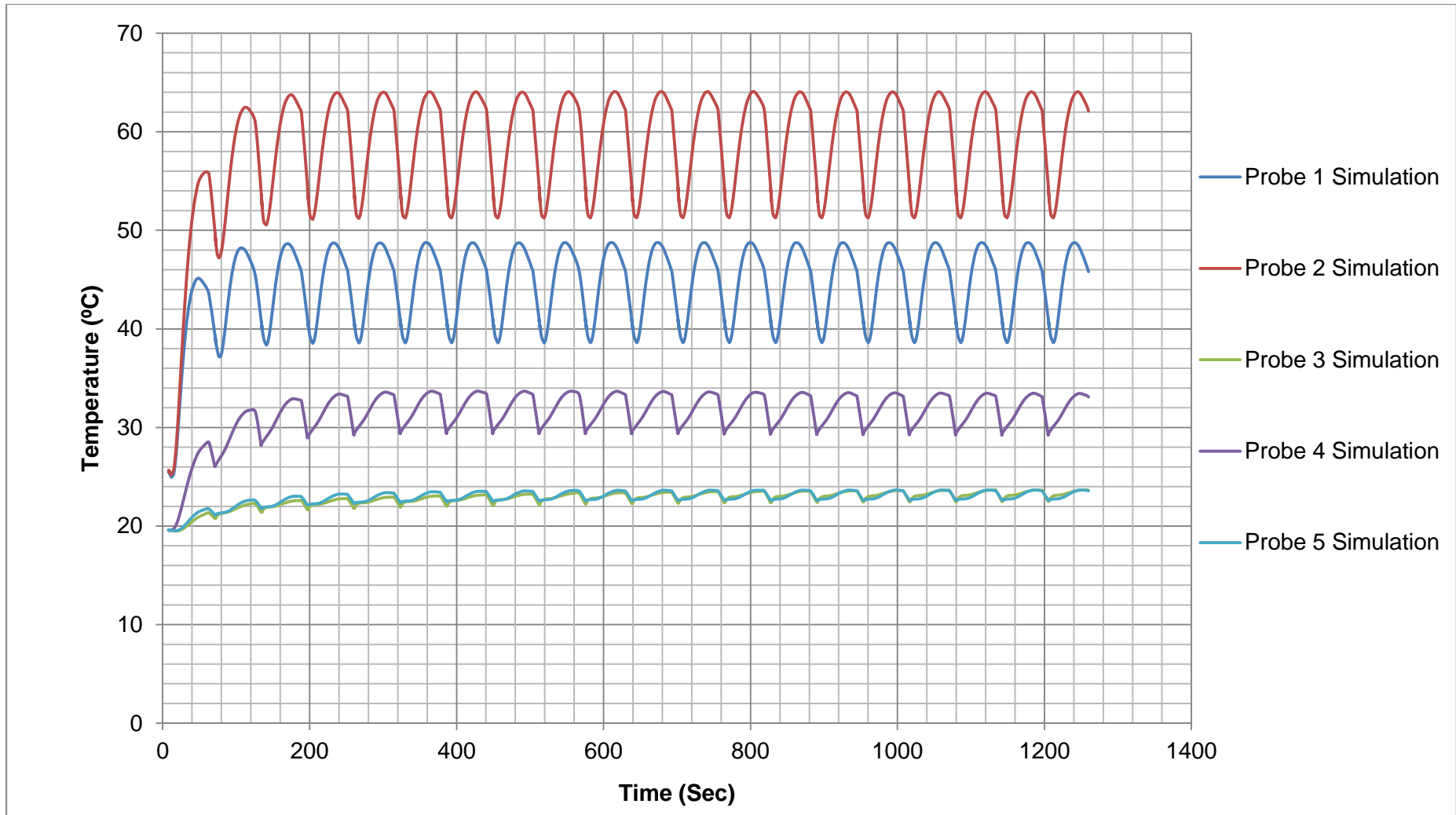


Figure 8.18: Graphs of Probes 1 to 5 (simulation), temperature vs time (captured from first cycle up to the 20<sup>th</sup> cycle)

## 8.5 FIELD TEST

The Alumide® inserts were manufactured on the LS machine as per design as shown in figures 8.19 and 8.20. The excess powder was then removed and the inserts were cleaned and fitted into the steel bolster, see Figure 8.21. Thermocouples to act as temperature probes were fitted to measure temperature on five points.



Figure 8.19: Alumide® core



Figure 8.20: Alumide® cavity

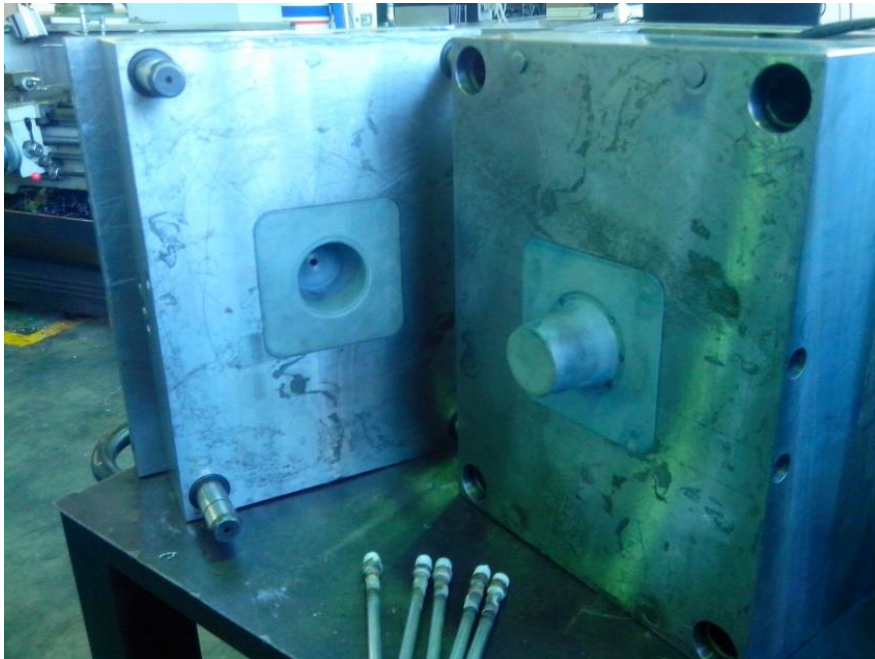


Figure 8.21: Alumide® inserts fitted in a steel bolster

### 8.5.1 Moulding parameters and procedure

Tests were performed on a Shine Well SW-90B IM machine with a screw diameter of 32 mm, see Figure 8.22. The experimental procedure is the same as the one used in Case Study 1 except for the moulding parameters.



Figure 8.22: Mould loaded in the injection moulding machine

#### Machine setting

The following machine settings were used as shown in Table 8.1.

Table 8.1: Machine setting, field test of Case 2

<b>Barrel Temperature (°C)</b>	
Rear/Middle/Nozzle	168/228/245
<b>Water flow rate (cm<sup>3</sup>/sec)</b>	40.8
<b>Cooling Time (sec)</b>	40
<b>Filling Time (sec)</b>	5
<b>Injection Pressure (kg/cm<sup>2</sup>)</b>	918

The water flow rate was set to 147 litres per hour on the water flow regulator.

### 8.5.2 Experiment results

The main focus of the experiment was to see whether mould temperatures of between 30 and 70°C could be achieved using Alumide® with the applied moulding parameters and cooling channel design. The second focus was to be able to cool the component efficiently without experiencing problems related to mould cooling such as an unfilled cavity due to the polymer cooling too fast before 100% filling was achieved. Temperatures as measured by the probes are shown in Table 8.2 below:

Table 8.2: Field test results on the probes, from first to the 20<sup>h</sup> cycle, Case 2

	Probe 1	Probe 2	Probe 3	Probe 4	Probe 5
Time (Sec)	Temp (°C)	Temp (°C)	Temp (°C)	Temp (°C)	Temp (°C)
0	26.4	26.5	22.5	19.3	17.1
20	32.4	34.7	22.8	21.4	18.3
40	30.4	35.8	23.0	22.7	19.0
60	36.2	43.1	23.1	23.3	19.2
80	39.4	47.1	23.5	24.2	20.1
100	36.3	46.5	23.8	24.8	20.3
120	39.8	51.5	23.9	25.7	20.5
140	42.4	54.2	23.7	26.2	20.7
160	38.9	51.6	24.1	26.8	21.3
180	41.2	54.7	24.1	27.0	21.4
200	44.2	57.5	24.4	27.6	21.7
220	39.9	54.2	24.2	28.1	21.7
240	40.8	55.7	24.7	28.0	21.4
260	44.0	57.9	25.0	29.0	21.7
280	41.1	55.4	24.8	29.0	22.0
300	40.9	56.4	24.9	28.1	21.7
320	44.6	58.5	25.3	29.3	22.0
340	41.1	56.2	24.9	29.4	22.2
360	40.7	55.7	25.1	29.2	21.8
380	44.7	58.7	24.9	29.7	22.0
400	41.9	56.2	25.2	29.8	22.6
420	39.9	55.7	25.6	29.9	22.0
440	44.3	58.6	25.2	29.5	22.0
460	42.0	56.3	25.3	30.1	22.5
480	40.0	55.1	25.6	30.3	22.8
500	45.1	58.5	25.7	30.3	22.3

Table 8.2 (Continues)

	Probe 1	Probe 2	Probe 3	Probe 4	Probe 5
520	42.4	56.7	25.9	30.6	22.9
540	39.0	53.9	25.5	30.4	22.6
560	44.3	58.1	25.8	30.3	22.5
580	42.7	56.6	25.8	30.5	22.7
600	38.4	53.4	26.7	30.5	22.5
620	43.6	57.3	26.1	30.2	22.4
640	43.3	57.2	26.0	30.8	23.1
660	38.9	53.71	26.0	31.1	23.0
680	43.4	57.9	26.2	30.3	23.0
700	43.7	57.8	26.3	30.5	22.8
720	39.5	54.0	25.9	30.7	23.2
740	44.0	58.4	26.1	30.8	23.0
760	44.4	58.6	26.3	30.5	23.0
780	40.5	54.4	26.0	31.1	23.4
800	43.1	57.7	26.2	30.4	22.5
820	44.0	58.1	26.0	31.4	22.6
840	40.2	55.4	26.2	31.1	23.3
860	42.7	57.7	26.3	30.4	22.8
880	44.61	58.5	26.3	30.8	23.4
900	40.6	54.7	26.3	31.1	23.2
920	42.0	57.4	26.0	30.6	22.8
940	44.6	58.7	26.1	30.5	23.1
960	41.1	56.1	26.5	31.0	23.3
980	41.6	56.4	26.0	30.7	22.7
1000	44.7	58.4	26.0	30.5	23.0
1020	41.3	55.7	26.3	31.2	23.1
1040	41.3	56.5	26.5	31.0	22.9
1060	44.6	58.6	26.4	30.7	23.1
1080	41.6	56.5	26.3	31.3	23.2
1100	41.3	56.4	26.7	31.0	23.2
1120	45.1	59.1	26.5	30.9	23.3
1140	42.7	56.7	26.2	31.0	23.6
1160	39.8	55.4	26.7	31.1	23.1

### Graphical representation of the field test results

Graphs in figures 8.23 to 8.28 demonstrate further that the ideal moulding temperature of the ABS material was achieved. Probes 3 and 5 do not reach a temperature above 30°C, this is because they are positioned further away from the cavity surface.

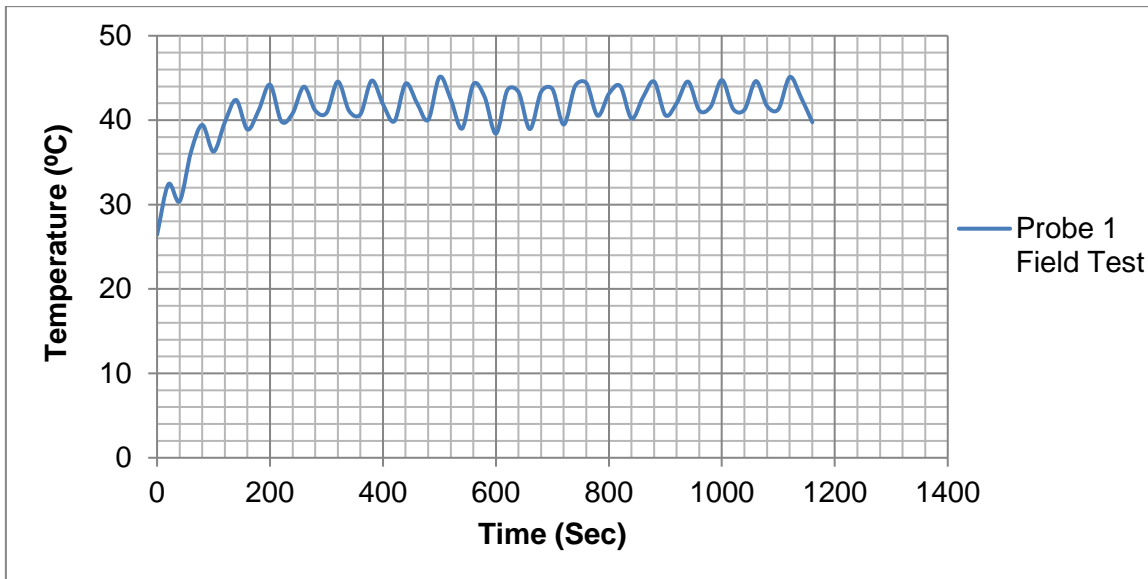


Figure 8.23: Graph of Probe 1 (field test), temperature vs time (captured from first cycle up to the 20<sup>th</sup> cycle)

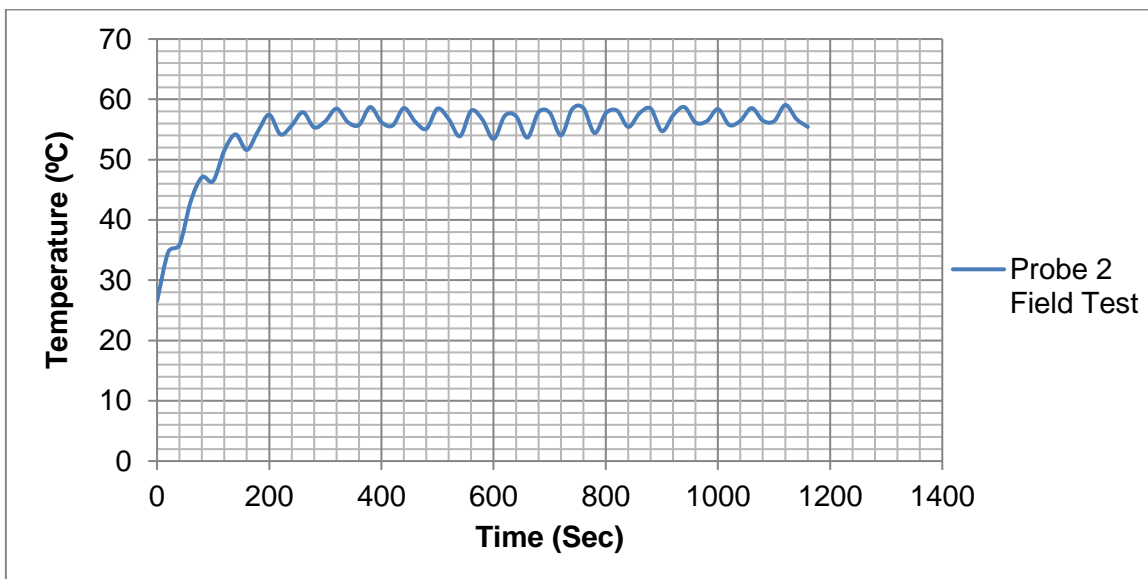


Figure 8.24: Graph of Probe 2 (field test), temperature vs time (captured from first cycle up to the 20<sup>th</sup> cycle)

