Temperature field numerical simulation and experimental study of rapid heat cycle molding in cooling process

Shaofei Jiang*, Zhifei Mao, Jiquan Li, Wei Zheng

Key Laboratory of Special Purpose Equipment and Advanced Processing Technology, Zhejiang University of Technology, Hangzhou 310014, China

Received 22 April 2014, www.cmnt.lv

Abstract

Rapid heat cycle molding (RHCM) is a new technology aimed at obtaining green and high surface quality of plastic products. In this paper, the finite element model of the mould cavity in cooling process with RHCM was established for the transient heat transfer simulation using ANSYS. Thermal analysis results of temperature field were modified by experimental analysis, the results of which showed a good temperature uniformity and extraordinary efficiency of the cooling rate.

Keywords: rapid heat cycle molding, finite element model, cooling process, temperature field

1 Introduction

Modern injection molding products are developing towards high performance, low-cost and green environmental protection. High stability and performance of moulding process and process equipment are requested due to their use in industry [1-3]. Rapid heat cycle molding technology is the key research direction of injection molding research field at present. This technology is becoming enormously a potential commercial technology, which can get extraordinary surface quality of plastic products without follow-up spraying process and save more material or energy than traditional process method with lower total production cost and a shorter production cycle.

The main research emphases of rapid heat cycle molding technology focus on the research and development of heating methods, which include steam heating, electric heating, high frequency electromagnetic induction heating, infrared radiation heating, flame heating, high temperature gas heating and other heating methods [4-6]. We can improve the fluidity of plastic melt during the filling stage effectively and decrease the quality defect of the plastic to satisfy quality requirement. But production efficiency will be reduced greatly owing to the cooling time increasing. The above disadvantage is not conducive to the application of the actual production. Therefore, research about the effect of heating and cooling stage in rapid heat cycle molding process should be studied to provide a theoretical basis for the development of the technology. Barone and Caulk [7] firstly used the boundary element method for two-dimensional analysis in cooling stage of traditional molding process, and optimized the cooling device settings, size and surface temperature at the same time. Domestic and foreign scholars began to study the three dimensional simulation of steady-state and transient temperature field in traditional molding process with the rapid development of polymer rheology, heat transfer theory, numerical calculation and other related disciplines, as well as a variety of simulation software such as Ansys, Abaqus [8-10]. However related research rarely involves cooling process of rapid heat cycle molding technology. In conclusion the uniformity of the temperature field during the cooling stage and the cooling rate are important influencing factors in the quality as well as the function of the plastic parts. Therefore, the correct simulation and analysis of mold cooling process are conducive to our understanding of the mold temperature field, and help us to adjust the parameters of temperature in the injection molding process effectively. So we can increase the production efficiency and the quality of plastic parts in rapid heat cycle molding technology.

The numerical simulation is an effective way to study the injection molding process [11], and the realization of the mold three-dimensional temperature field simulation provides a scientific basis and analytical tools for the control of the plastic product’s quality. It can promote the design and development of the injection mold effectively. In this study, the simulation of temperature field of cooling stage in rapid heat cycle molding with electric heating was proposed helping us knowing the distribution of cavity’s temperature field and the factor that influent the temperature variation better, through three dimensional simulation of temperature field in cooling stage and the contrast verification of experimental results. And the results will provide a theoretical basis for the design of electric heating mould and other moulds.

****Corresponding author*** e-mail: zjujsf@163.com

2 Simulation

2.1 ESTABLISHMENT OF THE GEOMETRIC MODEL

Electric heating mould is similar with the traditional injection mould. The difference lies in that the heating pipes used for installation of electrical heating rods are designed in a fixed mould plate. In order to study the thermal response law of mold temperature field in cooling process, and considering the symmetry of the mould plate at the same time, a quarter model of the mould was studied as the analysis object of numerical simulation, model size was set up according to the actual size of the mould. Moreover, the mold cavity surface was simplified as simple plane, ignoring the actual mold flash structure and the gap existed between fixed mould plate and movable mould plate in order to further reduce the complexity of the model. Figure 1 was the picture of geometric model built to analyse the mold temperature field.

