



Investigation of the Injection Moulding Plastic Flows Behaviour of PET Cylindrical Containers with Multiple-Cavity Mould

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ABSTRACT

The study aims to investigate the effect of injection moulding parameters on plastic flows behaviour of the multiple-cavity polyethylene terephthalate (PET) cylindrical containers via injection moulding process. The motivation of this study is to present an alternative manufacturing solution to make cylindrical type containers that are commonly used in packaging beverages, such as the 330 ml standard size for packaging carbonated soft drink. The PET cylindrical container was modelled using CATIA drawing software and the injection moulding simulation process was done via Moldflow software. The investigation was done by varying two significant moulding parameters; the material melt temperature and the mould temperature. The effects of these two parameters on the PET plastic flow behaviour were studied. In particular, the simulations of the model were analysed and focused on the mould filling time as well as the moulded PET cylindrical container's shrinkage occurrence. Three types of mould cavities structure were understudied; single-cavity, four-cavity and eight-cavity. Results show that the eight-cavity mould yielded higher production rate. The simulation results indicated that the production rate of 4-cavity and 8-cavity mould increased by 258.5% and 578.8% respectively. It was observed by increasing the melting temperature, the mould filling time is shorter and as a result, the production rate has increased by 7.75% per °C. But with this Moldflow setting, the volumetric shrinkage and the maximum deflection have been significantly affected; increased by 23.15% and 29.26% respectively. The mould filling time and maximum deflection did not show a steady trend line however, the volumetric shrinkage increased by 7.28% per °C.

Keywords: Injection moulding, mould filling time, moulding parameters, polyethylene terephthalate, shrinkage

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INTRODUCTION

The World Packaging Organisation (WPO) found that plastic packaging is replacing glass

and metals. It was highlighted by Demirel, Yaraş and Elçiçek (2011) that plastic industries are currently trying to improve their capabilities of packaging in order to take over the packaging of alcoholic drinks which is a challenge for plastic materials. The main challenge is to be able to contain the product for the required shelf life.

PET consists of multiple long fibre strands of polymers that are produced from continuous melt-phase polymerisation process between terephthalic acid (TA) and ethylene glycol (EG) as explained by Byrne, Ward, Hughes and Cullen (2011). The crystallinity of PET ranges from amorphous to very crystalline depending on the PET processing method. Different levels of crystallinity and morphology of PET affects the product properties. The level of crystallisation is induced thermally when the polymer is heated above the T_g and rapidly quenched (Demirel, Yaraş, & Elçiçek, 2011). A study was conducted using Differential Scanning Calorimetry (DSC) to determine the PET glass transition temperature T_g and melting temperature T_m . The obtained results were 77°C T_g and 252°C T_m , respectively with the degradation temperature of 435°C (Byrne, Ward, Hughes, & Cullen, 2011).

Safety concerns regarding the use of PET in food and beverage packaging have been clarified by various agencies around the world including European Union's (EU) European Food Safety Authority, Health Canada and the U.S. Food & Drug Administration. Bach et al. (2013) showed that under worst case scenario, when the water in PET bottles was exposed to a temperature of 60°C for 10 days, it did contain formaldehyde, acetaldehyde and antimony but the concentrations are far below the specific migration limit (SML). Another research also showed that the quality of the water was not affected by the photochemical ageing of the bottles and if any aldehyde or other organic photoproduct were detected at all, they would be far below the limits of safe drinking (Wegelin et al., 2001).

The development of injection moulding has enabled not only for plastics but also for other materials, such as metals, glass and ceramics, to be melted and injected into moulds. Injection moulding is one of the most important manufacturing processes for polymers because of its processing versatility in producing polymer products with complex and nearly limitless designs, low production energy, low production cost, light weight moulded parts, high production rate, minimal waste, high dimensional steadiness, and good mechanical properties (Chen, Chuang, Hsiao, & Tsai, 2009; Oktem, Erzurumlu, & Uzman, 2007; Song, Liu, Wang, Yu, & Zhao, 2007).

