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Article

Blow Molding Simulation using the Cross-Section Technique for Complex Shape Bottles

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Abstract. This research proposed the blow molding simulation method for determining of a cross-section thickness of bottles. The finite element method (FEM) was employed to simulate the extrusion blow molding process of the complex shape bottles. The full bottle shape of blow molding process had been attempted to simulate with a rectangular shape bottle for comparing with the cross-section technique. Particularly, the physical experiment of the extrusion blow molding process was performed to verify the FEM. The cross-section technique was obtained a deviation result less than the full bottle shape simulation. The average error of full bottle shape simulation was 32.35% while the cross-section simulation obtained an average error of 17.02% when they were compared with the experimental data of the blow molding process. The FEM of blow molding simulation using the cross-section technique which was developed in this research had been found the satisfactory method to determine the initial thickness of the parison flowing through the extrusion die. It was advantaged to shape dies of the extrusion blow molding process in order to achieve the complex shape of bottles.

Keywords: Blow molding, simulation, cross-section, bottle.

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1. Introduction

The plastic bottles are produced by the blow molding process. The extrusion blow molding process is referred to use for producing the large bottle size. The lubricant oil bottle is the most bottle type that is produced by the extrusion blow molding process. It is attractive by color and shape; therefore, many complex shapes of lubricant oil bottles were launched in the automotive market. In the lubricant oil bottle manufacturing, two important steps were concerned to form lubricant oil bottles. They consisted of the parison extruding through the die and the inflation of parison to contact completely on the surface of the mold cavity. The thickness of parison was regulated by the die gap programming or die shaping to form parison or plastic tube for blowing bottles. However, the calculation of the initial thickness of parison was supported by the blow molding theory [1, 2], it was not regularly to adjust the die gap for complex shape of bottles all at once. The lubricant oil bottle generally had a reflective symmetry shape which referred to use the die shaping method for preparing the plastic tube. The experience of the mold maker or the trial and error method was frequently used to shape the bottle die; therefore, the significant amount of the wasteful plastic, the cost and the time were lost at the parison setting.

Nowadays, the computer aided engineering (CAE) using the finite element method (FEM) is employed to simulate the lubricant oil bottle design [3, 4] and its producing process [5-7]. Thusneyapan and Rugsaj [8] proposed the non-linear FEM for the extrusion blow molding process. The parison model which was a uniformity thickness had been modeled for an axis symmetry bottle. Debbaut and Homerin [9] had simulated the blow molding process for the bottle with a handle. They began to prepare the blow molding model with the uniformity thickness of cylindrical parison. It was hard to control the final thickness of the plastic bottle. Some blow molding methods such as the stretch-blow modling had been simulated using FEM [10-13]. They had used a preform which was controlled its thickness using the plastic injection method. The preform was prepared for heating and blowing to form a bottle in the mold cavity; therefore, it was comfortable to prepare the preform thickness regarding to the desirable bottle thickness along the bottle height [14]. In the extrusion blow molding process, the thickness along bottle height was comfortable to control using the parison programming which controlled the mandrel to move up and down to reduce and increase parison thickness, respectively [15].

The optimal techniques had been applied with FEM to search an appropriate parison thickness of hollow products [16-18]. The optimal parison programming of extrusion blow molding process could use the neural network to determine for the uniform part thickness after the parison inflation. Jyh-Cheng *et al.* [19] proposed Taguchi's method to reduce the number of die gap data which was prepared by FEM for training by the artificial neural network (ANN). The uniform parison thickness around the horizontal cross section perimeter of an axis symmetry bottle was predicted by the neural network. The genetic algorithm (GA) was then applied to search for the optimal parison thickness for obtaining the target of the bottle thickness. Huang and Huang [20] used POLYFLOW 3.10 software to prepare the blow molding data of an axis symmetry bottles for the ANN which was combined to find the optimal parison thickness using the GA. The fuzzy neural-Taguchi network with GA (FUNTGA) was established to the target thickness of the parison programming. Yu and Juang [21] proposed fuzzy reasoning of the prediction reliability to evolve the ANN training to guide the GA searching. The bottle thickness around its perimeter which was sturdy to the mechanical testing load was determined by using the GA searching. Even though the AI method composing of the ANN, fuzzy logic and GA was used with FEM to optimize the parison thickness for the extrusion blow molding process, it was effective well with an axis symmetry bottle only and was not determined a suitable parison for the shaping die. Unfortunately, the lubricant oil bottle design was required the complex shape such as the rectangular shape, one handle and two handles for stylishness and usability. Particularly, the bottle thickness around its perimeter requested the die shaping method to adjust die gap and plastic flow for increasing the parison thickness on some sectors of a circular die gap for a bottle which had the complex shape.

This research developed the novel technique to simulate the blow molding process of complex shape bottles. The horizontal cross-section of bottle shape was reasonable to simulate using FEM instead the full shape bottle for the blow molding process with the shaping die. The final cross-section thickness of the blow molding bottle would be used to determine the parison thickness and to suggest for shaping of the extrusion die.

2. Experiment

The lubricant oil bottles are produced with the high density polyethylene (HDPE) grade 6140B of SCG Plastic Company Ltd using the blow molding machine, model 5000DC of Sinco Technology Co., Ltd (Fig. 1). The extrusion blow molding process of the lubricant oil bottles is set up the producing conditions as described in Table 1. The lubricant oil bottle which is produced using HDPE material has the reflective symmetry shape as shown in Fig. 2. The five parison tubes which are extruded through the shaping die have been selected to measure their thickness (Fig. 3). The columns were divided into fourteen sections around the parison perimeter and assigned points to measure the parison thickness along the height of the parison (10 points per one column). The thickness gauge, model MiniTest 7200 FH of ElektroPhysik, had been used to measure the parison thickness. Figure 4 shows the average thickness graph of parisons which are blown to be the lubricant oil bottles. The parison thickness around its perimeter was not uniform. Particularly, it was increased from the top to bottom by the effect of gravity force. The linear relation between parison height and thickness can be written by the following equation.

$$t_p = ah + b_{A-L} \tag{1}$$

where t_p is the parison thickness, h is the parison height, a is 2.492×10^{-3}, and b_{A-L} is constant regarding to the initial thickness of the parison flow through the die gap.

