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NUMERICAL PREDICTION AND EXPERIMENTAL VALIDATION OF TRANSIENT TEMPERATURE PROFILES DURING REHEATING PREFORM IN STRETCH BLOW MOLDING

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ABSTRACT

Reheating of the preform represents an important stage in the two-stage stretch blow molding (SBM) process. This work aimed at developing a temperature acquisition system with an emphasis on the design of both thermocouples and brush mechanism, which leads the acquisition system to be used to measure in real time the transient temperature profiles within the wall of the reheated preform as it rotates. The measured temperature distributions both through the thickness of the preform and along its length were then compared with numerical results predicted by solving a thermal model for the preform reheating in the SBM. Both the radiative and convective heat transfers were considered in the simulation. After being verified by experimental dada, the thermal model was used to predict the transient temperature profiles within reheated preform under different conditions, such as preform thickness, air convection coefficient, and reheating time. This work helps to better deepen the understanding of the preform reheating in the two-stage SBM process.

Key words: stretch blow molding; preform; reheating; temperature profiles; numerical simulation

INTRODUCTION

Blow molding is a major polymer processing technique for manufacturing a wide variety of hollow plastic parts. It is also one of the fastest growing industries worldwide. The blow molding is commonly subdivided into two main classes, i.e., the extrusion blow molding and injection stretch blow molding (ISBM). The former is widely used to produce containers of various sizes and shapes and is also adapted to make irregular complex hollow parts such as those supplied to the automobiles, office automation equipment, and pharmaceutical sectors, etc. The latter is extensively used in the commercial production of bottles for the food, beverage, and pharmaceutical industry. The formed bottles have biaxial molecular orientation. PET (polyethylene terephthalate) is most commonly used material in the ISBM, since it offers excellent clarity, good mechanical and barrier properties, and ease of processing. PET bottles are accounting to about 20% of the worldwide consumption in packaging. Until 2010 an increase to about 35 % is foreseen [1].

In the ISBM process, axial mechanical stretching of the preform is imposed by a stretch rod, prior to its inflation inside the stretch/blow mold cavity. This biaxial orientation provides enhanced physical properties, and gas barrier properties, which are all important in products such as bottles for carbonated beverages. There are two stretch blow molding (SBM) techniques. The one is the one-stage process and the other is the two-stage process. In the two-stage process, tube-shaped preforms are first made by injection molding, cooled to room temperature, and stored until required. They are then reheated to an appropriate temperature distribution above the glass transition temperature of the material and stretch blow molded into bottles using a reheat stretch blow molding machine. Because most polymers such as PET have a low thermal conductivity, heating techniques using convection or conduction not only require a long heating time, but also lead to microstructure heterogeneity across the thickness of the perform and thus cause cloudiness in the resultant bottle. In the two-stage SBM process, radiation with infrared waves is often used for reheating the preform. Infrared heating is particularly useful as the energy directly penetrates to the material interior and permits a rapid heating with heat flux proportional to the fourth power of the source temperature [2]. Near infrared radiation utilizes the short-wavelength infrared spectrum and can penetrate deep into the interior of the preform. This leads to rapid and uniform heating throughout the preform and yields shorter cycle times [3]. The thicker perform, such as with a thickness of above 5 mm, should be reheated by means of radio waves.

Reheating represents an important stage in the SBM process. Reheating produces temperature profiles, both through the thickness and along the length, of the tube-shaped preform. The temperature and its distributions of the reheated preform have a strong effect on the stretching and inflation of the preform and the orientation, crystallinity, critical performance characteristics (the mechanical properties, barrier performance, and transparency), and thickness distributions in the bottle. The hotter zones will extend and blow out faster and thin out more than colder zones. Furthermore, in the SBM process, there can be a significant difference between the inside and outside hoop stretch ratios. For example, for a 1.5 L PET bottle, the typical inside and outside hoop stretch ratios are 4.7:1 and 3.3:1, respectively. The stretch ratio, along with the stretching speed and temperature etc, determines the amount of orientation induced by stretching. This difference in stretch ratio leads to varying degree of orientation through the thickness of the bottle wall. Because properties depend on the amount of induced orientation, there will be a radial variation of properties through the thickness of the bottle. To ensure good uniformity of the stress distribution through the thickness of the bottle, it is necessary to deliberately develop a nonuniform temperature profile throughout the preform before stretch and blowing. So reheating is a decisive factor for the production of high quality bottles in the two-stage SBM process [4]. It is very important to investigate the temperature evolution within the preform during its reheating.