The material requires sufficient amount of heat in order to completely melt in the heating barrel. The melting temperature greatly affects the material flow ability, flow rate, and curing time (Huang & Tai, 2001). Dimensional shrinkage is one of the most critical dimensional flaws resulting from various factors of injection moulding process (Lal & Vasudevan, 2013; Oktem, Erzurumlu, & Uzman, 2007). According to Jansen, Dijkand and Husselman (1998), Nagahanumaiah (2009), and Mehat, Kamaruddin and Othman (2013), one of the main factors contributing to shrinkage is the melting temperature of the polymer. The result of higher packing pressure forces the material to completely fill in the mould during injection process, thus compensating for the shrinkage effect (Zhil'tsova, Oliveira, & Ferreira, 2009). Warpage is defined as the distortion or deflection of a moulded part after it is being ejected off the mould; due to the shrinkage variations within (Reddy & Kumar, 2009). Although the melting temperature and the pressure were mentioned to be the most significant in causing

warpage, many studies have taken mould temperature into account to determine warpage (Chen, Chuang, Hsiao, & Tsai, 2009; Huang & Tai, 2001; Kong, Kim, Member, & Yuen, 2003; Koszkuł & Nabialek, 2007; Kurataran, Ozcelik, & Erzurumlu, 2005; Oktem, Erzurumlu, & Uzman, 2007; Ozcelik & Sonat, 2009). Chen, Chuang, Hsiao and Tsai (2009) conducted a study using Moldflow simulation software in evaluating the characteristics of plastic flow in modern injection moulding process and concluded that by using computer simulation analysis a satisfactory representation of the real procedure can lead to better manufacturing design process.

The range of materials' melting temperature used during the injection moulding process mainly depends on their property. Theoretically, higher melting temperature increases the fluidity of the melted material but, all material will degrade at certain temperature (Sha, Dimov, Griffiths, & Packianther, 2007). From different sources of PET manufacturers, the bottle grade PET pellets will be heated at 5°C to 20°C above the minimum required temperature to remove the moisture content in the compound. This step will ensure all the pellets filled into the heating barrel are completely and evenly melted. The mould temperature also plays an important role in maintaining the fluidity of the melt once it passes through the nozzle from the heating cylinders or barrels. Taking into considerations of different types of PET and part thickness, industries had recommended a range of 90°C to 120°C of mould temperatures for injection moulding process (Sha, Dimov, Griffiths, & Packianther, 2007). This study aims to investigate the potential of producing and utilizing the PET 330 ml size cylindrical container in packaging beverages commonly contained in aluminium cans by investigating the effects of the moulding parameters on the plastic flow behaviour.

MATERIALS AND METHOD

The main idea of this design is to propose an alternative packaging method for the 330-ml size carbonated soft drinks using PET material. The concept design or dimensional specifications were benchmarked against the cans suppliers and manufactures. The common 330 ml size was chosen, thus the relevant specifications for the mould design process was gathered and analysed. Also, the ability of the PET cylindrical container to withstand the carbonated soft drink is critical. The PET must be able to endure the physical stress after being filled with pressurised carbonated soft drink content. The studied design should not be very different from the existing can design, and comply with customers' preferences in terms of size, shape and ergonomics. CATIA V5R21 software was used to draw 3D PET cylindrical container model. The design analysis indicated that cylindrical containers with 100 mm height and 70 mm diameter would be able to hold the required volume of beverage. The container must also have a thickness wall of 1mm with 50.44 mm circumference to enable the can to withstand the pressure build up when it is filled with carbonated soft drink. Comprehensive design processes and modifications were done using CATIA before the data being extracted into Moldflow platform. The 3D model was then validated and saved in the Certificate Trust List (.stl) extension format. In this format the information it is accessible or readable by the Moldflow program. The model was then imported into the Moldflow software for simulation and analysis.