The 1.0 liter bottles were collected to be samples and also were assigned column positions regarding to the parison columns. Figure 5 shows the average thickness graphs of the lubricant oil bottles along its bottle height. The column of parison which was far from cavity mold surface was thicker than other columns by die shaping to blow the bottle wall as far from the parison axis had been shaped the die for extrusion of the parison thickness more than other columns. The die shaping method depended on the experience of the die maker which was not regulated by the blow-up ratio. Otherwise, the number of shaping to obtain the final shape of die gap was related to the time and cost consuming for setting up the extrusion blow molding process of lubricant oil bottles.

(a) (b)

Fig. 1. (a) the extrusion blow molding machine, and (b) the parison extruding through the shaping dies of blow molding machine.

Table 1. The setting up data for extrusion blow molding process of lubricant oil bottles.

Condition	**Value**	**Unit**
Parison outer diameter	52	mm
Initial temperature	180	°C
Die gap opening	150	mm
Die closing speed	2.2	m/sec
Blow-up pressure	1	bar
Blow-up time	0.3	sec
Cooling time	2	sec

Fig. 2. The 1.0 liter lubricant oil bottle with flash or scrap.

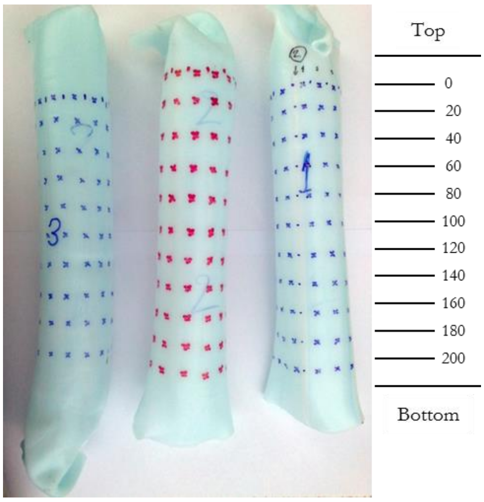

Fig. 3. The samples of parison for blowing the 1.0 liter lubricant oil bottle.

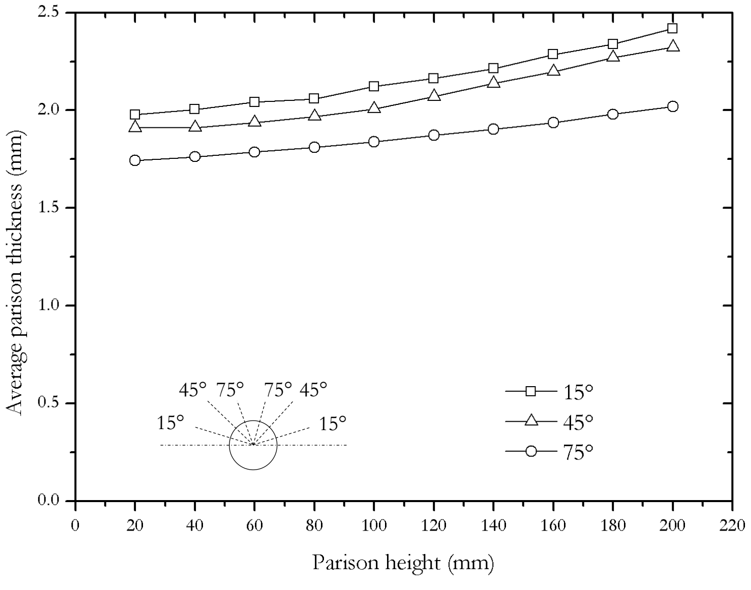

Fig. 4. The parison height vs. the average wall thickness of parison for blowing the lubricant oil bottles.

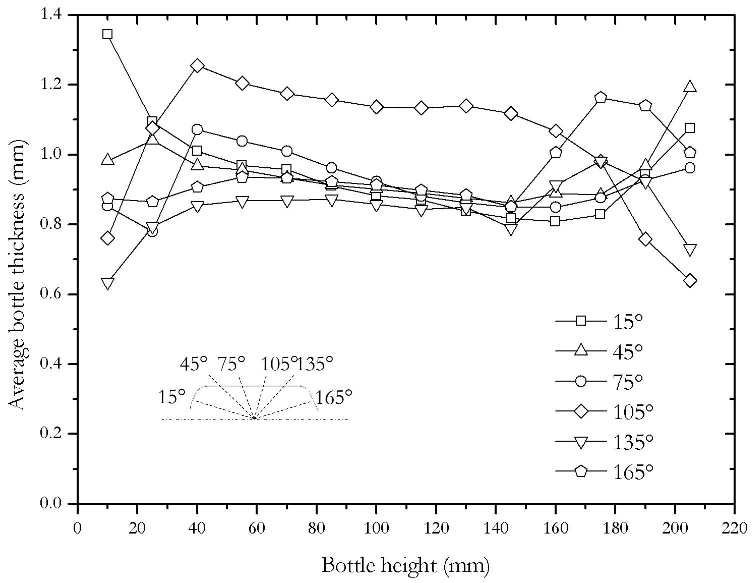

Fig. 5. The bottle height vs. the average wall thickness of lubricant oil bottles.

3. The Bottle Blow Molding Models

The 1.0 liter lubricant oil bottle model is shown in Fig. 6. It was carried out to create finite element model of the blow molding process. The discretized equations of the large deformation contact which happened on the blow molding simulation were clarified by [22, 23]. The full shape bottle blow molding process was performed from start at the mold clamping on parison to the bottle forming by the parison inflation. The horizontal cross-section shape bottle blow molding process was simulated at the interesting section which was high from the bottle bottom of 115.00 mm. The mold surface did not clamp on parison section; therefore, the clamping process was not necessary to create and perform by the cross-section bottle blow molding model. The bottle blow molding simulations were performed using the personal computer with Core-i5 CPU 3.3 MHz and 4 GB DDR III SDRAM memory.

3.1. Full and Half Shape Bottle

Three parts of finite element model comprising of two mold parts and one parison part were created for the full shape bottle blow molding model. Figure 7a shows the finite element model of full shape bottle blow molding process. The parison model was diameter and length of 52.00 and 300.00 mm, respectively. The parison model was divided by rectangular plate elements which had the total amount of 2,880 elements. The element dimension had a width and length of 3.75 and 4.53 mm, respectively. The mold parts were the surface model which placed on two sides of the parison model for the clamping and blowing simulation, respectively. The bottle mold models were assigned to be the rigid body surface model because the parison model was clamped and blown to contact just only on the inner surface of mold. The material model which was assigned on the parison model was the visco-elastic material regarding to Thusneyapan and Rugsaj [8]. The thickness of the parison model was assigned according to the measurement results of the parison thickness in a previous section. The half shape bottle had been performed to reduce the complex of full shape; therefore, it was used one mold part and a half of parison part. Figure 7b shows the finite element model of a half shape bottle blow molding model. The symmetry plan was assigned on the parting line of the parison. The element dimension was equal but the number of elements was reduced a half of the full shape bottle model.

