STUDY ON THE EFFECTS OF PARAMETERS TO PET BOTTLE THICKNESS IN BLOWING PROCESS

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Abstract – PET bottles are widely used for drinking water. PET bottles' quality depends on their thickness. The aim of this study is to find design variables and optimal parameters of the stretching blow molding (SBM) process of PET bottles in order to increase the uniformity of bottle thickness by using the simulation technique and Taguchi method. The finite element method is used to predict the results of the SBM process. The Taguchi method is performed with six variables that belong to two main factors, which are temperature positions and parison thickness. Through the analysis process, the optimal parameters are determined and verified, with a minimum objective function result of 0.000265. On the other hand, the temperature at *T4* positions and the preform thickness at *Th2* sections are the main influences on the uniformity of PET bottle thickness.

Key words – PET bottle; SBM process; Taguchi method.

1. Introduction

Stretching blow molding (SBM) is a two-dimensional deformation process of plastics that is the process of choice for the production of PET bottles, in particular for the food and beverage industry. The SBM process has three stages. Firstly, this is the reheat stage, where the preforms are heated to the appropriate forming temperature distribution. Secondly, the blowing stage, which is the preform, is stretched by a cylindrical rod. Finally, this is the solidification stage; the high pressure is kept for 1 or 2 seconds to cool the bottle, and exhaust is needed to get the final product [1]. The SBM process is a complex deformation process because it is influenced by many different specifications [2, 3]. The performance of a bottle depends not only on its thickness distribution but also on its mechanical, structural, and optical properties. There are three main factors affecting the final properties of a bottle: PET material properties, rheological behavior under biaxial stretching, and process conditions. To respond to market requirements, products are changed in shape and improved in quality. To achieve the performance specifications of the manufacturers, the products must pass a large number of tests used to gauge their functional properties. In order to solve the above problem, computational models and simulation are the most optimal solutions.

The aim of numerical simulation is to improve accuracy and predictability to efficiently assist in the design of polymer parts. There are many computational models to predict the parameters and results of stretching blow molding [2–7]. For example, Lee and Soh used the finite element method (FEM) optimization to define the optimal profile thickness of the preform for a blow-molded part and then presented the wall thickness distribution requirements [7]. S. Suraya et al. assessed the deformation of a polymeric material during the blow molding process of a two-dimensional model [4]. The investigation of the effect of stretch rod velocity and pre-blow pressure magnitude on the final product wall thickness distribution was made by A. Lontos et al. [3]. On the other hand, several optimal analyses are presented with different methods and boundary conditions [1, 8]. F. Thibault et al. used shape optimization algorithms with the FEA (finite element analysis) tools to employ the preform geometry and operating parameters to get the required container thickness distribution [1]. M. Bordival et al. presented a numerical modeling of the full SBM process that is mainly based on a coupling between finite-volume and element simulations of the IR heating and forming stages, respectively [8]. This study aims to investigate the effects of parameters of SBM processing on PET bottle thickness and the optimization of the Taguchi method. In order to reduce the implementation cost and achieve a quick result, the simulation technique is the most optimal solution to create data for analysis using the Taguchi method. In this study, the finite element method (FEM) is used to simulate the material behavior model, which is viscoelastic, non-linear within viscosity, and non-isothermal to mold.

2. Computational model

2.1. PET bottle shape

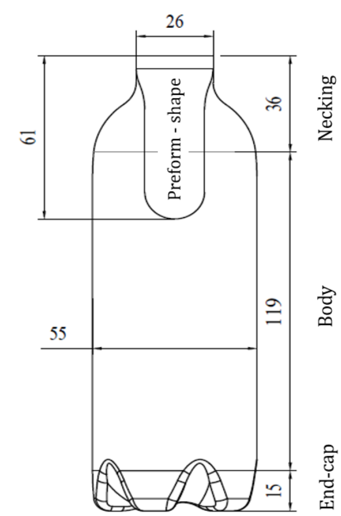

Figure 1. *The dimension of the PET bottle shape*

The PET bottle has a volume of 350 ml as presented in Figure 1 used in this study. The shape is divided into three sections: necking, body, and end-cap sections. The height and diameter of the necking, body, and end-cap parts are 36 x 26 mm, 119 x 55 mm, and 15 x 55 mm, respectively. By using the injection stretch blow molding process, the formed bottle is produced from the preformand has dimension height and diameter is 61 x 26 mm.