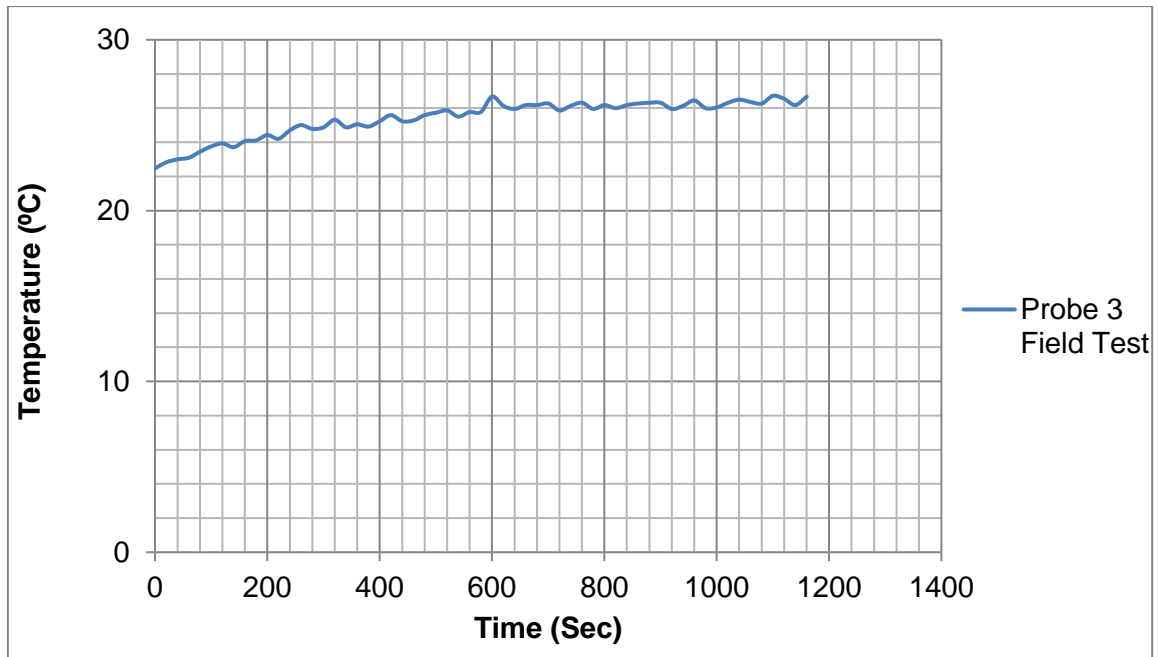


Figure 8.25: Graph of Probe 3 (field test), temperature vs time (captured from first cycle up to the 20<sup>th</sup> cycle)

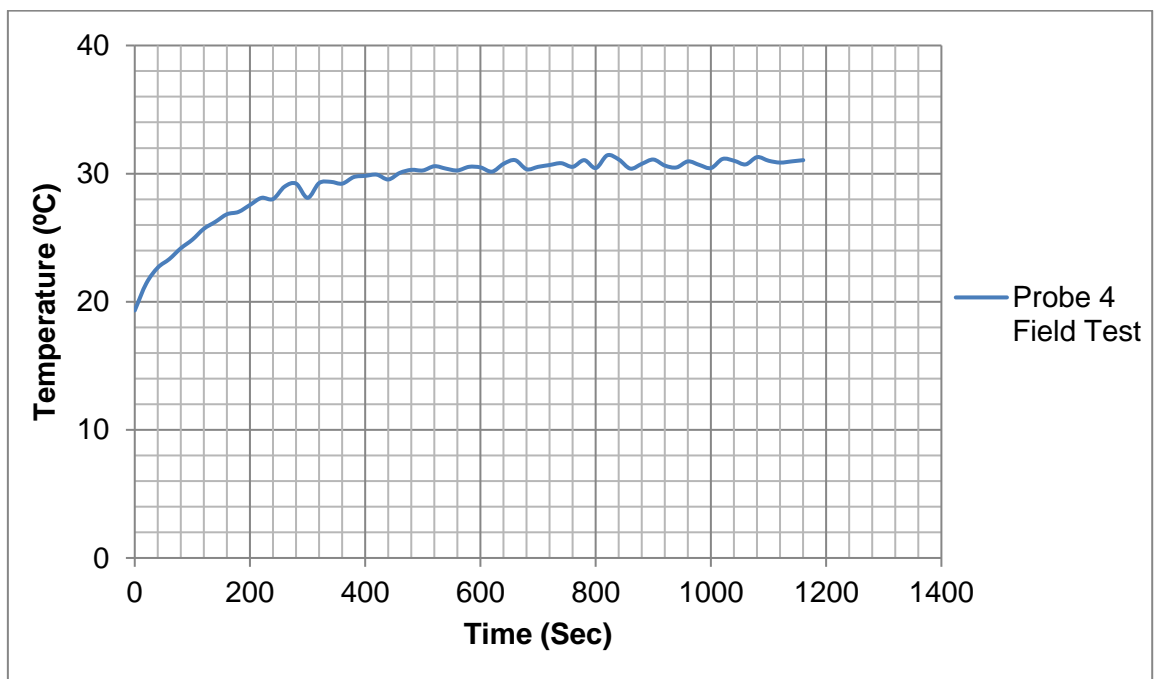


Figure 8.26: Graph of Probe 4 (field test), temperature vs time (captured from first cycle up to the 20<sup>th</sup> cycle)

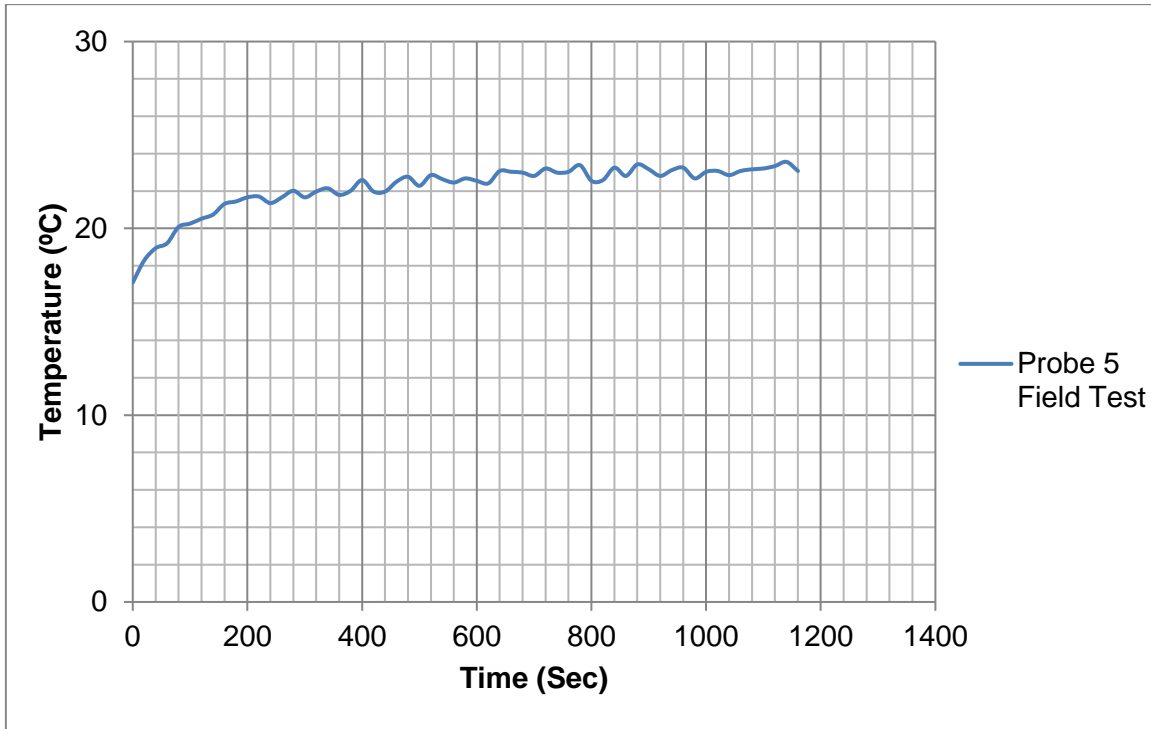


Figure 8.27: Graph of Probe 5 (field test), temperature vs time (captured from first cycle up to the 20<sup>th</sup> cycle)

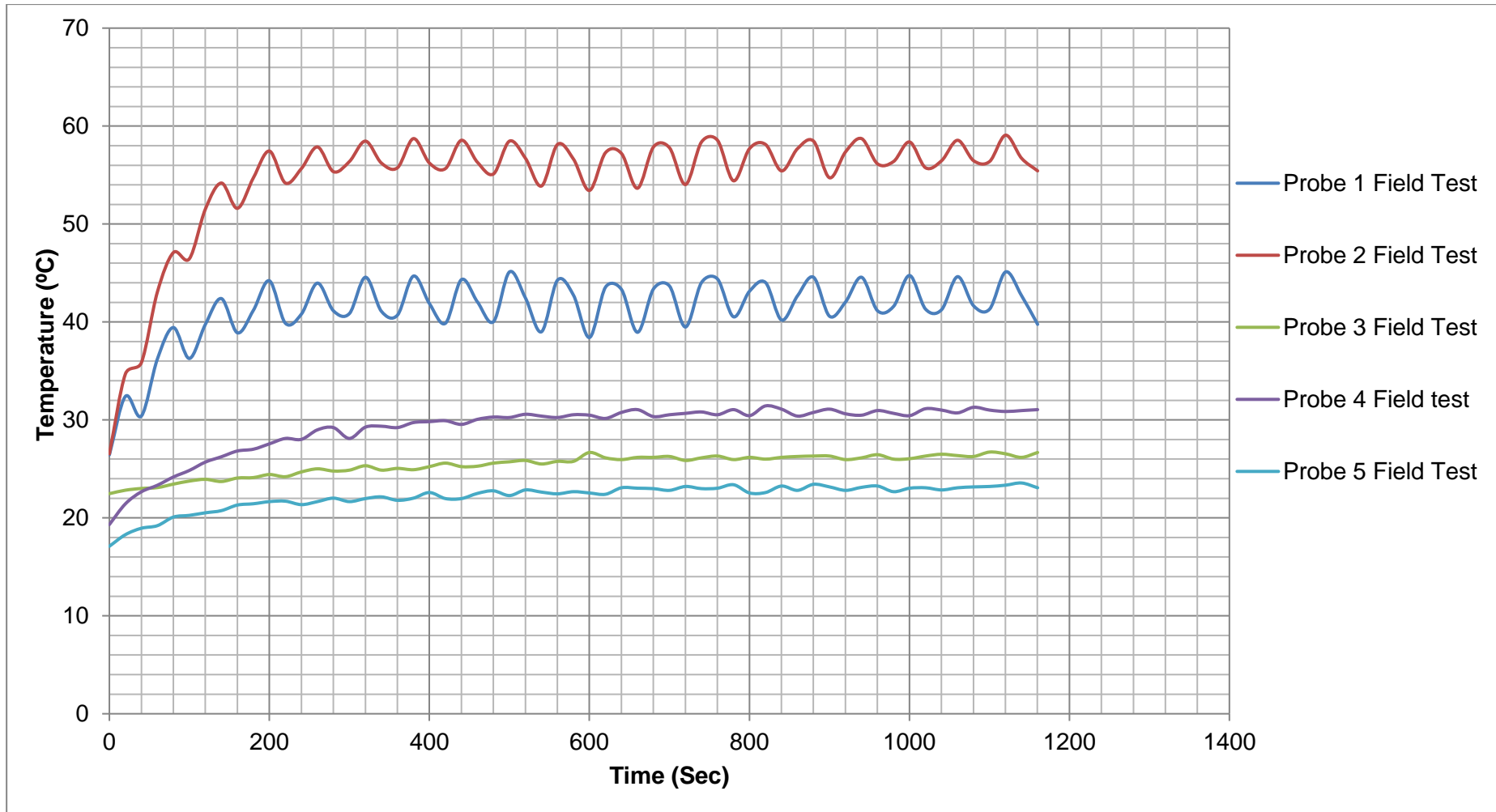


Figure 8.28: Graphs of Probes 1 - 5 (field test), temperature vs time (captured from first cycle up to the 20<sup>th</sup> cycle)

## 8.6 COMPARISON OF RESULTS: SIMULATION vs FIELD TEST

The temperature outputs simulated by Sigmasoft® were compared with the field test temperatures captured in LabView. The graphs in figures 8.29 to 8.33 demonstrate temperatures of the five probes both from simulation and the field test.

### a) Probe 1 comparison

Probe 1 recorded the average high temperature of 48.6 and 44.4°C during simulation and field test respectively, resulting in a deviation of 8.6%. The average low temperatures recorded at Probe 1 were 39.1 and 40.5°C during simulation and field test respectively, resulting in a deviation of 3.5%.

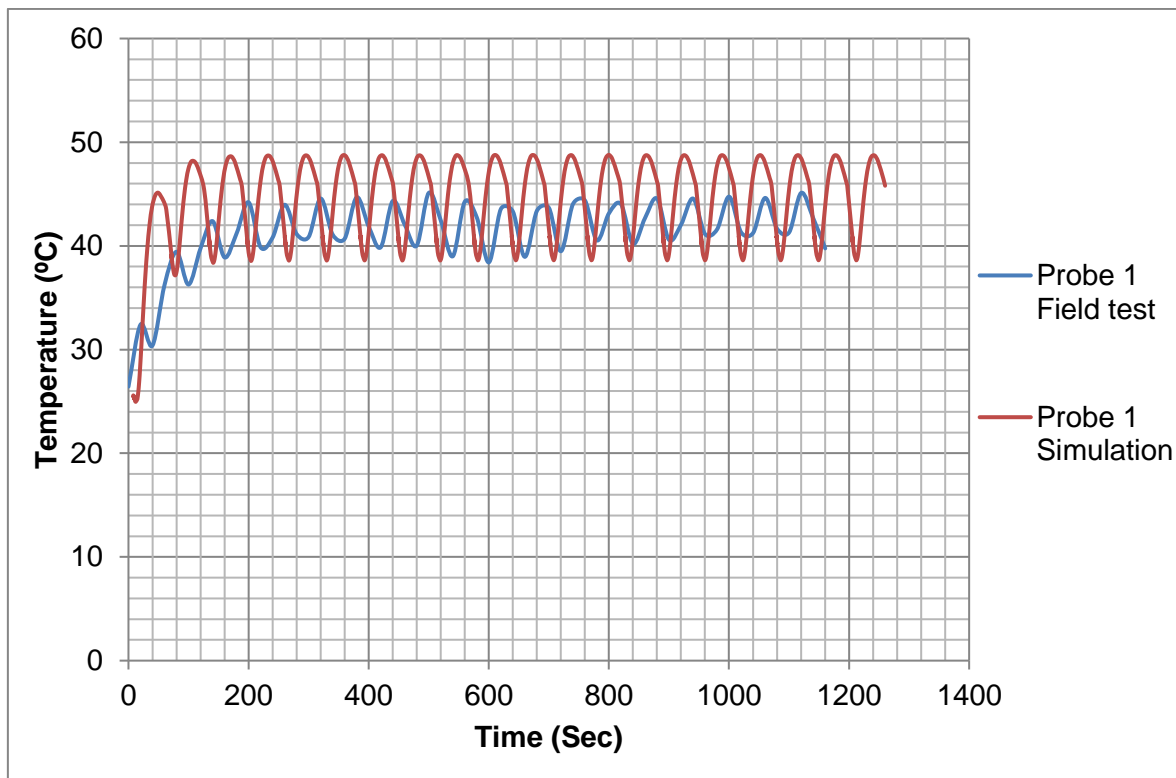


Figure 8.29: Comparison, Probe 1 graphs, temperature vs time (Case 2, field test vs simulation, for 20 cycles)

### b) Probe 2 comparison

Probe 2 recorded the average high temperature of 63.3 and 58.5°C during simulation and field test respectively, resulting in a deviation of 7.6%. The average low temperatures recorded at Probe 2 were 51.5 and 55°C during simulation and field test respectively, resulting in a deviation of 6.4%.