A few efforts have been conducted in order to represent the heat transfer inside an infrared oven. Shelby [5] performed a simple finite element analysis to determine the transient one-dimensional temperature profile through the thickness of the preform during reheating. The outside preform surface temperature was measured using an infrared thermometer. He investigated the effects of infrared lamp temperature and other variables on the reheat rate of a PET preform. It was found that the lamp temperature has a significant effect on a number of reheat characteristics. Venkateswaran et al. [6] obtained the temperature profile through the thickness of the PET preform by solving the one-dimensional energy equation with radiation as the heating source. The computed temperature profile was verified by measuring the inside and outside preform surface temperatures using infrared pyrometers. Martin et al. [7] proposed a numerical model to predict the preform temperature distributions after reheat. A high-speed thermal image camera was used to measure the apparent preform surface temperature profiles prior to stretch blow molding. The measurements showed that the model is capable of representing the effects of reheating oven settings on the temperature profiles of the preform. Monteix et al. [2] simulated the temperature distribution of the PET preform or sheet using control-volume method. An infrared camera was employed to determine the surface distribution of the transmitted heat flux by measuring the temperature distribution on the sheet surface. Numerical simulations were compared with experimental data. But because of the complexity of the radiative transfer in a transparent preform, the problem still remains open. Moreover, to the knowledge of the authors, in the previous research on the reheating stage of the two-stage ISBM process, the predicted temperature profiles were verified by only measuring the preform surface temperatures [5–8]. As stated by Michaeli et al. [8] that the temperature distribution across the wall thickness of the reheated preform can not be obtained by measurements and so regarding the reheating simulation only the surface temperature distribution can be compared to the simulation results.

In the present work, a PC based temperature acquisition system, which can be used to measure the transient temperature profiles within the wall of the reheated preform, was developed. A numerical model used to determine the temperature distribution in the preform heating by means of infrared radiation was presented. This model takes into account the combining effects of both the radiation and convection heat transfer. The transient temperature profiles of the preform were predicted by using finite element software ANSYS to solve the model. Numerical results were compared with experiments performed on an instrumented heat oven in the reheat stretch blow molding machine. The comparative temperature measurements were carried out at different locations across the thickness of the preform and along its length using a data acquisition system.

DEVELOPMENT OF TEMPERATURE ACQUISITION SYSTEM

Figure 1 schematically shows the experimental setup for measuring the transient temperatures of the reheated preform in two-stage stretch blow molding. The temperature acquisition system consisted of a PC, a data acquisition card (model PCL-818HG, manufactured by Advantech Ltd), and copper-constantan thermocouples (Type T). The data acquisition card used can provide 16 bit analog input. The thermocouples, with a wire diameter of 0.3 mm, were specially designed by authors to allow for their penetration into the preform. In order to obtain a uniform temperature distribution around the circumference of the preform, the temperature measurement should be carried out as it rotated. So a special brush mechanism (as schematically shown in Figure 1) was designed. The support and rotating shaft in the brush mechanism were made of bakelite. The rotating shaft rotated together with the preform and so the measurement could be made as the preform rotated.

Temperature measurement experiments were carried out using a reheat stretch blow molding machine (model WL-A03, manufactured by WeiLi Plastics Machinery Co. Ltd). Its heat oven had eight far infrared tungsten lamps. In order to concentrate the lamp energy on the preform, reflectors were situated on the opposite side of lamps. In addition, a ventilation fan in the oven could blow air to cool down the outer surface of the preform through forced convective heat transfer and so to prevent the overheat of its outer surface while heating up its inner surface sufficiently. The preform used in the experiments was 55 g, 125 mm long, with a diameter of 28.6 mm and a thickness of 4.3 mm. The material used to injection mold the preform was an industrial grade PET (grade CB-602) manufactured by Far Eastern Industries (Shanghai) Ltd. It has an intrinsic viscosity of about 0.8.

The thermocouples were calibrated prior to the actual measurement. For the sake of measuring convenience, the preform only rotated between the heating lamps and the reflectors in the oven but was not conveyed through it. During measurement, the data from data acquisition card were temporarily stored in RAM (random access memory) through DMA (direct memory access) channel. The DMA is a technique for transferring data between device and RAM without the intervention of CPU (central processor unit). Finally, all data of every measurement in RAM were written to the hard disk of the PC. The test results showed that the delay time for the acquisition system was less than 0.2 s. The data were then processed using software MATLAB and transferred to the temperature profile curves.

The acquisition system mentioned above was tested through a series of experiments on industrial stretch blow molding machines under different conditions, such as the kind of heating lamps and their voltage settings during reheating of the preform [9].