The fixed boundary condition was defined on nodes at the top edge of the parison models. This boundary was employed to hold the parisons as the stop extrusion step of blow molding machine. The surface molds were assigned to clamp parisons and to hold until the parisons were blown to form the final shape of bottle. The blowing pressure of 607.95 kPa was defined on the inner surface of parison models for the inflation step of blow molding process. The temperature of parisons was 180 °C while the environmental temperature was 35 °C. The temperature was accorded to the temperature of HDPE material for extruding through the shaping die.

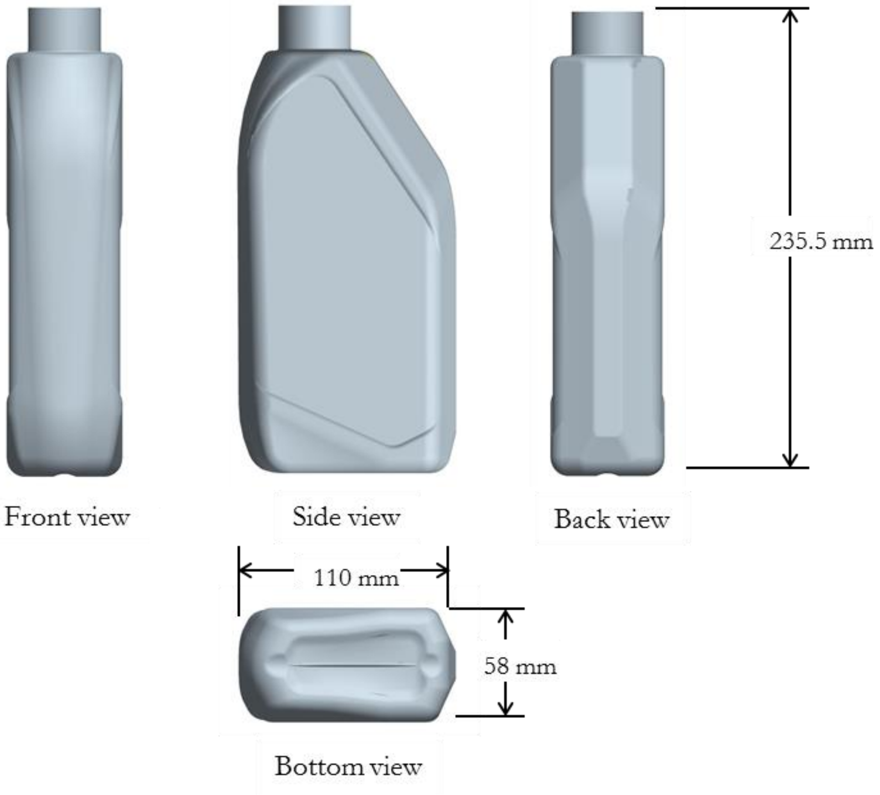

Fig. 6. The 1.0 liter lubricant oil bottle model.

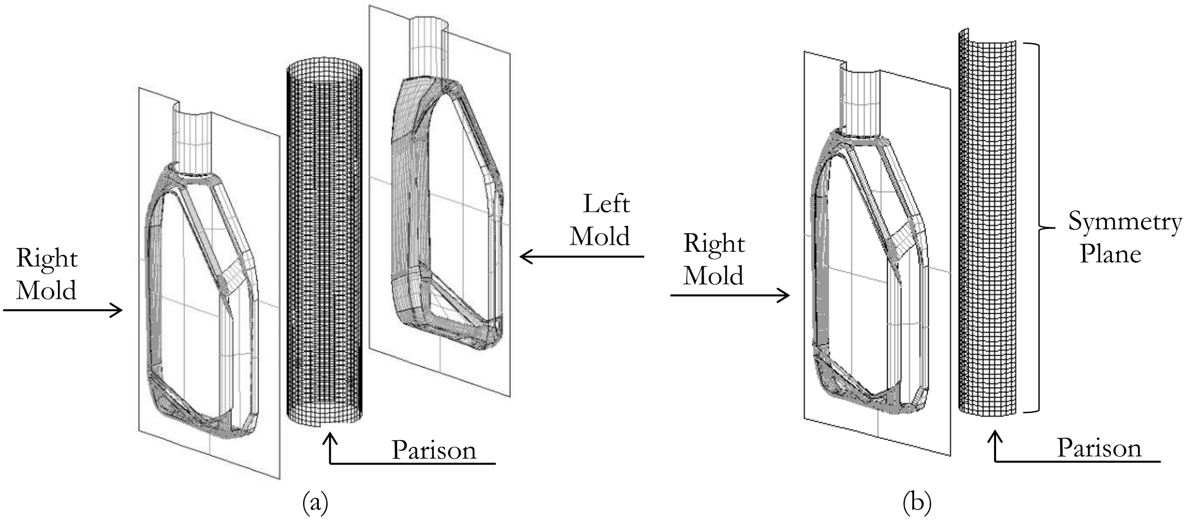

Fig. 7. The finite element model of: (a) full shape bottle and (b) half shape bottle blow molding process.

3.2. Cross-Section Shape Bottle

The horizontal cross-section shape bottle was interested at the bottle height of 115.00 mm which was the label position of the 1.0 liter bottle. Therefore, the finite element model of cross-section shape bottle blow molding process was created using two parts of the finite element model. Figure 8 shows the cross-section shape bottle model for simulation of the blow molding process. It was distinctly advanced more than the full shape bottle blow molding simulation. This bottle section was not concerned the clamping process of the bottle mold. The horizontal cross-section parison model is created and placed in the closed bottle mold as shown in Fig. 8. The hollow circular shape of parison model had the outer diameter of 52.00 mm and it was divided by the rectangular plate elements. The parison model was used the total element of 120 elements that were less than the full shape bottle model of 24 times. The finite element model of cross-section parison was employed the adaptive meshing to refine parison elements when they were contacted on the mold surface. The material property of parison was defined as same as the parison model in the full shape bottle blow molding process. Otherwise, the conditions comprised of the internal pressure and environment temperature also defined as same as the full shape bottle.