The first step in FEM modeling is the mathematical formulation of the objective function. Many factors were described in the objective function example one expression, the part specifications, the design variables, and the cost associated with processing and part quality. Each target function assessment requires the automatic creation of a finite element mesh of the preform and a consequent performing of a nonlinear FEA (finite element analysis) of the SBM process. To appraise the thickness parameter of the bottle at the end of the forming stage, the objective function is Eq. (1) [1].

$$\sigma(X)^2 = \sum_{i=1}^{N_e} (T_i - T_t(y))\frac{S_i}{S} \tag{1}$$

Which represents the bottle thickness variance around the thickness target (T_t) defined by the designer along with the bottle in the y-direction, N_e and T_i correspond to the number of finite elements in the mesh and the nodal finite element thickness, respectively. The deviation is the area by the ratio of the local element surface (S_i) to the total bottle surface (S), which will not be affected by the mesh topology [1].

The uniformity of bottle thickness widely depends on $\sigma(X)^2$, which means that the value $\sigma(X)^2$ is smaller leading to the larger uniformity of bottle thickness. In this study, the value $\sigma(X)^2$ was divided into two sections to ensure the thickness requirements of each other on a different part of the bottle as Eq. (2).

$$\sigma(X)^2 = \sigma(X)^2{}_{ne-end} + \sigma(X)^2{}_{body} \tag{2}$$

While $\sigma(X)^2{}_{ne-end}$ is function value of finite elements at the necking and end-cap section, $\sigma(X)^2{}_{body}$ is operation at body of the bottle, respectively.

There are many factors that affect to SBM process and PET bottle results. The temperature and preform thickness are parameters used for analysis in this study. Figure 2 illustrates the positions of temperature and thickness sensors on the preform in the simulation process. The temperature positions described in Figure 2a represent the boundary condition temperature positions used in the simulation, where temperature sensors are placed to preheat the preform before actual blowing process. Similarly, Figure 2b indicates the positions that determine the preform's thickness in the simulation, corresponding to the actual thickness determined by the shape of the PET bottle preform mold. To perform the Taguchi method with more variables will spend a larger source and processing time. By using simulation screening, our team selected six variables including four temperature variables which are denoted T_1, T_2, T_3, and T_4, subsequently, and two preform thickness variables that stand for Th_2 and Th_5, respectively.

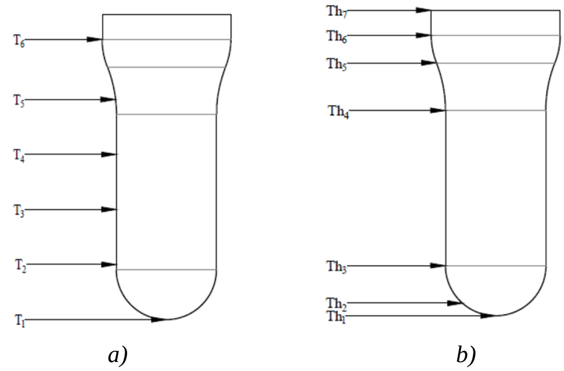

Figure 2. *The position of the temperature and thickness sensors on the preform*

2.2. Establishing FEM model and boundary condition

Tables 1, 2 show the processing parameters and different preform thickness conditions and PET material properties, respectively.

Table 1. *The preform thickness conditions of FEM model*

Parameters	Value	Unit
Pull velocity	0.4	m/s
Minimum pressure	3	bar
Maximum pressure	25	bar
T_5 temperature	120	°C
T_6 temperature	100	°C
Th_1 thickness	1.5	mm
Th_3 thickness	2.3	mm
Th_4 thickness	2.3	mm
Th_6 thickness	1.5	mm
Th_7 thickness	1.5	mm

Table 2. *The PET material properties*

Parameters	Value	Unit
Viscosity	2000	Pa.s
Density	1300	Kg/m^3
Thermal conductivity	0.15	W/m.K
Specific heat capacity	1000	J/Kg.K

The liquid viscosity is highly affected by heat, which means the viscosity decreases with an increase in temperature. In this study, Ansys student software is used and the Williams-Landel-Ferry Equation (WLF Equation) is an empirical associated with time-temperature superposition. The WLF equation has form Eq. (3) [10].

$$log(a_T) = \frac{-C_1(T - T_r)}{C_2 + (T - T_r)} \tag{3}$$

Where, $log(a_T)$ is the decadic logarithm of the WLF shift factor, T is the temperature, T_r is a reference temperature chosen to construct the compliance master curve, and C_1, C_2 are empirical constant adjusted to fit the value of the superposition parameter a_T.

The setup parameters of the FEM model are shown in Table 3 and the meshing model is shown in Figure 3 with a mesh size of 0.7 mm and a number of elements of 117887.