THEORETICAL ANALYSIS

Physical model

As mentioned above, the preform is often reheated by infrared radiation in the two-stage SBM process. Corresponding to above-mentioned experiments, the reheating system used in the simulation consisted of eight infrared tungsten filament lamps. The preform was conveyed through the oven while rotating between the heating lamps and the reflectors. This rotation allows for uniform heat distribution around the circumference of the preform. To consider the rotation of the preform, the heating lamps were regarded as a set of annular heating zones around a stationary preform, as shown in Figure 2. The bottom of the preform was regarded as a semi-sphere.

Mathematical model

The reheating of the preform is a complicated transient heat transfer problem. It involves the radiant heat transfer between the preform and the heat source, the convective heat transfer between internal and external surfaces of the preform and the air blown from the ventilation fan in the oven, and the conductive heat transfer both through the thickness and along the length of the preform. It also refers to the density, specific heat, and thermal conductivity of the preform material and the emissivity of the heat source. In view of the complexity of the present heat transfer problem, for the sake of convenience and revealing its essence, the following assumptions are made: (1) before reheating, the preform keeps an initial uniform temperature, T_0; (2) the heat source has a constant emissivity; (3) the reheated PET preform is an opaque medium and has a constant wall thickness; (4) the preform material has constant density and thermal conductivity during reheating.

For three-dimensional non-steady heat conduction, the energy equation can be written as:

$$\rho C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_z \frac{\partial T}{\partial z}\right) + \dot{Q} \quad (1)$$

where T is the temperature change with time (t) and position (x, y, z), $\dot{Q}$ is the internal heat source density, ρ is the material density, C_p is the material specific heat capacity, and k_x, k_y, and k_z are the thermal conductivities along the x, y, and z directions, respectively.

The total radiative heat flux received on the preform surface is the sum of each heater contribution and is calculated by:

$$q_r = \sum_i \sigma \varepsilon_i F_{ij} (T_i^4 - T^4) \quad (2)$$

where σ is the Stefan-Boltzmann constant, ε_i is the effective emissivity of the heat source, T_i is the temperature of the heat source, and F_{ij} is the radiation view factor and can be expressed as:

$$F_{ij} = \frac{1}{A_i} \int_{A_i} \int_{A_j} \frac{\cos\theta_i \cos\theta_j}{\pi r^2} dA_j dA_i \quad (3)$$

where r is the distance between two differential surfaces (dA_i and dA_j), θ is the angle between the surface normal of dA and the line between two differential surfaces.

The convective heat flux between the air blown from the ventilation fan in the oven and the outside of the preform is calculated by:

$$q_c = h(T_a - T) \quad (4)$$

where h is the air convection coefficient, T_a is the air temperature in the oven.

Solution to mathematical model

The energy equation 1 was solved by using finite element software ANSYS. The radiative and convective heat fluxes, given in Eqs. 2 and 4, respectively, were applied on the preform as heat loads in the solution. Table Ⅰ gives the physical properties of the PET used to injection mold the preform. The oven setting parameters listed in Table Ⅱ were chosen referring to Ref. 7. Three different lamp filament temperature settings that correspond to the voltage settings in the experiments, shown in Table Ⅲ, were used in the simulation. The difference among the three cases is that highest and lowest lamp temperatures were used for cases Ⅰ and Ⅲ, respectively. The initial temperature of the preform before reheating, T_0, was set at 24°C. The preform used in all simulations had a length of 125 mm and a diameter of 28.6 mm.

A two-dimensional solid element (PLANE55), a four-node one, and a three-dimensional solid element (SOLID70), an eight-node hexahedron one, were used to model the preform. The heating lamps were modeled using a shell element (SHELL57), a radiant one. The finite element meshes in the preform and heating lamps are shown in Figure 3.

The time step during the solution was set at 0.1 s, the iterative number was 25 for each time step. The step load was applied. Figure 4 illustrates the preform and heating lamps when applying the loads.

RESULTS AND DISCUSSION

Three cases, that is, three different voltage settings or filament temperatures of heating lamps (as shown in Table Ⅲ), were considered in the experiments or simulation. The wall thickness of the preform used was 4.3 mm. The transient temperature profiles of three locations both through the thickness of the preform and along its length (as shown in Figure 5) were simulated and then compared with measurement results. The wires of three thermocouples were inserted into different positions through the wall of the preform or along its length simultaneously prior to the measurement. For the temperature through the preform wall, the measurements were conducted at locations with a distance of 2, 3, and 4 mm from the external surface of the preform, respectively, around the circle (denoted as B shown in Figure 5) with a distance of 45 mm from the preform shoulder (denoted as A). The reheating was stopped when the temperature of the location at 2 mm from the external surface of the preform reached 110°C. The transient temperature profiles were continuously acquired during the entire reheating stage. Figure 6 displays the comparison between simulated and measured temperature evolution as a function of reheating time at three different locations through the preform thickness.