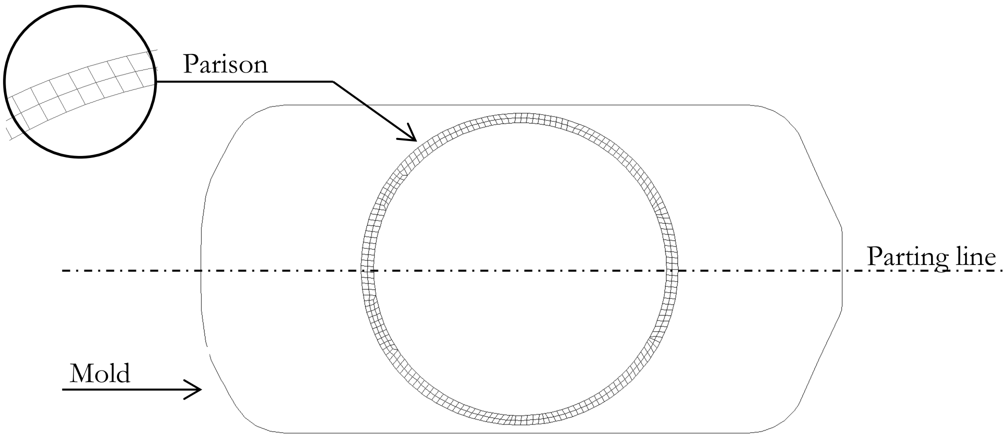

Fig. 8. The horizontal cross-section shape bottle model for the blow molding process simulation.

4. Results and Discussion

4.1. Full and Half Shape Bottle

The simulation result of the full shape bottle has been shown by the sequent images of blow molding process in Fig. 9. The mold models were closed and clamped parison completely at 0.4 sec. Subsequently, the parison was blown to inflate and form the 1.0 liter bottle. The side surfaces of bottle mold were contacted with the inflating parison first. The thickness of the bottle from the start to finish the blow molding process was represented by the color contour. The minimum thickness was shown by blue while the maximum thickness was yellow. The minimum thickness happened distinctly on the bottle corners while the maximum thickness happened at the flash or scrap of the 1.0 liter bottle blow molding process. The final thickness of bottle model around its perimeter at the bottle height of 115 mm was compared with the experimental data.

The simulation result of half shape bottle is illustrated by the sequent images of blow molding process in Fig. 10. The color contour happened on the half bottle surface as like as the full shape bottle at the same time. Figure 11 shows comparison graphs of bottle thickness between physical experiment and simulations. The simulation graphs had trended as similar as the experimental graph. The finite element analysis (FEA) for full shape bottle obtained an average deviation of 32.35% while the half shape bottle was 33.59% when compared with the experimental data. The bottle thicknesses of FEA were thicker than the physical experiment because the initial thickness of parison was thicker than the parison in blow molding process. The half shape bottle was calculated more rapidly than the full shape bottle but it was similar to give the final bottle thickness. Even though the half shape bottle model was easy to establish and rapid calculation, it could not be accurate to predict the final thickness of the bottle. The average deviation of the half shape bottle model from the experimental data was increased a little cause of the axisymmetric plane condition.

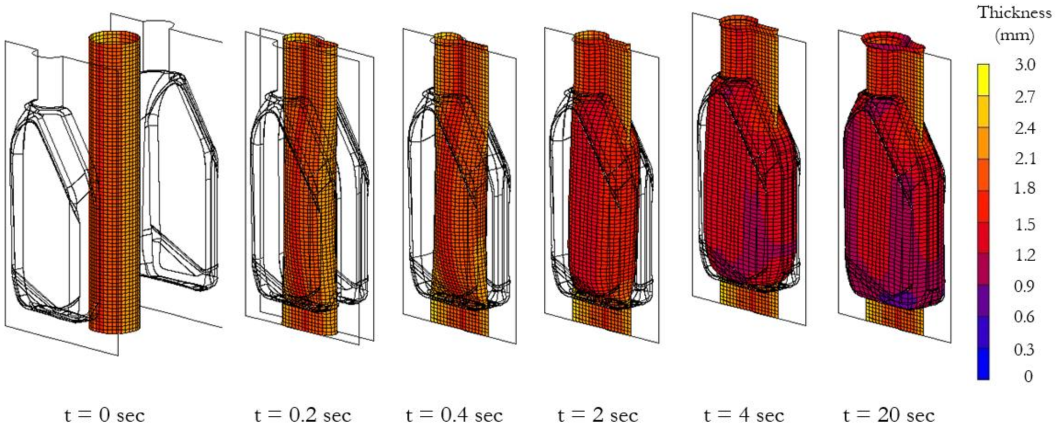

Fig. 9. The sequent image of simulation result of full shape bottle blow molding process.

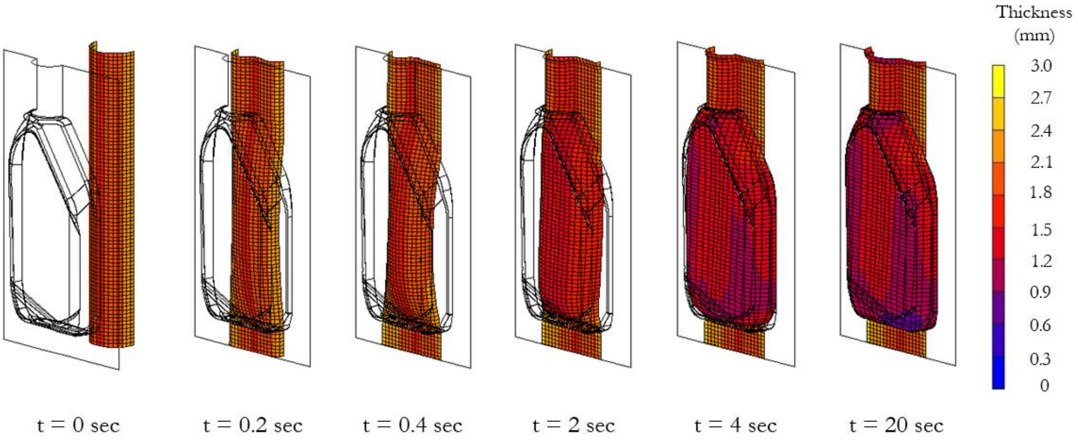

Fig. 10. The sequent image of simulation result of half shape bottle blow molding process.

