SCHOOL OF MATERIALS AND MINERAL RESOURCES ENGINEERING

UNIVERSITI SAINS MALAYSIA

NUMERICAL INVESTIGATION OF NON- NEWTONIAN FLUID DURING MOLD FILLING PROCESS WITH PHASE CHANGE CONSIDERATION

By

MOHD. NUR FAHMIE IKHWAN BIN MILUS

Supervisor: Ir. Dr. Muhammad Khalil bin Abdullah@Harun

Dissertation submitted in partial fulfillment

of the requirements for the degree of Bachelor of Engineering with Honours

(Polymer Engineering)

Universiti Sains Malaysia

JUNE 2018

DECLARATION

I hereby declare that I have conducted, completed the research work and written the dissertation entitled “Numerical Investigation of Non- Newtonian Fluid During Mold Filling Process with Phase Change Consideration”. I also declare that it has not been previously sent for the award of any degree or diploma and other similar title for any other examining body, Institution or University.

Name of student : Mohd. Nur Fahmie Ikhwan bin Milus

Signature :

Date :

Witnessed by

Name of supervisor : Ir. Dr. Muhammad Khalil bin Harun@ Abdullah

Signature :

Date :

ACKNOWLEDGEMENTS

Alhamdulillah, most thankful and grateful to Allah S.W.T, the Most Gracious and the Most Merciful for giving me the chances and opportunity to complete my research work titled “Numerical Investigation of Non- Newtonian Fluid During Mold Filling Process with Phase Change Consideration”.

Specially dedicated my very own thank you and sincere appreciation to my beloved supervisor, Ir. Dr. Muhammad Khalil bin Harun@ Abdullah for the guidance, support, suggestion and encouragement that helped me during the whole process of my research and dissertation writing. Despite of being extraordinarily busy with duties, still took time out to hear, guide and keep me on the correct path while I am doing my research work.

I would like to use this opportunity to express my profound sense of gratitude to all lecturers for giving and delivering knowledges from the beginning to the end of my studies. I personally need and use the knowledges for my research work. With all the knowledge given, I able to complete my project on time.

My grateful thanks to all technical staffs from School of Materials and Mineral Resources Engineering (PPKBSM) who directly and indirectly helped me throughout my final year project. Thanks for helping me while handling laboratory work, running the equipment and analyzing the data as well as providing me with general supplies needed.

Besides, I would like to thank my friends who have been helping and supporting me throughout my project. I want to thank them for all their help, interest, courage and others.

Discussions that had done together gave me excitement and enjoyment while completing my research work.

Finally, this journey would not have been possible without the support of my family for their eternal love, support and blessing. I am extremely grateful to my parents, who supported me emotionally and financially during my year of academic achievements and throughout my studies in Universiti Sains Malaysia. I always knew that they believed in me and wanted the best for me.

TABLE OF CONTENTS

Contents Page

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

AMFA	Autodesk Moldflow Advisor
CFD	Computational Fluid Dynamic
DSC	Differential Scanning Calorimetry
FEMFDM	Finite Element Finite Difference
GNF	Generalized Newtonian Fluid
HDPE	High Density Polyethylene
LDPE	Low Density Polyethylene
MFA	Melt Flow Area
MFV	Melt Flow Velocity
MSDS	Material Safety Data Sheet
PP	Polypropylene
VOF	Volume of Fluid

LIST OF SYMBOLS

τ	Shear Stress
η	Viscosity
$\dot{\gamma}$	Shear Rate
τ^*	Torque
ρ	Density
C_p	Specific Heat
F_i	External Body Force
g_i	Gravitational Acceleration
K	Thermal Conductivity
T	Temperature
ΔH	Enthalphy
λ	Lambda

KAJIAN ANALISIS BERANGKA PADA KETIKA KEMASUKAN CECAIR NON-NEWTONIAN KE DALAM ACUAN DENGAN PERTIMBANGAN PERUBAHAN FASA

ABSTRAK

Satu kajian berangka telah dilakukan pada reologi leburan Low Density Polyethylene (LDPE) tentang tingkah laku perubahan fasa di dalam acuan. Tujuan kajian ini adalah untuk memerhati dan memahami tingkah laku aliran cecair penipisan ricih di dalam acuan. Satu model acuan berbentuk ‘dumbbell’ spesimen tiga dimensi telah dibentangkan. Perisian simulasi ANSYS FLUENT 15.0 telah digunakan untuk mengesahkan model kelikatan (Model Cross). Kesan perubahan dalam parameter proses seperti suhu acuan dan masa penyejukan yang berlainan pada tingkah laku reologi telah dikaji. Suhu acuan didapati mempunyai pengaruh yang jelas ke atas kelikatan LDPE dan corak pengaliran dan tingkah laku perubahan fasa atau juga dikenali sebagai lapisan “kulit beku”. Masa penyejukan juga memberi kesan yang jelas pada tahap pembentukan kristal untuk LDPE di mana ia juga berperanan untuk menentukan tahap pembentukan kristal dengan memberi masa yang cukup untuk orientasi pengenduran untuk rantaian molekul dan penyelarasan kedudukan pada arah tensil. Kajian ini telah dijalankan oleh beberapa pengkaji tapi ramai di antara mereka tidak membuat analisis eksperimen untuk membezakan dengan keputusan simulasi. Pembezaan di antara simulasi dan eksperimen haruslah dilakukan untuk menilai perbezaan di antara nilai teori dan nilai sebenar dan juga untuk mengukuhkan lagi hasil kajian. Banyak parameter yang telah dipertimbangkan di dalam kajian ini untuk menilai kesannya pada perubahan fasa dan sumbangannya pada tahap pembentukan kristal. Kelakuan perubahan fasa telah ditentukan dengan membandingkan tahap suhu maksima dari spesimen yang telah dikeluarkan dari acuan dalam eksperimen dan suhu maksima dari model spesimen selepas tamat masa penyejukan. Kedua-dua keputusan simulasi dan eksperimen adalah bagus dan nilai teori dan nilai sebenar tidak menunjukkan perbezaan yang ketara.

