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**Effect of gas on the polymer temperature in external
gas-assisted injection molding**

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Abstract: The introduction of gas is the principal difference between external gas-assisted injection molding (EGAIM) and conventional injection molding. In this study, the effects of gas on polymer temperature were discussed on the gas thickness and gas delay time. A modified one-dimensional transient heat conduction model of polymer was established to reveal that there are relationships between polymer temperature and gas thickness, gas delay time in EGAIM. The temperature histories of polymer were obtained by the simulation method including Moldflow and ANSYS, and was verified by comparing of experimental data to numerical simulation results. The effects of gas thickness and gas delay time on the temperature histories of polymer will be discussed in detail. The results showed that the temperature of polymer is strongly affected by heat preservation of gas, and the heat preservation of gas increases with the increase of gas thickness and delay time. This paper provides quantitative methods and theoretical guidance for the study of the effect of gas on the temperature of polymer in EGAIM.

Keywords: external gas-assisted injection molding; gas; heat preservation effect; temperature.

1 Introduction

External gas-assisted injection molding (EGAIM) is used widely because it can eliminate sink mark, reduce warpage deformation, improve product precision and produce high surface quality products efficiently [1, 2]. The EGAIM is more complicated than conventional injection molding (CIM) due to the introduction of gas. After filling the cavity with polymer, gas with certain pressure (range: 3-5 Mpa [1]) is injected between the cavity surface of the mold and the solidified polymer

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4 formed during filling. Gas pressure is maintained till packing and cooling are
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6 terminated. The pressure pushes the solidified polymer to compensate for the
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8 shrinkage of the polymer caused by the temperature decrease during packing and
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10 cooling, which will improve the quality of plastic parts.
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15 The advantages and complexity of EGAIM have attracted the attention of
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17 different research groups. Chen et al. [3] investigated the packing effects of EGAIM
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19 on shrinkage and sink marks of plastic parts under various rib designs and compared it
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21 to that of CIM. The results showed that EGAIM can further reduce parts shrinkage if
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23 the gas pressure and gas packing time are both increased. Heng et al. [2] also reduced
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25 the ghost marks in plastic parts by EGAIM, moreover, the parts quality can be
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27 improved by increasing the mold temperature, melt temperature, injection speed and
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29 pressure, but exhibited limitations. Jiang et al. [4] discussed the relationship between
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31 process parameters and part quality by single factor test method, and developed the
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33 physical model describing the influence of gas-melting interaction on the sink marks
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35 [5].
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44 Aforementioned studies have reduced product defects and produced parts with
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46 certain quality requirement. However, theoretical and quantitative analysis of process
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48 parameters are not clearly enough to further improve the quality of parts, in which
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50 research on the applied gas is an important aspect. In EGAIM, the gas will push the
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52 solidified polymer to compensate the shrinkage of the polymer caused by the
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54 temperature decrease. The gas will also affect the temperature decrease of the
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56 polymer, so it is significant to study the effect of the gas on the polymer temperature
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in EGAIM.

Already a lot of authors have indicated the effect of the applied gas on to the temperature of materials in various fields, which showed the heat preservation or heat dissipation of gas in different occasions. The typical heat preservation is the application of gas in insulation material [6-8], in which a number of holes are formed in the material with gas, and the gas serves to prevent heat loss [9, 10]. Therefore, it is considered that the thermal insulation properties of the material are strongly dependent on the gas content [11, 12]. While the gas acts oppositely in the field of internal gas assisted injection molding (IGAIM) [13, 14]. Wang [15, 16] found that there was a deviation between the fitting cooling curve and the actual cooling curve of the polymer. The reason was that the gas absorbed the heat of the polymer and accelerated the temperature decrease of the polymer by heat dissipation.

Gas exhibits contradictory effects in different fields as shown in aforementioned studies. While the effect of gas on the temperature of polymer has not been discussed in EGAIM yet. In this paper, the effect of gas on the polymer temperature will be discussed based on theory, numerical simulations and experiments investigating the effects of gas thickness and gas delay time on temperature histories. In the theoretical approach, the effect of gas on temperature of polymer was discussed based on a modified one-dimensional transient heat conduction model and the main parameters of gas were determined. The temperature histories of polymer were obtained by the simulation method including Moldflow and ANSYS, in which the method was verified by comparing experimental and simulation results. This provides quantitative

analysis methods to discuss the temperature of polymer in EGAIM. The effects of main parameters of gas on polymer temperature were detailed discussed based on simulations.