For investigating the temperature profiles along the preform, three locations denoted as C, D, and E, with a distance of 25, 45, and 65 mm from the preform shoulder (as shown in Figure 5), respectively, were considered. All measurements for these three locations were conducted at a distance of 2 mm from the external surface of the preform. The reheating was stopped when the temperature at location C reached 110°C. Shown in Figure 7 is the comparison between simulated and measured temperature profiles along the preform at different reheating times.

As can be seen form Figures 6 and 7 that the voltage or the temperature of heating lamps has a strong effect on the heatup rate of the preform. Increasing the heating lamp temperature leads to a faster heatup rate. Whereas the lamp temperature has little effect on the temperature difference through the wall of the preform at the end of reheating. The heatup rate decreases with the increase of the distance from the external surface of the preform.

From Figures 6 and 7 it can also been seen that the agreement between simulation and experimental results is reasonably good, considering a number of assumptions made in developing theoretical models. In fact, for example, the constant density and thermal conductivity of the preform material are temperature dependent.

The theoretical model developed in the present work was verified by experimental data and was used to predict the temperature profiles under various conditions. In the following simulations, the heating lamp temperature settings of case Ⅱ were used. The preform had a thickness of 4 mm unless specially noted.

Figure 8 compares the temperature profiles across the wall for the preforms with a thickness of 3 and 5 mm. It can be seen from Figure 8 that the temperatures across the overall wall of the former are higher than those of the latter. Moreover, the temperature difference between the external and internal surfaces of the preform for the former is twice as large as that for the latter.

Shown in Figure 9 is the effect of the convection coefficient between the external surface of the preform and the air blown from the ventilation fan in the oven on the temperature profiles through the thickness of the preform. As can be seen that increasing the air convection coefficient lowers the temperatures. Furthermore, the temperature difference across the thickness of the preform is 33.4, 28.8, and 25.2°C under the convection coefficient of 50, 70, and 90 W/m^2/°C, respectively. So the temperature difference across the thickness decreases with the increase of the convection coefficient.

Figure 10 illustrates the transient temperature vs. reheating time distributions at four different locations through the preform thickness and along the preform. As can be seen that the heatup rate decreases with the increase of the reheating time. Figure 11 presents the temperature distributions both through the preform thickness and along the preform at different reheating times. The temperature difference across the thickness of the preform gradually decreases with the increase of the reheating time (as shown in Figure 11a).

CONCLUSIONS

A PC based temperature acquisition system was developed in this work. Two issues were addressed. First, the thermocouples in the acquisition system were specially designed by authors to allow for their penetration into the wall of the reheated preform. Secondly, in order to measure the temperature of the reheated preform as it rotated, a special brush mechanism was designed.

A thermal model was developed for the preform reheating in the two-stage stretch blow molding. Both the radiative and convective heat transfers were considered in the model. The transient temperature distributions through the thickness of the preform and along its length were obtained by solving the model with finite element method. With the use of real-time temperature measuring system, the theoretically predicted temperature profiles were verified by measuring the temperature evolution at different locations across the thickness of the preform and along its length as the preform rotated. The comparison results showed that the agreement between simulation and experimental results is reasonably good. After being verified by experimental dada, the thermal model was used to predict the transient temperature profiles within the reheated preform under different conditions.

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Table Ⅰ. Physical properties of PET used in simulation

Properties	Value
Density (kg/m^3)	1335
Thermal conductivity (W/m/°C)	0.25292
Specific heat (J/kg/°C)	(1033+4.21T)

Table Ⅱ. Oven setting parameters used in simulation

Parameters	Value
Air convection coefficient (W/m^2/°C)	50, 70, 90
Air temperature in the oven (°C)	60
Average emissivity of lamps	0.25

Table Ⅲ. Voltage settings and corresponding filament temperatures of heating lamps

Lamp no.	Ⅰ		Ⅱ		Ⅲ	
	Voltage (V)	Temp. (℃)	Voltage (V)	Temp. (℃)	Voltage (V)	Temp. (℃)
1	80	1935	70	1850	60	1750
2	70	1850	60	1750	50	1360
3	60	1750	50	1360	45	1165
4	60	1750	50	1360	45	1165
5	60	1750	50	1360	45	1165
6	60	1750	50	1360	45	1165
7	40	970	30	725	25	600
8	20	680	15	600	10	240

