A numerical investigation of the effect of preform length for the fabrication of 1.5Lt PET bottle through the injection stretch blow molding process

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Abstract. This study carries the numerical effort for the investigation of effect of preform length on the final product wall thickness distribution. For the investigation, three different preform length cases were taken under consideration. Preform A, preform B and preform C of length 144.75mm, 165.7mm and 186.65mm respectively. All the preforms were stretched up to a same critical point respect to mold length so that the axial deformation during blowing was fair for all the preform cases. Blowing conditions were the same for all cases. The stretching period for each case was set in accordance to the to the limit of critical stretching point. The mass of all preform cases was 58.33grams. It was found that preform B and C result in more uniform thickness distribution. The optimum results are given by preform C, since the resulting product appears the less spots with excess usage of raw material. The heavier bottle bottom region resulting from preform C enhances the steadiness of the bottle.

1. Introduction

Injection Stretch Blow Molding process is a widely used fabrication technique for the production of hollow plastic containers [1], [2] [3] [4] [5] [6] [7], [8]. It comprises the stretching and blowing at the same time, of a preheated preform. The preform is similar to a test tube. Both stretching and blowing take place in a mold, which has the shape of the desired bottle/container. Thus the blown preform takes the desired volume [9]. The contact between the blown preform and the cooler mold walls reduced the temperature of the blown preform and therefore solidification of plastic initiates. Poly(Ethylene Terephthalate) (PET) is the most common choice for bottle/container fabrication due to its good mechanical and barrier properties [3].

One of the most crucial parameters in Stretch Blow Molding (SBM) is the temperature distribution along the preform length. Temperature highly affects the consistency of the raw material and therefore influences the kinematics during stretching and blowing [1] [10]. An earlier research lists the effort of optimization of preform temperature distribution via infrared (IR) radiation preform reheating step [1]. The researchers implemented a finite-volume software for the simulation of the reheating step while the SBM simulation was employed in ABACUS. For the optimization of temperature distribution three optimization variables were taken into consideration corresponding to three temperature locations along the preform length. They used Cubic Hermite Interpolating Polynomial was to extract the optimization temperature between the three temperature locations [11]. The study indicated that the final bottle wall thickness distribution is 80% more uniform after the temperature optimization.

An earlier study implementing the Oldroyd B type constitutive model to simulate the behavior of PET during the SBM process [12]. The temperature balance equation was approximated by the Crank-Nicholson scheme. The study also involves experimental investigations. It was found that by increasing the preblow time delay, more material is transferred from the neck of the preform to its lower body which is in agreement with more recent studies [3]. The authors performed the simulations with isothermal and non-isothermal model. The numerical results obtained using the non-isothermal model were closer to the experimental SBM. In addition, during both simulations and experiments the final temperature distribution is slightly higher than the initial temperature distribution due to energy dissipation during SBM.

The commercial simulation package POLYFLOW has been implemented in another study for the investigation of blowing pressure and stretch rod velocity on the final thickness distribution along the surface of a 680ml PET bottle [13]. The SBM process was also investigated experimentally. The comparison between the experimental and simulation results revealed that the simulated thickness distribution follows the similar trend with the experimental.
Although, in contrast with the experimental results, the simulations indicated that the increase in blowing pressure does not provide any change on the thickness distribution. The conclusions extracted from the experiments indicate that the higher blowing pressure provides a slight difference on thickness distribution, especially on the bottle length [13].

The current effort deals with the numerical investigation of the effect of preform geometry on the final product wall thickness distribution. More specifically, three different preform length cases were taken under consideration. The preform length is a parameter that has not been investigated before. The study also comprises the effect of the preform temperature as much as possible above the glass-rubber limit which is about 80°C [14]. Stretching preform above this limit induces crystallization [14]. Stretching may also occur during the material deformation while the blown preform fills the mold cavities. The amount of induced crystallization is influenced by the deformation and strain-rate modes [14] [15] [16] [17]. The highest the percentage of crystals in the material, the highest is the strength [18].