2 Materials and methods

The material used in this study were ABS (XR-401, LG Chemical Information Electronic Materials Co Ltd, Korea) and PC (IM401-11, Trinseo S.A., USA). The material parameters and processing parameters of ABS and PC were listed in Table 1 [17-19]. Temperatures were measured on the cavity surface at different positions (Figure 1. Points *C*, *D* and *E*) by temperature sensors (6189AG and 6190AG, Kistler Instrument Co Ltd, Switzerland). An injection molding machine (MA3800/2250, Haitian International Holdings Ltd, China) was used to produce parts with the dimensions of 150mm × 100mm × 3mm. After filling with a later time, the inert gas (*N*₂) with certain pressure was injected between the solidified polymer and cavity surface of moving mold, as shown in Figure 1, the function of the como injection is to collect the temperature data of polymer, and the computer is to process and store data.

3 Theoretical model

The heat transfer process of polymer in conventional injection molding (CIM) is a typical transient heat conduction process [20-22]. It should be mentioned that from

the viewpoint of heat transfer, the edge effects along the width direction can thus be negligible when the ratio of width/height (W/H) is larger than 10 for a rectangular cavity. And the polymer in cavity has the characteristic of a two-dimensional object [23, 24]. Therefore, the heat transfer process of polymer can be simplified to a one-dimensional unsteady heat conduction process in thickness direction. The governing differential equation of polymer in thickness direction is as follows [25]:

$$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left(k \frac{\partial T}{\partial x} \right) \quad (1)$$

where, ρ is material density, c is specific heat, k is thermal conductivity, T , t and x represent temperature, time and distance, respectively.

The differential equation after integration is shown in Eq. (2) within one-dimensional control volume (V) and time interval (Δt).

$$\int_t^{t+\Delta t} \int_V \rho c \frac{\partial T}{\partial t} dV dt = \int_t^{t+\Delta t} \int_V \frac{\partial}{\partial x} \left(k \frac{\partial T}{\partial x} \right) dV dt \quad (2)$$

The Gauss formula and the central difference method [26] are used to approximate the Eq. (2) for eliminating integral, as shown in Eq. (3). The physical model of Eq. (3) in CIM is shown in Figure 2(a), where points W , P and E represent the position of polymer. Points w and e are the boundaries of control volume, δx_{wp} and δx_{pe} are the distance between point w and point P , point P and point e , δx_{we} is length of control volume, and $\delta x_{we} = \delta x_{wp} + \delta x_{pe}$.

$$\rho c(T_P - T_P^0)\Delta V = \int_t^{t+\Delta t} \left[\left(k_e A \frac{T_E - T_P}{\delta x_{PE}} \right) - \left(k_w A \frac{T_P - T_W}{\delta x_{WP}} \right) \right] dt \quad (3)$$

In Eq. (3), the δx_{PE} and δx_{WP} represent the distance between point P and point E , point W and point P , respectively. T_P , T_E and T_W represent the temperature of the point P , point E , point W at time $(t + \Delta t)$, respectively. T_P^0 indicates the temperature of point P at time t , k_e and k_w represent the thermal conductivity of the right and left sides of the point P , respectively. A is surface area of control volume. $\Delta V = A\Delta x$, where Δx is length of control volume (δx_{we}).

Weighted combination and explicit computing format are applied to Eq. (3) to calculate time integration, as shown in Eq. (4). T_E^0 and T_W^0 indicate the temperature of points E and W at time t . Eq. (4) can describe the temperature history of polymer in thickness direction during CIM.

$$\rho c \left(\frac{T_P - T_P^0}{\Delta t} \right) \Delta x = \frac{k_e (T_E^0 - T_P^0)}{\delta x_{PE}} - \frac{k_w (T_P^0 - T_W^0)}{\delta x_{WP}} \quad (4)$$

In EGAIM, the one-dimension control volume of polymer in thickness direction can be obtained by adding gas and molds in Figure 2(a), which is shown in Figure 2(b). δ_1 , δ_2 and δ_3 represent the thickness of polymer, gas and moving mold, respectively. k_{melt} , k_{gas} and k_{mold} represent the thermal conductivity of polymer, gas and mold, respectively. To describe the temperature history of polymer in EGAIM, Eq. (4) is modified based on the following assumptions: (1) the temperature at the infinity point of the mold is constant [27], $T_W = T_E = T$; (2) thermally conductive material consists of polymer, mold and gas. Since the proportion of gas

mass and volume is small, the effects of gas on density and specific heat of thermally conductive material can be neglected, as shown in Eq. (5).

$$\rho c \left(\frac{T_p^0 - T_p}{\Delta t} \right) \Delta x = \frac{k_e (T_p^0 - T)}{\delta x_{PE}} + \frac{k_w (T_p^0 - T)}{\delta x_{WP}} \quad (5)$$

When the gas is injected between solidified polymer and cavity surface of moving mold with rib structures, Gas thickness and gas delay time will directly affect thermal conductivity k_e , so the temperature drop rate $\frac{T_p^0 - T_p}{\Delta t}$ of polymer will change in EGAIM.