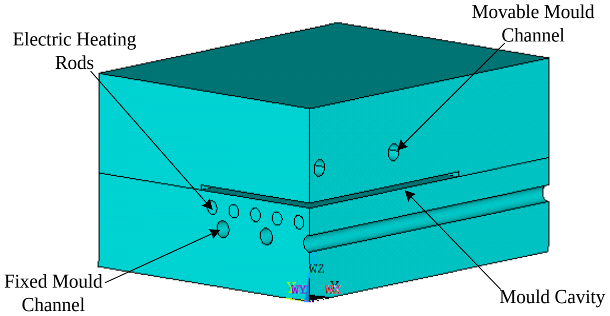


FIGURE 1 Geometric model

2.2 ESTABLISHMENT AND SIMPLIFICATION OF THE MATHEMATICAL MODEL OF COOLING PROCESS

The heat exchange within the injection mold in the cooling stage with electric heating has three main aspects:

1) Plastic melt is contacted directly with the mould cavity, and the heat was transferred to the mould by heat conduction.

2) The cooling pipe inside the mould will transfer most of the heat to the coolant, which is a convection heat transfer process.

3) The mould will release part of the heat directly to surrounding air through thermal convection and thermal radiation. The absolute heat releasing of plastic parts is equal to the sum of the heat taken away from the mould outer surface and the cooling system.

Therefore, the heat transfer process of the cooling stage is composed of the following control equation decision:

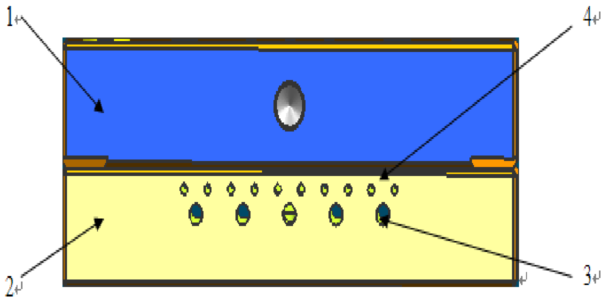
$$\rho c\frac{\partial T}{\partial t}-\frac{\partial}{\partial x}(\lambda_x\frac{\partial T}{\partial x})-\frac{\partial}{\partial y}(\lambda_y\frac{\partial T}{\partial y})-\frac{\partial}{\partial z}(\lambda_z\frac{\partial T}{\partial z})-h(T_m-T_c)-\alpha(t_w-t_\infty)=0, \quad (1)$$

where represents the material density of the mold (kg/m³). Letter c represents the materials specific heat of the mold ($Jkg^{-1}K^{-1}$), letter T represents the temperature (K), letter t represents the time(s), λx, λy, λz represents the thermal conductivity ($Wm^{-1}K^{-1}$) along the three main directions of the object (x, y, z), h represents the surface heat transfer coefficient between cooling pipe and the mould ($Wm^{-2}K^{-1}$), T_m, T_c respectively represent for the mold wall surface temperature and the temperature of the cooling medium (K), α represents the composite surface heat transfer coefficient ($Wm^{-2}K^{-1}$), t_w, t_∞ respectively represent for the temperature of the air around the mold and the mould surface (K).

The mould exchanges the heat through the cooling channel in the cooling stage. Taking into account the rapid flow of the cooling water, we assume that the initial temperature of the water of mold cooling channel remains consistent.

2.3 PHYSICAL MODELS AND MATERIAL PROPERTIES

Figure 2 describes a part of rapid heat cycle mould with electrical heating, where the size of the fixed mould plate and movable mould plate respectively is 450×350×55.6mm, 450×350×60mm. Compared with the traditional injection molding, the main difference is that a row of heating pipe holes were designed around the mould cavity in rapid heat cycle mould. This can improve the surface quality of plastic though controlling the heating pipe. The fixed mould plate and movable mould plate are made of SP400, which has excellent thermal stability and thermal transmission to ensure the heat generated by the heating rod transfer to the cavity surface rapidly and reduce the heat dissipation of the midway. The material properties of the mould were shown in the following (Table 1).