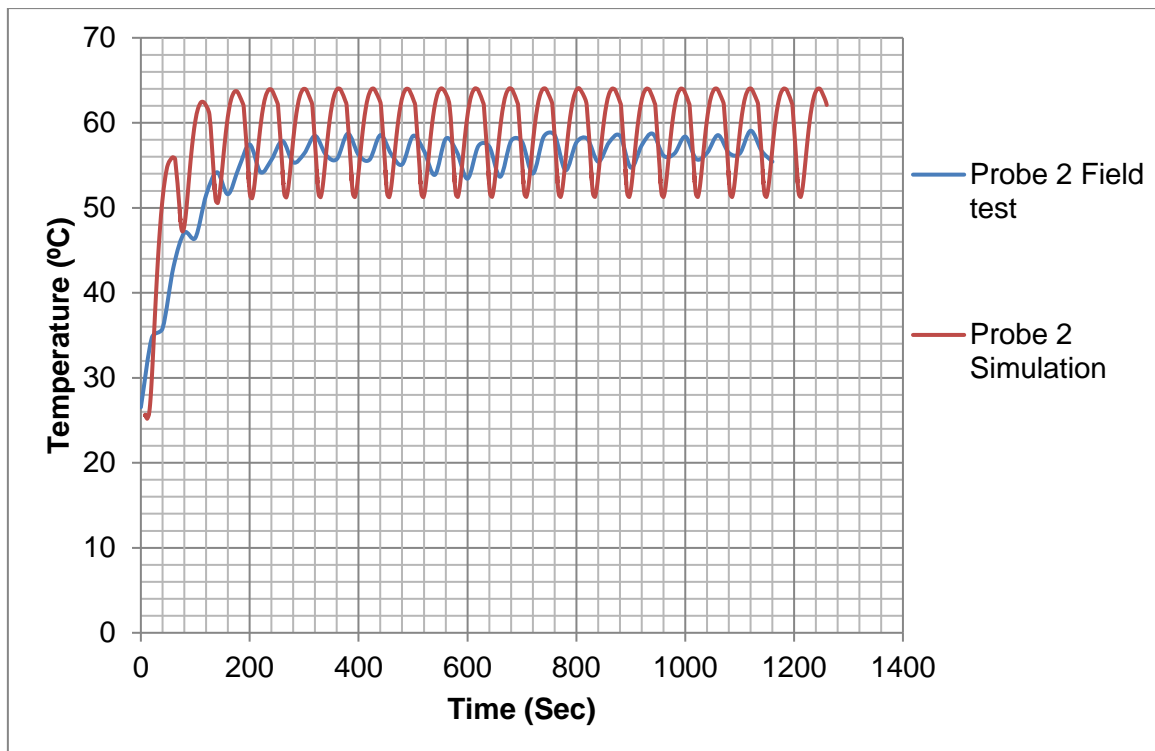


Figure 8.30: Comparison, Probe 2 graphs, temperature vs time (Case 2, field test vs simulation, for 20 cycles)

### c) Probe 3 comparison

Probe 3 recorded average high temperatures of 23.4 and 26.2°C during simulation and field test respectively, resulting in a deviation of 10.7%. The average low temperatures recorded at Probe 3 were 22.8 and 26.2°C during simulation and field test respectively, resulting in a deviation of 13%. It could be observed that there was no significant change in temperature

during filling and cooling stage as shown in Figure 8.31. This was because Probe 3 was position further away from the surface of the cavity.

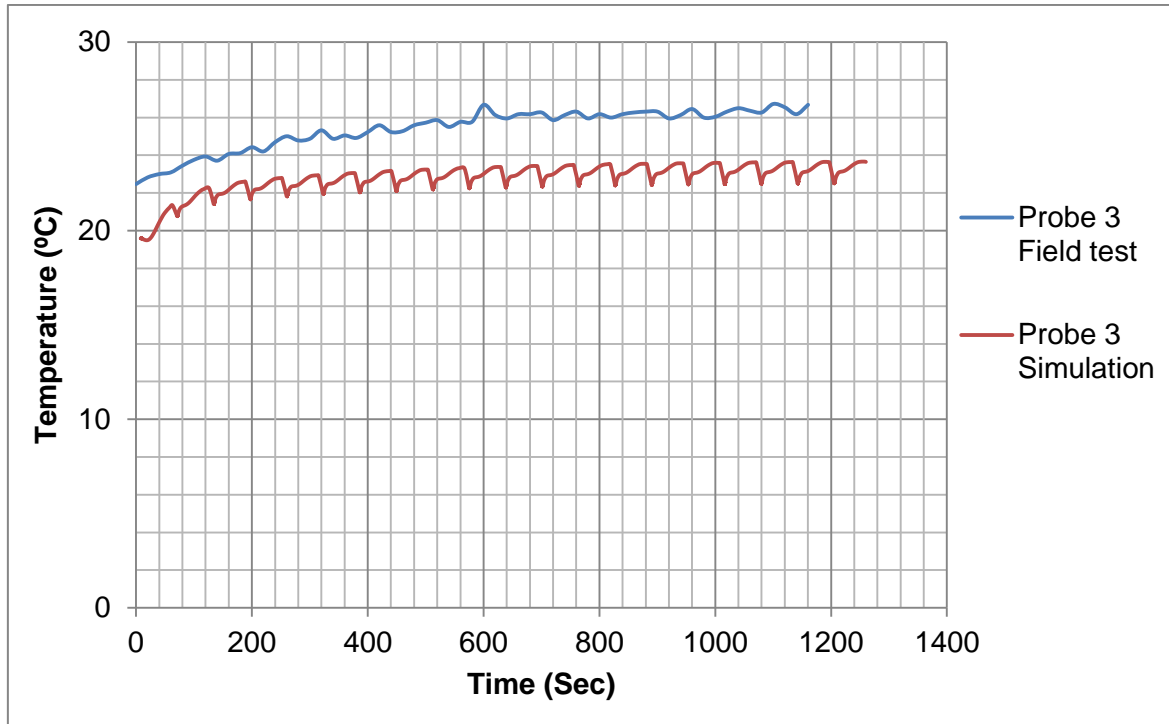


Figure 8.31: Comparison, Probe 3 graphs, temperature vs time (Case 2, field vs simulation, for 20 cycles)

#### d) Probe 4 comparison

Probe 4 recorded average high temperatures of 33 and 31°C during simulation and field test respectively, resulting in a deviation of 6%. The average low temperatures recorded at Probe 4 were 29.8 and 31°C during simulation and field test respectively, resulting in a deviation of 3.9%.

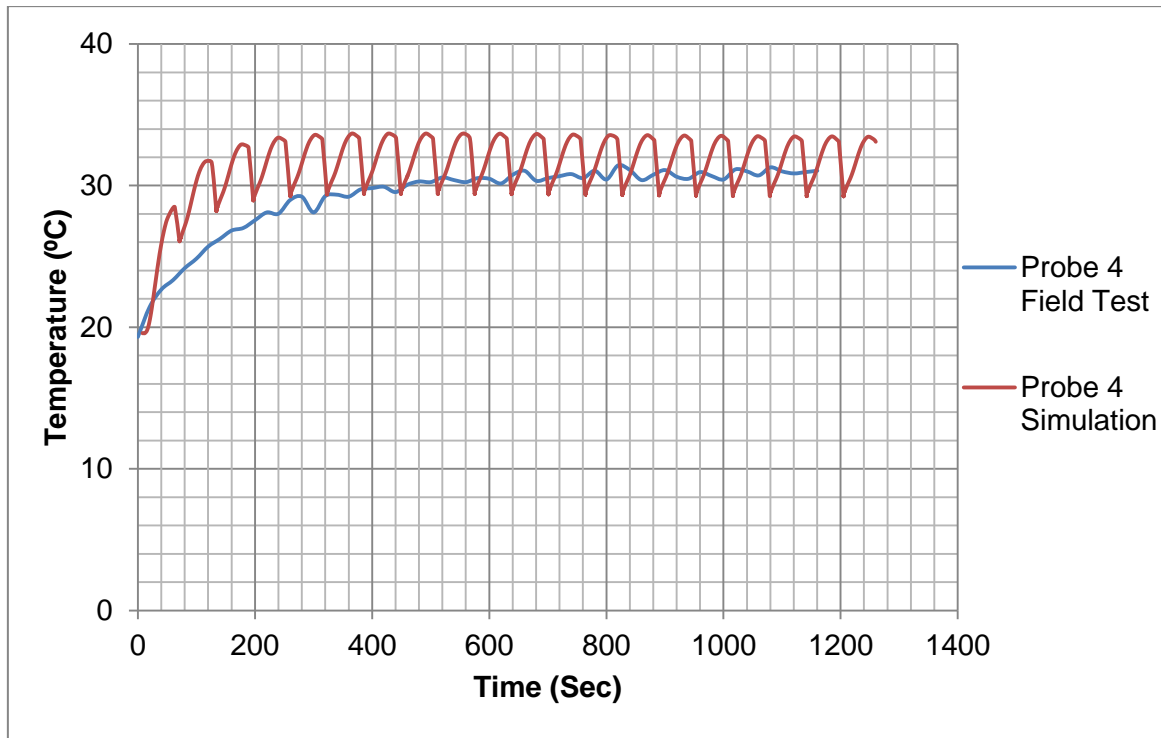
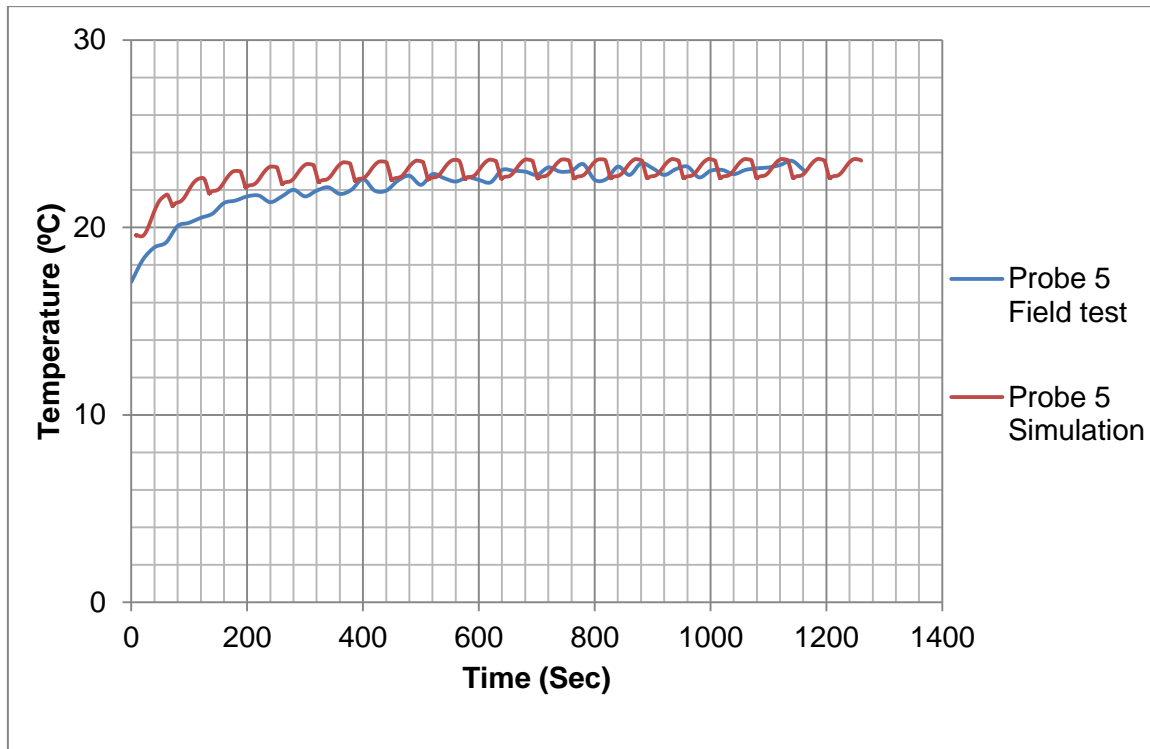


Figure 8.32: Comparison, Probe 4 graphs, temperature vs time (Case 2, field test vs simulation, for 20 cycles)

#### e) Probe 5 comparison

Probe 5 recorded average high temperatures of 23.4 and 23°C during simulation and field test respectively, resulting in a deviation of 1.7%. The average low temperatures recorded at Probe 5 were 22.7 and 23°C during simulation and field test respectively, resulting in a deviation of 1.3%. The change in temperature between filling and cooling stage was 0.4°C, this is a small change due the position of measuring probe.



*Figure 8.33: Comparison, Probe 5 graphs, temperature vs time (Case 2, field test vs simulation, 20 cycles)*

To simplify the comparison between simulation and field tests, temperatures are tabulated in Table 8.3. From Table 8.3 it can be observed that the deviation between simulation and field tests is within 6.3% on average, which is an acceptable value. The deviation may be caused by a factor such as room temperature during field testing.

Table 8.3: Case Study 2, average high and low probe temperatures during simulation and field tests (Deviations provided)

	<b>Simulations (°C)</b>	<b>Field tests (°C)</b>	<b>Deviation (%)</b>
Probe 1, average high temperatures	48.6	44.4	8.6
Probe 1, average low temperatures	39.1	40.5	3.5
Probe 2, average high temperatures	63.3	58.5	7.6
Probe 2, average low temperatures	51.5	55	6.4
Probe 3, average high temperatures	23.4	26.2	10.7
Probe 3, average low temperatures	22.8	26.2	13.0
Probe 4, average high temperatures	33	31	6
Probe 4, average low temperatures	29.8	31	3.9
Probe 5, average high temperatures	23.4	23	1.7
Probe 5, average low temperatures	22.7	23	1.3

## 8.7 DISCUSSION OF RESULTS

The prescribed moulding temperature of ABS material is between 30 to 70°C. This condition was achieved during simulation and field test. Probes 1 and 2 experienced higher temperatures due to their position close to the sprue. These two probes were also positioned close to the surface of the cavity (at 3 mm); therefore, provided good feedback on the mould temperature during the moulding process. Probes 3, 4 and 5 needed to be positioned further away from the surface due to space restrictions because of the position of the cooling channels. It can be observed that these probes do not reach temperatures of over 34°C because less heat was conducted from the cavity during moulding at these areas. The deviations tabulated in Table 8.4 present good correlations of results achieved between simulations and field tests.

ABS polymer with a melt temperature of 243°C was injected into the mould resulting in a surface temperature of 48.4°C at the end of cooling after 20 cycles, this amounts to a cooling efficiency of 80%. Three hundred products were produced, (Figure 8.34) whereafter the mould started to show wear on the side of the core where the cooling channels were positioned, (Figure 8.35).



Figure 8.34: Cups manufactured

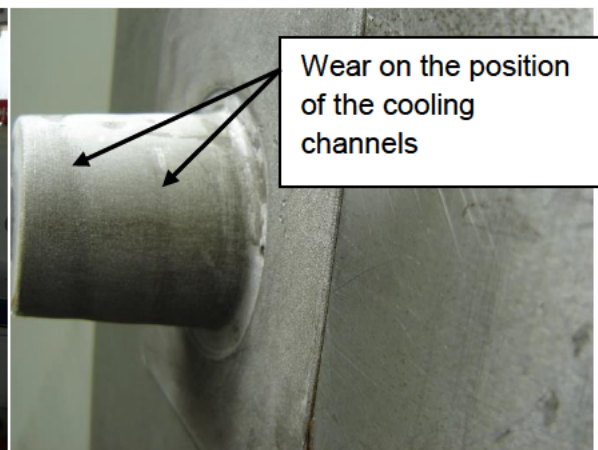


Figure 8.35: Alumide® core insert showing wear

## 8.8 CHAPTER SUMMARY

Case study 2 investigated the manufacturing of a polymer cup with a height of 72 mm, a top diameter of 55 mm, a wall thickness of 2 mm and a draft angle of 5°C. The design of the cooling channels were simulated in Sigmasoft® before the actual inserts were manufactured on the EOS P380 AM machine. Only 20 IM cycles were simulated using the software in order to speed-up the simulation time.

The focus was to investigate the cooling efficiency of Alumide® inserts with the designed cooling channels and moulding parameters during polymer IM cycles. The study shows that the mould temperature reached a steady state after the fourth cycle except for probe 3 which started to stabilize at the seventh cycle.

By comparing simulation and field results it can be observed that the temperatures measured with the probes fall within the moulding temperature for the ABS material used in this research, which is between 30 and 70°C.