NUMERICAL INVESTIGATION OF NON-NEWTONIAN FLUID DURING MOLD FILLING PROCESS WITH PHASE CHANGE CONSIDERATION

ABSTRACT

A numerical study of Low Density Polyethylene (LDPE) melt on its phase changes behaviour in mold cavity was carried out. The aim of the study was to observe and understand the behaviour of the flow of shear thinning fluids through mold cavity. Three dimensional model simulation of polymer rheology in a dumbbell shape of mold cavity was used. The ANSYS FLUENT 15.0 simulation software was used to demonstrate viscosity model (Cross Model). The effect of variation in process parameters such as mold temperature and cooling time on the rheological behaviour were studied. The mold temperature was found to have slightly influence on LDPE melt viscosity and flow in the mold cavity and also the phase changes or also known as “frozen skin” layer behaviour. The cooling time also gives the slightly effect on the crystallinity of LDPE in which cooling time plays a role as to determine the degree of crystallinity by giving a time for relaxation-orientation of molecular chains and align at tensile direction. This research was studied by several researchers but most of them did not do the experimental analysis as to compare with simulation results. The comparison between the simulation and experimental analysis must be made in order to determine the discrepancies between theoretical values and actual values and to strengthen the findings. A lot of parameters were considered in this study in order to determine the effect on phase changes and its contribution towards degree of crystallinity. The phase change behaviour was determined by comparing the maximum temperature of ejected specimen from mold in experimental and maximum temperature of specimen model after cooling time finished. Both simulation and experimental results are good and the theoretical and actual values does not show the significant different.

CHAPTER 1

INTRODUCTION

1.1 Introduction to Injection Molding

The injection molding process is the most widely used manufacturing process for the production either for single part or many parts of plastic products. The process is so versatile which is able to adapt or be adapted to many different functions or activities. This process can be used for various production such as small electronic, medical parts, or for the production of very large automotive and building components. The growth in injection molding industry continues due in large part to advances in both plastic material and injection molding process technologies.

However, designing molded plastic parts can be extremely difficult task due to the complexities of both the part geometry and the molding process. Even though for expert and experienced designers, to work with new plastic material grades is still very difficult task that may process and perform in a different manner than those materials used previously. It is in fact very difficult to design a plastic part that is functional, manufacturable, and esthetically pleasing. The part design process involves a series of tradeoffs or compromises so that each of these important demands can be met.

Injection molding machine consists of several parts, which are hopper, screw barrel and mold. Mold is one of the essential parts in the injection molding machine, to form the melting feed stock to the desired product design. Prior to the process, the raw material is preheated in the feed zone to remove moisture. Then, the polymer becomes hot and melts after feeding through the screw barrel equipped with heaters. This hot mixture is injected into the mold to form the shape based on the design of the mold cavity. It is very important in getting the form and surface of the desired product in the cavity. For instance, the proper cavity pressure will produce products with precise dimensions.

Moreover, improper flow of melting material in the mold cavity will affect the product quality such as incomplete form part, high injection time and the material were freeze before entering and completing the mold cavity. Therefore, accurate and detailed ways determination of polymeric materials with appropriate design must be conducted in order prevent these problems. Conventionally, high cost of tooling and mold development causing irrelevant cost-effective pre-molding analysis need to be conducted. Besides, the interplay of parameters change in injection molding process will influence other parameters.

There are three commonly types of polymer that are used for producing a product such as thermoplastic, thermoset and elastomer. However, the most commonly plastic materials that are used in the injection molding process is thermoplastic. Thermoplastics are linear or branched polymeric materials that “soften” when heated, and “resolidify” when cooled. Thermoplastic materials are available in a variety of types and grades with properties that range from rigid to elastomeric. Robert A. Malloy (2010) stated that the processing of thermoplastic materials involves only physical changes (e.g., phase changes), therefore the materials can be readily recycled. Thermoplastic materials are recyclable; however, it is very likely that at least some small degree of chemical change (e.g., oxidation, thermal degradation) will take place during processing. Thermoplastic materials also behave like non-Newtonian fluid under pseudoplastic curve.

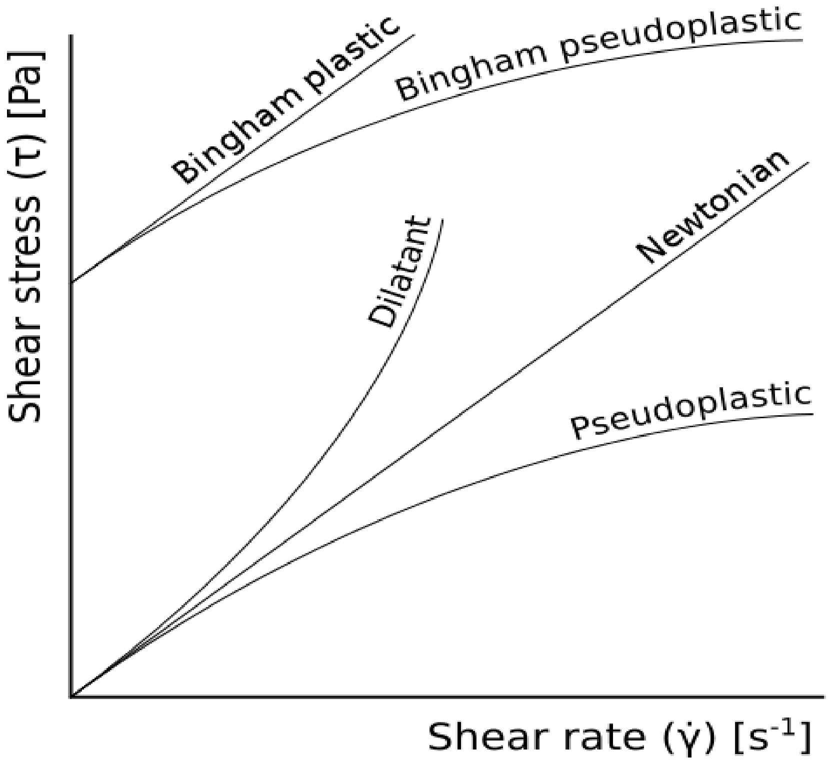

Figure 1.1 The classification of fluid with shear stress as a function of shear rate (M.Subramaniam, 2016)