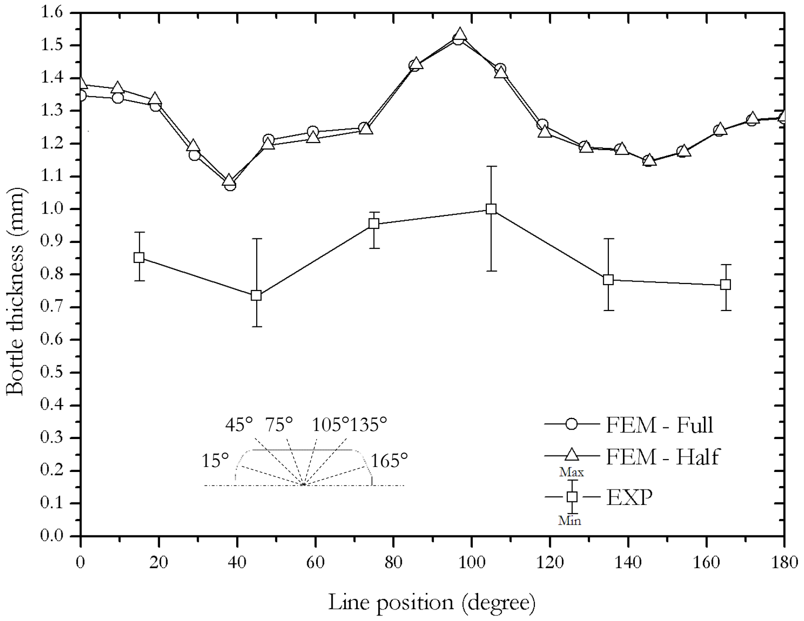

Fig. 11. The column line position vs. wall thickness of the 1.0 liter lubricant oil bottle comparison between FEM and experiment at the bottle height of 115 mm.

4.2. Cross-Section Shape Bottle

Figure 12 shows the simulation results of the horizontal cross-section shape bottle blow molding process. The cross-section of prison was inflated to form the horizontal cross-section shape of bottle at its height of 115.00 mm. The parison wall which was close to the mold surface was expanded to form on the internal mold surface before other sectors of the parison wall. Therefore, the side of bottle wall was thicker than the front and back wall of the bottle. The deformation of parison was represented using the color contour. The cross-section bottle thickness could be measured by the distance between inner and outer perimeter of finite element model at the final simulating step of blow molding process. The thin area was shown by the maximum strain and the thickness area was the minimum strain. The minimum thickness area would be yellow while the maximum thickness area was blue. The thin area of horizontal cross-section bottle happened at bottle corners.

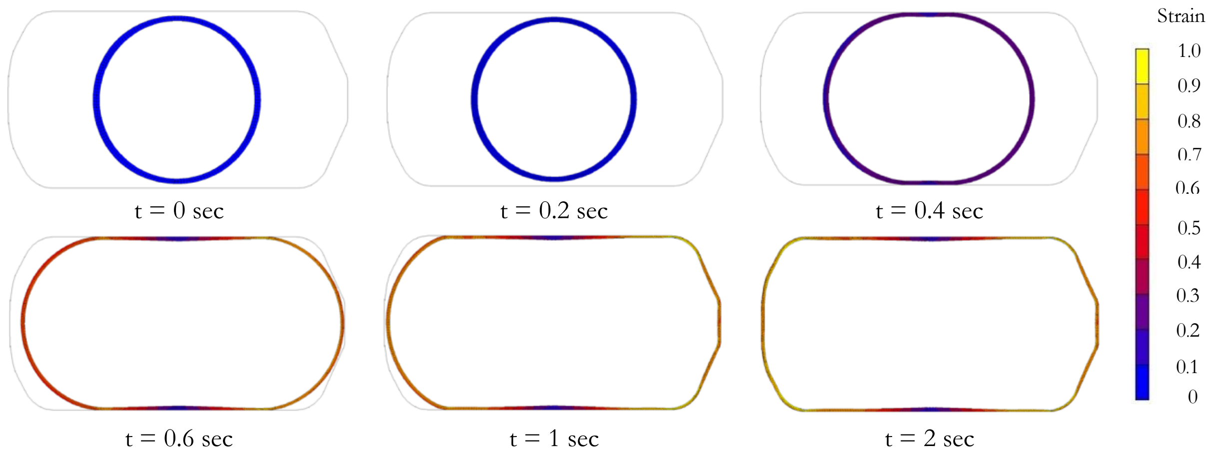
t = 0 sec
t = 0.2 sec
t = 0.4 sec
t = 0.6 sec
t = 1 sec
t = 2 sec

Fig. 12. The sequent image of simulation result of cross-section shape bottle blow molding process.

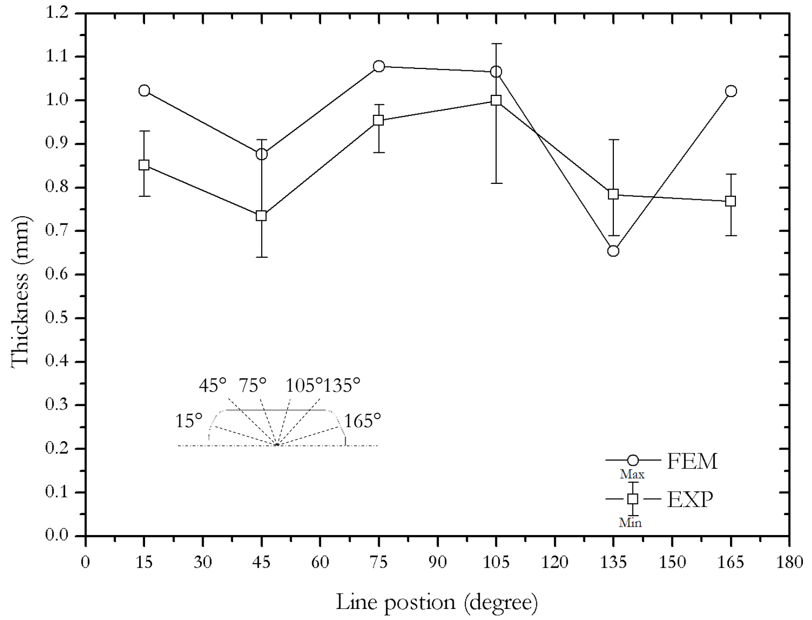

Fig. 13. The column line position vs. wall thickness of lubricant oil bottles comparison between experiment and simulation.