## CHAPTER 9: CONCLUSION AND RECOMMENDATIONS

### 9.1 CONCLUSIONS

The main focus of this study was to optimize cooling in Alumide<sup>®</sup> inserts in order for the material to be used as a tooling material for limited run IM of polymer parts. LS of Alumide<sup>®</sup> is performed at a temperature of 180°C which is close to the melting point of most polymer materials generally used for IM. Only one polymer material namely ABS was investigated in this study for use with Alumide<sup>®</sup> tooling. This material has a melting point of 230°C which is 50°C higher than the melting point of Alumide<sup>®</sup>.

In this dissertation, two preliminary experiments and two case studies were performed on Alumide<sup>®</sup> moulds manufactured through LS and the conclusions are presented below.

#### 9.1.1 Investigation into powder removal from straight channels and conformal cooling channels

In the powder removal from cooling channel experiment, it proved relatively easy to clear unsintered powder from straight channels, which are on the same plane, taking into consideration the size of the channel. The experiments on straight channels in Chapter 6 showed that channels with diameters of 4 mm, 6 mm, 8 mm, 10 mm and 12 mm could be cleared. A 2 mm diameter channel could not be cleared. The conclusion on this experiment was that smaller diameters should be avoided wherever possible during the design of cooling channels. Another factor to be considered is the method used for removing the powder. In this case, a thin wire of 1 mm in diameter and compressed air of 0.6 MPa were used.

Powder removal from conformal cooling channels with more complex shapes proved to be a difficult task. Cooling channels in the test samples were of a spiral design and four different samples with channel diameters of 4 mm, 6 mm and 8 mm were used. It was only possible to remove 80% of the loose powder from the 8 mm channel of the test sample.

From the study of powder removal in conformal cooling channels it was concluded that smaller diameters should be avoided. Cooling channels with sharp bends should also be avoided since this will make it easier for the wire to pass through the channels and loosen the powder.

### **9.1.2 Investigation of a safe wall thickness between the mould cavity and cooling channels for Alumide<sup>®</sup> inserts produced by laser sintering**

Experiments were conducted to identify a safe wall thickness between the cooling channels and the mould cavity suitable to prevent leakage of water in Alumide<sup>®</sup> inserts. An Alumide<sup>®</sup> test sample with six straight channels of diameter 8 mm and wall thicknesses of 0.5 mm; 1 mm; 1.5 mm; 2 mm; 2.5 mm and 3 mm was manufactured. All the channels were closed off at one end. Tests were performed by forcing water into each channel using a hand pump capable of 6000 KPa. From the results of the wall thickness experiment it was concluded that a thickness of 2 mm and above will be safe for preventing leakage into the cavity of the mould.

### **9.1.3 Case study 1 – Flat component**

The focus of Case study 1 was to determine if a polymer component of simple geometry can be successfully manufactured in Alumide<sup>®</sup> moulds with conformal cooling channels. Moulds for a flat component of dimensions 80 mm x 80 mm x 3 mm were designed and manufactured through LS in Alumide<sup>®</sup> and inserted into steel bolsters. The mould design included cooling channels placed on a single plane both in the fixed and moving sides of the mould. Moldex3D software was used in Case Study 1 to analyse the cooling design. To verify the simulation model, heat sensing probes were inserted into the Alumide<sup>®</sup> moulds through holes designed into the moulds for this purpose. The position of the eight measuring points were also indicated as nodes on the simulation model of the moulds. The probes were placed 3 mm below the surface of the cavity. It was important that the mould temperature remained between 30 and 70°C which is the mould temperature for the ABS

material used as specified by the manufacturer. Field experiments were also performed on an IM machine and mould temperatures of the measuring points were compared with the simulation results by capturing the data using LabView.

A cooling time of 50 seconds was set for both the simulation and field experiments with the ABS melt temperature at 220°C. Probe measurements in the average low temperatures ranged from 38.2 to 56.1°C during simulation. For the field tests, the probe measurements in the average low temperatures ranged from 35.8 to 58.1°C. Probe measurements in the average high temperatures ranged from 52.9 to 67.8°C during simulation whereas for the field tests temperatures ranged from 39.3 to 62.5°C. Considering these results, Moldex3D proved successful in predicting the heat distribution in Alumide® moulds of simple geometry.

A test to check the tensile strength of the ABS parts produced by Alumide® tools was conducted. The tensile strength measured 7.5% below that specified in the manufacturer's specifications for the material, which is considered acceptable.

In conclusion to Case study 1, it was observed that 500 parts were produced without any damage to the mould and the parts were ejected without any difficulty. The cooling channels incorporated into the Alumide® moulds successfully cooled the moulds for the temperature to remain between 30 and 70°C which is an ideal condition for the ABS used. In the average high temperatures, the simulation temperature predictions were higher compared to what was measured in the field tests. The reason for this may be attributed to a number of factors including the room temperature at the time of moulding and the chiller water temperature. A cooling time of 50 seconds was sufficient for cooling the moulds during production resulting in a cooling efficiency of 95.4%.

#### 9.1.4 Case study 2 – Polymer Cup

A cup geometry was decided on for Case study 2 since it would absorb more heat over a larger volume of the cavity and core. The geometry would therefore allow for the advantages of conformal cooling to be clearly demonstrated. As with Case Study 1, the focus in Case Study 2 was to design cooling channels for the Alumide<sup>®</sup> tool and use correct moulding parameters during IM of the polymer part. For Case Study 2, Sigmasoft<sup>®</sup> simulation software was used to analyse the effectiveness of the cooling channels on the moulds. Conformal cooling channels for the single cavity mould were designed on both the cavity insert and the core. A spiral cooling channel design was chosen with a core pitch of 18.5 mm and the cavity with a pitch of 22 mm. This design was chosen because it easily conforms to the shape of the cavity and core. A rectangular geometry of 8 mm x 10 mm was used for the cooling channels because it covers more surface area compared to the round geometry and also it provided turbulent flow. The design was also provided with five measuring points in order to monitor the mould temperature.

Melt temperatures of 243 and 245°C for the ABS material were used for the simulation and field test respectively with a cooling time of 40 seconds. Twenty cycles were simulated and compared with twenty cycles of the field test. The simulation showed a temperature distribution of 48.4°C at the cavity surface. As expected, the area around the sprue experienced a higher temperature of 77.8°C.

The mould temperature in the core provided a better indication of the temperature in the moulding cavity since Probes 1 and 2 were placed 3 mm from the core surface as opposed to the probes 3, 4 and 5 which were placed 13 mm, 11.5 mm and 13.5 mm away from the surface of the cavity respectively. Probes 1 and 2 predicted average high temperatures of 48.6 and 63.3°C respectively during simulation. During field test, probes 1 and 2 recorded average high temperatures of 44.4 and 58.5°C respectively. These temperatures fell within the allowable moulding temperature of the ABS material used in the experiments.

Sigmasoft® was successful in predicting the temperature distribution within the Alumide® mould.

Three hundred parts were produced before the mould started to show defects in the form of a dent forming along the cooling channels on the core insert's surface. This may have been caused by the Alumide® deflecting inwards along the channels although the cooling channels were spaced 4 mm from the cavity surface. It may also be that the core experienced more heat than the cavity as the product shrunk onto the core during cooling.

With a cooling efficiency of 80% it can be concluded that conformal cooling was successful in cooling the Alumide® moulds for PIM, with 300 parts produced.

#### **9.1.5 General conclusion**

Case study 1 achieved a cycle time of 75 seconds while Case study 2 achieved a cycle time of 63 seconds. These cycle times are satisfactory considering that Alumide® tooling is for short production runs. The tensile strength of the parts produced gave satisfactory values compared to the manufacturer's specifications. During this study, Alumide® moulds have shown excellent results. Having included cooling channels directly into the Alumide® inserts proved to be beneficial by keeping the mould temperature within the range of the polymer being moulded. For the ABS material used in this research the mould temperatures were optimized to 58.1 and 55°C in the field test at the end of cooling for Case Study 1 and 2 respectively. These mould temperatures are suitable for IM of the ABS material. The research presented has successfully validated the use of Moldex3D and Sigmasoft for simulating heat transfer in Alumide® moulds for ABS.

## **9.2 FUTURE WORK**

Alumide® inserts proved to be weak around the cooling channels which affects the quality of the products. The distance between the channels and the cavity was found to play a significant role. In this study, wall thicknesses for water flowing through channels were checked, as described in Chapter 6. It was shown that a thickness of 2 mm was sufficient

to prevent water from entering the mould cavity. How the moulding pressure and temperatures during IM would affect the mould life was not investigated. The results of the studies showed that the design of cooling channels may affect the mould life after a number of cycles. In Case Study 1, after 500 parts, no visible defects were observed. In this instance, the cooling channels were spaced 6 mm from the surface of the cavity. Case Study 2 showed defects along the cooling channels after only 300 parts were produced. Cooling channels were spaced 4 mm from the surface of the cavity and core, but the defects only appeared on the core. Although Alumide® moulds are for short production runs, further research can be performed to investigate how to prolong the life of these moulds. From this study it can be concluded that further research is necessary such as:

- An investigation into the suitability of polymers with low, medium and high melting points for IM in Alumide® moulds.
- Further case studies on Alumide® moulds to investigate how to prevent defects along cooling channels by changing channel design and moulding parameters.
- Perform surface characterization of Alumide® inserts to determine if the roughness induced by the AM process is acceptable for IM moulds.
- Previous tests on laser sintered Alumide® moulds performed by Booysen et.al. (2006), showed good dimensional accuracy on the produced parts [6]. More dimensional testing however need to be performed on components manufactured in Alumide® moulds that require assembly.
- PIM design rules for Alumide® moulds need to be established such as minimum allowable wall thicknesses, draft angles etc.
- The research presented have validated the use of Moldex3D and Sigmasoft for simulating heat transfer in Alumide® moulds for IM of ABS. Heat transfer can also be simulated for other engineering thermoplastic polymers in Alumide® moulds.

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## Appendix A

Table 1: Thermal diffusivity of plastic material and mould bases

Material	Thermal Diffusivity (m <sup>2</sup> / hr x 10 <sup>3</sup> )
<b>Resins</b>	
ABS	0.480
Acetal	0.456
Acrylic	0.557
Epoxy	1.320
Nylon	0.398
Phenylene Oxide	0.555
Polypropylene	0.254
Polycarbonate	0.452
Polyester	0.489
Polyethylene	0.681
Polystyrene	0.312
Vinyl, PVC	0.389
<b>Mould bases</b>	
Aluminium	187
Beryllium Copper	155
H13	29.4
P6	46.7
P20	36.3
S7	24.2
414SS; 420SS	25.1

## Appendix B

### SPECIFICATIONS FOR THE SW INJECTION MOULDING MACHINE SERIES

An SW-90B injection moulding machine with a 32 mm screw diameter was used for the case studies

MODEL	UNIT	SW-90B	SW-120B	SW-150B	SW-190B	SW-230B	SW-270B	SW-320B														
<b>Injection Unit</b>																						
Screw Diameter	mm	32	36	40	36	40	45	40	45	50	45	50	55	50	55	60	55	60	65	60	65	70
Injection Pressure	kg/cm <sup>2</sup>	2297	1815	1470	2177	1763	1393	2166	1711	1386	1948	1578	1304	1844	1524	1281	2036	1711	1458	1919	1635	1410
Theoretical Shot Volume	cm <sup>3</sup>	145	183	226	204	251	318	289	366	452	390	491	594	530	641	763	713	848	995	905	1062	1232
Shot Weight (PS)	gram	122	154	190	171	211	267	243	307	379	334	412	499	445	539	641	599	713	836	760	892	1034
Injection Rate	cm <sup>3</sup> /sec	65	82	101	84	103	131	98	124	154	135	167	202	176	213	254	186	221	259	232	272	316
Plasticizing Capacity (PS)	kg/hr	37	47	58	47	58	74	58	74	91	74	91	110	91	110	131	110	131	154	131	154	179
Theoretical Screw Revolution	rpm	0 - 200		0 - 200		0 - 180		0 - 180		0 - 170		0 - 160		0 - 150								
Injection Stroke	mm	180		200		230		250		270		300		320								
<b>Clamping Unit</b>																						
Clamping Force	ton	90		120		150		190		230		270		320								
Mould Opening Stroke	mm	330		360		430		460		525		570		620								
Space Between Tie Bars	mm	360 x 360		395 x 395		425 x 425		470 x 470		515 x 515		555 x 555		620 x 620								
Platen Dimension (HxV)	mm	540 x 540		595 x 595		660 x 660		720 x 720		790 x 790		850 x 850		930 x 930								
Mould Height Min.-Max.	mm	130 - 400		140 - 440		150 - 500		160 - 540		180 - 580		200 - 610		220 - 670								
Max Opening Daylight	mm	730		820		930		1020		1105		1180		1290								
Ejector Stroke	mm	100		100		140		140		170		170		190								
Ejector Force	ton	4.6		4.6		5.4		5.4		6.2		6.2		7.0								
<b>Others</b>																						
Pump Driving Motor	HP/kw	15/11.19		20/14.92		25/18.65		30/22.38		30/22.38		40/29.84		50/37.30								
Heating Capacity	kw	4.6		6.1		7.9		11.5		13.7		17.4		19.8								
Thermo Controller	set	(0~399) x 3		(0~399) x 4		(0~399) x 4		(0~399) x 4		(0~399) x 5		(0~399) x 5		(0~399) x 5								
Oil Tank Capacity	L	290		350		410		440		580		740		900								
Machine Dimension (LxWxH)	m	4.3 x 1.25 x 1.6		4.8 x 1.3 x 1.65		5.2 x 1.35 x 1.7		5.6 x 1.4 x 1.75		6.0 x 1.5 x 1.8		6.5 x 1.6 x 1.9		7.0 x 1.7 x 2.0								
Machine Weight	ton	3.6		4.5		5.5		7.2		8.8		10.6		12.4								

Suitable electricity: AC 220V 60Hz


Specification subject to change without notice

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## Appendix C

### DATA SHEET FOR THE ABS (POLYLAC PA737) USED DURING INJECTION

#### MOULDING OF CASE 1 AND CASE 2

POLYLAC® PA-737 Acrylonitrile Butadiene Styrene CHI MEI CORPORATION		 <b>Prospector</b>	
<b>General</b>			
Material Status	• Commercial: Active		
Availability	• Africa & Middle East	• Europe	• North America
	• Asia Pacific	• Latin America	• South America
Features	• High Flow • Medium Impact Resistance		
RoHS Compliance	• RoHS Compliant		
Forms	• Pellets		
Processing Method	• Injection Molding		
<b>Physical</b>			
	Nominal Value	Unit	Test Method
Specific Gravity	1.04	g/cm <sup>3</sup>	ASTM D792 ISO 1183
Melt Mass-Flow Rate (MFR) (200°C/5.0 kg)	3.0	g/10 min	ASTM D1238
Melt Volume-Flow Rate (MVR) (220°C/10.0 kg)	33.0	cm <sup>3</sup> /10min	ISO 1133
<b>Mechanical</b>			
	Nominal Value	Unit	Test Method
<b>Tensile Strength</b>			
Yield, 3.18 mm <sup>2</sup>	36.2	MPa	ASTM D638
Yield	38.0	MPa	ISO 527-2/50
Break	32.0	MPa	ISO 527-2/50
<b>Tensile Elongation</b>			
Break, 3.18 mm <sup>2</sup>	22	%	ASTM D638
Break	20	%	ISO 527-2/50
<b>Flexural Modulus</b>			
3.18 mm <sup>3</sup>	1930	MPa	ASTM D790
-4	1900	MPa	ISO 178
<b>Flexural Strength</b>			
6.35 mm <sup>3</sup>	57.9	MPa	ASTM D790
-4	60.0	MPa	ISO 178

## Data sheet for POLYLAC PA 737 continues

Injection	Nominal Value Unit
Drying Temperature	80.0 to 85.0 °C
Drying Time	2.0 to 4.0 hr
Rear Temperature	180 to 220 °C
Middle Temperature	190 to 230 °C
Nozzle Temperature	190 to 230 °C
Mold Temperature	30.0 to 70.0 °C

**Notes**

<sup>1</sup> Typical properties: these are not to be construed as specifications.