Moldflow Simulation

Once the material properties were made available in the Moldflow, the PET cylindrical container model was then imported from the CATIA database in . stl format. The steps for the simulation process are as follows:

1. The model was verified and modified of any mould defects during the data importing process. Once the can model was successfully checked, the data importing step into Moldflow was completed.
2. The next step was to set the Injection Location(s). This step is required for the melt flow routing logic into the mould cavity during the simulation process.
3. Subsequently, specified the material used for the cylindrical container model; PET,
 Manufacturer: UltrPET
 Trade Name: Bottle Grade Reprocessed
4. In the Analysis Wizard, the Sequence of the simulation was chosen. Here, the Fill+Pack command was selected to analyse the required plastic flow behaviour.
5. The Process Setting is where the process parameters of the simulation were applied and varied. The mould and melt temperatures were set according to Tables 1, 2, and 3.
6. Once the simulation was completed, the simulation results based on the set moulding parameters were tabulated. The results were analysed and recorded. Effects of varying melt temperature and mould temperature were conducted based on 8-cavity PET cylindrical container model.

Table 1
 Process parameters for (i) single-cavity, (ii) 4-cavity, (ii) 8-cavity mould comparison

Melt Temperature	Mould Temperature
285°C	110°C

Table 2
 Process parameters for varying melt temperatures

Melt Temperature	Mould Temperature (constant)
270°C	110°C
280°C	110°C
290°C	110°C
300°C	110°C

Table 3
 Process parameters for varying mould temperatures

Melt Temperature (constant)	Mould Temperature
285°C	90°C
285°C	100°C
285°C	110°C
285°C	120°C

RESULTS AND DISCUSSION

Single, Multiple Cavity Fill Time Comparison

Generally, manufacturers would opt for multiple cavities injection moulding for better production yield. However, the number of cavities was not the only consideration in achieving good mould design and performance. The moulds designed must be able to operate at its optimum with less rejection. The goal is to achieve high production yield. A very straight forward approach in achieving high production rate is by producing more parts in one injection cycle. Thus, multiple cavities are the most optimal option. In order to see how much the production rate can be improved, the PET cylindrical container model was duplicated into four cavities and eight cavities moulds. From here the moulding fill time of the multiple cavities was compared with the single cavity mould. Figure 1 shows the multi-cavity system which was modelled using MouldFlow.

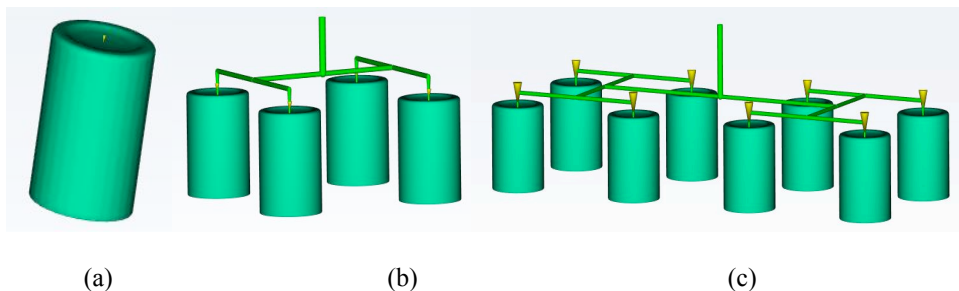


Figure 1. (a) Single-cavity; (b) 4-cavity; and (c) 8-cavity moulds structure

All the three simulation models; single-cavity; 4-cavity; and 8-cavity moulds structure showed a complete and successful filling of the mould cavities but with different filling times (Figure 2). It was observed that more cavities mould reduces the rate of melt fill. This is because of the larger volume of total cavities needed to be filled from a single sprue. A single-cavity mould achieved complete melt fill at 0.25 s. But for a 4-cavity and 8-cavity mould, at the same melt fill time, the melt had only filled a small percentage of the cavity base and hardly reached the base of mould respectively. The time lag for the melt to reach the mould cavity of the 4-cavity and 8-cavity is most likely due to the existence of the runner structure that was compulsory in any mould design. The 8-cavity mould has a longer total length of runner, thus slowing down the melt to reach into the mould cavity.