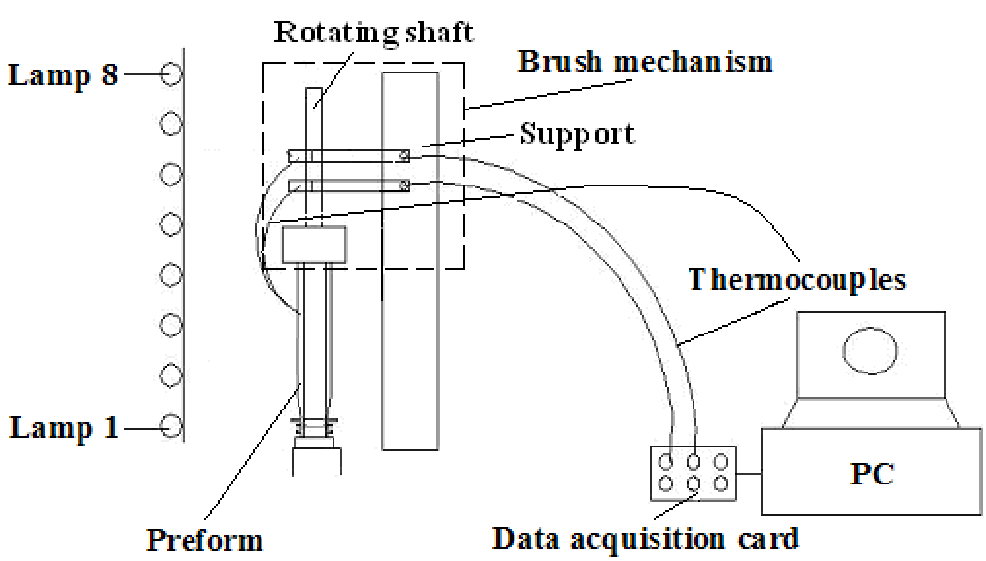


Figure 1. Schematic of the experimental setup for measuring the transient temperature during reheating of preform.

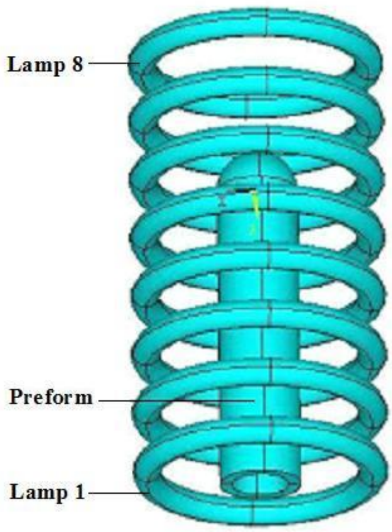


Figure 2. Physical model for reheating the preform.

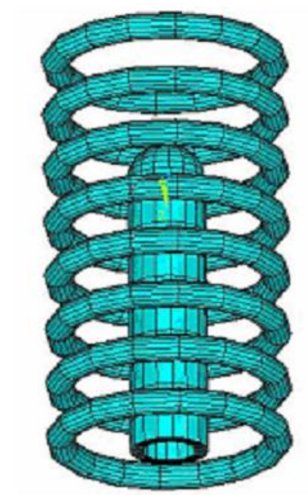


Figure 3. Finite element meshes in preform and heating lamps.

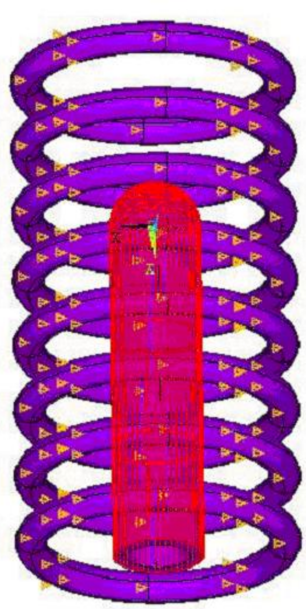


Figure 4. Preform and heating lamps when applying the loads.