2. Numerical problem formulation

2.1. Solution domain and boundary conditions

Figure 1 illustrates the symmetry plane of the 3D shell solution domain with the three preform length cases. The solution domain consists of two half moving molds, the preform and small tip (red color) representing the stretch rod. At the initiation of the simulation, the two half molds move towards the preform and provide the clamping force. The lengths of the three preform length cases – preform A, preform B and preform C – are 144.75mm, 165.7mm, and 186.65mm respectively. T_in represents the initial temperature on the preform walls. T_in obtained by allowing the three preforms to quench within the mold from 378K or 105°C for 3.5 seconds. During the real SBM process, there is a short time delay before stretching and blowing. This time delay is often called ‘preform cooling’ time [2]. In this study, it was assumed that the preform cooling time is 3.5 seconds. The mold temperature is represented by T_a. In an effort to maintain the temperature as longer as possible above the glass-rubber limit ̴ 80°C, the mold temperature was set 343K or 70°C. The concept beyond this selection is to investigate the PET kinetics during the deformation mode while the material is constrained by the mold walls. In the actual SBM process, such mold temperature selection is expected to induce more crystals within the material [14], thus affecting the strength performance of the bottle [18]. The stretch rod velocity is represented by V_s, which was -0.8 m/s for all cases. Although the stretching period is different in each case so that at the end of the stretching process, the bottom of each preform case is located at the same point respect to the mold length. The reason is to obtain similar axial deformation during blowing for all cases, since the length of each preform case is different. Table 1 indicates the stretching and blowing period for each case. The time delay presented in Table 1 is the time interval between the initiation of each process and the beginning of whole SBM. The heat transfer between the preform and mold walls is described by the conduction heat flux boundary condition shown in eq. 1.

\[ q = -k \nabla T \]

Where,

k is the thermal conductivity of mold material (for aluminum \( k = 205 \frac{W}{mK} \)) and T is the temperature between the preform and the mold walls. Once the preform touches mold walls, the motion of constrained by the sticking boundary condition imposed on the mold walls. The sticking boundary condition (non-slip) obtains due to the force exerted by the blown preform. The sticking boundary condition is: earlier SBM study [12].
2.2. Mesh, material model and initial SBM simulation conditions

The non-isothermal viscoelastic behavior of PET has been modeled using the KBK-Z model provided in ANSYS POLYFLOW. The material parameters were taken by earlier SBM and experimental studies. [13], [19]. ANSYS POLYFLOW has also been employed for the investigation of PET SBM by another study [13]. The initial discretized domain consists of 270735, 270857 and 271016 finite elements for the case of preform A, B and C respectively. For more accuracy, mesh refinement has been imposed at the preform contact regions. Figure 2 shows the discretized domain of each preform case. The initial preform temperature obtained by preform cooling as referred in section 2.1 has been predicted using the Eulerian approach for the solution of heat transfer equations. The Eulerian approach has also been used for the solution of the constitutive equations that govern the kinetics of PET during SBM process. Figure 3 indicates the thickness of each preform case temperature after preform cooling and temperature after preform cooling. Each preform weighs 58.3 grams. To eliminate the effect of variable thickness distribution each preform has uniform length. Each preform has the same thickness(1.5mm) at the uppermost region which is the region that molds clamp the preform. This region also contains the threads for the bottle cover and obviously is the thickest region of a bottle. To maintain the same mass for all the preform cases, the neck to the lowest bottom region of preform A has thickness 3.427mm while its counterparts preform B and C have thickness 3.015mm and 2.63mm respectively.
3. Results and discussion

Figures 4-6 indicate the thickness, strain rate and stresses contours after the end of stretching process for preform A, B and C. In all cases preblowing initiates in a short time interval before the end of stretching process. It can be observed that the preform A has the greater regions with the less thickness. The less extent of the region with the less thickness after the end of the stretching process belongs to preform C.
From Figures 4-6 it can be noticed that the extent of the preform volumes after the end of the stretching process is described by a trend characterized by the length of the preforms. Preform A has the greater volume while preform C has the less volume. This can be explained by Figure 5. The highest strain rate values obtain on the wall of preform A as an indication that more material migrates from the upper regions to the lower regions of preform during the stretching process. The highest strain rate values at the center of preform A indicate resulting from the transverse deformation due to preblowing. Since the preform C has greater extent of thicker regions after the stretching process, allow less deformation during the stretching preblowing. In Figure 5, it is clearly shown that at the end of stretching process preform C has the lowest strain rate values. As indicated in Figure 6, the stresses follow similar trend with the strain rate contours. The highest stresses values obtain at the center of preform A due to the high deformation rate.
Figure 6. Stresses contours after the end of stretching process for the three numerical cases (Preform A, B and C) for preform A, B and C.