The pattern of melt flow is similar for all three types mould cavity, with the single-cavity mould achieving the highest percentage of cavity filled, followed by 4-cavity mould and 8-cavity; comparison was made against the same filling time. The mould was completely filled with the melt at 1.27 s for the single-cavity mould, 1.417 s for the 4-cavity mould and 1.497 s for the 8-cavity mould. The minor difference of fill time between single and multiple cavities may be due to the difference in actual injection pressure set during the simulation. The results showed that for the single-cavity mould, it took 95.727 MPa of actual injection pressure, compared to 139.701 MPa for 4-cavity mould and 160.516 MPa for the 8-cavity

mould, respectively. The increase in actual injection pressure showed in the Moldflow can be adopted as the requirement to compensate the increase of cavity volume needed for the injection moulding machine to fill. Therefore, higher actual injection pressure decreases the total fill time for the multiple cavities mould.

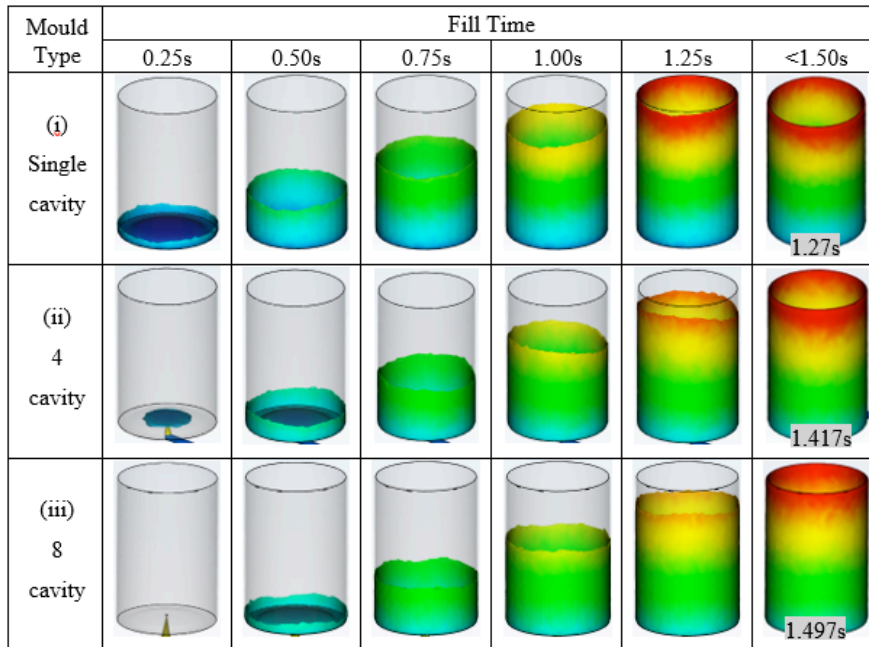


Figure 2. Fill time comparison of single-cavity, 4-cavity, and 8-cavity moulds

By comparing the fill time against the single-cavity mould, the 4-cavity structure mould took 0.147 s longer to fill in the moulds completely but produces four moulded products per shot. Thus, the 4-cavity mould yielded an increment in the production rate by 258.5%. Similarly, for the 8-cavity mould, the mould filling time was 0.227 s longer, but producing eight moulded products per shot compared to the single-cavity mould. Thus, the production rate is 578.7% as compared against the single-cavity mould and it is obviously higher than the 4-cavity mould too. Thus showing that the mould cavity numbers have a direct impact on the increment in the production rate.

Varying Melt Temperature

Based on the plotted results in Figure 3, the filling time was clearly affected by the melting temperature - higher melt temperature led to shorter filling time. This is because the higher melt temperatures increase the fluidity of the melt thus the filling capabilities inside the mould cavities increases accordingly. Fast melt flows were observed from the heating cylinder, through the nozzle and into the mould cavities. The result shows the time taken for the melt to reach different parts of the mould cavities, starting from the centre bottom of the cylindrical container and ending at its top.