4 Results and discussion

4.1 Simulation results of polymer temperature

The temperature history of polymer in EGAIM can not be predicted by current commercial available numerical simulation tools for injection molding. In this paper, the temperature histories of polymer were solved by the combination of Moldflow and ANSYS. Firstly, the temperature field of polymer with different delay time before injection of gas was simulated by Moldflow, and the result showed multi-layers on the basis of the constant temperature interval in thickness direction. Then, polymer with multi-layered temperature distribution was rebuilt in ANSYS. Lastly, gas with a certain thickness was constructed between solidified polymer and cavity surface of

moving mold with rib structures, and the simulation was continued by ANSYS to solve the temperature histories of polymer after injection of gas.

Part geometry was imported from UG 10 to Autodesk Moldflow Insight 2018. The temperature fields of polymer with different delay time before injection of gas were simulated by Moldflow, the mesh type was 3D mesh and the analysis model consisted of 222916 tetrahedral elements. Then, polymer of the section, with multi-layered temperature distribution, was rebuilt in ANSYS 15.0. The density, specific heat and heat conductivity coefficient of polymer were also input into ANSYS. The element size was 0.1mm in mesh of ANSYS, the initial time step, minimum time step and maximum step time were 0.1s, 0.001s and 3s, respectively.

By aforementioned solution, the temperature histories of point *E* were compared with that by the temperature sensors with different molding process, as shown in Figure 3. Figure 3(a) showed the results in CIM without gas. The ANSYS solution started at the end of filling, and the start time of ANSYS is 5 s. As a result, the error between experiment and simulation is not more than 5°C. Figure 3(b) shows the results in EGAIM with gas thickness of 0.1 mm and delay time of 3 s. The ANSYS solution started at the end of the delay time, and it was 8 s in this solution. The results showed that the error between experiment and simulation is not more than 3°C, and the maximum error of previous research results is 8°C.

The results of other points in CIM were shown in Figure 4. The results showed that the initial temperature of the stationary mold was higher than the initial

temperature of the moving mold because of the runner and gate. All the results showed that the simulation method has high accuracy.

The temperature fields of the polymer part were also solved in CIM at the end of cooling by aforementioned solution, and the results were compared with those of Moldflow, as shown in Figure 5. The temperature fields are obviously similar, and the data are almost same. The temperature gradients are all very significant, especially in the region with the maximum aspect ratio (rib width/part thickness). The highest temperature is about 78°C in the region, the lowest temperature in this region is about 32°C, the temperature of the polymer varies by 46°C in the thickness direction of 3mm.

By the aforementioned discussion, the simulation method combined with Moldflow and ANSYS is accurate enough to solve the temperature histories and temperature fields. So this paper applied this simulation method to solve the temperature histories of the polymer.

Based on the method, the temperature histories of points at different positions were solved to discuss the effect of gas on temperature, i.e. point *A* and *B* as shown in Figure 1. Point *A* is at the position with highest temperature, which was the center of rib structure. Point *B* is a point near the cavity surface and far away from point *A*.

4.2 Effect of gas on the temperature in polymer at point *A*

The temperature histories of ABS and PC were solved at point *A* located inside the polymer with different gas thicknesses and delay times by aforementioned simulation, as shown in Table 2. The temperature variation of polymer with gas is smaller than that without gas, especially when the gas thickness is 1 mm. The temperature difference of ABS at point *A* with gas thickness of 1 mm and 0 mm is very obvious at 25 s, and the temperature difference of PC with gas thickness of 1 mm and 0 mm is very obvious at 15 s. The temperature difference increases with time, which indicates that the heat preservation of gas affects the temperature of polymer in EGAİM.