Figure 13 shows the comparison graph of cross-section bottle thickness between physical experiment and simulation. The FEA result of the cross-section shape bottle blow molding process was good agreement with the experimental data more than the full shape bottle blow molding simulation. The average deviation of the cross-section shape bottle blow molding simulation was less than 17.02% when compared with the physical experiment.

The blow molding simulations can improve for more accuracy by the assignation of other material model such as the K-BKZ material model which was followed the works by [24-26]. However, the final thickness of bottle of the cross-section shape bottle blow molding simulation was found the good agreement with the experiment data more than the full shape bottle. Moreover, it was comfortable to prepare the finite element model and consumed simulated time less than the full shape bottle model based on the same complex bottle shape. Particularly, the full shape bottle model might fail to simulate the blow molding process using FEM for highly complex shape of the lubricant oil bottles.

4.3. Die Shaping Guide

The parison tubes of two complex shape bottles which had capacity of 1.00 liter were collected from the extrusion blow molding process. The parison tubes of A-shape and B-shape bottle are shown positions to measure the thickness in Fig. 14. After these parisons are blown to be the bottles, they have complex shape as shown in Fig. 15. The interesting cross-section of A-shape and B-shape bottle was at the bottle height of 118.0 and 112.5 mm, respectively. The front side of A-shape bottle had the right angle curves; therefore, they were difficult to blow more than the obtuse angle curves of the previous 1.0 liter bottle. The horizontal cross-section which was cut from the B-shape bottle depicted the small and sharp curves at the front side of bottle. These points were very difficult to blow the parison to form the bottle shape completely using the full shape bottle blow molding simulation. The horizontal cross-section shape bottle blow molding simulation was performed on the A-shape and B-shape bottle. The outside diameter of parison cross-section both the A-shape and B-shape bottle were 52.0 mm. The thickness which was measured from a physical parison of A-shape and B-shape bottle was assigned to create the parison of A-shape and B-shape bottle model, respectively.

Figure 16 shows the sequence of the horizontal cross-section shape bottle blow molding process of the A-shape bottle. The cross-section of parison was inflated to form the horizontal cross-section shape of bottle at its height of 118.00 mm. The parison sector which was on the front side of A-shape bottle mold was thicker than other parison wall cause of the die shaping. The parison wall which was close to the mold surface was expanded to meet the internal mold surface before other area of the parison wall; therefore, the side wall of bottle was also thick. The deformation of parison to form the A-shape bottle was represented using the color contour. The strain on the cross-section bottle thickness could be expressed by the color contour. The thick bottle wall was shown by blue because it was the little strain. The thin area was happened strain more than other area then it was shown by yellow. The thin wall of horizontal cross-section bottle did not happen at its corners because the die shaping enforced the thick wall on the parison columns that expanding to be the bottle corners.

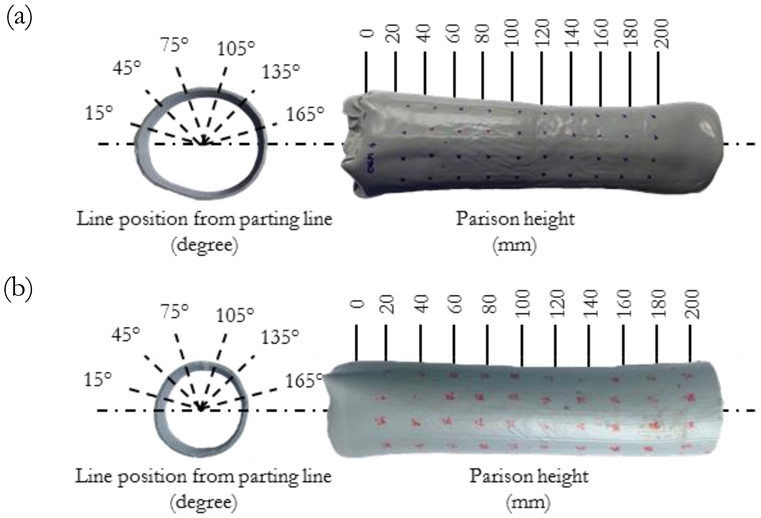

Fig. 14. The samples of parison for blowing of: (a) the A-shape and (b) the B-shape lubricant oil bottle.

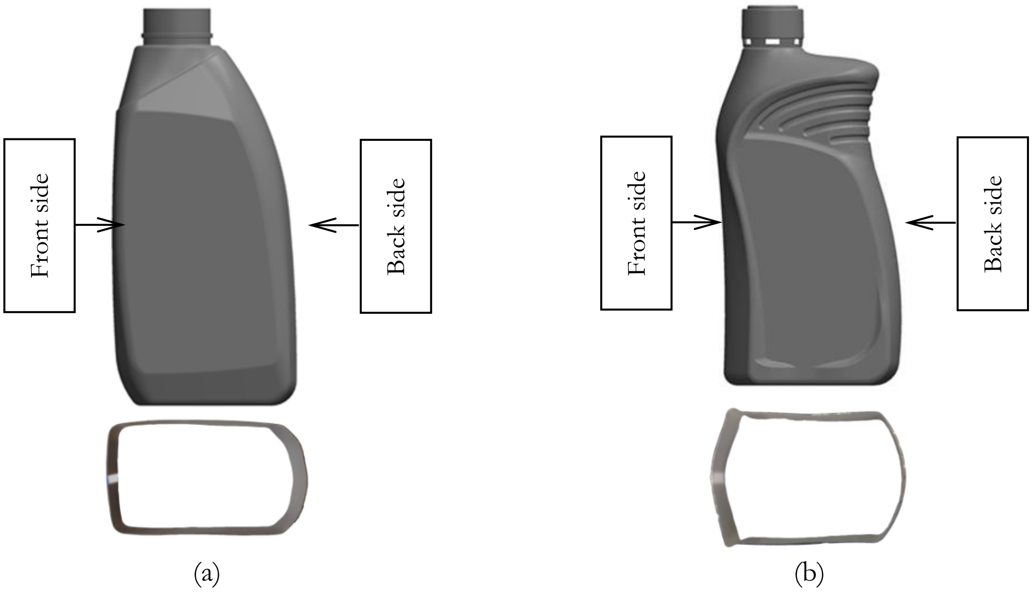

Fig. 15. The sample of lubricant oil bottle and its cross-section of: (a) A-shape and (b) B-shape.