In rheology, pseudoplastic is a shear thinning of non-Newtonian behaviour of fluids whose viscosity decreases under shear strain and is usually defined as excluding time-dependent effects, such as thixotropy. Shear-thinning behaviour is generally not seen in pure liquids with low molecular mass, or ideal solutions of small molecules like sucrose or sodium chloride, but is often seen in polymer solutions and molten polymers, and complex fluids and suspensions like ketchup, whipped cream, blood, paint, and nail polish.

In injection molding process, the shear stress is given by a screw to the thermoplastic and melted into low viscosity from solid to liquid. In this process, it involves chain scission where the long molecular chain such as polyethylene (PE) is cut into smaller molecules and shorter chains until the shear stress is constant as no more molecules available for scission. Therefore, thermoplastic materials are pseudoplastic of non-Newtonian fluid.

1.2 Background of Study

When conducting the injection molding process, the manufacturer itself cannot be apart from several parameters such as mold temperature, melt temperature, injection pressure, screw speed, mold ejection temperature, filling time and cooling time. This is because the injection moulding is the most commonly used process to realize plastic parts with high production rates and good control on the product dimensions. Galantucci & Spina (2003) stated that injection molding cyclical process is carried out in three phases: (i) filling, (ii) packing and (iii) cooling.

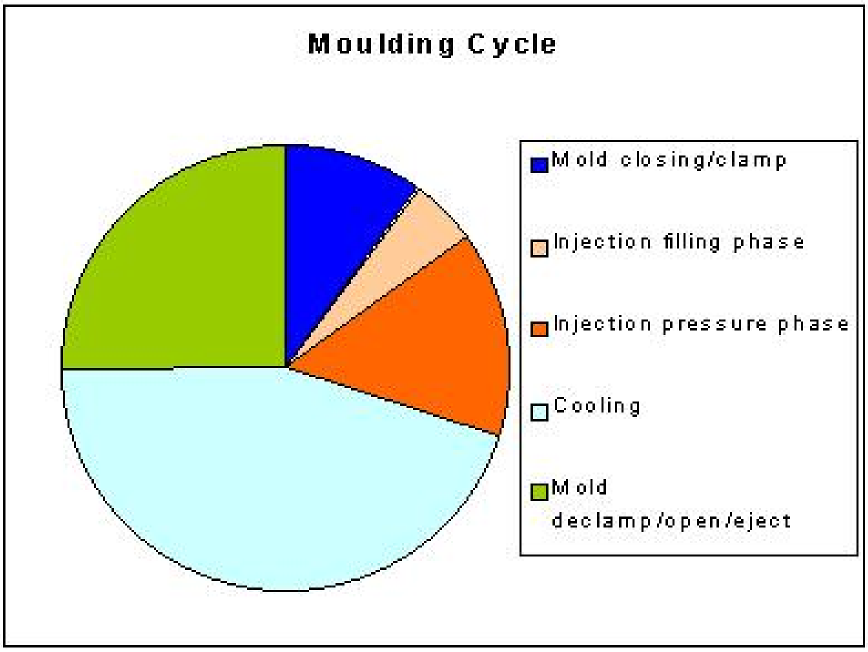

Figure 1.2 The injection molding process cycle

The changes in any parameters above such as pressure, filling time, temperature and cooling time, will affect the product quality. For example, when the injection pressure is too high, the filling time will be shorter as it will affect unfilled part of the mold such as dead corners and small or complex shape. Thus, the outcome product will be incomplete as the time for plastic melt to fill in the mold is not enough. The change in temperature also can affect the outcome product as the temperature level will determine the viscosity level of the plastic melt, the flow rate of the plastic melt inside the mold and also the time require to cool the product after injected into the mold.

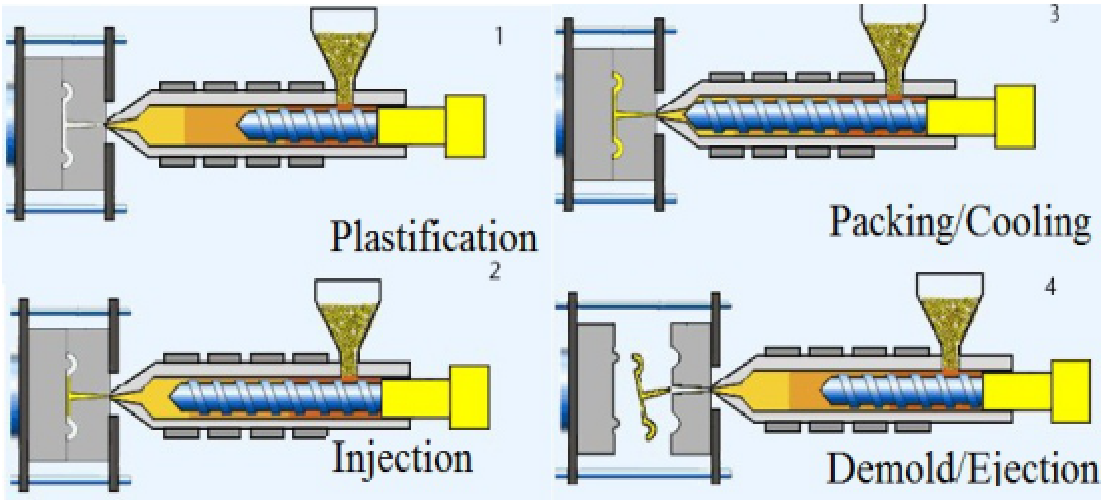

Figure 1.3 The illustration of injection molding process cycle

Based on Figure 1.3 above, the injection molding process can be divided into several process as stated below. Each of the process plays important role on determining the injection cycle following the production rate. Injection molding cycle time is one of the biggest factors in the efficiency of molding process.