When the gas is injected into cavity, the thermal conductivity on the right side of polymer is converted from $k_e = \frac{\delta_1 k_{melt} + \delta_3 k_{mold}}{\delta_1 + \delta_3}$ to $k'_e = \frac{\delta_1 k_{melt} + \delta_2 k_{gas} + \delta_3 k_{mold}}{\delta_1 + \delta_2 + \delta_3}$, and the difference between them Δk_e is as following:

$$\begin{aligned} \Delta k_e &= k_e - k'_e \\ &= \frac{\delta_1 k_{melt} + \delta_3 k_{mold}}{\delta_1 + \delta_3} - \frac{\delta_1 k_{melt} + \delta_2 k_{gas} + \delta_3 k_{mold}}{\delta_1 + \delta_2 + \delta_3} \\ &= \frac{\delta_1 \delta_2 (k_{melt} - k_{gas}) + \delta_2 \delta_3 (k_{mold} - k_{gas})}{(\delta_1 + \delta_3) \times (\delta_1 + \delta_2 + \delta_3)} > 0 \end{aligned} \quad (6)$$

So $k_e > k'_e$, and the temperature drop rate $\frac{T_p^0 - T_p}{\Delta t}$ of polymer will decrease in EGAİM through Eq (5), because of the injection of gas between the solidified polymer and cavity surface of moving mold with rib structures. And the heat preservation of gas increases with decreased temperature drop. The value of temperature drop rate $\frac{T_p^0 - T_p}{\Delta t}$ differs with different gas thicknesses and delay times, as shown in Figure 6.

The temperature drop rate of PC is higher than that of ABS at the same gas thickness and delay time, the difference of temperature drop rate between ABS and PC is 0.5-1.7°C/s. When the gas thickness is 0 mm and the delay time is 5 s, the difference of temperature drop rate is 0.5°C/s, and the difference of temperature drop rate is 1.7°C/s when the 1 mm of gas thickness and 0 s of delay time. The values of most material parameters of ABS and PC are similar, such as heat conductivity, density, etc., however, the difference of specific heat between them is 284 J/(Kg.K), about 14% in Table 1. The specific heat is negatively correlated with temperature drop rate from Eq. (5), the temperature drop rate increases with the decrease of specific heat, therefore, the temperature drop rate of PC is higher than that of ABS.

The temperature drop rate decreases with the increase of gas thickness. When the thickness of gas increases from 0 to 0.1 mm, the decreasing value of temperature drop rate is very small in ABS and PC, so the heat preservation of gas can be ignored. The temperature drop rate decreases greatly with the increase of gas thickness from 0.1 mm to 1 mm. In Figure 6(a), the temperature drop rate drops by 25.0% from 4.4°C/s to 3.3°C/s with delay time of 0 s, by 21.4% from 4.2°C/s to 3.3°C/s with delay time of 3 s, and by 20.0% from 4.0°C/s to 3.2°C/s with delay time of 5 s. In Figure 6(b), the temperature drop rate drops by 5.7% from 5.3°C/s to 5.0°C/s with delay time of 0 s, by 9.6% from 5.2°C/s to 4.7°C/s with delay time of 3 s, and by 8.9% from 4.6°C/s to 4.2°C/s with delay time of 5 s.

The heat preservation of gas increases dramatically. This is because that the thermal conductivity decreases from $k'_e = \frac{\delta_1 k_{melt} + 0.1 \times k_{gas} + \delta_3 k_{mold}}{\delta_1 + 0.1 + \delta_3}$ to $k'_e = \frac{\delta_1 k_{melt} + 1 \times k_{gas} + \delta_3 k_{mold}}{\delta_1 + 1 + \delta_3}$ with the gas thickness increases from 0.1 mm to 1 mm, and the temperature drop rate $\frac{T_p^0 - T_p}{\Delta t}$ of polymer decrease intensely.

The variation of the delay time affected inevitably the polymer temperature.

Figure 6 also showed the effect of delay time on temperature drop rate. The temperature drop rate decreases with the increase of delay time at the same gas thickness, and the heat preservation of gas increase with the increase of delay time. The increase of heat preservation is because thermal conductivity of gas k_{gas} decreases gradually with the decrease of temperature [28]. The temperature is lower with longer delay time, because the polymer cools continuously before gas was injected. So the thermal conductivity of gas k_{gas} decreases with the increase of delay time. Accordingly, the thermal conductivity on the right side of polymer $k'_e = \frac{\delta_1 k_{melt} + \delta_2 k_{gas} + \delta_3 k_{mold}}{\delta_1 + \delta_2 + \delta_3}$ and the temperature drop rate at point A decrease with the increase of delay time.

In short, the heat preservation is the main effect of gas on the temperature of polymer. And the heat preservation of gas gradually increases with the increase of gas thickness and delay time.