1 Movable mould plate 2 Fixed mould plate
3 Electric heating rods 4 Cooling channel

FIGURE 2 Part of the electric heating mould

TABLE 1 Material properties of the mould plate

Material properties	Parameters
Density	7.8×10^3(Kg/m³)
Heat Conductivity	34 (W/mK)
Specific Heat	460 (J/Kg)
Thermal Expansion	11.8×10^{-6}

2.4 THE BOUNDARY CONDITIONS

Mould and plastic part: The process of heat transfer between the mould and the plastic parts was simplified as pure heat conduction process owing to the neglect of latent heat, and the physical parameters were considered as a constant. As the temperature value of the cavity surface was obtained by simulating the filling and packing stage, so the process was controlled by the first boundary condition:

$$t_w = f(x, y, z, \tau),\ \tau > 0\,. \tag{2}$$

Mould and cooling channel: The heat transfer between the mold and the cooling channel was completed by heat convection and heat transfer. The particle of coolant was mixed to reduce the heat. As the temperature difference between the mold wall and the cooling channel, the heat was also transferred by thermal conduction. The basic heat transfer process can be expressed as the expression:

$$q = h\left(T_m - T_c\right). \tag{3}$$

We could obtain convective heat transfer coefficient from the third boundary condition. Letter h represents surface coefficient of heat transfer between the mould and cooling channel ($Wm^{-2}K^{-1}$), T_m, T_c respectively represents the temperature of the mold surface and the cooling medium (K). The speed of the cooling process was determined by the value of h, which is closely related to the flow of the coolant state. This relationship can be reflected by the Reynolds number Re.

Mould and surrounding environment: The outer surface of the mold was exposed in the ways of heat transfer include both heat convection and heat radiation, which belonged to the third kind boundary condition. Expressions of heat transfer boundary condition could be written as follows:

$$q_w = -\lambda \frac{\partial t}{\partial n}\Big|_w = \varepsilon\sigma(T_w^4 - T_{sur}^4) + h(T_w - T_f) = \alpha(t - t_\infty)\,. \tag{4}$$

The significance of each parameter was the same as the heating process.

2.5 INITIAL CONDITIONS

The ambient air temperature was 27°C. The heat transfer coefficient of mold and the surrounding environment was $25Wm^{-2}K^{-1}$ according to the actual production environment of injection molding cooling stage. The heat transfer coefficient of the mold and cooling pipes was 5707.6 $Wm^{-2}K^{-1}$.

3 Experimental

3.1 INITIAL CONDITIONS

In order to verify the rapid heat cycle molding technology in improving the quality of plastic product, we used electric heating as an example and designed the structure of plastic product. And then we designed a set of electric heating mould (as showed in Figure 2) and set up the experimental platform of the electric heating mould process.

The type of the injection molding machine is Haitian HTFX5 series MA3800 in this experiment, maximum clamping force of 3800KN, the biggest melt volume is 1239cm3, the maximum injection pressure can reach 182Mpa. This machine is suitable for demanding precision plastic molding.

The type of the electric heating controller is MTS-32II, which uses a three-phase and five-wire system supplied by 380V power, a single maximum output power of 6.5KW,Temperature control range of 0-399.9, time control accuracy of 10ms, maximum controllable loop digital 24.

Electric heating rods in this experiment are also known as the high-density single end electric heating tube or tube electric tube. The parameters of the electric heating rods respectively are 220V/270W, diameter 4mm, length of 450mm and 220V/210W, diameter of 4mm, length of 134mm, respectively marked as the type I and type II.

3.2 EXPERIMENTAL DESIGN OF RAPID HEAT CYCLE MOLDING WITH ELECTRIC HEATING

Engineering plastics HDPE was used in the experiment. Electric heating controller adjusts the temperature of electric heating rods to heat the mold firstly. Therefore we can know the changes of temperature through the measurement of the thermocouple in a fixed mould plate. We can read and record the temperature of the mould from the screen. The correctness of the simulation process should be verified next by comparing the simulation temperature information at the corresponding position in the thermocouple of the measured temperature information and fully taking into account the impact of the experimental error as well as the simplified model on the results of experiment and simulation. The installation position of the thermocouples was shown in Figure 3, where thermocouple 1. and 2., 3. and 4. respectively on the fixed mould template central symmetric.