i. **Resin heating:** In this initial stage, the base resin is heated to a temperature that liquefies it and brings it to the ideal viscosity and flow rate for injection.
ii. **Injection:** The heated material is injected into the mold cavity or cavities.
iii. **Packing and holding:** Injection continues as some of the material that has already been injected begins to cool and shrink. The pack/hold stage injects additional material to ensure that the cavity is completely filled, and “holds” the material there to prevent any backflow.
iv. **Cooling:** Once packing/holding is complete, the cooling stage is considered to have begun. Although material begins to cool as soon as it exits the heated injection nozzle and enters the mold cavity, cooling time should only be

calculated as a separate phase, after packing and holding. At this point, the liquefied resin begins to re-solidify and hold the shape of the mold cavity.

v. **Ejection:** Once the material has cooled and solidified to a point where it will hold its shape, the part can be ejected via the mold ejector pins.

Temperature can be divided into several parts which are melt temperature, mold temperature, injection temperature, ejection temperature and product temperature after ejected from the mold. For example, the melt temperature of polymer melt determine the viscosity level of the polymer melt. As the melt temperature increase, the viscosity of the polymer melt is decreases. This will easier for the polymer melt to flow into the mold. But the consequences of having lower viscosity is the possibility of the polymer melt to overflow from the mold creating 'flash' that needed to trim after process. Thus, the right temperature must be applied in this process in order to reduce the material used when injected into the mold. The temperature of the mold must be lower the melt temperature in order to reduce the cooling time and surely to prevent overflow of the material from the mold. Extreme temperature level or higher than the melting temperature of the polymer itself may causes degradation.

The flow rate of the polymer depends on the viscosity level of the polymer. As the viscosity decreases, the flow rate is also decreases in which the ability of the polymer to flow through time is low due to high resistance to flow inside the mold. Thus, the flow rate can be increase if the temperature applied on the polymer is sufficient for it to flow under pressure through the mold cavity. Therefore, the flow rate is inversely proportional to the viscosity.

The other parameter that depends on the temperature level that applied during processing is cooling time. The cooling rate which is defined as the mass of the polymer that cooled or turn from molten state into solid state in unit of time, is depends on the level of the temperature applied during processing either for melt temperature or mold temperature. For example, the higher temperature of the polymer melt will requires longer time to cool the plastic melt. The mold temperature also gives significant effect on cooling rate.

The mold temperature plays as major role on determining the cooling rate level of the injection molding process. This cooling rate will give a time for the chain to align either on amorphous or crystalline or both of them. The cooling rate also will determine how long cycle time of injection molding process. At low cooling rate, the mass of solidification of polymer melt is low and longer time taken to cool the polymer. Thus, at this situation, the cycle time will be increases. Therefore, low amount of products that are produced in one day. At high cooling rate, the mass of solidification of polymer melt is high with shorter time needed. Thus, the cycle time will reduce and high amount of products that fabricated in one day.

1.3 Problem Statement

Mendoza R. et, al (2003) stated that for injection molded amorphous polymers, the molecular orientation is due to the non-relaxed orientation generated by the melt flow. When the polymer melt enters the gate flow into the cavity, molecular orientation will arise in the polymer due to the stresses induced by the flow. The molecular chains oriented following the Fountain flow of polymer melt, thus resulting low crystalline orientation at tensile direction and resulted to high amorphous region. This was because of the viscoelastic nature of polymers both shear and normal stresses are present. When the cooling rates were high, layers with much orientation directly solidify without being able to relax especially the polymer melt that nearest to the wall which will results to low the mechanical and chemical properties of molded product.

The right mold temperature and cooling time must be determined in order to improve the relaxed molecular orientation. As mentioned above, the mold temperature also plays important role on the flow rate of polymer melt. As the mold temperature increase, the flow rate is high due to resistance of the molten polymer to flow inside the cavity is low. However, if the mold temperature is high, longer cooling time needed to solidify the polymer melt. Therefore, it is necessary for mold temperature is lower than injection temperature and melt temperature as to reduce the cooling time instead of overflow of material.

Although, the solidification of polymer from molten state to solid state is called 'phase change'. During the phase change, the molecular chains are move freely and tends to form amorphous structure in which this situation will occur during cooling phase. The cooling phase is responsible either the structure in product exhibit high crystalline region that has higher strength or high amorphous region that has lower strength.

1.4 Scope of Research

The purpose of this study is to determine the ideal combination of mold temperature and cooling time in order to get the maximum crystallization region in injection molding process for non-Newtonian behaviour of semi-crystalline polymer. As mentioned earlier, the cooling phase is responsible for making the polymer either exhibit high amorphous or high crystalline. The crystalline region has high strength due to highly packing order of the molecular chains in only one direction. This molecular orientation will make the polymer exhibit higher strength that are required for various application.

1.5 Significance of Study

The significant of this study is the determination of the ideal combination of mold temperature and cooling time during injection molding process by using thermoplastic LDPE material. The study approach is to find the range value of cooling time and mold temperature level. The other significant is the cycle time can be reduced and the excellent properties of final product can be obtained, so that the products have excellent performance and low cycle time. Hence, the products can be produced in large amount per day with the excellent properties followed by can reduce the cost.

1.6 Objectives

i. To study the flow behavior of non-Newtonian fluid in the mold cavity during filling phase and cooling phase.
ii. To determine influence of mold temperature and cooling time towards the phase changes behavior by using numerical simulation and experimental approaches.
iii. To identify the relationship between optimum cooling time and the degree of crystallinity of the polymer matrix.