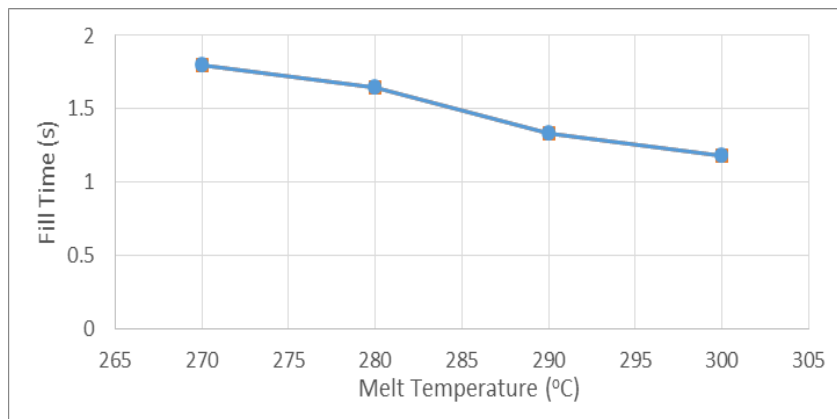


Figure 3. Graph of fill time with varying melt temperature

Contrasting the fill time effect, it was found the volumetric shrinkage (shown as a percentage of the original volume) increased as the melt temperature increased (Figure 4). Volumetric shrinkage is referring to the moulded part shrunk as it is being exposed or cured at the room temperature. For all the simulated melt temperatures, all the parts showed uniform values of shrinkage on the moulded part's wall and base. Thus, the warping effect can be reduced or totally avoided. Also, there were no sink mark signs observed on the moulded parts.

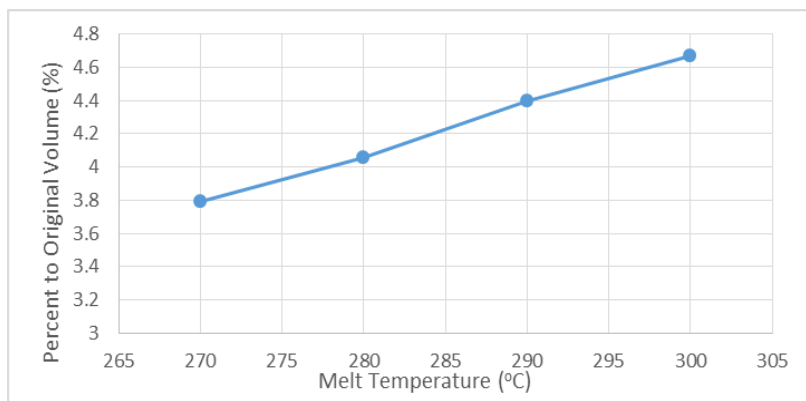


Figure 4. Graph of maximum volumetric shrinkage with varying melt temperature

Similarly, the maximum deflection increased as the melt temperature increased as exhibited in Figure 5. The simulation result indicates the maximum deflection effect at each node of the part. All the moulded parts experienced positive deflection with concave effect; the moulded parts contracted inwards from the expected cylindrical size. The maximum deflections were detected at the rim of the moulded parts, where the melt flow reached latest. The results below are based on the deflected part compared against the expected cylindrical size of the mould cavity.