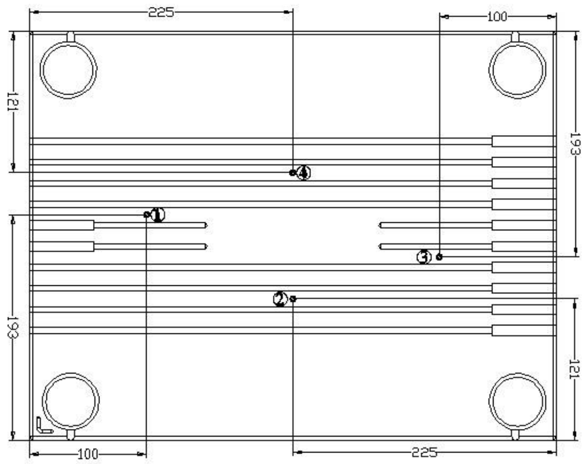


FIGURE 3 The installation position of the thermocouples

Six observation points were selected uniformly in the direction of the mold cavity surface. They were marked by P1, P2, P3, P4, P5 and P6, the distance between each point is 18mm. Three observation points were selected uniformly in the direction of the vertical cavity surface. And they were marked by P3, P7 and P8. The location of point P1-P8 was shown in Figure 4.

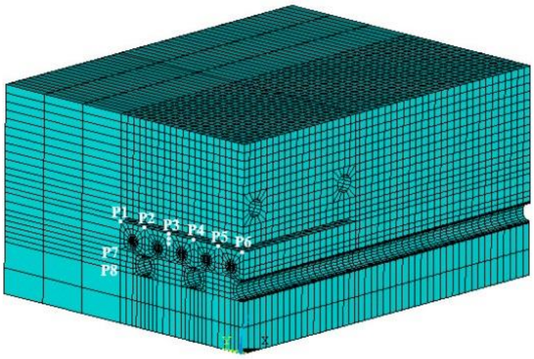


FIGURE 4 The location of observation points

Consequently we recorded the temperature value of the mold cavity corresponding to the position of the thermocouples installed in a fixed mould plate according to the measuring temperature. The location of the thermocouples was shown in Figure 3. We need only observe the thermocouple temperature of position 1. and 4. in this experiment due to the symmetries of the installation location of the thermocouples and the position of electric heating rods. The data of each point were collected every 5 seconds in this experiment. The temperature data of thermocouple 1. and 4. in the entire cooling process (25 seconds) were shown in the following (Table 2).

TABLE 2 Temperature data in cooling process

Time(s)	Thermocouple 1. (℃)	Thermocouple 4. (℃)
0	100.4	95.8
5	95.1	92.0
10	88.0	85.8
15	81.2	78.3
20	75.2	72.7
25	70.6	67.1

3.3 EXPERIMENTAL VERIFICATIONS

The contrast temperature graph of experiment and simulation of thermocouple 1. and thermocouple 4. is shown in Figure 5. From the graph, we can see that the cooling speed of mould is gradually decreased and the temperature of mould drops slightly slows in cooling process. The value of the simulation and experimental maintains the consistent trend of cooling rate. Nonetheless, the mold cooling rate in the simulation was obviously higher than the cooling rate of mold in the experiment at the same time, and the temperature difference gradually expanded along with the cooling process. The case of the tendency is that the release of latent heat of plastic melt has been ignored in model simplification.

The plastic melts generate phase transition by the changing of temperature. The process of phase transition will release plenty of latent heat, which supplies the loss of heat owing to the cooling effect of water. So the mould temperature in experimental is always higher than the temperature in the simulation process at the same time, and the gap can be regarded as the additional value obtained by releasing the latent heat of plastic melt.