1.7 Thesis Outline

There are five main chapters contain in the thesis. The first chapter discuss mainly on the introduction on the project description, background of research and the objectives to achieve in the study. This is to ensure that we understood about the title on "Numerical investigation of non-Newtonian fluid during mold filling process with phase change consideration" in injection molding process. Moreover, this chapter also contains the summarized of overview taken to finish the project given.

For the next chapter, chapter 2 is focusing more on the literature review where it is a critical part and need detailed evaluation on the previous research that related to the title. Literature review also can be a summary and synopsis of the research title. This chapter normally based on the previous studies and can be used to enhance the idea that relate with this topic.

The methodology or procedures in every simulation analysis and experimental analysis are included in chapter 3. The procedures needed to study effect of mold temperature and cooling time on the flow of LDPE melt, viscosity and the phase change behaviour. There are many tests conducted to via simulation and experimental approaches on the viscosity, phase changes and crystallinity of the product. The discrepancies between results of simulation and experimental analysis of each test for each observation on mold temperature and cooling time will be analyzed and compared.

In chapter 4, all the results will be presented and analyzed accordingly. The data present must be concise, clear and detailed. After that, discussion will be made to correlate the results with the objective of the project. The result will be analyzed and can be determine by plotting graph, calculation etc. In discussion, any new or unusual results must be explained and pointed out so that we can analyze the problems occur in this project.

The last chapter, chapter 5 will be the conclusion from the result of this research and future research will be suggested to study more about the problem related to this field. This is to enhance and improve the knowledge in engineering design study to develop new project related to the properties of the product in injection molding industries.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Many researchers had conducted the flow of non-Newtonian fluid with several considerations. Multifarious injection molding researches had been reported in the literature. There are several researchers have similar studies on non-Newtonian fluid but having different methods and also different consideration such temperature, pressure and phase change. Therefore, numerical simulation has become an important tool to simulate the injection molding process due to more effective in terms of cost and time and also important to investigate the parameters involved in injection molding process. Simulation is useful as a pre-analysis technique to detect any defect and requirement of process parameter before the actual mold being manufactured. This method is an alternative way than the trial-and-error methods, which consumes time and money if involves any major modification or revamp.

2.2 Numerical Simulation

Simulation process is a powerful software tool that allows refinery owners, operators, and engineers to virtually model a process in extreme detail without having to spend the time, manpower, or money physically testing their design in a real-world environment. Simulation modeling solves real-world problems safely and efficiently. It is an important method of analysis which is easily verified, communicated, and understood. Computer simulation is used in industries when conducting experiments on a real system is impossible or impractical, often because of cost or time.

For industry that used injection molding machine, to fulfill the customer requirements, the good properties and high production rate is needed in order to save times and enhance the product performance. The development of product must be simulated in order to predict the properties and performance of the product before marketed. The molten material may exhibit different flow behaviors in different designs of the mold cavity. The design parameters such as position of inlet and outlet, gate size, mold partition, thickness of the mold cavity are always concerned in the mold design. To minimize the mold part modification, the simulation analysis of the injection molding process is crucial to provide valuable information for the mold designer. The simulation analysis helps the mold designer to understand the flow-ability of the molten material during the injection molding process.

Several studies had been proposed by researchers regarding to the simulation analysis such as Smith et al. (2008) that used ANSYS FLUENT 6.3 simulation software in order to study the cooling phase of injection molding process. Additional information that unavailable in the experiment can be collected by using numerical models. Volume of Fluid (VOF) and Finite Volume Method (FVM) was used by Rudert & Schwarze (2001) to simulate Carbopol gel cavity filling flow pattern and filing time. The governing equations were solved using OpenFOAM and FLUENT software. Good agreement had been achieved between experimental and simulation results. The other study had been proposed by Tutar & Karakus (2010) which the single cavity and multi-cavity injection molding process had been simulated. They also used FVM and VOF in the simulation modeling. Cross model had been applied in the previous works for the viscosity model.

Second investigation conducted by Kyeong-Hee Han & Yang-Taek Im (1997), where in order to predict the shrinkage, warpage and mechanical properties of the injection molded parts, it is necessary to know the history of the flow field during injection molding processes. In the present investigation a numerical simulation program was developed to predict the flow field in filling and post-filling stages of injection molding. To simulate the real molding conditions more accurately, a generalized Hele-Shaw model for a non-Newtonian fluid was assumed considering the effects of phase change and compressibility of the resin. A finite-element-finite-difference (FEMFDM) hybrid scheme with control volume approach was employed as the solving technique.

For modelling the viscosity of the resin, a modified Cross model was used with a double-domain Tait equation of state being employed in describing the compressibility of the resin during molding. The energy balance equation, including latent-heat dissipation for semi-crystalline materials, was solved in order to predict the solidified layer and temperature profile in detail. For verification purpose, the simulation results were compared with the experimental results obtained from the test mold set designed in the current study using commercial-grade PP and the data available in the literature. Based on a comparison between experiments and simulations, it was found that the currently developed program was useful in unified simulations of filling and post-filling in injection molding processes when considering the phase-change effect.

Rusdi et al., (2016) had studied the numerical simulation analysis of the injection molding process using ANSYS FLUENT 14. The setting pressure and operating temperature were considered in their investigation. The influence of these two process parameters towards injection molding process in terms of filing time, flow front advancement, velocity profile was also studied. The injection molding and rheological experiments were carried out to substantiate the predictions of ANSYS FLUENT 15 in solving injection molding problems.