<sup>2</sup> 6.0 mm/min

<sup>3</sup> 2.8 mm/min

<sup>4</sup> 2.0 mm/min

<sup>5</sup> Rate A (50°C/h)

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The information presented on this datasheet was acquired by IDES from the producer of the material. IDES makes substantial efforts to assure the accuracy of this data. However, IDES assumes no responsibility for the data values and strongly encourages that upon final material selection, data points are validated with the material supplier.

**Revision History**  
Document Create  
Added to Prospect  
Last Updated: 5/1

[53]

## Appendix D

Table 2: Temperatures of the sensor nodes in Moldex3D, captured after 30 cycles. (Case study 1)

Time [sec]	SN1 Temp [°C]	SN2 Temp [°C]	SN3 Temp [°C]	SN4 Temp [°C]	SN5 Temp [°C]	SN6 Temp [°C]	SN7 Temp [°C]	SN8 Temp [°C]
0.0	43.8	44.7	37.0	39.7	40.1	44.6	54.6	55.0
0.9	43.5	44.4	36.8	39.4	39.8	44.4	54.3	54.7
1.8	43.2	44.1	36.5	39.0	39.4	44.0	54.0	54.4
2.8	42.9	43.8	36.2	38.6	39.0	43.7	53.7	54.1
3.7	42.6	43.5	36.0	38.3	38.7	43.4	53.4	53.8
3.7	42.5	43.4	35.9	38.2	38.5	43.3	53.3	53.7
3.7	42.4	43.3	35.9	38.2	38.5	43.2	53.3	53.7
3.7	42.4	43.3	35.8	38.1	38.5	43.2	53.2	53.6
3.7	42.4	43.3	35.8	38.1	38.5	43.2	53.2	53.6
3.7	42.4	43.3	35.8	38.1	38.5	43.2	53.2	53.6
3.7	42.4	43.3	35.8	38.1	38.5	43.2	53.2	53.6
3.7	42.4	43.3	35.8	38.1	38.5	43.2	53.2	53.6
3.7	42.4	43.3	35.8	38.1	38.5	43.2	53.2	53.6
3.7	42.4	43.3	35.8	38.1	38.5	43.2	53.2	53.6
3.7	42.4	43.3	35.8	38.1	38.5	43.2	53.2	53.6
3.8	42.4	43.3	35.8	38.1	38.5	43.2	53.2	53.6
3.8	42.4	43.3	35.8	38.1	38.5	43.2	53.2	53.6
3.8	42.4	43.3	35.8	38.1	38.5	43.2	53.2	53.6
3.8	42.4	43.3	35.8	38.1	38.4	43.2	53.2	53.6
3.9	42.3	43.3	35.8	38.1	38.4	43.2	53.2	53.6
4.0	42.3	43.3	35.8	38.1	38.4	43.2	53.2	53.6
4.0	42.3	43.3	35.8	38.1	38.4	43.1	53.2	53.6
4.1	42.3	43.3	35.8	38.1	38.4	43.1	53.1	53.6
4.3	42.3	43.3	35.8	38.1	38.4	43.1	53.1	53.5
4.4	42.2	43.3	35.8	38.1	38.4	43.1	53.1	53.5
4.6	42.2	43.3	35.8	38.1	38.4	43.1	53.0	53.5
4.8	42.2	43.4	35.8	38.1	38.4	43.1	53.0	53.5
5.2	42.2	43.5	35.8	38.2	38.4	43.2	53.0	53.5
5.6	42.3	43.7	36.0	38.4	38.6	43.3	53.0	53.5
6.1	42.5	44.1	36.2	38.6	38.8	43.5	53.0	53.6
6.7	42.9	44.9	36.6	39.2	39.3	44.0	53.2	53.8
7.4	43.5	45.7	37.3	39.8	39.9	44.6	53.4	54.2
8.2	44.2	46.7	38.1	40.7	40.7	45.3	53.8	54.7
9.0	45.1	47.8	39.1	41.6	41.7	46.3	54.4	55.4
9.5	45.9	48.7	39.9	42.4	42.6	47.1	54.9	55.9
9.5	46.3	49.1	40.4	42.8	43.0	47.5	55.1	56.2
9.6	46.5	49.4	40.6	43.0	43.2	47.6	55.3	56.4

Table 2 (Continues)

<b>Time [sec]</b>	<b>SN1 Temp [°C]</b>	<b>SN2 Temp [°C]</b>	<b>SN3 Temp [°C]</b>	<b>SN4 Temp [°C]</b>	<b>SN5 Temp [°C]</b>	<b>SN6 Temp [°C]</b>	<b>SN7 Temp [°C]</b>	<b>SN8 Temp [°C]</b>
9.7	46.6	49.5	40.7	43.2	43.3	47.8	55.4	56.5
9.9	46.8	49.7	40.9	43.3	43.5	48.0	55.5	56.6
10.1	47.0	49.9	41.2	43.6	43.7	48.2	55.7	56.8
10.4	47.4	50.3	41.6	43.9	44.1	48.6	55.9	57.1
10.9	47.8	50.8	42.1	44.4	44.6	49.0	56.3	57.5
11.4	48.4	51.4	42.8	45.0	45.2	49.6	56.8	58.0
12.1	49.1	52.1	43.5	45.7	46.0	50.3	57.3	58.7
12.9	50.0	53.0	44.5	46.5	46.8	51.1	58.0	59.4
13.9	50.9	53.9	45.5	47.4	47.8	52.0	58.9	60.3
14.9	51.9	54.8	46.6	48.3	48.8	52.9	59.7	61.2
15.9	52.8	55.6	47.6	49.2	49.7	53.8	60.5	62.0
16.9	53.5	56.4	48.5	50.0	50.6	54.5	61.3	62.8
17.9	54.2	57.0	49.3	50.7	51.3	55.1	62.0	63.5
18.9	54.8	57.5	50.0	51.3	51.9	55.7	62.6	64.2
19.9	55.4	58.0	50.7	51.8	52.5	56.2	63.2	64.8
20.9	55.8	58.3	51.2	52.3	53.0	56.6	63.7	65.3
21.9	56.1	58.6	51.6	52.6	53.4	56.9	64.2	65.7
22.9	56.4	58.9	52.0	53.0	53.7	57.2	64.6	66.1
23.9	56.7	59.0	52.3	53.2	54.0	57.4	64.9	66.4
24.9	56.8	59.2	52.5	53.4	54.2	57.5	65.2	66.7
25.9	56.9	59.2	52.7	53.6	54.3	57.6	65.5	66.9
26.9	57.0	59.2	52.8	53.7	54.5	57.7	65.7	67.1
27.9	57.0	59.2	52.9	53.7	54.5	57.7	65.8	67.3
28.9	57.0	59.2	52.9	53.7	54.5	57.7	65.9	67.4
29.9	57.0	59.1	52.9	53.7	54.5	57.6	66.0	67.4
30.9	56.9	59.0	52.8	53.7	54.5	57.5	66.1	67.5
31.9	56.8	58.8	52.7	53.6	54.4	57.4	66.1	67.5
32.9	56.7	58.8	52.7	53.5	54.4	57.4	66.1	67.5
33.9	56.6	58.6	52.5	53.4	54.2	57.3	66.1	67.4
34.9	56.4	58.4	52.3	53.3	54.1	57.1	66.0	67.4
35.9	56.3	58.2	52.1	53.1	53.9	57.0	66.0	67.3
36.9	56.1	58.0	51.9	53.0	53.7	56.8	65.9	67.2
37.9	55.9	57.7	51.7	52.8	53.5	56.6	65.8	67.1
38.9	55.6	57.5	51.4	52.5	53.3	56.4	65.7	66.9
39.9	55.4	57.2	51.1	52.3	53.1	56.2	65.5	66.8
40.9	55.2	57.0	50.8	52.1	52.8	55.9	65.4	66.6
41.9	54.9	56.7	50.5	51.8	52.6	55.7	65.2	66.4
42.9	54.6	56.4	50.2	51.6	52.3	55.4	65.0	66.2
43.9	54.4	56.1	49.9	51.3	52.0	55.2	64.8	66.0
44.9	54.1	55.8	49.5	51.0	51.8	54.9	64.6	65.8
45.9	53.8	55.5	49.2	50.7	51.5	54.6	64.4	65.5

Table 2 (Continues)

<b>Time [sec]</b>	<b>SN1 Temp [°C]</b>	<b>SN2 Temp [°C]</b>	<b>SN3 Temp [°C]</b>	<b>SN4 Temp [°C]</b>	<b>SN5 Temp [°C]</b>	<b>SN6 Temp [°C]</b>	<b>SN7 Temp [°C]</b>	<b>SN8 Temp [°C]</b>
46.9	53.5	55.2	48.8	50.4	51.2	54.4	64.1	65.3
47.9	53.2	54.9	48.5	50.1	50.9	54.1	63.9	65.0
48.9	52.9	54.6	48.1	49.8	50.6	53.8	63.7	64.7
49.9	52.6	54.2	47.8	49.5	50.2	53.5	63.4	64.5
50.9	52.3	53.9	47.4	49.2	49.9	53.3	63.1	64.2
51.9	52.0	53.6	47.1	48.9	49.6	53.0	62.9	63.9
52.9	51.7	53.3	46.7	48.6	49.3	52.7	62.6	63.6
53.9	51.4	53.0	46.3	48.3	49.0	52.4	62.3	63.3
54.9	51.0	52.5	45.8	47.8	48.5	52.0	61.9	62.9
55.9	50.7	52.2	45.4	47.5	48.2	51.7	61.6	62.6
56.9	50.4	51.9	45.1	47.2	47.9	51.4	61.3	62.3
57.9	50.1	51.6	44.7	46.9	47.5	51.1	61.0	61.9
58.9	49.8	51.3	44.4	46.6	47.2	50.9	60.7	61.6
58.9	49.6	51.1	44.2	46.4	47.0	50.7	60.5	61.4
58.9	49.5	51.0	44.1	46.3	46.9	50.6	60.5	61.4
59.0	49.5	51.0	44.1	46.3	46.9	50.6	60.4	61.3
59.0	49.5	51.0	44.0	46.3	46.9	50.6	60.4	61.3
59.0	49.5	51.0	44.0	46.3	46.9	50.6	60.4	61.3
59.0	49.5	50.9	44.0	46.3	46.9	50.6	60.4	61.3
59.1	49.5	50.9	44.0	46.2	46.9	50.6	60.4	61.3
59.2	49.5	50.9	44.0	46.2	46.9	50.5	60.4	61.3
59.5	49.4	50.9	43.9	46.2	46.8	50.5	60.3	61.2
60.0	49.3	50.8	43.8	46.1	46.7	50.4	60.2	61.1
61.0	49.1	50.5	43.6	45.9	46.5	50.2	60.0	60.9
62.0	48.8	50.2	43.3	45.5	46.2	50.0	59.8	60.6
63.0	48.5	49.8	42.9	45.2	45.8	49.6	59.5	60.3
64.0	48.2	49.5	42.6	44.9	45.5	49.4	59.2	60.1
65.0	47.9	49.1	42.2	44.4	45.0	49.0	58.9	59.7
66.0	47.4	48.6	41.8	43.9	44.6	48.5	58.5	59.3
67.0	47.0	48.2	41.3	43.4	44.1	48.1	58.1	58.9
68.0	46.7	47.8	41.0	43.1	43.7	47.7	57.9	58.6
69.0	46.2	47.3	40.5	42.6	43.2	47.3	57.5	58.2
70.0	45.8	46.8	40.1	42.0	42.6	46.8	57.1	57.7
71.0	45.0	46.0	39.3	41.2	41.7	46.0	56.3	57.0
72.0	44.6	45.6	38.8	40.7	41.2	45.5	55.9	56.6
73.0	44.2	45.1	38.3	40.2	40.7	45.1	55.5	56.1
73.5	43.9	44.8	38.0	39.8	40.3	44.7	55.2	55.8
73.5	43.8	44.7	37.9	39.7	40.2	44.7	55.2	55.8
74.4	43.5	44.4	37.6	39.3	39.8	44.3	54.8	55.4
75.3	43.1	44.0	37.2	38.9	39.4	44.0	54.5	55.0
76.3	42.8	43.7	36.9	38.5	39.0	43.6	54.1	54.7

Table 2 (Continues)

<b>Time [sec]</b>	<b>SN1 Temp [°C]</b>	<b>SN2 Temp [°C]</b>	<b>SN3 Temp [°C]</b>	<b>SN4 Temp [°C]</b>	<b>SN5 Temp [°C]</b>	<b>SN6 Temp [°C]</b>	<b>SN7 Temp [°C]</b>	<b>SN8 Temp [°C]</b>
77.2	42.4	43.4	36.6	38.2	38.6	43.3	53.8	54.4
77.2	42.3	43.3	36.5	38.1	38.5	43.2	53.7	54.3
77.2	42.3	43.3	36.5	38.0	38.5	43.1	53.7	54.2
77.2	42.3	43.2	36.5	38.0	38.5	43.1	53.7	54.2
77.2	42.3	43.2	36.5	38.0	38.5	43.1	53.7	54.2
77.2	42.3	43.2	36.5	38.0	38.5	43.1	53.7	54.2
77.2	42.3	43.2	36.5	38.0	38.5	43.1	53.7	54.2
77.2	42.3	43.2	36.5	38.0	38.5	43.1	53.7	54.2
77.2	42.3	43.2	36.5	38.0	38.5	43.1	53.6	54.2
77.2	42.3	43.2	36.5	38.0	38.5	43.1	53.6	54.2
77.3	42.3	43.2	36.5	38.0	38.4	43.1	53.6	54.2
77.3	42.2	43.2	36.5	38.0	38.4	43.1	53.6	54.2
77.3	42.2	43.2	36.5	38.0	38.4	43.1	53.6	54.2
77.4	42.2	43.2	36.5	38.0	38.4	43.1	53.6	54.2
77.4	42.2	43.2	36.5	38.0	38.4	43.1	53.6	54.2
77.5	42.2	43.2	36.5	38.0	38.4	43.1	53.6	54.2
77.6	42.2	43.2	36.5	38.0	38.4	43.1	53.6	54.2
77.7	42.2	43.2	36.4	38.0	38.4	43.0	53.5	54.1
77.8	42.1	43.2	36.4	37.9	38.4	43.0	53.5	54.1
77.9	42.1	43.2	36.4	37.9	38.3	43.0	53.5	54.1
78.1	42.1	43.2	36.4	38.0	38.3	43.0	53.5	54.1
78.4	42.1	43.3	36.4	38.0	38.4	43.0	53.4	54.1
78.7	42.1	43.4	36.5	38.1	38.4	43.1	53.4	54.1
79.1	42.2	43.6	36.6	38.2	38.5	43.2	53.4	54.1
79.7	42.4	44.1	36.8	38.5	38.8	43.4	53.4	54.2
80.3	42.8	44.8	37.2	39.1	39.3	43.9	53.6	54.4
81.0	43.4	45.6	37.9	39.7	39.9	44.5	53.8	54.7
81.8	44.1	46.6	38.7	40.5	40.7	45.2	54.2	55.2
82.6	45.0	47.7	39.7	41.5	41.7	46.2	54.8	55.9
83.1	45.8	48.6	40.5	42.4	42.6	47.0	55.3	56.5
83.2	46.2	49.1	41.0	42.8	43.0	47.5	55.6	56.8
83.2	46.5	49.4	41.2	43.0	43.3	47.7	55.7	57.0
83.3	46.6	49.5	41.4	43.2	43.4	47.8	55.8	57.1
83.5	46.8	49.7	41.6	43.3	43.6	48.0	56.0	57.2
83.7	47.0	50.0	41.8	43.6	43.8	48.2	56.1	57.4
84.1	47.3	50.3	42.2	43.9	44.2	48.6	56.4	57.7
84.5	47.8	50.8	42.7	44.4	44.7	49.0	56.7	58.1
85.1	48.4	51.4	43.3	45.0	45.3	49.6	57.2	58.6
85.8	49.1	52.1	44.1	45.7	46.0	50.3	57.8	59.2
86.6	50.0	53.0	45.0	46.5	46.9	51.1	58.5	60.0
87.6	50.9	53.9	46.1	47.4	47.9	52.0	59.3	60.8

Table 2 (Continues)