***Table 3.** The setup parameters of FEM model*

Parameters	Value	Unit
Size elements	0.7	mm
Total elements	117887	
Sliding ratio	1e+9	
Penalty ratio	1e+9	
Corresponding tolerance	0.1	mm
Start time	0	
Minimum timestep	1e-9	s
Maximum timestep	0.01	s
Maximum time	1	s
Time tolerance	0.01	s
Maximum steps	600	

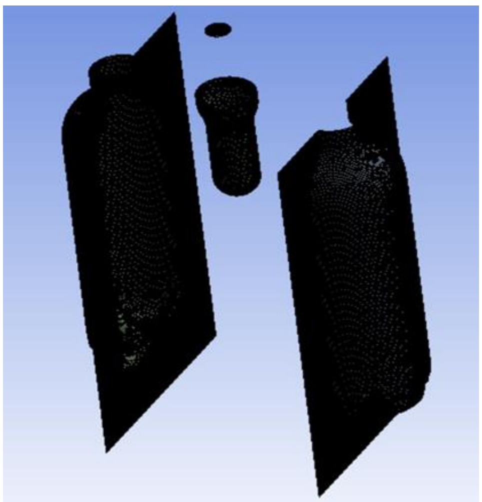

***Figure 3.** The meshing model to setup parameters for FEM model*

2.3. Experimental planning by Taguchi method

Table 4 is showing processing factors and levels of the Taguchi method. The experimental design consists of six parameters and three levels, and thus L27 orthogonal array [11] is utilized with the required minimal experiment number of twenty-seven (Table 5).

***Table 4.** Selected factors at different levels*

Parameters	Levels			Unit
	1	2	3	
T_1	80	85	90	°C
T_2	80	90	100	°C
T_3	90	100	110	°C
T_4	90	105	120	°C
Th_2	1.5	2	2.5	mm
Th_3	1.5	2.25	3	mm

***Table 5.** Orthogonal array L_{27}*

Exp. #	T_1	T_2	T_3	T_4	Th_2	Th_5
1	1	1	1	1	1	1
2	1	1	1	1	2	2
3	1	1	1	1	3	3
4	1	2	2	2	1	1
5	1	2	2	2	2	2
6	1	2	2	2	3	3
7	1	3	3	3	1	1
8	1	3	3	3	2	2
9	1	3	3	3	3	3
10	2	1	2	3	1	1
11	2	1	2	3	2	2
12	2	1	2	3	3	3
13	2	2	3	1	1	1
14	2	2	3	1	2	2
15	2	2	3	1	3	3
16	2	3	1	2	1	1
17	2	3	1	2	2	2
18	2	3	1	2	3	3
19	3	1	3	2	1	1
20	3	1	3	2	2	2
21	3	1	3	2	3	3
22	3	2	1	3	1	1
23	3	2	1	3	2	2
24	3	2	1	3	3	3
25	3	3	2	1	1	1
26	3	3	2	1	2	2
27	3	3	2	1	3	3
27	3	3	2	1	3	3

The objective function of this study is the unevenness of PET bottle thickness. Analysis data to determine the effect of the process factors on the response measure. Signal-to-Noise ratio (SN) provides a measurement of the effect of each parameter on performance. A factor set considered is optimal when its SN is the smallest. Taguchi proposed using three loss functions and SN calculation depending on the type of performance characteristics, including Smaller-the-better (STB), Larger-the-better (LTB), and Nominal-the-best (NTB). According to depends on the requirement for minimum performance characteristics, the loss function STB is used and calculated as Eq. (4) [11].

$$SN_i = -10\, log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \quad (4)$$

Where SN_i is the SN of given simulation i^{th}, n is the number of trials of the simulation i^{th}, i is the simulation number, y_i is the value of the measured performance characteristic for a given trial. The value of n is 1, and i value is 27 in this study.

3. Results and Discussion

3.1. The result of Taguchi experiment method

The responding value and SN ratio of 27 simulation times are shown in Table 6.

The average value of all trial times has the same value is shown in Table 7. The value of delta (Δ) is calculated by Eq. (5), which reflects the influence rating of each parameter on the responding value.

$$\Delta = Max(SN) - Min(SN) \quad (5)$$

From Table 7, it can be observed that the optimal parameter values corresponding to T_1, T_2, T_3, T_4, Th_2, and Th_5 are 85°, 100°, 110°, 120°, 1.5mm, and 2.25mm, respectively. For further analysis, the SNs are used for ANOVA statistical model. ANOVA results for this factors are presented in Table 8. The significance of process factors in ANOVA is determined by comparing the F-ratios of each factor. The optimal parameters are determined and verified with a minimum objective function result of 0.000265. That is a smaller response value than the results of 27 previous experiments. The temperature at the *T4* position is the most significant parameter with 99.8% reliability to PET bottle thickness, after that are parameters Th_2, T_2, Th_5, T_3, and T_1, respectively.