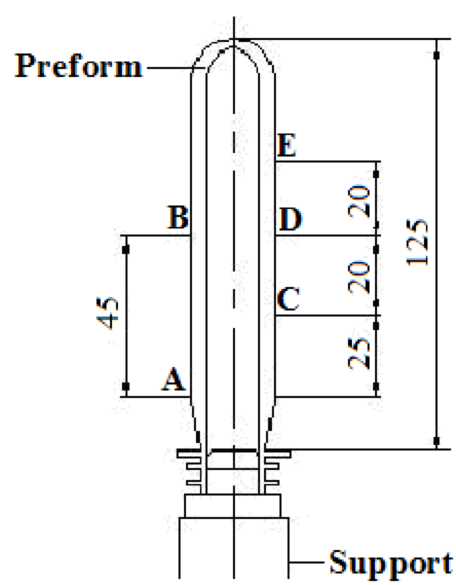
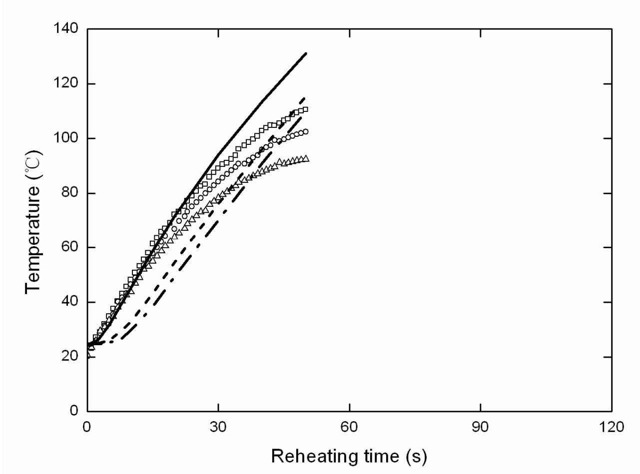
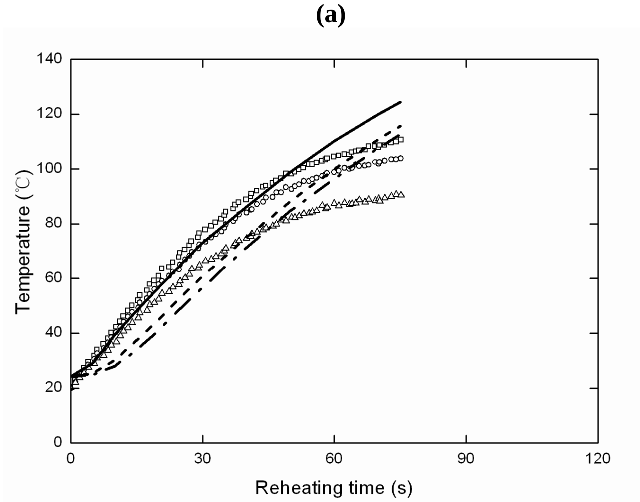


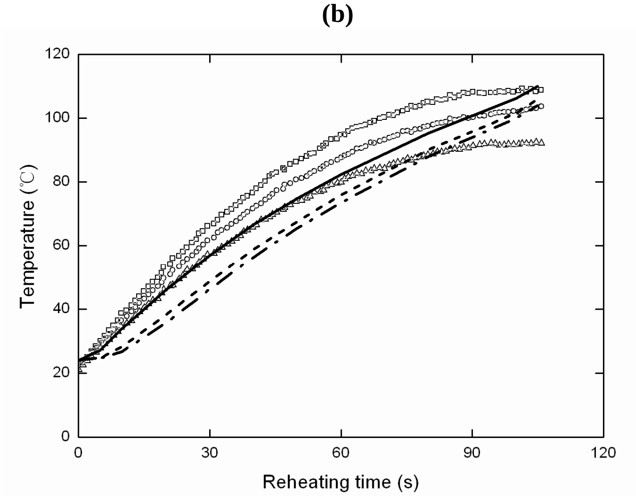
Figure 5. Schematic of measurement locations during reheating of preform. All dimensions are in mm.



(a)

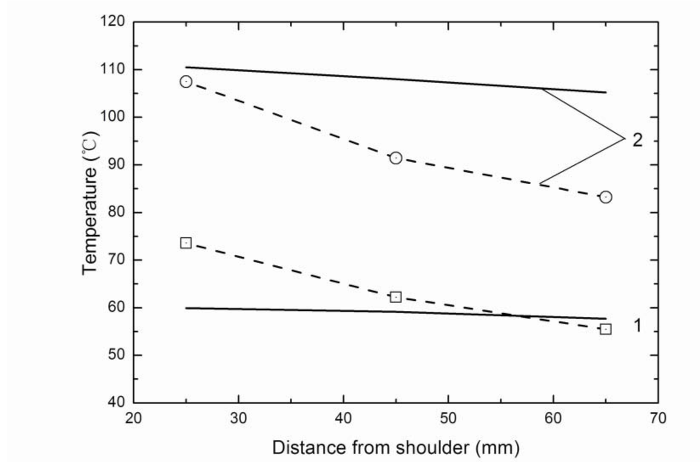


(b)