<b>Time [sec]</b>	<b>SN1 Temp [°C]</b>	<b>SN2 Temp [°C]</b>	<b>SN3 Temp [°C]</b>	<b>SN4 Temp [°C]</b>	<b>SN5 Temp [°C]</b>	<b>SN6 Temp [°C]</b>	<b>SN7 Temp [°C]</b>	<b>SN8 Temp [°C]</b>
88.6	51.8	54.8	47.1	48.3	48.9	52.9	60.1	61.7
89.6	52.7	55.6	48.1	49.2	49.8	53.7	60.9	62.5
90.6	53.5	56.3	49.0	49.9	50.6	54.5	61.7	63.3
91.6	54.2	56.9	49.7	50.6	51.3	55.1	62.4	64.0
92.6	54.8	57.5	50.4	51.2	51.9	55.7	63.0	64.6
93.6	55.3	57.9	51.0	51.8	52.5	56.1	63.6	65.2
94.6	55.7	58.3	51.5	52.2	53.0	56.5	64.1	65.7
95.6	56.1	58.6	52.0	52.6	53.4	56.8	64.5	66.1
96.6	56.3	58.8	52.3	52.9	53.7	57.1	64.9	66.5
97.6	56.6	58.9	52.6	53.1	54.0	57.3	65.2	66.8
98.6	56.7	59.1	52.8	53.3	54.2	57.4	65.5	67.1
99.6	56.8	59.1	53.0	53.5	54.3	57.5	65.8	67.3
100.6	56.9	59.1	53.1	53.6	54.4	57.6	66.0	67.5
101.6	56.9	59.1	53.1	53.6	54.5	57.6	66.1	67.6
102.6	56.9	59.1	53.1	53.6	54.5	57.6	66.2	67.7
103.6	56.8	59.0	53.1	53.6	54.5	57.5	66.3	67.8
104.6	56.8	58.8	53.0	53.6	54.4	57.5	66.3	67.8
105.6	56.6	58.7	52.9	53.5	54.3	57.3	66.4	67.8
106.6	56.5	58.5	52.7	53.4	54.2	57.2	66.3	67.8
107.6	56.3	58.3	52.5	53.2	54.0	57.1	66.3	67.7
108.6	56.2	58.1	52.3	53.1	53.9	56.9	66.2	67.6
109.6	56.0	57.9	52.1	52.9	53.7	56.7	66.2	67.5
110.6	55.8	57.6	51.9	52.7	53.5	56.5	66.0	67.4
111.6	55.5	57.4	51.6	52.5	53.3	56.3	65.9	67.2
112.6	55.3	57.1	51.3	52.2	53.0	56.1	65.8	67.1
113.6	55.0	56.9	51.0	52.0	52.8	55.8	65.6	66.9
114.6	54.8	56.6	50.7	51.7	52.5	55.6	65.4	66.7
115.6	54.5	56.3	50.4	51.5	52.3	55.4	65.3	66.5
116.6	54.3	56.0	50.0	51.2	52.0	55.1	65.1	66.3
117.6	54.0	55.7	49.7	50.9	51.7	54.8	64.8	66.0
118.6	53.7	55.4	49.3	50.7	51.4	54.6	64.6	65.8
119.6	53.4	55.1	49.0	50.4	51.1	54.3	64.4	65.6
120.6	53.1	54.8	48.6	50.1	50.8	54.0	64.2	65.3
121.6	52.8	54.5	48.3	49.8	50.5	53.8	63.9	65.0
122.6	52.5	54.1	47.9	49.5	50.2	53.5	63.6	64.8
123.6	52.2	53.8	47.6	49.2	49.9	53.2	63.4	64.5
124.6	51.9	53.5	47.2	48.8	49.6	52.9	63.1	64.2
125.6	51.6	53.2	46.8	48.5	49.2	52.6	62.8	63.9
126.6	51.3	52.9	46.5	48.2	48.9	52.3	62.6	63.6
127.6	51.0	52.6	46.1	47.9	48.6	52.1	62.3	63.3
128.6	50.9	52.4	45.9	47.8	48.5	51.9	62.1	63.1

Table 2 (Continues)

<b>Time [sec]</b>	<b>SN1 Temp [°C]</b>	<b>SN2 Temp [°C]</b>	<b>SN3 Temp [°C]</b>	<b>SN4 Temp [°C]</b>	<b>SN5 Temp [°C]</b>	<b>SN6 Temp [°C]</b>	<b>SN7 Temp [°C]</b>	<b>SN8 Temp [°C]</b>
129.6	50.6	52.1	45.6	47.4	48.1	51.6	61.8	62.8
130.6	50.3	51.8	45.2	47.1	47.8	51.4	61.5	62.5
131.6	50.0	51.5	44.9	46.8	47.5	51.1	61.2	62.2
132.6	49.7	51.2	44.5	46.5	47.2	50.8	60.9	61.9
132.6	49.5	50.9	44.2	46.3	46.9	50.6	60.7	61.7
132.6	49.4	50.9	44.2	46.2	46.9	50.5	60.6	61.6
132.6	49.4	50.8	44.1	46.2	46.8	50.5	60.6	61.6
132.6	49.4	50.8	44.1	46.1	46.8	50.5	60.6	61.6
132.7	49.4	50.8	44.1	46.1	46.8	50.5	60.6	61.5
132.7	49.4	50.8	44.1	46.1	46.8	50.5	60.6	61.5
132.8	49.3	50.8	44.1	46.1	46.8	50.5	60.6	61.5
132.9	49.3	50.8	44.1	46.1	46.8	50.4	60.6	61.5
133.1	49.3	50.7	44.0	46.1	46.7	50.4	60.5	61.5
133.7	49.2	50.6	43.9	46.0	46.6	50.3	60.4	61.4
134.7	49.0	50.5	43.7	45.8	46.4	50.2	60.3	61.2
135.7	48.8	50.1	43.4	45.5	46.1	49.9	60.0	60.9
136.7	48.4	49.8	43.0	45.1	45.8	49.6	59.7	60.6
137.7	48.2	49.5	42.8	44.8	45.5	49.3	59.5	60.3
138.7	47.8	49.0	42.4	44.4	45.0	48.9	59.1	60.0
139.7	47.4	48.6	41.9	43.9	44.6	48.5	58.8	59.6
140.7	46.6	47.7	41.1	43.1	43.7	47.7	58.1	58.9
141.7	46.2	47.3	40.7	42.5	43.2	47.3	57.7	58.4
142.7	45.7	46.8	40.2	42.0	42.6	46.8	57.3	58.0
143.7	45.3	46.3	39.8	41.5	42.1	46.3	56.9	57.6
144.7	45.0	46.0	39.4	41.1	41.7	46.0	56.6	57.3
145.7	44.5	45.5	38.9	40.6	41.2	45.5	56.2	56.8
146.7	44.1	45.1	38.5	40.1	40.7	45.1	55.8	56.4
147.0	43.8	44.8	38.1	39.8	40.3	44.7	55.5	56.1
147.0	43.7	44.7	38.0	39.7	40.2	44.6	55.4	56.0
147.9	43.4	44.3	37.7	39.3	39.8	44.3	55.1	55.7
148.8	43.1	44.0	37.3	38.9	39.4	43.9	54.7	55.3
149.8	42.7	43.6	37.0	38.5	39.0	43.6	54.4	54.9
150.7	42.4	43.3	36.7	38.2	38.6	43.3	54.1	54.7
150.7	42.3	43.2	36.7	38.1	38.5	43.2	54.0	54.6
150.7	42.2	43.2	36.6	38.0	38.5	43.1	53.9	54.5
150.7	42.2	43.2	36.6	38.0	38.5	43.1	53.9	54.5
150.7	42.2	43.2	36.6	38.0	38.5	43.1	53.9	54.5
150.7	42.2	43.2	36.6	38.0	38.5	43.1	53.9	54.5
150.7	42.2	43.2	36.6	38.0	38.5	43.1	53.9	54.5
150.7	42.2	43.2	36.6	38.0	38.5	43.1	53.9	54.5
150.7	42.2	43.2	36.6	38.0	38.5	43.1	53.9	54.5
150.7	42.2	43.2	36.6	38.0	38.5	43.1	53.9	54.5

Table 2 (Continues)

<b>Time [sec]</b>	<b>SN1 Temp [°C]</b>	<b>SN2 Temp [°C]</b>	<b>SN3 Temp [°C]</b>	<b>SN4 Temp [°C]</b>	<b>SN5 Temp [°C]</b>	<b>SN6 Temp [°C]</b>	<b>SN7 Temp [°C]</b>	<b>SN8 Temp [°C]</b>
150.7	42.2	43.2	36.6	38.0	38.5	43.1	53.9	54.5
150.8	42.2	43.2	36.6	38.0	38.4	43.1	53.9	54.5
150.8	42.2	43.2	36.6	38.0	38.4	43.1	53.9	54.5
150.8	42.2	43.2	36.6	38.0	38.4	43.1	53.9	54.5
150.9	42.2	43.2	36.6	38.0	38.4	43.1	53.9	54.5
150.9	42.2	43.2	36.6	38.0	38.4	43.1	53.9	54.5
151.0	42.1	43.1	36.6	38.0	38.4	43.0	53.8	54.4
151.1	42.1	43.1	36.6	38.0	38.4	43.0	53.8	54.4
151.2	42.1	43.1	36.6	37.9	38.4	43.0	53.8	54.4
151.3	42.1	43.1	36.5	37.9	38.4	43.0	53.8	54.4
151.4	42.1	43.1	36.5	37.9	38.3	43.0	53.7	54.4
151.6	42.0	43.2	36.5	38.0	38.3	43.0	53.7	54.3
151.9	42.0	43.3	36.6	38.0	38.4	43.0	53.7	54.3
152.2	42.0	43.3	36.6	38.1	38.4	43.1	53.7	54.3
152.7	42.1	43.6	36.7	38.2	38.5	43.2	53.7	54.4
153.2	42.3	44.0	36.9	38.5	38.8	43.4	53.7	54.4
153.8	42.7	44.7	37.4	39.1	39.3	43.9	53.8	54.7
154.5	43.3	45.6	38.0	39.7	39.9	44.5	54.1	55.0
155.3	44.0	46.5	38.8	40.5	40.7	45.2	54.5	55.5
156.2	45.0	47.7	39.8	41.5	41.7	46.2	55.0	56.2
156.6	45.8	48.6	40.6	42.4	42.6	47.0	55.6	56.8
156.7	46.3	49.2	41.2	42.9	43.1	47.5	55.9	57.2
156.8	46.5	49.4	41.4	43.1	43.3	47.7	56.0	57.3
156.9	46.6	49.6	41.6	43.2	43.5	47.9	56.1	57.4
157.0	46.8	49.8	41.7	43.4	43.7	48.0	56.2	57.6
157.3	47.0	50.0	42.0	43.6	43.9	48.3	56.4	57.8
157.6	47.4	50.4	42.4	44.0	44.3	48.6	56.7	58.1
158.1	47.8	50.9	42.9	44.4	44.8	49.1	57.0	58.4
158.7	48.4	51.5	43.5	45.0	45.4	49.7	57.5	58.9
159.4	49.1	52.2	44.3	45.7	46.1	50.4	58.1	59.6
160.3	50.0	53.0	45.2	46.5	47.0	51.2	58.8	60.3
161.3	50.9	53.9	46.2	47.4	47.9	52.1	59.6	61.1
162.3	51.8	54.8	47.2	48.3	48.9	53.0	60.4	62.0
163.3	52.7	55.6	48.2	49.2	49.8	53.8	61.2	62.8
164.3	53.5	56.3	49.1	50.0	50.6	54.5	62.0	63.6
165.3	54.2	56.9	49.9	50.6	51.3	55.1	62.6	64.3
166.3	54.7	57.5	50.5	51.2	52.0	55.7	63.3	64.9
167.3	55.3	57.9	51.1	51.8	52.5	56.1	63.8	65.5
168.3	55.7	58.2	51.6	52.2	53.0	56.5	64.3	66.0
169.3	56.0	58.5	52.1	52.6	53.4	56.8	64.8	66.4
170.3	56.3	58.7	52.4	52.9	53.7	57.1	65.1	66.8

Table 2 (Continues)

<b>Time [sec]</b>	<b>SN1 Temp [°C]</b>	<b>SN2 Temp [°C]</b>	<b>SN3 Temp [°C]</b>	<b>SN4 Temp [°C]</b>	<b>SN5 Temp [°C]</b>	<b>SN6 Temp [°C]</b>	<b>SN7 Temp [°C]</b>	<b>SN8 Temp [°C]</b>
171.3	56.5	58.9	52.7	53.1	54.0	57.3	65.5	67.1
172.3	56.7	59.0	52.9	53.3	54.2	57.4	65.8	67.3
173.3	56.8	59.1	53.0	53.5	54.3	57.5	66.0	67.5
174.3	56.8	59.1	53.1	53.6	54.4	57.6	66.2	67.7
175.3	56.9	59.1	53.2	53.6	54.5	57.6	66.3	67.8
176.3	56.8	59.0	53.2	53.6	54.5	57.6	66.4	67.9
177.3	56.8	58.9	53.1	53.6	54.4	57.5	66.5	68.0
178.3	56.7	58.8	53.1	53.5	54.4	57.4	66.5	68.0
179.3	56.6	58.6	52.9	53.4	54.3	57.3	66.6	68.0
180.3	56.4	58.4	52.8	53.3	54.2	57.2	66.5	68.0
181.3	56.3	58.3	52.6	53.2	54.0	57.0	66.5	67.9
182.3	56.1	58.1	52.4	53.0	53.9	56.9	66.4	67.8
183.3	55.9	57.8	52.1	52.9	53.7	56.7	66.3	67.7
184.3	55.7	57.6	51.9	52.7	53.5	56.5	66.2	67.6
185.3	55.5	57.3	51.6	52.4	53.3	56.3	66.1	67.4
186.3	55.2	57.1	51.3	52.2	53.0	56.1	66.0	67.3
187.3	55.0	56.8	51.0	52.0	52.8	55.8	65.8	67.1
188.3	54.7	56.5	50.7	51.7	52.5	55.6	65.6	66.9
189.3	54.5	56.2	50.4	51.5	52.3	55.3	65.4	66.7
190.3	54.2	55.9	50.1	51.2	52.0	55.1	65.2	66.5
191.3	53.9	55.6	49.7	50.9	51.7	54.8	65.0	66.2
192.3	53.7	55.3	49.4	50.6	51.4	54.6	64.8	66.0
193.3	53.4	55.0	49.0	50.3	51.1	54.3	64.6	65.7
194.3	53.1	54.7	48.7	50.0	50.8	54.0	64.3	65.5
195.3	52.8	54.4	48.3	49.7	50.5	53.7	64.1	65.2
196.3	52.5	54.1	48.0	49.4	50.2	53.5	63.8	64.9
197.3	52.2	53.8	47.6	49.1	49.9	53.2	63.6	64.7
198.3	51.9	53.5	47.2	48.8	49.6	52.9	63.3	64.4
199.3	51.6	53.2	46.9	48.5	49.2	52.6	63.0	64.1
200.3	51.3	52.8	46.5	48.2	48.9	52.3	62.7	63.8
201.3	51.0	52.5	46.2	47.9	48.6	52.0	62.4	63.5
202.3	50.8	52.4	46.0	47.7	48.4	51.9	62.3	63.3
203.3	50.5	52.1	45.6	47.4	48.1	51.6	62.0	63.0
204.3	50.2	51.7	45.3	47.1	47.8	51.3	61.7	62.7
205.3	50.0	51.4	44.9	46.8	47.5	51.1	61.4	62.4
206.3	49.7	51.1	44.6	46.5	47.2	50.8	61.1	62.1
206.3	49.4	50.9	44.3	46.2	46.9	50.5	60.9	61.8
206.3	49.3	50.8	44.2	46.1	46.8	50.5	60.8	61.7
206.3	49.3	50.7	44.1	46.1	46.8	50.4	60.8	61.7
206.3	49.3	50.7	44.1	46.1	46.8	50.4	60.7	61.7
206.3	49.3	50.7	44.1	46.1	46.8	50.4	60.7	61.7



Table 2 (Continues)