Figure 7a shows the resulting bottle with the thickness contours for each examined preform case. In cases the thickness distribution is more uniform at the center of the bottle body. Although as the preform length increases A-C the thickness on the uppermost region of the bottle decreases while the opposite happens at the lowermost region of the bottle resulting in generally more uniform distribution along the entire bottle for case C. Figure 7b represents the thickness contours on the bottom of the bottle. As the initial length of the preform increases the pointless material concentration at the center of the bottom is being reduced. In addition, the increase on the preform initial length increases the material concentration at the side bottom walls increasing the inherent and therefore the steadiness of a filled bottle. Figure 8 indicates the plot of thickness distribution as function of the bottle length. The reduction on the material concentration at the center of the lowermost bottle region for case C can be noticed at the beginning of the chart. Furthermore, the reduction of thickness at the neck of the bottle as the initial preform length increases is also observed. The general conclusion that can be extracted from the chart is that preform B and C the thickness is distribution follows similar trend. Although case C seems to be the optimum due to the reduction of the excess material concentration at the center of the lowermost region and to the increase of the thickness at the bottom side walls.
Figures 6 and 7 show the stresses contours after the end of the stretching process for the three numerical cases (Preform A, B, and C). Figure 7a displays the resulting bottle with the thickness contours for each examined preform case. The thickness distribution is more uniform at the center of the bottle body. As the preform length increases from A to C, the thickness on the uppermost region of the bottle decreases while the opposite happens at the lowermost region, resulting in a more uniform distribution along the entire bottle for case C. Figure 7b represents the thickness contours on the bottom of the bottle. As the initial length of the preform increases, the pointless material concentration at the center of the bottom is reduced. Additionally, the increase in the preform initial length increases the material concentration at the side bottom walls, increasing the inherent and therefore the steadiness of a filled bottle.

Figure 8 indicates the plot of thickness distribution as a function of the bottle length. The reduction in the material concentration at the center of the lowermost bottle region for case C can be noticed at the beginning of the chart. Furthermore, the reduction of thickness at the neck of the bottle as the initial preform length increases is also observed. The general conclusion that can be extracted from the chart is that preform B and C have a similar thickness distribution trend. Although case C seems to be the optimum due to the reduction of the excess material concentration at the center of the lowermost region and the increase of the thickness at the bottom side walls.

Figures 9 and 10 present the contours strain rate and stresses contours once the preform initiates to touch the mold walls. The highest strain rate values obtain at the bottom of the case A while their lower counterparts take place on the walls of case C. Since case A has the thicker regions after the end of the stretching process, it is more readily deformed during the bi-axial pressure loading. The higher strain rate at the side bottle walls for the selected time step indicates that the higher deformation rates take place earlier for the case A. A worthing observation is that at
Although the final product obtained in cases B and C is characterized by a more uniform material concentration similar trend. In all cases it was observed that the thickness distribution on the main bottle body was uniform.

Different length. It was found that in cases the thickness distribution along the bottle length is described by a function. SBM parameters such as stretching and preform length is 60.99% of the mold length respectively. As a conclusion it can be said that the optimum case of preform length is 60.99% of the mold length. Although this statement requires further investigation, because the desired characteristics of a bottle are affected by a combination of parameters including the process conditions (stretch rod velocity, preblow and blowing pressure and preform and mold temperatures).

**Figure 9.** Strain rate while the blown preform contacts the mold walls for the three numerical cases (Preform A, B and C)

**Figure 10.** Stresses while the blown preform contacts the mold walls for the three numerical cases (Preform A, B and C)

### 4. Conclusions

The effect of preform length on a 1.5Lt PET bottle wall thickness distribution has been investigated numerically. For the simulation three preform case were taken under consideration. The preform length examined are 144.75mm, 165.7mm and 186.65mm which are the 47.3%, 54.15% and 60.99% of the axial mold length. The mass remained equal to 58.33gr for all cases. All the cases were stretched up to the same axial location respect to the mold length in an effort to eliminate the effect of the axial deformation during the blowing process since the preform cases have different length. It was found that in cases the thickness distribution along the bottle length is described by a similar trend. In all cases it was observed that the thickness distribution on the main bottle body was uniform. Although the final product obtained in cases B and C is characterized by a more uniform material concentration.
along the entire bottle length. Further, the increase of preform length implies in less material concentration on the bottle neck while the opposite happens on the bottom side walls which is desirable since it enhances the steadiness of filled bottle. A disadvantage of SBM process is that during stretching material is accumulated at the center of the bottom region. This material concentration does not avail in anything. Thus the reduction of the material concentration at that area is an optimization parameter on the reduction of the bottle weight without influencing its mechanical performance. The simulation results indicated that the concentration of material at the center of the bottom is being reduced with the increase of initial preform length. Summarizing the above, the most optimum preform length is 60.99% of the axial mold length. Although this statement requires further investigation since the material distribution along the bottle length is described by a function SBM parameters such as stretching and blowing conditions and governing temperatures.

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