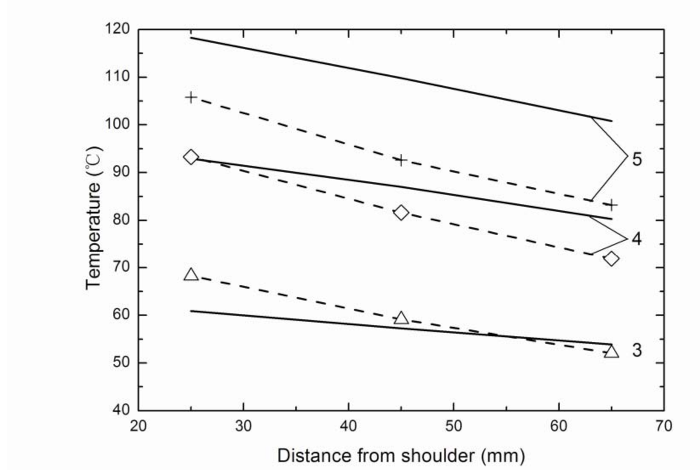


(c)

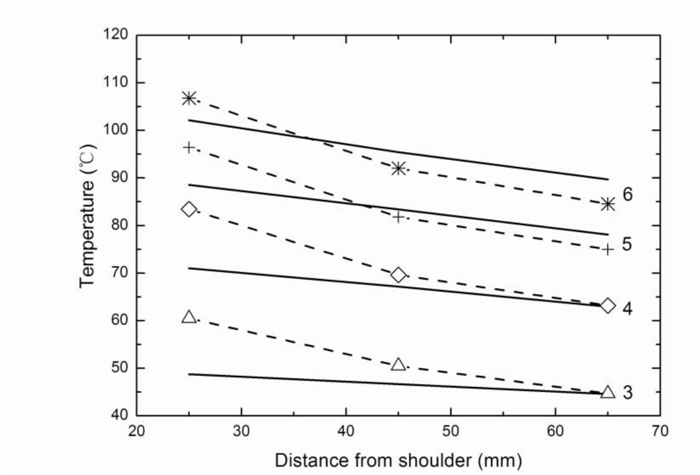
Figure 6. Comparison between simulated and measured temperature evolution at different locations through the preform thickness for (a) case Ⅰ, (b) case Ⅱ, and (c) case Ⅲ. The line and symbol represent the simulated and measured results, respectively. The distance from external surface (mm): (——, □) 2; (------,○) 3; (— - —, △) 4.



(a)



(b)



(c)

Figure 7. Comparison between simulated and measured temperature profiles along the preform for (a) case Ⅰ, (b) case Ⅱ, and (c) case Ⅲ. The solid and dash lines represent the simulated and measured results, respectively. Reheating time (s): (1) 15; (2) 37; (3) 20; (4) 40; (5) 60; (6) 80.

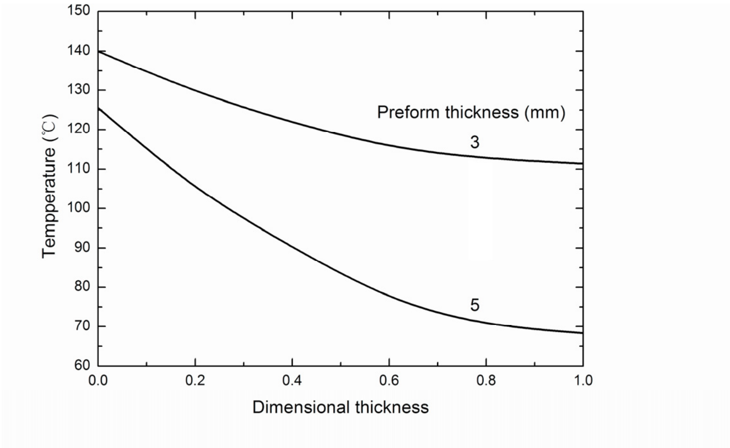


Figure 8. Comparison of the temperatures across the wall for the preforms with a thickness of 3 and 5 mm at the reheating time of 60 s.