<b>Time [sec]</b>	<b>SN1 Temp [°C]</b>	<b>SN2 Temp [°C]</b>	<b>SN3 Temp [°C]</b>	<b>SN4 Temp [°C]</b>	<b>SN5 Temp [°C]</b>	<b>SN6 Temp [°C]</b>	<b>SN7 Temp [°C]</b>	<b>SN8 Temp [°C]</b>
224.8	42.1	43.1	36.6	38.0	38.4	43.0	54.0	54.6
224.9	42.0	43.1	36.6	38.0	38.4	43.0	53.9	54.6
225.1	42.0	43.2	36.6	38.0	38.4	43.0	53.9	54.5
225.4	42.0	43.3	36.6	38.0	38.4	43.0	53.9	54.5
225.7	42.0	43.3	36.6	38.1	38.4	43.1	53.9	54.5
226.2	42.1	43.6	36.7	38.2	38.6	43.2	53.8	54.6
226.7	42.3	44.0	37.0	38.5	38.8	43.4	53.9	54.6
227.4	42.7	44.7	37.4	39.1	39.3	43.9	54.0	54.9
228.1	43.3	45.5	38.0	39.7	39.9	44.5	54.3	55.2
228.9	44.0	46.5	38.8	40.6	40.7	45.2	54.7	55.7
229.7	44.9	47.7	39.8	41.5	41.7	46.2	55.2	56.4
230.2	45.8	48.6	40.7	42.4	42.6	47.1	55.8	57.0
230.3	46.3	49.2	41.3	42.9	43.2	47.6	56.1	57.4
230.4	46.5	49.5	41.5	43.2	43.4	47.8	56.3	57.6
230.5	46.7	49.6	41.7	43.3	43.6	48.0	56.4	57.7
230.6	46.8	49.8	41.8	43.5	43.8	48.1	56.5	57.8
230.9	47.1	50.1	42.1	43.7	44.0	48.4	56.7	58.0
231.2	47.4	50.4	42.5	44.0	44.4	48.7	56.9	58.3
231.7	47.9	50.9	43.0	44.5	44.8	49.2	57.3	58.7
232.3	48.5	51.5	43.6	45.1	45.4	49.7	57.7	59.2
233.0	49.2	52.2	44.4	45.8	46.2	50.4	58.3	59.8
233.9	50.0	53.0	45.3	46.6	47.0	51.2	59.0	60.5
234.9	50.9	53.9	46.3	47.5	48.0	52.1	59.8	61.4
235.9	51.9	54.8	47.3	48.4	49.0	53.0	60.6	62.2
236.9	52.7	55.6	48.3	49.2	49.9	53.8	61.4	63.0
237.9	53.5	56.3	49.2	50.0	50.7	54.5	62.2	63.8
238.9	54.2	56.9	49.9	50.7	51.4	55.2	62.8	64.5
239.9	54.8	57.5	50.6	51.3	52.0	55.7	63.5	65.1
240.9	55.3	57.9	51.2	51.8	52.6	56.2	64.0	65.7
241.9	55.7	58.2	51.7	52.2	53.0	56.6	64.5	66.1
242.9	56.0	58.5	52.1	52.6	53.4	56.9	64.9	66.6
243.9	56.3	58.7	52.4	52.9	53.7	57.1	65.3	66.9
244.9	56.5	58.9	52.7	53.2	54.0	57.3	65.6	67.2
245.9	56.7	59.0	52.9	53.3	54.2	57.5	65.9	67.5
246.9	56.8	59.1	53.1	53.5	54.3	57.5	66.2	67.7
247.9	56.8	59.1	53.2	53.6	54.4	57.6	66.3	67.9
248.9	56.8	59.0	53.2	53.6	54.5	57.6	66.5	68.0
249.9	56.8	59.0	53.2	53.6	54.5	57.6	66.6	68.1
250.9	56.8	58.9	53.2	53.6	54.4	57.5	66.7	68.2
251.9	56.7	58.8	53.1	53.5	54.4	57.4	66.7	68.2
252.9	56.6	58.6	52.9	53.5	54.3	57.3	66.7	68.2

Table 2 (Continues)

<b>Time [sec]</b>	<b>SN1 Temp [°C]</b>	<b>SN2 Temp [°C]</b>	<b>SN3 Temp [°C]</b>	<b>SN4 Temp [°C]</b>	<b>SN5 Temp [°C]</b>	<b>SN6 Temp [°C]</b>	<b>SN7 Temp [°C]</b>	<b>SN8 Temp [°C]</b>
253.9	56.4	58.4	52.8	53.3	54.2	57.2	66.7	68.1
254.9	56.3	58.2	52.6	53.2	54.0	57.1	66.7	68.1
255.9	56.1	58.0	52.4	53.0	53.9	56.9	66.6	68.0
256.9	55.9	57.8	52.2	52.9	53.7	56.7	66.5	67.9
257.9	55.7	57.6	51.9	52.7	53.5	56.5	66.4	67.7
258.9	55.5	57.3	51.7	52.4	53.3	56.3	66.3	67.6
259.9	55.2	57.1	51.4	52.2	53.0	56.1	66.1	67.4
260.9	55.0	56.8	51.1	52.0	52.8	55.8	66.0	67.2
261.9	54.7	56.5	50.8	51.7	52.5	55.6	65.8	67.0
262.9	54.5	56.2	50.4	51.5	52.3	55.3	65.6	66.8
263.9	54.2	55.9	50.1	51.2	52.0	55.1	65.4	66.6
264.9	53.9	55.6	49.8	50.9	51.7	54.8	65.2	66.4
265.9	53.6	55.3	49.4	50.6	51.4	54.6	65.0	66.1
266.9	53.3	55.0	49.1	50.3	51.1	54.3	64.7	65.9
267.9	53.1	54.7	48.7	50.1	50.8	54.0	64.5	65.6
268.9	52.8	54.4	48.4	49.8	50.5	53.7	64.2	65.4
269.9	52.5	54.1	48.0	49.4	50.2	53.5	64.0	65.1
270.9	52.2	53.8	47.6	49.1	49.9	53.2	63.7	64.8
271.9	51.9	53.5	47.3	48.8	49.6	52.9	63.4	64.5
272.9	51.6	53.1	46.9	48.5	49.2	52.6	63.2	64.2
273.9	51.3	52.8	46.6	48.2	48.9	52.3	62.9	63.9
274.9	51.0	52.5	46.2	47.9	48.6	52.1	62.6	63.6
275.9	50.8	52.4	46.0	47.7	48.4	51.9	62.4	63.5
276.9	50.5	52.0	45.6	47.4	48.1	51.6	62.2	63.2
277.9	50.2	51.7	45.3	47.1	47.8	51.3	61.9	62.9
278.9	49.9	51.4	44.9	46.8	47.5	51.1	61.6	62.5
279.9	49.6	51.1	44.6	46.5	47.2	50.8	61.3	62.2
279.9	49.4	50.8	44.3	46.2	46.9	50.5	61.0	61.9
279.9	49.3	50.7	44.2	46.1	46.8	50.4	60.9	61.9
279.9	49.3	50.7	44.1	46.1	46.7	50.4	60.9	61.8
279.9	49.2	50.7	44.1	46.1	46.7	50.4	60.9	61.8
279.9	49.2	50.7	44.1	46.1	46.7	50.4	60.9	61.8
279.9	49.2	50.7	44.1	46.1	46.7	50.4	60.9	61.8
280.0	49.2	50.7	44.1	46.0	46.7	50.4	60.8	61.8
280.1	49.2	50.7	44.1	46.0	46.7	50.4	60.8	61.8
280.4	49.2	50.6	44.0	46.0	46.7	50.3	60.8	61.7
280.9	49.1	50.5	43.9	45.9	46.6	50.3	60.7	61.7
281.9	49.0	50.4	43.8	45.8	46.4	50.1	60.6	61.5
282.9	48.7	50.1	43.5	45.5	46.1	49.9	60.3	61.2
283.9	48.1	49.5	42.9	44.8	45.5	49.3	59.8	60.7
284.9	47.8	49.0	42.5	44.4	45.1	48.9	59.5	60.3

Table 2 (Continues)

<b>Time [sec]</b>	<b>SN1 Temp [°C]</b>	<b>SN2 Temp [°C]</b>	<b>SN3 Temp [°C]</b>	<b>SN4 Temp [°C]</b>	<b>SN5 Temp [°C]</b>	<b>SN6 Temp [°C]</b>	<b>SN7 Temp [°C]</b>	<b>SN8 Temp [°C]</b>
285.9	47.3	48.6	42.0	44.0	44.6	48.5	59.1	59.9
286.9	46.9	48.1	41.6	43.5	44.1	48.1	58.7	59.5
287.9	46.6	47.7	41.2	43.1	43.7	47.8	58.4	59.2
288.9	46.2	47.3	40.8	42.6	43.2	47.3	58.0	58.8
289.9	45.7	46.8	40.3	42.1	42.7	46.8	57.7	58.4
290.9	45.3	46.3	39.9	41.6	42.2	46.4	57.2	57.9
291.9	45.0	46.0	39.5	41.2	41.8	46.0	56.9	57.6
292.9	44.5	45.5	39.0	40.7	41.3	45.6	56.5	57.2
293.9	44.1	45.1	38.6	40.2	40.7	45.1	56.1	56.8
294.0	43.8	44.8	38.2	39.8	40.3	44.8	55.8	56.4

## Appendix E

Table 3: Field test results (temperatures of the probes, case 1)

	Probe 1	Probe 2	Probe 3	Probe 4	Probe 5	Probe 6	Probe 7	Probe 8
Time (Sec)	Temp (°C)	Temp (°C)	Temp (°C)	Temp (°C)	Temp (°C)	Temp (°C)	Temp (°C)	Temp (°C)
0	43.4	50.4	46.8	38.9	35.4	50.0	54.1	53.8
10.0	43.4	50.7	47.0	39.5	36.0	50.3	55.0	54.4
20.1	42.9	50.1	46.0	38.8	35.9	49.5	54.7	53.8
30.1	41.5	48.8	44.8	36.9	34.8	48.2	53.3	52.0
40.1	40.1	46.8	42.7	35.2	33.4	46.6	51.5	49.9
50.2	41.1	48.6	44.6	36.3	33.8	48.0	52.9	51.8
60.2	44.2	52.1	47.4	38.9	35.8	51.0	55.6	55.1
70.1	45.5	53.7	48.9	40.6	37.2	52.7	57.5	56.9
80.1	45.5	54.1	48.8	40.9	37.9	53.0	58.2	57.2
90.1	44.7	53.0	48.1	40.5	37.4	51.9	58.1	56.9
100.1	43.2	51.5	46.7	38.7	36.2	50.5	56.7	55.0
110.1	41.7	49.6	44.7	36.9	34.7	48.9	55.0	53.1
120.1	43.0	51.2	46.5	37.9	35.2	50.3	56.2	55.1
130.1	45.5	54.1	49.4	40.4	36.9	53.2	58.7	57.7
140.1	47.0	55.8	50.3	41.7	38.5	54.5	59.9	59.1
150.1	46.8	55.9	50.2	41.8	38.8	54.7	60.3	59.1
160.1	45.8	54.9	49.1	41.0	38.1	53.7	59.9	58.2
170.1	44.2	53.1	47.7	39.2	36.8	51.9	58.6	56.5
180.2	42.5	50.9	45.8	37.4	35.3	50.3	56.7	54.4
190.2	43.8	52.7	47.7	38.4	35.8	51.7	57.6	56.4
200.2	46.3	55.3	50.0	40.8	37.5	54.4	60.0	58.9
210.2	47.4	56.5	51.0	42.2	38.7	55.1	61.3	60.5
220.2	47.1	56.5	50.9	42.2	38.9	55.2	61.5	60.0
230.2	46.3	55.3	49.6	41.3	38.2	54.1	61.0	59.2
240.2	44.8	53.8	47.9	39.2	37.0	52.4	59.3	57.5
250.2	42.9	51.3	46.0	37.5	35.4	50.6	57.3	54.9
260.2	43.8	52.6	47.4	38.0	35.5	51.8	58.0	56.5
270.2	46.3	55.3	49.9	40.6	37.2	54.2	60.2	59.5
280.2	47.7	56.8	50.9	42.0	38.7	55.3	61.5	61.0
290.2	47.4	56.7	50.7	42.0	38.9	55.3	61.9	61.2
300.2	46.3	55.4	49.9	41.2	38.2	54.4	61.5	60.0
310.2	45.0	54.2	48.1	39.2	37.2	52.8	59.5	58.3
320.2	43.2	51.7	46.0	37.4	35.5	50.9	57.6	56.2
330.2	44.2	53.0	47.4	38.0	35.7	51.9	58.2	57.1
340.2	46.7	55.4	50.2	40.6	37.2	54.5	60.7	59.9
350.2	47.8	57.0	51.3	42.0	38.7	55.8	61.8	61.1

Table 3 (Continues)

	Probe 1	Probe 2	Probe 3	Probe 4	Probe 5	Probe 6	Probe 7	Probe 8
Time (Sec)	Temp (°C)	Temp (°C)	Temp (°C)	Temp (°C)	Temp (°C)	Temp (°C)	Temp (°C)	Temp (°C)
360.2	47.8	57.0	50.9	42.2	39.1	55.6	62.0	61.4
370.2	46.5	55.4	50.3	41.4	38.4	54.6	61.8	60.3
380.2	45.2	53.7	48.3	39.4	37.2	53.0	60.0	58.9
390.2	43.4	51.3	46.5	37.8	35.7	51.0	58.3	56.8
400.2	44.3	53.3	48.2	38.6	36.0	52.4	58.9	57.7
410.2	46.9	56.1	50.6	40.9	37.8	55.0	60.8	60.2
420.2	47.8	56.9	51.8	42.3	38.7	55.8	62.6	61.6
430.2	47.8	57.0	51.3	42.3	39.0	55.6	62.5	61.6
440.2	46.8	55.7	50.1	41.3	38.6	54.7	61.6	60.6
450.2	45.3	53.8	48.4	39.3	37.4	53.0	59.8	58.6
460.2	43.4	51.5	46.5	37.7	35.8	51.4	58.1	56.5
470.2	44.9	53.6	48.3	38.9	36.2	52.8	59.3	58.1
480.2	47.1	56.3	50.8	41.0	37.8	55.2	61.3	60.3
490.2	48.2	57.2	51.8	42.3	38.9	55.9	62.6	61.7
500.2	47.8	57.1	51.1	42.2	39.3	55.6	62.5	61.5
510.2	46.8	55.7	49.9	41.3	38.6	54.5	61.7	60.3
520.2	45.2	53.6	48.3	39.2	37.3	52.9	60.0	58.7
530.2	43.2	51.0	46.3	37.1	35.5	50.9	57.9	56.0
540.2	43.0	51.2	46.7	37.2	34.8	50.9	57.9	56.1
550.2	45.7	54.6	49.4	39.5	36.6	53.8	59.6	58.8
560.2	47.3	56.1	51.0	41.5	38.0	55.0	61.5	61.0
570.2	47.6	56.4	50.8	41.9	38.8	55.4	62.0	61.1
580.2	46.7	55.4	50.2	41.3	38.4	54.6	61.5	60.3
590.3	45.2	53.4	48.9	39.7	37.2	53.1	60.3	58.8
600.2	43.6	51.2	46.8	37.7	35.9	51.4	58.0	56.5
610.3	44.0	52.7	47.7	38.1	35.8	52.0	58.2	56.9
620.3	46.5	55.1	50.4	40.8	37.2	54.3	60.8	59.8
630.3	48.1	57.0	51.4	42.2	38.9	55.7	61.9	61.0
640.3	47.7	56.8	51.6	42.5	39.2	55.7	62.6	61.1
650.3	46.8	55.8	50.6	41.5	38.7	54.8	61.9	60.3
660.3	45.4	53.8	48.9	39.9	37.6	53.1	60.3	58.9
670.3	43.4	51.1	47.0	37.7	35.9	51.3	58.4	56.5
680.3	43.0	51.0	46.4	37.4	35.1	50.6	57.6	56.1
690.3	45.6	54.3	49.3	39.5	36.5	53.6	59.4	58.5
700.3	47.4	56.1	51.0	41.4	38.1	55.2	61.4	60.7
710.3	47.8	56.6	51.0	42.0	38.9	55.6	61.8	61.0
720.3	47.2	55.9	50.3	41.4	38.7	54.9	61.4	60.3
730.3	45.8	54.0	49.0	40.2	37.7	53.4	60.3	59.1
740.3	43.9	51.5	47.4	38.2	36.0	51.5	58.7	56.8
750.3	43.5	51.8	47.0	37.6	35.5	51.4	57.8	56.2
760.3	45.9	54.5	49.9	40.3	36.8	53.8	60.2	59.1