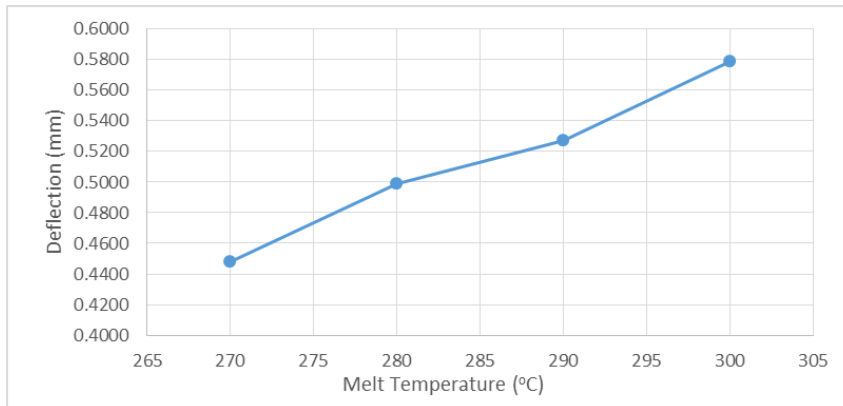


Figure 5. Graph of maximum deflection of part with varying melt temperature

Table 4 presents the overall simulation results obtained by varying the melt temperatures of PET the modelled cylindrical containers. Fill time improved when the melt temperature increased. However, the volumetric shrinkage and the maximum deflections increased with higher melt temperature. The shorter fill time would be most favourable for manufacturers as it would result in higher production rate. But, the volumetric shrinkage and maximum deflection would be increased and led to moulded parts quality issues.

Table 4
Results of PET can simulation varying melt temperatures from 270°C to 300°C

Melt Temperature (°C)	Fill Time (s)	Maximum Volumetric Shrinkage (%)	Maximum Deflection (mm)
270	1.796	3.793	0.4480
280	1.643	4.053	0.4990
290	1.332	4.397	0.5274
300	1.180	4.671	0.5791

Varying Mould Temperature

Figure 6 highlights the results of mould temperature versus the fill time. The fill time gradually increased at the initial stage; between mould temperatures of 90°C to 100°C and significantly shoot up at the mould temperature range between 100°C to 110°C. The fill time becomes steady after it reaches 110°C. It is observed that, further increased in the mould temperature setting above 110°C, does not seem to affect the mould fill time. Similar results were obtained by Sha, Dimov, Griffiths and Packianther (2007), suggested that this behaviour could be due to the expanding air residual which might have hindered the polymer melt flow.

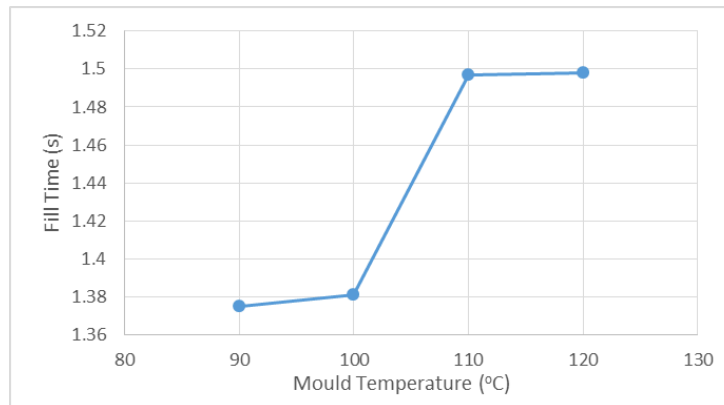


Figure 6. Graph of fill time with varying mould temperature

Figure 7 presents the volumetric shrinkage percentage of moulded parts with the original volume as simulated using MouldFlow. The results show an almost linear trend between the volumetric shrinkage percentage and the mould temperature. This further confirms that mould temperature setting does not directly affect the quality of PET cylindrical container. But the increment in the volumetric shrinkage will have a direct impact on the quality of the moulded parts. A uniform volumetric shrinkage throughout the body and base of the mould cavities and will not encourage warp formation.

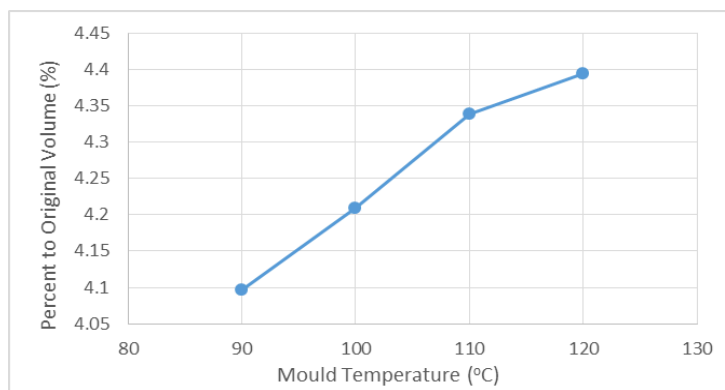


Figure 7. Graph of maximum volumetric shrinkage with varying mould temperature

A notable increment on the maximum deflection is observed for the temperature range between 90°C to 110°C (Figure 8). But the trend drastically decreased after the temperature reaches 110°C. A similar pattern of the maximum deflection effect against the mould temperature was also observed for all the three PET mould cavity design structures.