Table 6. *The responding value of orthogonal array L27*

Exp. #	Responding value	SN ratio
1	0.00151813	56.37382
2	0.001392262	57.12558
3	0.001170409	58.63325
4	0.000903172	60.88459
5	0.000839251	61.52216
6	0.000973181	60.23613
7	0.000614166	64.23428
8	0.000661191	63.59346
9	0.000961791	60.33839
10	0.000721874	62.83077
11	0.001044706	59.62012
12	0.001103866	59.14167
13	0.000895676	60.95698
14	0.00094451	60.49587
15	0.001474583	56.62662
16	0.000649762	63.74491
17	0.000836035	61.55551
18	0.001114273	59.06017
19	0.000823358	61.68823
20	0.00114092	58.8549
21	0.001162564	58.69166
22	0.000881779	61.0928
23	0.000922123	60.70422
24	0.000915508	60.76676
25	0.000756446	62.42444
26	0.001300966	57.71468
27	0.001042403	59.63929

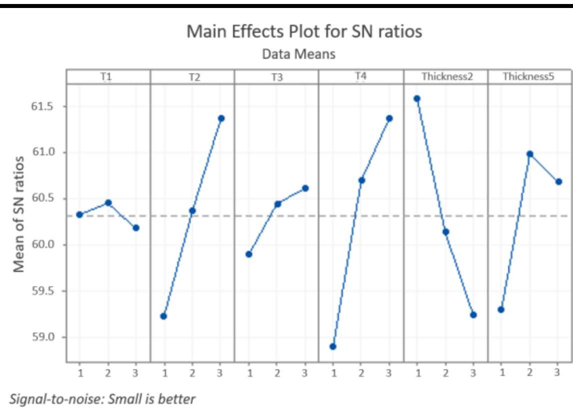

Figure 4. *SN ratio plot for six factors and three levels*

Table 7. *The SN ratio*

Factors	T_1	T_2	T_3	T_4	Th_2	Th_5
1	60.33	59.22	59.90	58.89	61.58	59.29
2	60.45	60.37	60.45	60.69	60.13	60.99
3	60.18	61.37	60.61	61.37	59.24	60.68
Δ	0.27	2.15	0.71	2.48	2.34	1.70
Rank	6	3	5	1	2	4

Table 8. *The result of ANOVA statistical model*

Factors	DOF	Seq SS	MS	F	P
T_1	2	0,336	0,1682	0,12	0,888
T_2	2	20,822	10,4112	7,42	0,006
T_3	2	2,518	1,2589	0,90	0,430
T_4	2	29,619	14,8097	10,56	0,002
Th_2	2	25,188	12,5940	8,98	0,003
Th_5	2	14,709	7,3544	5,24	0,020
Residual Error	14	19,635	1,4025		
Total	26	112,828			

3.2. The result of FEM simulations

Using the optimal parameters to apply to the FEM model and run the calculation, we have the result about the distribution of the material thickness on the PET bottle as shown in Figure 5, 6. Viewing the contour in Figure 5, the thickness is uniform in the body section and thicker in the necking and end-cap section. Figure 6 is the plot of thickness visualized by the unit of meter on the axial vertical section of the bottle. The positions have thicker mainly concentrated in thread edges of the necking and concave edges of the end-cap section, which is pretty accurate.

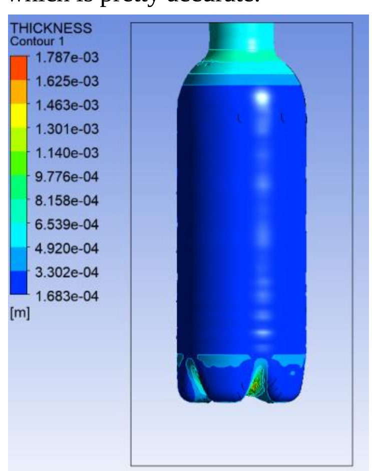

Figure 5. *The result of simulation process on FEM software*

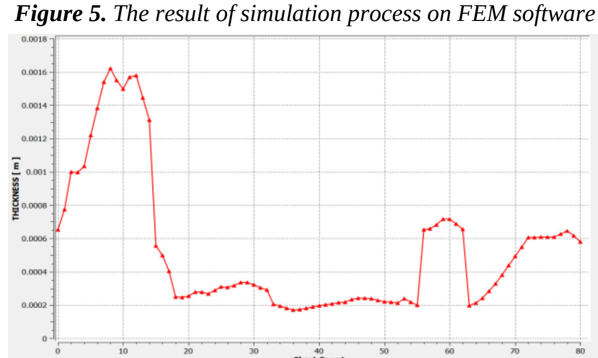

Figure 6. *The thickness of bottle on the axial vertical section*

4. Conclusion

This article presented effects of SBM parameters such as temperature and preform thickness to the thickness of the PET bottle. With the optimal parameters through the experiment method, the temperature at the *T4* position is the significant factor to control the uniformity of PET bottle thickness. The thickness at the *Th2* section on preform is found as the second most important factor. This study will provide a deep understanding for real applications.

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