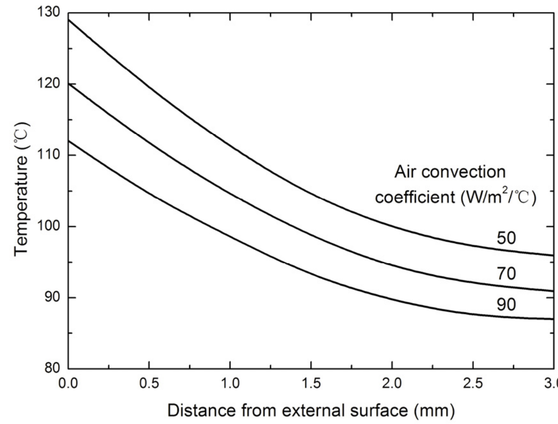


Figure 9. Effect of the air convection coefficient on the temperature profiles through the thickness of the preform with 3 mm thickness at the reheating time of 40 s.

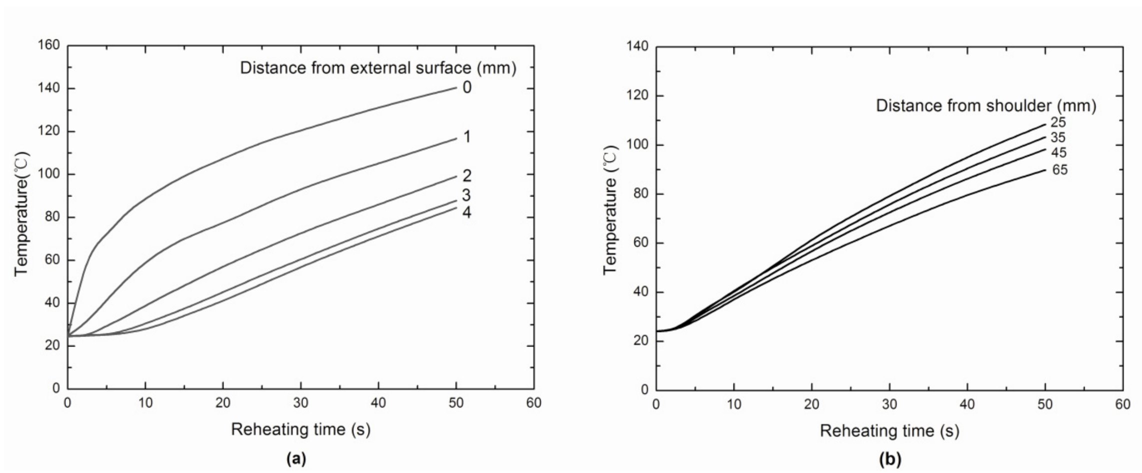


Figure 10. Simulated temperature profiles at four different locations (a) across the preform thickness and (b) along the preform.

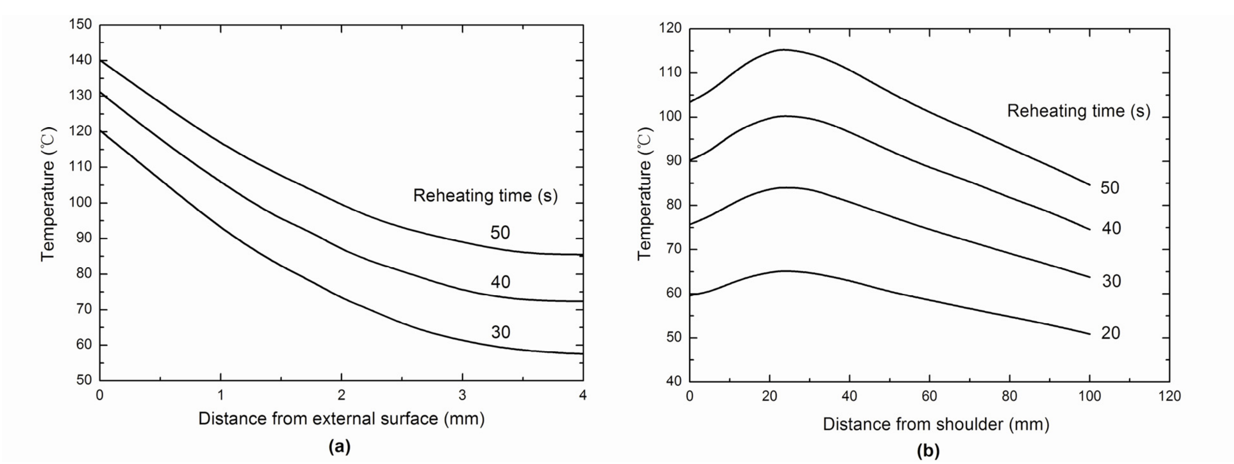


Figure 11. Simulated temperature distributions both (a) through the preform thickness and (b) along the preform at different reheating times.