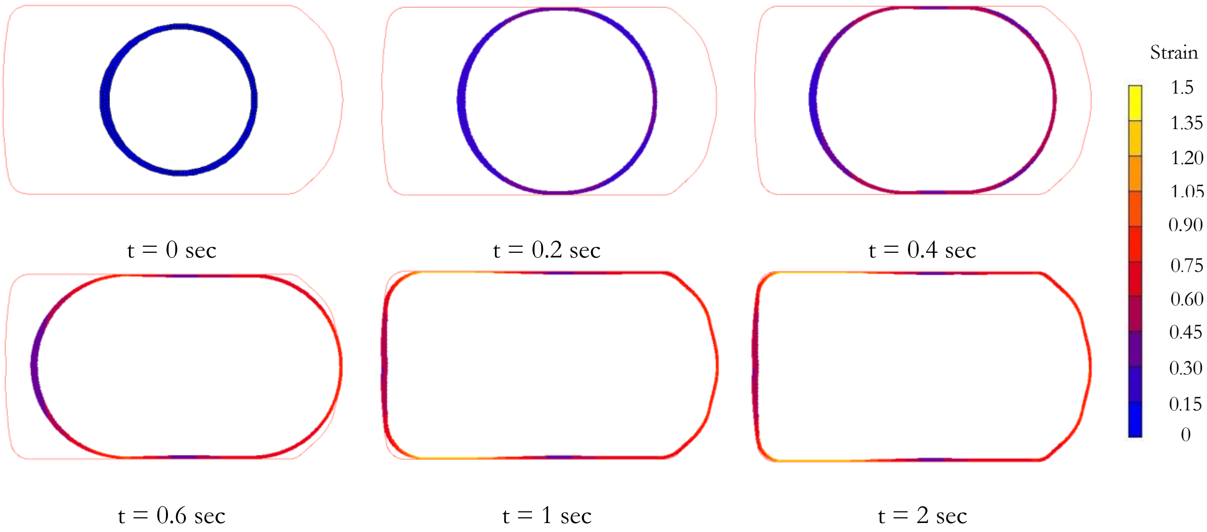

Fig. 16. The sequent image of simulation result of cross-section shape bottle extrusion blow molding process of A-shape bottle.

Figure 17 shows the simulation results of the horizontal cross-section shape bottle blow molding process of the B-shape bottle. The cross-section of prison was inflated to form the horizontal cross-section shape of bottle at its height of 112.50 mm. The parison wall which was close to the back side of bottle mold was thicker than other area by die shaping. The side walls of bottle mold were contacted the parison which was expanded before other sides. The final expansion of parison happened at the sharp curves in back of the B-shape bottle. The strain which was happened by the deformation of parison was represented by the color contour. The minimum strain was blue while the maximum strain was yellow. The cross-section bottle thickness at the final step of blow molding was measured by the distance between inner and outer perimeter of finite element model. The thin area was shown by the maximum strain while the thick area was the minimum strain. The horizontal cross-section of B-shape bottle thickness was very thin at two corners of the back side.

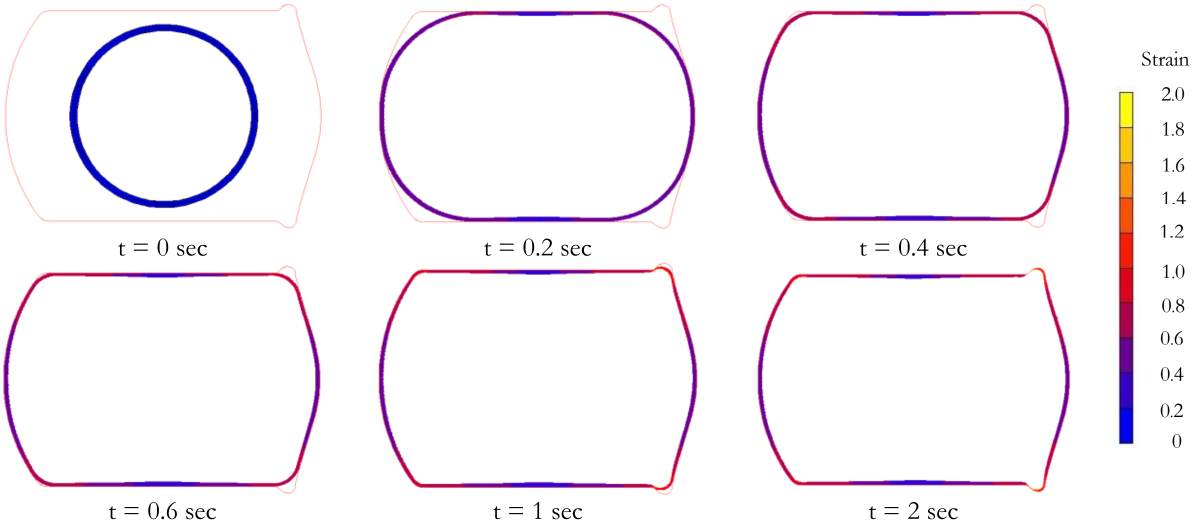

Fig. 17. The sequent image of simulation result of cross-section shape bottle extrusion blow molding process of B-shape bottle.

The right angle curves in the front side of the A-shape bottle were the critical area to create the blow molding simulation model by the full or half shape bottle. The small and sharp curves of the B-shape bottle were harder than the A-shape bottle to create the full or half shape bottle for the blow molding simulation. The FEM of blow molding of these both cases might be diverse to obtain the final thickness of bottles.

Figure 18 shows the comparison graph of cross-section bottle thickness between physical experiment and simulation for the A-shape bottle. The FEA results of the cross-section shape bottle blow molding process of A-shape bottle were good agreement with the physical experiment. The average deviation of the cross-section shape bottle blow molding simulation was less than 28.48% when compared with the experimental data. The die shaping and parison collection had the parison wall on the front of A-shape bottle model thicker than the real process; therefore, the high thickness error happened at the line position of 15 degrees. Figure 19 shows the comparison graph for the cross-section bottle thickness between physical experiment and simulation of the B-shape bottle. The FEA results of the cross-section shape bottle blow molding process of B-shape bottle were also good agreement with the physical experiment. The average deviation of the cross-section shape bottle blow molding simulation of B-shape bottle was less than 10.19% when compared with the experimental data. The thickness of the parison for the horizontal cross-section shape bottle blow molding process of A-shape and B-shape bottle could use to calculate the thickness on top of parison which flow through the shaping die. The A-shape and B-shape bottle have the parison thickness which is used Eq. (1) for calculation are described in Table 2. The parison thickness from the shaping dies which was predicted using the horizontal cross-section blow molding simulation and Eq. (1) was good agreement with the experimental data. The average error of A-shape and B-shape bottle was 2.30 and 2.32% when compared with the physical experiment.