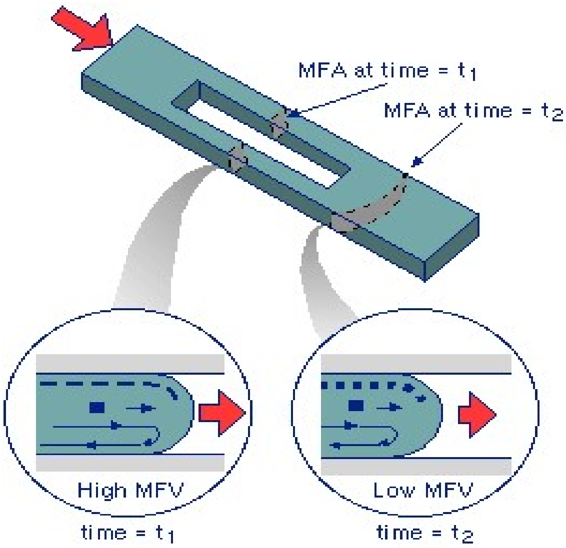

Figure 2.1 The illustration of melt front velocity at different time

The results revealed the system pressure is dominant to filling time, flow front advancement and velocity profile. Inversely, operating temperature only vaguely affects the current injection molding process, due to the small variations of polypropylene viscosity at temperature 185 –195 ^{o}C.

For any mold that has a complex cavity geometry, a constant ram speed (or, equivalently, a constant volumetric flow rate) does not necessarily guarantee a constant velocity at the advancing melt front. Whenever the cross-sectional area of the cavity varies, part of the cavity may fill faster than other areas. The figure above shows an example where the MFV increases around the insert, even though the volumetric flow rate is constant. This creates high stress and orientation along the two sides of the insert and potentially results in differential shrinkage and part warpage. The relationship of volumetric flow rate, MFA, and an averaged MFV can be expressed as:

$$\text{Melt Flow Velocity} = \frac{\text{Volumetric Injection Flow Rate}}{\text{Melt Flow Area (MFA)}} \tag{2.1}$$

Rusdi et al. (2016) also conducted the numerical investigation on the effect of injection pressure on melt front pressure and velocity drop by using a thermoplastic polypropylene (PP). The Computational Fluid Dynamic (CFD) was used to simulate the injection molding process of a tray. The study focuses on pressure distribution and velocity drop during the injection process and ANSYS FLUENT 14 was utilized in this study. Molten PP was used as the molten material in this study. The molten PP was then injected from the inlet of the tray (sprue) to the cavity. The tray-shape mold cavity in Figure 2.3 was designed by using SOLIDWORKS 2012 and then exported to CFD software for meshing and simulation analysis.

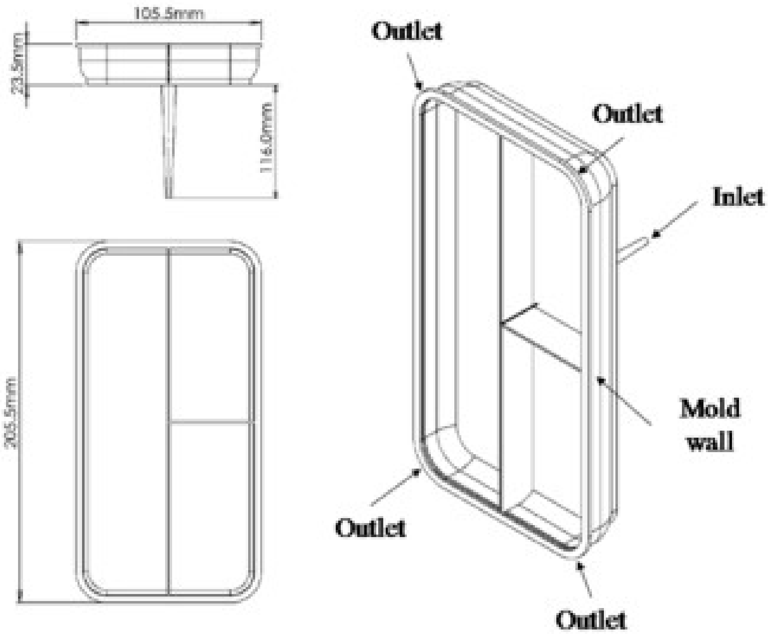

Figure 2.2 The design dimensions and boundary conditions of the tray mold cavity

CFD software solved the governing equation by using Cartesian spatial coordinates and velocity components. The governing equations that used to describe the simulation process are conservation of momentum, energy and mass. Volume of Fluid (VOF) method was used to locate the melt front movement of the molten PP. The Cross viscosity model was applied in the simulation. The FVM simulation software ANSYS FLUENT 15 was employed as the simulation modelling tool in this study.

As a result, the melt front pressure in the mold cavity shows that it was affected by the shape of mold cavity and filling stage. CFD simulation using ANSYS FLUENT 15 was used to simulate the injection molding process of molten PP into a tray-shape mold cavity. Significant effect was observed on the mold shape and filling stage on the melt front pressure where the pressure slightly drops when the melt front reached the rib section. The pressure also increases rapidly when the mold is about to be fully filled. At the constant mold shape (without rib) and early filling stage, the pressure was nearly constant. The velocity is higher when the higher injection pressure is set at the inlet. The velocity drops as the melt front move further away from the sprue and will decrease rapidly when the melt front reaches the final stage of filling process.

2.3 Non-Newtonian Fluid

In reality, most of the fluids are non-Newtonian because of their viscosity dependent on shear rate (shear thinning or shear thickening). A non-Newtonian fluid has viscosity that changes with the applied shear force. These fluids are characterized by measuring or computing several rheological properties such as viscosity and normal stress. The relationship between viscosity and shear rate can be represents as equation below.

$$\tau = \eta\,(\dot{\gamma})\,\dot{\gamma} \qquad (2.2)$$

Different constitutive equations, giving rise to various model of non-Newtonian fluids had been proposed in order to express the viscosity as a function of the strain rate. Non-Newtonian fluids are usually divided into three classes, although in reality these classification are often by no means distinct or sharply defined. (Skelland et al., 1967)

Time-independent fluids are which the strain rate at given point is dependent on the instantaneous stress at the point. Viscoelastic fluids are those that show partial elastic recovery upon removal of a deforming stress such as material both properties of viscous and elastic behavior.