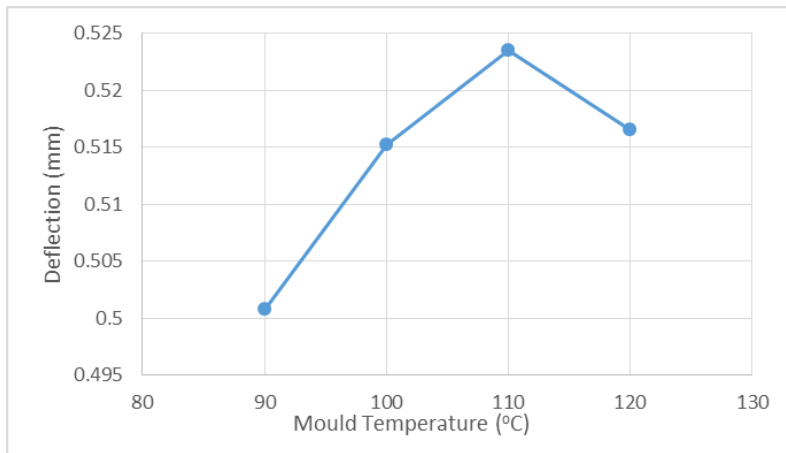


Figure 8. Graph of maximum deflection of part with varying mould temperature

Table 5 showcases the results of the mould temperature effect on the volumetric shrinkage and maximum deflection. The mould temperature was not directly affecting the moulding process of the PET cylindrical containers. It was observed that, the fill time, volumetric shrinkage and deflection were not directly impact the part’s moulding quality as long as the moulding parameters were set at the optimal setting. The mould fill time is a trade-off between the moulding productivity and rejection rate; moulding quality. The challenge is to identify the optimal setting to achieve the most optimum production yield. Simulation results suggests that a lower moulding temperature setting for the PET cylindrical containers reduces the injection moulding time and results in better product quality and higher production rate is.

Table 4

Results of PET can simulation by varying mould temperatures from 90°C to 120°C

Melt Temperature (°C)	Fill Time (s)	Maximum Volumetric Shrinkage (%)	Maximum Deflection (mm)
90	1.375	4.096	0.5008
100	1.381	4.209	0.5152
110	1.497	4.338	0.5235
120	1.498	4.394	0.5165

CONCLUSION

The potential of producing 330 ml size PET cylindrical containers as an alternative packaging solution carbonated soft drinks instead of aluminium cans was thoroughly studied. The mould flow effect of the multiple mould cavities (single cavity, four cavities and eight cavities) concerning the plastic flow and fill time were investigated. The calculated increment of production rate (number of parts produced per second) was 258.5% for 4-cavity mould. With 8-cavity mould, the production rate increased by 578.7%, despite of the fill time increases; as the number of cavities increased. Meanwhile, with a constant mould temperature, it is

observed that higher melt temperature would reduce the time taken to fill the mould cavities. This is because higher melt temperature would result in better fluidity of the melt material thus reducing mould fill time. From the investigation using MouldFlow simulation software, it can be concluded that the moulding parameter setting must be benchmarked according to the material manufacturers' recommendation as well as the mould size condition. Production trials for any new mould design in obtaining the optimal setting parameters is recommended.