The minimum thickness was happened at 45 degrees of the A-shape lubricant oil bottle or at the right angle curves. There was the critical area which the bottle could be leaked easily when it was supported an internal pressure or impact load. This critical area was not interested in this research. However, the suitable thickness of bottle which was sturdiest to the internal pressure, top load and impact load could be determined by the FEM before the bottle design and manufacturing [27-29].

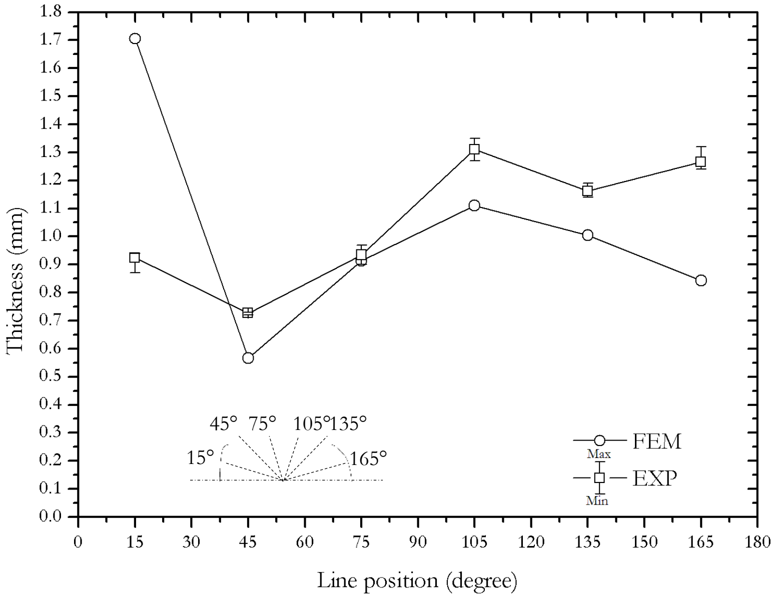

Fig. 18. The column line position vs. the wall thickness of A-shape lubricant oil bottle comparison between FEM and experiment at bottle height of 118.0 mm.

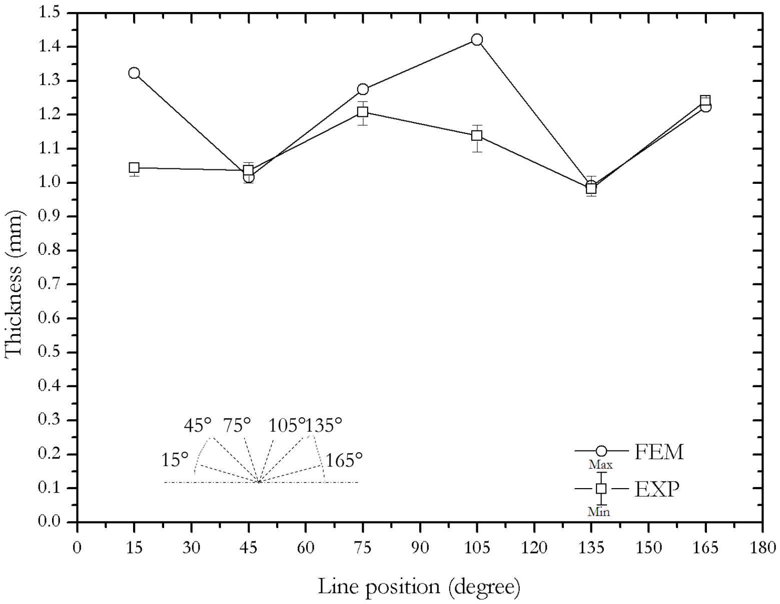

Fig. 19. The column line position vs. the wall thickness of B-shape lubricant oil bottle comparison between FEM and experiment at bottle height of 112.5 mm.

Table 2. Initial thickness of parison extrusion through the shaping die.

Bottle Shape	Method	Thickness of Parison at Column line (mm)					
		A	B	C	D	E	F
A	FEA	2.16	1.88	1.78	1.80	1.93	2.01
	EXP.	2.20	1.93	1.82	1.85	1.99	2.04
B	FEA	2.30	2.22	2.05	2.01	2.03	2.06
	EXP.	2.24	2.14	2.00	1.96	2.00	2.04

5. Conclusions

This research had developed a novel approach to blow parison under the extrusion blow molding process. The horizontal cross-section of the bottle was developed to simulate the blow molding process using the FEM. The full and half shape bottle blow molding process were attempted to simulate using FEM. The complex shape of 1.0 liter bottle had effects for creating of the full and half shape bottle blow molding process model. They were consumed the preparation of finite element model and the simulating time. The horizontal cross-section shape bottle blow molding process model was demonstrated that more advantage than the finite element model of the full and half shape bottle. Otherwise, the cross-section of bottle blow molding simulation was validated with the physical experiment. The thicknesses of horizontal cross-section bottle at the interesting height of 1.0 liter bottle were obtained the simulated results in the good agreement with the experimental data and had an average deviation less than 17.02%. The simulation of half shape bottle blow molding could not perform with two complex shape bottles. The 1.0 liter bottles which were more complex shape than the previous bottle shape were simulated the blow molding process at different height using the horizontal cross-section technique. The implementation of novel technique found the average deviation of 19.34% when it was compared with the physical experiment. The horizontal cross-section shape bottle blow molding simulation of two different shape bottles was applied to determine the parison thickness which was extruded through the shaping dies using the parison thickness equation. The prediction of parison thickness was good agreement with the experimental data. It was obtained an average error less than 2.31%. The parison thickness which obtained by the novel approach could be a good guide for shaping the extrusion die by using with the simplified relationship equation between the parison height and thickness. This developed approach to determine initial thickness of parison which was extruded through the die will advantage to guide the die markers for shaping of the die gap in the further works.

Acknowledgement

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