Wang et al. (2013) proposed the studies by modelling and simulation of non-Newtonian fluid mold filling process by phase change consideration. As a matter of fact, the temperature on the side walls of the mold cavity is much lower than that of the melt. As a result, near the mold walls, the viscosity is higher due to the decreased temperature. The polymer tends to solidify as the viscosity increases, which is known as phase change or “frozen skin” layer. Meanwhile, great amount of heat, known as latent heat, will be released at the moment that the melt begins to solidify. The latent heat will stop the melt from solidifying. Since “frozen skin” layer is not desirable because it contributes to the “molded in” strains in the molded article, the phase change and the temperature variation should be studied carefully.

In their research, a model for the simulation of a power-law fluid mold filling process with the consideration of phase change is proposed. To avoid dealing with the complex boundary conditions at the melt interface, we consider simultaneously both the melt phase and the gas phase in the cavity as has been done by Yang et al. (2010). The governing equations for the melt and air in the cavity, including the mass conservation, momentum conservation and energy conservation equations, are unified into one system of equation. A finite volume method on non-staggered grid is used to solve the system.

The level set method is used to capture the interface evolution during the mold filling process. One reason for the establishment of the Enthalpy method is to avoid capturing the interface between the solid and liquid during solidification and the Enthalpy can be calculated on fixed grids. The other contribution of the Enthalpy method is the introduction of a narrow mush area between the solid and liquid areas, which takes the position of the mutation interface so that singularities at the interface are removed. In this paper, we set up the model with the consideration of latent heat using the Enthalpy Method.

In order to describe the phase change during the mold filling process, a revised Enthalpy method, which can be used for both the melt and air in the mold cavity, is proposed to describe the phase change during the mold filling. The “frozen skin” layers under different temperature and velocities conditions are discussed in detail. Since they consider simultaneously the polymer melt and the air in the cavity, the Enthalpy model must include the relationship between Enthalpy H and temperature T for both melt phase and air phase. In addition, the Cross-WLF model also used and also important which is the most appropriate model for studying both filling and packing phases, has been chosen to assess the total viscosity h of the polymer melt and adjust better the temperature and pressure sensitivities of zero shear rate viscosity. (Boronat et al., 2009)

$$\eta_l\,(T,\ \dot{\gamma}, p) = \frac{\eta_0(T,p)}{1 + (\eta_0\ \dot{\gamma}/\tau^*)^{1-n}} \qquad (2.3)$$

Where $\eta_0(T,\ p)$ is the melt viscosity under zero-shear-rate condition, τ^* is a constant that gives the shear stress rate from which the pseudoplastic behavior of the melt starts. n is the non-Newtonian index chosen so that the pseudoplastic behaviour gradient is 1-n; $\dot{\gamma}$ is the shear rate.

A 2D non-isothermal injection molding process for a non-Newtonian viscous pseudoplastic fluid is simulated with phase change. A modified Enthalpy model for two-phase flow is proposed to describe the phase change in the mold filling process. The information including the melt interface and the physical quantities such as temperature, pressure and velocity are all obtained. The decrease of temperature near cavity walls leads to high viscosity values and the reduction of the velocities in this zone, where a “frozen skin” layer will appear. The influences of the solid wall temperature, the melt temperature and injection velocity on “frozen skin” layer are discussed in detail. The “frozen skin” layer can be effectively reduced or eliminated by higher injection pressure (resulting in higher flow rate), higher melt temperature, and to a lesser but appreciable degree by increasing mold temperature.

2.3.1 Low Density Polyethylene (LDPE)

One of the polymer that possess non-Newtonian fluid of shear thinning behavior is LDPE. This thermoplastic polymer from polyolefin that has highly branched molecular chain compared to other polyolefin. These highly branched contributes to lower its mechanical and chemical properties due to highly amorphous region than crystalline region. However, this amorphous region also contributes to high flexibility, high transparency and high impact strength.

The flexibility of the polymer chains results the product having more ductile. This ductility properties is important in order to sustain the impact energy, thus arising the impact strength properties. LDPE is also widely used for manufacturing various containers, dispensing bottles, wash bottles, tubing, plastic bags for computer components, and various molded laboratory equipment. However, it is most common used in production of plastic bags. Therefore, the usage of LDPE can reduce the cost for production as it is easier to be processed.