Table 3 (Continues)

	Probe 1	Probe 2	Probe 3	Probe 4	Probe 5	Probe 6	Probe 7	Probe 8
Time (Sec)	Temp (°C)	Temp (°C)	Temp (°C)	Temp (°C)	Temp (°C)	Temp (°C)	Temp (°C)	Temp (°C)
770.3	47.8	56.7	51.4	41.8	38.6	55.7	61.7	61.0
780.3	48.0	57.0	51.5	42.5	39.1	55.6	62.6	61.8
790.3	47.3	56.1	50.7	41.7	38.9	55.2	62.0	60.4
800.3	45.9	54.6	49.2	40.3	38.1	53.9	60.5	58.9
810.3	44.1	52.0	47.6	38.2	36.3	51.7	58.7	56.9
820.3	43.6	52.0	47.2	37.9	35.7	51.7	58.2	56.5
830.4	46.2	55.0	49.9	40.5	37.2	53.8	60.2	59.7
840.4	47.7	56.5	51.6	42.2	38.5	55.6	62.2	61.4
850.4	47.9	56.9	51.8	42.7	39.1	55.8	62.6	61.8
860.5	47.5	56.4	50.6	41.8	39.1	55.0	61.8	60.9
870.5	46.0	54.6	49.3	40.2	38.1	53.8	60.3	59.1
880.5	44.2	51.8	47.4	38.1	36.4	51.5	58.6	57.0
890.5	43.0	51.0	46.4	37.3	35.1	50.7	57.6	55.7
900.6	45.4	54.0	49.2	39.4	36.5	53.3	59.4	57.8
910.6	47.3	56.1	51.2	41.6	38.0	55.1	61.7	60.0
920.6	47.8	56.7	51.5	42.2	38.9	55.8	62.2	60.5
930.6	47.3	56.3	50.7	41.7	38.8	55.2	61.8	60.0
940.7	45.9	54.4	49.6	40.7	37.9	53.6	61.0	59.1
950.7	44.5	52.1	47.7	38.3	36.5	51.9	58.8	57.0
960.7	43.8	52.0	46.9	37.8	35.8	51.4	58.0	56.3
970.7	46.1	55.0	49.8	40.0	37.0	54.1	59.9	59.0
980.7	48.1	56.7	51.4	42.0	38.7	55.7	62.0	61.2
990.7	48.4	57.4	51.5	42.5	39.4	56.3	62.5	61.5
1000.7	47.6	56.5	51.0	42.1	39.1	55.2	62.4	61.2
1010.7	46.3	55.1	49.7	40.5	38.2	54.2	60.8	59.2
1020.7	44.6	52.7	47.7	38.4	36.8	52.2	58.9	56.9
1030.7	43.9	52.4	47.5	38.1	35.9	51.7	58.6	56.9
1040.7	46.5	55.4	50.1	40.4	37.5	54.5	60.3	59.5
1050.7	48.2	57.2	51.8	42.2	38.9	56.1	62.2	61.2
1060.7	48.2	57.4	52.0	42.7	39.5	56.3	62.8	61.7
1070.7	47.8	56.5	51.0	42.0	39.2	55.5	62.5	61.3
1080.7	46.3	54.9	49.7	40.6	38.2	53.8	61.1	59.6
1090.7	44.5	52.4	47.7	38.5	36.6	51.9	59.2	57.0
1100.7	44.6	53.1	47.9	38.5	36.3	52.3	58.9	57.4
1110.7	47.0	56.0	50.7	40.9	37.8	55.0	60.9	60.2
1120.7	48.5	57.5	52.1	42.5	39.1	56.4	62.7	61.7
1130.7	48.4	57.4	52.3	43.1	39.5	56.4	63.4	62.4
1140.7	47.6	56.7	51.4	42.0	39.2	55.5	62.6	61.0
1150.7	46.4	55.0	49.7	40.4	38.1	53.9	61.1	59.4
1160.7	44.6	52.5	47.5	38.3	36.6	52.0	58.9	57.0
1170.7	44.6	53.1	48.5	38.7	36.2	52.6	59.5	57.7

Table 3 (Continues)

	Probe 1	Probe 2	Probe 3	Probe 4	Probe 5	Probe 6	Probe 7	Probe 8
Time (Sec)	Temp (°C)	Temp (°C)	Temp (°C)	Temp (°C)	Temp (°C)	Temp (°C)	Temp (°C)	Temp (°C)
1180.7	47.2	56.1	51.0	41.0	37.9	55.3	61.4	60.1
1190.7	48.5	57.5	52.4	42.7	39.0	56.6	63.1	61.9
1200.7	48.4	57.4	52.3	43.0	39.5	56.3	63.5	62.2
1210.7	47.6	56.5	51.4	42.1	39.0	55.4	62.8	61.2
1220.8	46.3	54.7	49.5	40.0	38.1	54.0	61.0	59.1
1230.8	44.3	52.2	47.6	38.0	36.3	52.2	58.8	56.5
1240.8	44.5	52.8	48.1	38.5	36.0	52.2	58.9	57.4
1250.9	47.1	55.7	50.6	40.9	37.7	54.8	61.0	60.0
1260.9	48.3	57.0	52.2	42.6	38.8	56.0	62.7	61.8
1270.9	48.3	57.1	52.0	42.7	39.2	56.2	63.1	61.8
1281	47.5	56.4	50.9	41.7	38.9	55.4	62.0	60.5
1291	46.0	54.4	49.4	39.8	37.9	53.9	60.5	58.9
1301	44.3	51.6	47.4	38.1	36.1	51.7	58.7	56.5
1311	44.4	52.7	48.3	38.6	35.8	52.4	59.0	57.5
1321.1	47.0	55.8	50.6	41.0	37.7	55.0	60.7	59.9
1331.1	48.4	57.0	52.0	42.6	38.9	56.0	62.4	61.8
1341.1	48.2	57.1	52.1	42.7	39.1	56.1	62.7	61.7
1351.1	47.3	56.1	51.0	41.7	38.8	55.3	62.1	60.4
1361.1	46.0	54.3	49.3	39.8	37.8	53.9	60.3	58.6
1371.2	44.1	51.5	47.4	37.7	36.0	51.7	58.5	56.4
1381.2	42.7	49.9	45.7	36.6	34.6	50.3	57.0	54.7
1391.2	45.0	52.9	48.3	38.7	35.8	52.6	58.6	57.3
1401.2	47.0	55.4	50.6	40.9	37.3	54.9	60.3	59.5
1411.2	47.9	56.1	51.3	42.0	38.4	55.4	61.5	60.7
1421.2	47.3	55.7	50.8	41.5	38.5	55.0	61.4	60.1
1431.3	46.3	54.4	49.4	40.4	37.9	53.9	60.2	58.9
1441.3	44.6	51.9	47.7	38.3	36.3	52.0	58.6	56.9
1451.3	43.0	50.4	46.4	37.2	35.0	50.7	57.3	55.2
1461.4	45.4	53.4	48.9	39.3	36.2	53.0	58.9	57.8
1471.4	47.2	55.6	51.2	41.7	37.7	55.0	61.0	60.2
1481.4	48.2	56.6	51.5	42.5	38.9	55.7	61.9	60.9
1491.4	47.8	56.3	50.9	42.0	38.9	55.2	61.5	60.5
1501.5	46.3	54.5	50.0	40.9	37.9	53.9	61.0	59.3
1511.5	44.6	52.1	48.1	38.7	36.5	52.0	59.2	57.1
1521.5	43.5	51.4	47.0	37.5	35.5	51.4	57.6	55.9
1531.5	45.7	54.4	49.6	39.8	36.7	53.8	59.3	58.3
1541.5	47.9	56.5	51.4	42.0	38.3	55.6	61.2	60.7
1551.6	48.1	56.8	52.1	42.6	39.0	56.2	62.6	61.5
1561.6	47.8	56.4	51.4	42.0	39.0	55.8	62.1	60.7
1571.6	46.5	55.0	50.0	40.9	38.2	54.3	61.0	59.7
1581.6	44.8	52.3	48.2	38.7	36.6	52.4	59.3	57.5

Table 3 (Continues)

	Probe 1	Probe 2	Probe 3	Probe 4	Probe 5	Probe 6	Probe 7	Probe 8
Time (Sec)	Temp (°C)	Temp (°C)	Temp (°C)	Temp (°C)	Temp (°C)	Temp (°C)	Temp (°C)	Temp (°C)
1591.6	43.9	51.7	47.2	37.8	35.8	51.7	58.1	56.2
1601.7	46.0	54.6	50.0	40.0	37.0	54.1	60.0	58.9
1611.7	47.8	56.4	52.0	42.3	38.4	55.8	62.2	61.1
1621.7	48.5	57.4	52.0	42.5	39.4	56.6	62.5	61.3
1631.7	47.8	56.5	51.5	42.2	39.1	55.6	62.4	61.1
1641.7	46.4	55.1	50.3	40.8	38.3	54.5	61.0	59.2
1651.7	44.8	52.5	48.3	38.5	36.7	52.5	59.3	57.4
1661.7	43.3	50.9	46.7	37.3	35.3	51.2	57.7	55.7
1671.7	45.4	53.7	49.3	39.4	36.2	53.2	59.4	58.1
1681.7	47.4	56.1	51.5	41.6	37.9	55.4	61.5	60.3
1691.8	48.3	56.7	52.0	42.7	38.9	56.0	62.6	61.3
1701.8	47.9	56.5	51.5	42.0	39.0	55.7	62.2	60.7
1711.8	46.5	55.1	50.1	41.0	38.2	54.3	61.3	59.5
1721.8	44.9	52.7	48.6	38.6	36.8	52.7	59.5	57.3
1731.8	43.3	50.3	46.2	37.0	35.3	50.9	57.5	55.0
1741.8	44.4	52.5	47.9	38.1	35.5	52.2	58.1	56.9
1751.8	46.8	55.3	50.4	40.5	37.3	55.0	60.1	59.2
1761.8	48.1	56.4	51.6	41.9	38.5	55.8	61.8	60.9
1771.8	47.6	56.4	51.5	41.9	38.8	55.8	61.9	60.7
1781.8	46.8	55.1	50.4	41.1	38.3	54.7	61.4	59.7
1791.8	45.4	53.1	48.9	39.1	37.2	53.1	59.8	58.1
1801.8	43.6	51.0	47.2	37.7	35.7	51.7	58.3	55.9
1811.9	45.2	53.9	48.9	39.0	36.5	53.4	58.9	57.6
1821.9	47.6	56.5	51.3	41.4	38.2	55.8	61.0	60.2
1831.9	48.6	57.6	52.2	42.7	39.4	56.6	62.2	61.5
1842	48.2	57.1	51.9	42.3	39.4	56.6	62.6	61.1
1852	47.1	56.2	50.7	41.3	38.9	55.4	61.5	60.2
1862	45.4	53.7	49.3	39.3	37.4	53.6	60.2	58.2
1872	44.1	51.5	47.2	37.8	36.0	52.0	58.3	56.4
1882	45.4	54.3	49.4	39.3	36.8	53.7	59.3	58.2
1892	47.8	56.9	51.6	41.7	38.5	56.1	61.2	60.6
1902	48.6	57.8	52.5	42.7	39.5	56.9	62.5	61.6
1912.1	48.3	57.0	51.7	42.6	39.3	56.1	62.3	61.4
1922.1	47.2	56.3	50.9	41.3	39.0	55.5	61.5	60.0
1932.1	45.6	54.0	49.0	39.1	37.7	53.6	59.8	57.9
1942.1	43.9	51.6	47.3	37.8	36.0	52.0	58.3	56.0
1952.1	45.5	54.2	49.1	39.2	36.7	53.6	59.2	58.0
1962.1	47.6	56.4	51.8	41.9	38.1	55.9	61.6	60.6
1972.2	48.6	57.5	52.4	42.8	39.4	56.5	62.6	61.7
1982.2	47.9	56.6	52.3	43.2	39.7	56.9	62.5	60.1
1992.2	47.4	56.2	50.7	41.5	39.0	55.4	61.8	60.2

Table 3 (Continues)

	Probe 1	Probe 2	Probe 3	Probe 4	Probe 5	Probe 6	Probe 7	Probe 8
Time (Sec)	Temp (°C)	Temp (°C)	Temp (°C)	Temp (°C)	Temp (°C)	Temp (°C)	Temp (°C)	Temp (°C)
2002.2	45.7	53.9	49.2	39.1	37.6	53.9	59.9	58.2
2012.2	44.1	52.0	47.5	38.0	36.2	52.5	58.6	56.5
2022.2	46.0	54.9	49.7	39.6	37.1	54.1	59.6	58.8
2032.2	47.8	56.8	52.1	41.9	38.6	56.3	61.9	61.1
2042.2	48.8	57.8	52.6	42.9	39.6	56.9	63.1	62.1
2052.2	48.6	57.6	52.0	42.5	39.9	56.6	62.7	61.8
2062.3	47.4	56.5	50.7	41.2	39.1	55.6	61.8	60.1
2072.3	45.8	53.9	49.1	39.0	37.6	53.7	60.1	58.4
2082.3	44.0	51.7	47.4	37.9	36.1	52.0	58.7	56.5
2092.3	45.4	54.4	49.6	39.4	36.8	53.8	60.0	58.7
2102.3	47.9	57.1	51.8	41.7	38.6	56.3	61.5	60.8
2112.4	48.9	57.9	52.6	42.8	39.5	56.9	62.7	61.8
2122.4	48.2	57.2	52.3	42.5	39.6	56.5	62.9	61.6
2132.4	47.4	56.3	51.0	41.3	39.1	55.4	61.8	60.3
2142.4	45.5	54.0	49.3	39.1	37.7	53.6	60.0	58.3
2152.5	43.9	51.8	47.2	37.5	36.2	52.1	58.2	56.2
2162.5	45.3	54.0	49.1	38.9	36.6	53.7	59.1	57.6
2172.5	47.8	56.7	51.3	41.4	38.5	55.8	61.0	60.4
2182.5	48.5	57.7	52.6	42.7	39.5	56.9	62.6	61.4
2192.5	48.3	57.6	52.4	42.5	39.7	56.8	62.7	61.5
2202.5	47.4	56.4	51.3	41.7	39.2	55.6	62.2	60.7
2212.6	46.0	54.2	49.6	39.5	37.9	53.8	60.4	58.9
2222.6	44.1	51.7	47.6	37.8	36.3	52.1	58.6	56.3
2232.6	45.1	54.0	49.1	39.0	36.7	53.2	59.1	57.9
2002.2	45.7	53.9	49.2	39.1	37.6	53.9	59.9	58.2
2012.2	44.1	52.0	47.5	38.0	36.2	52.5	58.6	56.5
2022.2	46.0	54.9	49.7	39.6	37.1	54.1	59.6	58.8
2032.2	47.8	56.8	52.1	41.9	38.6	56.3	61.9	61.1
2042.2	48.8	57.8	52.6	42.9	39.6	56.9	63.1	62.1
2052.2	48.6	57.6	52.0	42.5	39.9	56.6	62.7	61.8
2062.3	47.4	56.5	50.7	41.2	39.1	55.6	61.8	60.1
2072.3	45.8	53.9	49.1	39.0	37.6	53.7	60.1	58.4
2082.3	44.0	51.7	47.4	37.9	36.1	52.0	58.7	56.5
2092.3	45.4	54.4	49.6	39.4	36.8	53.8	60.0	58.7
2102.3	47.9	57.1	51.8	41.7	38.6	56.3	61.5	60.8
2112.4	48.9	57.9	52.6	42.8	39.5	56.9	62.7	61.8
2122.4	48.2	57.2	52.3	42.5	39.6	56.5	62.9	61.6
2132.4	47.4	56.3	51.0	41.3	39.1	55.4	61.8	60.3