4.3 Effect of gas on the temperature of polymer at point *B*

The temperature histories of ABS and PC were solved at point *B* with different gas thicknesses and delay times, as shown in Table 3. Temperature of polymer is also affected by gas thickness and delay time. The heat preservation of gas increases with the increased gas thickness. And the heat preservation of gas increases also with the increased delay time, but not so much as that of gas thickness. The heat preservation of gas is very significant especially with the gas thickness of 1 mm and delay time of 0 s.

The effect of gas on temperature histories at point *B* is similar to that at point *A* when the thickness of gas increases from 0 to 0.1 mm, as shown in Table 2 and Table 3. But the effect varies with the increased gas thickness. The temperature decreases at point *B* is much slower than that at point *A*. Especially when the gas thickness is 1 mm, the temperature of ABS at point *B* is almost constant till 15 s, 12 s, 13 s respectively with delay time of 0 s, 3 s, and 5 s, the constant time of PC is longer than that of ABS, which is 18 s, 15 s, 17 s, respectively. The lower temperature decreasing indicates that the heat preservation at point *B* is greater than that at point *A*.

The temperature drop rates of ABS and PC at point *A* and point *B* were solved with different gas thicknesses and delay times, as shown in Figure 7. The temperature drop rate of the polymer at point *A* is obviously higher than that at point *B*, but the variation of the temperature drop rate of point *A* is smaller than that of point *B*. The

bigger variation of point *B* is because the polymer at point *B* is closer to the mold, which accelerates the temperature variation of polymer.

So, the effects of gas on temperature of polymer are all the heat preservation for point *A* and point *B*. The heat preservation of gas increases with the increases of the gas thickness and delay time, but the heat preservation at point *B* is greater than that at point *A*, especially with the gas thickness of 1 mm and delay time of 0 s.

5. Conclusions

In this paper, the effect of gas thickness and gas delay time on the temperature of polymer were discussed in EGAİM. According to the results obtained in this study, the following conclusions can be drawn. (1) The heat preservation is the main effect of gas on the temperature of polymer, and the heat preservation of gas increases with the increases of gas thickness and delay time. (2) The heat preservation of gas is different at different positions of polymer. The heat preservation of gas near cavity surface is greater than that in the center of rib. (3) The variation of temperature drop rate varies with the positions of polymer. The variation of temperature drop rate of the polymer near cavity surface is greater than that of polymer located in the center of rib. In general, this paper provides theoretical support and simulation method for studying the effect of gas on temperature of polymer in EGAİM.

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Table 1: The parameters of ABS and PC.

		ABS	PC
Material parameters	Melt flow index (g/10 min)	10	11
	Glass transition temperature (°C)	90	145
	Density (g/cm ³)	1.04	1.05
	Specific heat (J/(Kg·K))	2044	1760
	Heat conductivity coefficient (W/(m·K))	0.2	0.2
	Filling time (s)	5	
Processing parameters	Injection temperature (°C)	210	
	Injection pressure (MPa)	50	
	Cooling time (s)	30	
	Coolant temperature (°C)	25	

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Table 2: Temperature histories of ABS and PC at point A under different gas layer thicknesses and

delay times: (a) delay time 0 s, (b) delay time 3 s, and (c) delay time 5 s.

Table 3: Temperature histories of ABS and PC at point B under different gas layer thicknesses and delay times: (a) delay time 0 s, (b) delay time 3 s, and (c) delay time 5 s.

Fig. 1. Distribution of temperature sensors in plastic parts.

273x166mm (300 x 300 DPI)

Fig. 2. One-dimension control volume of polymer in thickness direction under different processes: (a) CIM, (b) EGAIM.

161x139mm (300 x 300 DPI)

Fig. 3. Comparison of the temperature histories of point E by experiment and simulation under different molding process: (a) CIM, (b) EGAIM.

367x151mm (300 x 300 DPI)

Fig. 4. Comparison of temperature histories by temperature sensors and simulation method in CIM: (a) point C of moving mold, (b) point D of moving mold.

356x146mm (300 x 300 DPI)

Fig. 5. Temperature fields of polymer in CIM obtained by different methods: (a) Moldflow, (b) the simulation method including Moldflow and ANSYS.

284x108mm (300 x 300 DPI)

Fig. 6. Effects of gas parameters on temperature drop rate at point A of different materials: (a) ABS, (b) PC.

275x111mm (300 x 300 DPI)

Fig. 7. Comparison of temperature drop rates at different positions of ABS and PC in EGAIM: (a) ABS, (b) PC.

135x199mm (300 x 300 DPI)