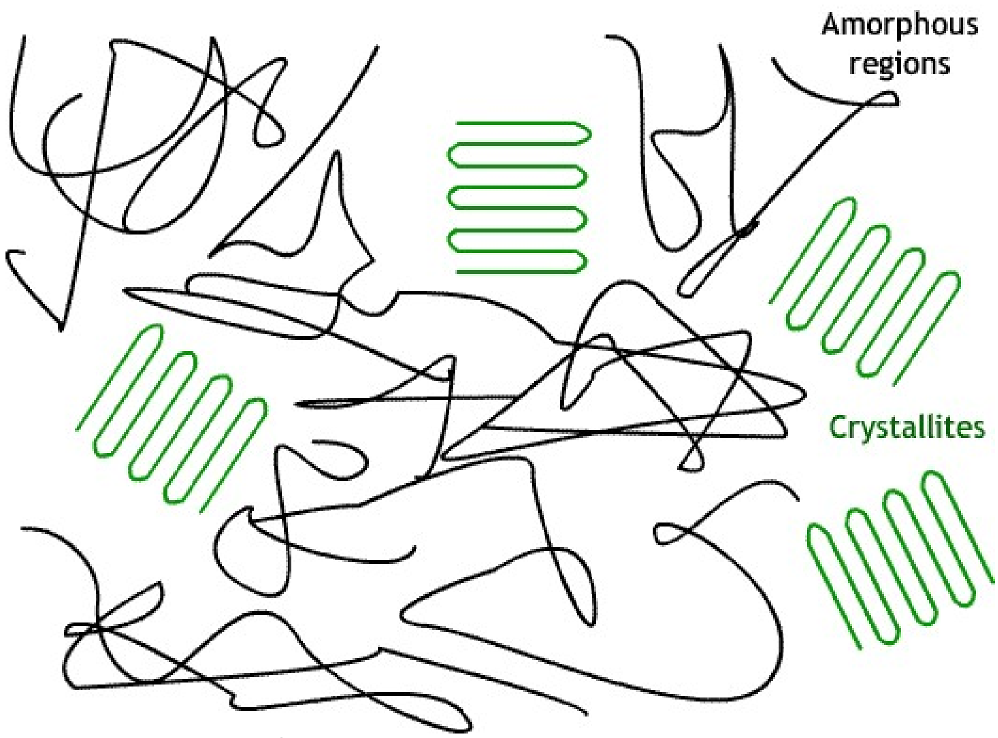

Figure 2.3 The illustration of semi-crystalline polymer which exhibit amorphous and crystalline

The crystalline region that exhibit higher strength is due to highly packed between the molecular chains creating strong bonding between them. In this study, the thermoplastic polymer of high-density polyethylene (LDPE) purchased from ETILINAS is used to determine the relationship between the combination of the temperature and cooling time with the molecular orientation during phase changes. The LDPE exhibit high crystallinity due to short branches and high linear molecular orientation in one direction.

The LDPE is normally used in piping and high resistance to the chemical required high strength and highly packed of chains in order to reduce the impact of load that applied by soil and the high chemical reactivity during application such as shampoo and liquid detergent. Even though the type of bonding between the chains is

Van der Waals interaction, but it is strong enough to hold them together and forming high crystallinity of polymer.

The amorphous region exhibits lower strength and low chemical resistance due to loosely packed and random orientation which is the molecular chains are on top of each other and high entanglement. The random orientation makes the polymer exhibit low crystallinity followed by low interaction between the chains. It will result to lower strength and low chemical resistance during the application. For example, the linear low-density polyethylene (LDPE) has naturally has high amorphous structure due to large and high amount of branches on its structure.

The branches structure restricts the molecular chains to form the crystal structure as the bulky side group is too large and restrict to form strain induced crystallization when stretched into tensile direction. Therefore, it is also necessary to determine on what combination level of temperature and cooling time that exhibit high amorphous structure.

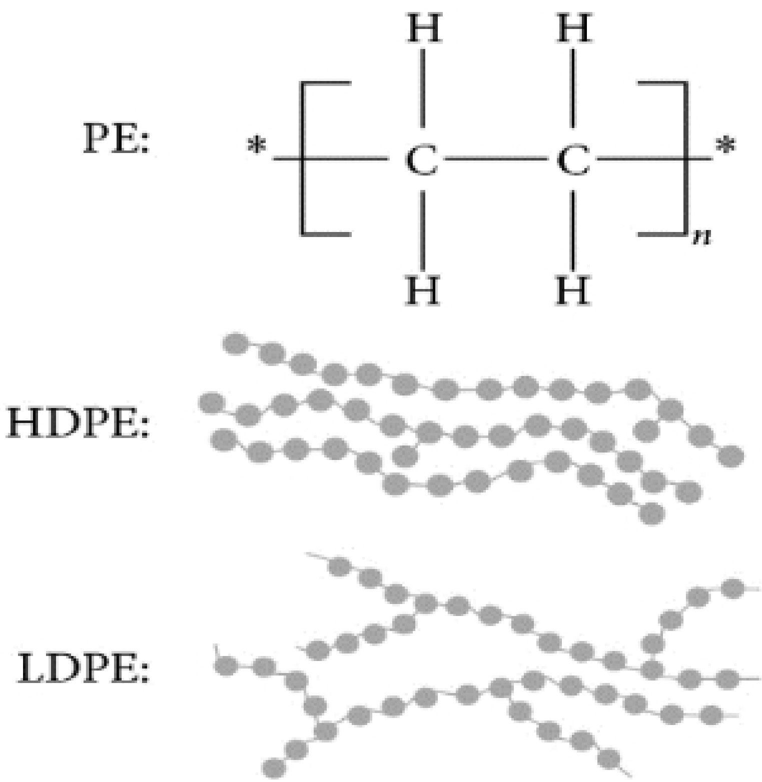

Figure 2.4 The illustration of molecular structure of LDPE and LDPE

2.4 Injection Molding Parameters

Injection molding parameters are one of the important criteria to manufacture products. This is due to the quality of the products is depending on the molding conditions as shown in Figure 2.5. In order to arise the quality of the molded products, the parameters are needed to be optimized as the processing condition is affected by injection molding parameters during process. The parameters such as barrel temperature, injection pressure, injection speed, holding pressure, holding time, mold temperature and cooling time plays an important roles towards processing.

Barrel temperature brings the sufficient energy to heat up the polymer resin in the injection unit in order to reduce the viscosity of the polymer. The barrel temperature was used in injection molding process is depends on the type of polymer used since they have different melting temperature in which if the polymer is heated above this temperature, it will causes the degradation of polymer that will no longer can be used to produce the products. Thus, the barrel temperature can be set to the processing by referring the process temperature which is stated in the MSDS of the polymer used (He et. al, 1997).

Injection pressure produced when the polymer melt is injected into the mold cavity. The function of injection pressure is to ensure that the polymer melt from the barrel fills the mold cavity following by packing while consistent solidification of the melt is maintained according to the mold temperature applied. Otherwise, insufficient injection pressure will cause the defect to occur due to the polymer melt is not fully filed the mold cavity and thus reduce the appearances quality and properties of the molded products. In order to achieve the filling and packing of the polymer melt, the injection pressure can be divided into two stages. The first stage is the injection pressure in order to fill the polymer melt in the cavity while the second stage is the injection pressure that applied during packing phase of the polymer melt in the cavity until the cooling time is completed. Usually, the pressure applied to the polymer melt at second stage is larger than at first stage (Rosato et. al, 2000).