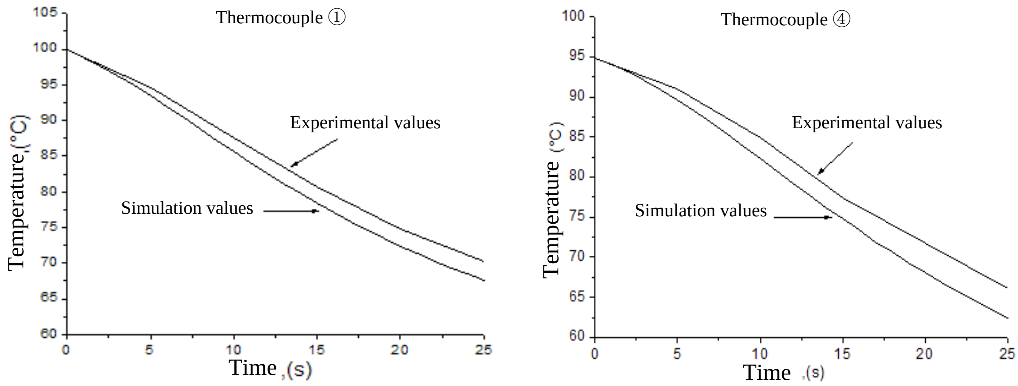


FIGURE 5 The contrast of experiment and simulation temperature in cooling process

We concluded that the simulation process is good to reflect the change of the temperature field in cooling stage with electric heating without considering the latent heat released through the phase transition of plastic melt.

4 Results and discussion

4.1 DISCUSSION ABOUT THE RESULTS OF SIMULATION

It is known that the uniformity and cooling rate of cavity surface temperature in cooling stage has a significant impact on the quality and production efficiency of plastic products. On one hand, the gradients of cavity surface temperature will result in the inhomogeneity of parts surface and excessive internal residual stress of plastic parts. It may be deformed or even failure in the process of using plastic parts because of the release of stress. On the other hand, cooling rate directly affects the cycle of plastic injection molding process, and the overlong molding cycle will cause a decrease in productivity. So it is necessary to study the temperature field in cooling stage of rapid heat cycle molding with electric heating. We can be faster and more intuitive understanding of the temperature field of the mold cavity in the cooling stage. It also can provide reasonable structural design of mould for us.

4.2 TEMPERATURE UNIFORMITY

Figure 6 shows the temperature distribution of the mold cavity surface around the fixed mould plate in the cooling time of 25 seconds. The overall temperature of the cavity surface is less than 75°℃, which is lower than the glass transition temperature of the plastic melt. We can see from the picture that cavity surface temperature is slightly reduced from the cavity centre to the edge of the cavity. The maximum temperature of the cavity surface was 73.7°℃, the lowest temperature was 40.5°℃, the average temperature of the cavity surface is 59.1°℃. The temperature of the red zone in this picture was significantly higher than the cavity edge part. This is caused by the high power of type II electric heating rods in the heating stage, which is caused by local heating too fast. The temperature of the cavity edge is lower than the average temperature of the entire cavity surface. This is because the arrangement of the electric heating rods in the heating stage is not sufficient heating to the cavity edge part. So the temperature is always lower than the centre of the cavity in the cooling stage. And this results in a phenomenon of poor uniformity of the cavity temperature.

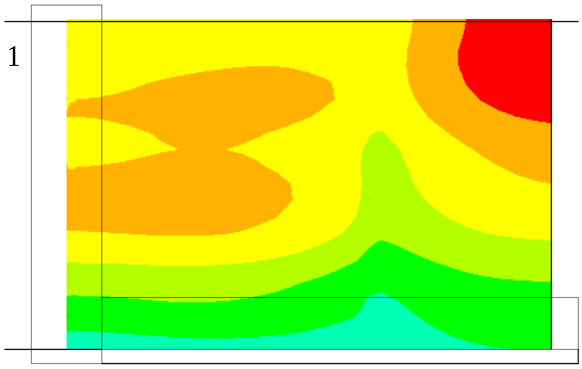


FIGURE 6 The temperature field of the cavity surface

4.3 COOLING RATE

Figure 7 is the temperature change graph of point P1-P6 in the cooling time of 40 seconds. The average cooling rate of P1-P6 respectively are 0.37°C/s, 0.96°C/s, 1.08°C/s, 1.12°C/s, 0.84°C/s and 0.75°C/s. It can be seen through point P1 and point P2 that the temperature of P1 is far less than point P2 at the beginning, but the distance between the cooling pipe the distance between point UP and cooling pipe is smaller than PLY. The heat can be passed rapidly through the mould to cooling water. Moreover, decrease heat of natural convection from the mould surface is much less than the heat, which is loosed from the mould and cooling water. So the application of cooling water can effectively reduce the total cycle of injection molding.