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REFERENCES

- Bach, C., Dauchy, X., Severin, I., Munoz, J., Etienne, S., & Chagnon, M. (2013). Effect of temperature on the release of intentionally and non-intentionally added substances from polyethylene terephthalate (PET) bottles into water: Chemical analysis and potential toxicity. *Food Chemistry*, 139(1-4), 672-680.
- Byrne, F., Ward, P. G., Hughes, D., & Cullen, J. (2011). Comparative study of the processing conditions required for PLA and PET polymers. *Solutions*, 4-6.
- Chen, C. P., Chuang, M. T., Hsiao, Y. H., & Tsai, C. H. (2009). Simulation and experimental study in determining injection molding process parameters for thin-shell plastic parts via design of experiments analysis. *Expert Systems With Applications*, 36(7), 10752-10759.
- Demirel, B., Yaraş, A., & Elçiçek, H. (2016). Crystallization behaviour of PET materials. *Balıkesir Üniversitesi Fen Bilimleri Enstitüsü Dergisi*, 13(1), 26-35.
- Huang, M. C., & Tai, C. C. (2001). Effective factors in the warpage problem of an injection-molded part with a thin shell feature. *Journal of Materials Processing Technology*, 110(1), 1-9.
- Jansen, K. M. B., Dijk, D. J. V. A. N., & Husselman M. H. (1998). Effect of processing conditions on shrinkage in injection molding. *Polymer Engineering and Science.*, 38(5), 838-846.
- Kong, J. W. Y., Kim, J., Member, S., & Yuen, M. M. F. (2003). Warpage in Plastic Packages: Effects of process conditions, geometry and materials. *IEEE Transactions on Electronics Packaging Manufacturing*, 26(3), 245-252.
- Koszkul, J., & Nabialek, J. (2007). Selected methods of modelling of polymer during the injection moulding process. *Journal of Achievements in Materials and Manufacturing Engineering*, 24(1), 253-259.
- Kurataran, H., Ozcelik, B., & Erzurumlu, T. (2005). Warpage optimization of a bus ceiling lamp base using neural network model and genetic algorithm. *Journal of Materials Processing Technology*, 169(2), 314-319.
- Lal, S. K., & Vasudevan, H. (2013). Optimization of injection moulding process parameters in the moulding of low density polyethylene (LDPE). *International Journal of Engineering Research and Development*, 7(5), 35-39.

- Mehat, N. M., Kamaruddin, S., & Othman, A. R. (2013). Modeling and analysis of injection moulding process parameters for plastic gear industry application. *ISRN Industrial Engineering*, 2013, 1-10.
- Nagahanumaiah, B. R. (2009). Effects of injection molding parameters on shrinkage and weight of plastic part produced by DMLS mold. *Rapid Prototyping Journal*, 15(3), 179-186.
- Oktem, H., Erzurumlu, T., & Uzman, I. (2007). Application of Taguchi optimization technique in determining plastic injection molding process parameters for a thin-shell part. *Materials and Design*, 28(4), 1271-1278.
- Ozcelik, B., & Sonat, I. (2009). Warpage and structural analysis of thin shell plastic in the plastic injection molding. *Materials and Design*, 30(2), 367-375.
- Reddy, B., & Kumar, J. (2009). Application of soft computing for the prediction of warpage of plastic injection molded parts. *Journal of Engineering Science and Technology*, 2(1), 56-62.
- Sha, B., Dimov, S., Griffiths, C., & Packianther, M. S. (2007). Investigation of micro-injection moulding: Factors affecting the replication quality. *Journal of Materials Processing Technology*, 183(2-3), 284-296.
- Song, M. C., Liu, Z., Wang, M. J., Yu, T. M., & Zhao, D. Y. (2007). Research on effects of injection process parameters on the molding process for ultra-thin wall plastic parts. *Journal of Materials Processing Technology*, 187-188, 668-671.
- Wegelin, M., Canonica, S., Alder, C., Marazuela, D., Suter, M. J. F., Bucheli, T., ... & Larroque, M. (2001). Does sunlight change the material and content of polyethylene terephthalate (PET) bottles. *Journal of Water Supply: Research and Technology. – AQUA*, 50(3), 125-133.
- Zhil'tsova, T. V., Oliveira, M. S. A., & Ferreira, J. A. F. (2009). Relative influence of injection molding processing conditions on HDPE acetabular cups dimensional stability. *Journal of Materials Processing Technology*, 209, 3894-3904.