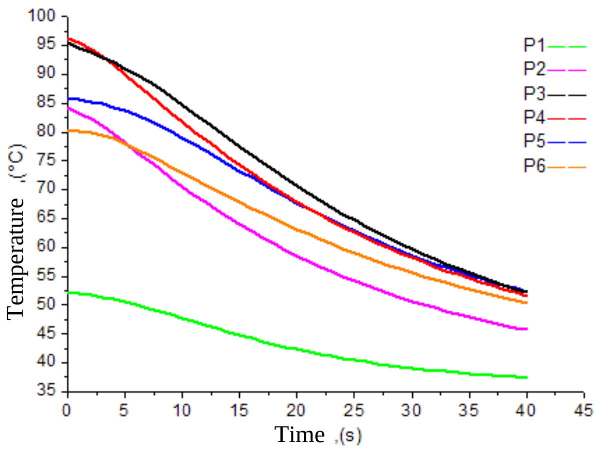


FIGURE 7 Temperature change graph of P1-P6 in cooling stage

It can be seen by comparing the cooling process of point P2 and point P3 that the cooling rate basically consistent in each process. The distance between point P2 and each cooling pipe is very close to point P3. We can see that the cooling rate of point P4 is permanently greater than point P3 in each process of cooling stage, and the distance between point P4 and each cooling pipe is smaller than point P3. In conclusion, we can conclude that the speed of the cooling rate in somewhere was inversely related to the distance between the cooling pipe and the point. Namely, the cooling rate is decreased with the increasing distance from the cooling pipe. It also can be seen from the temperature change trend that the cooling rate decreases with the decrease of temperature. The temperature difference between each point and the cooling water is gradually reduced and the temperature gradient becomes slightly smaller along with the cooling process. In order to shorten the time required for the cooling stage, we should try to reduce the temperature of cooling water and accelerate the flow rate of the cooling water in the cooling pipe under the working conditions. The cooling water which is rose due to heat exchange should be drainage outside the mould quickly.

5 Conclusions

In this study, the main emphasis is placed on the problem of the distribution of cavity's temperature field in cooling stage with RHCM. The geometric model of the temperature field of electric heating mould was establishment. The proposed model is verified through experimental study. The paper showed a good temperature uniformity and extraordinary efficiency of the cooling rate The results was obtained helping us knowing the distribution of cavity's temperature field and the factor which affected the temperature variation better. And the results will provide a theoretical basis for the design of electric heating mould and other moulds.

Acknowledgments

The research work was supported by national natural science foundation of China (51375451), Zhejiang province science and technology innovation team project (2012R10002-03&2012R10002-04).

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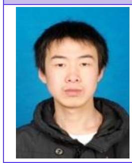
Authors

Shaofei Jiang, born in August, 1975, Datong, China

Current position, grades: the professor of Zhejiang University of Technology, China, a Senior member of Chinese Mechanical Engineering Society.
University studies: Ph.D. degree in mechanical design from Zhejiang University, China, in 2004.
Scientific interest: the theory of product design, the advanced of mold technology, manufacturing industry informatization.
Publications: 35 papers, 17 patents.



Zhifei Mao, born in April, 1990, Quzhou, China

Current position, grades: M.S. degree student in Zhejiang University of Technology, China.
University studies: B.S. degree in mechanical engineering and automation from Lishui University, China, in 2012.
Scientific interest: the theory of product design.

Jiquan Li, born in November, 1977, Jinhua, China

Current position, grades: the associate professor of Zhejiang University of Technology, China.
University studies: Ph.D. degree in mechanical design from Shanghai Jiao Tong University, China, in 2008.
Scientific interest: injection molding process and equipment, polymer material processing and forming principle.
Publications: 20 articles, 10 patents.

Wei Zheng, born in June, 1987, Changsha, China

University studies: M.S. degree in Zhejiang University of Technology, China, in 2014.
Scientific interest: rapid heat cycle injection molding technology and EGAIM.