Design and Development of Large Collapsible PET Water Cooler Bottles

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Abstract

The vast majority of 15-litre water cooler bottles produced in the world today are made of blow moulded polycarbonate (PC) plastic and are returnable / refillable. This paper presents the design and development of a collapsible, recyclable 15-litre blow moulded water cooler bottle made of PET plastic to replace the traditional refillable type polycarbonate bottle. The innovative bottle design geometry allows it to be easily crushed after use, and also offers several advantages in terms of light weight, stability and environmental amiability. The paper presents the detailed process of design, analysis and optimisation using the finite element analysis software considering structural stability and crushing behaviour under various orientations and loading conditions.

1. Introduction

Polycarbonate bottles popularly known as 15 litre water cooler bottles are seen at every offices and commercial activity centres now a days. In USA and Europe, the overall market for traditional 5-gallon (19 litres) water cooler bottles is growing at double figure rates [1]. Many leading bottle-manufacturing companies choose polycarbonate (PC) as the common choice of material for bulk packaging of drinking water. PC is an amorphous engineering thermoplastic with excellent balance of toughness, clarity and high-heat deflection temperatures. Constructing 15-litre water bottles of polycarbonate resin now constitutes one of the industry’s largest and fastest-growing, blow- moulding applications. Polycarbonate bottles are the only bottles that offer a combination of the advantages of 65 to 130 trips per life for refilling.

However, one of the main limitations of these PC water cooler bottles is that they have to be collected on a regular basis and taken back to refilling stations. This is partly due to high cost of PC compared to other plastics and the economics of existing production systems. The process of refilling starts of mainly with cleaning the bottle with caustic and chemicals, bleaching it and the sterilizing the bottle and then the bottle is refilled and brought back to customers. In addition to transportation and processing costs, this process may have some serious implications related to health and hygiene. Moreover, there are other problems to be taken into account. Bottles, after the final use most often find their way into the landfill. Since these PC bottles cannot be crushed or collapsed by normal load, there is a problem in collection and transportation of these bottles, and storage before progressing on to recycling or landfilling. This may well add up to the final cost of the bottle.

The rapid growth of the 15-litre bottle market and the high cost of bottle washing and disinfecting highlights the need for more cost effective, efficient production systems and the introduction of single trip, recyclable bottles. One effective solution would be to design and develop a bottle of an appropriate material and shape that can be easily collapsed and crushed after its first use and disposed off for recycling.

In recent years, large PET water cooler bottles imitating the PC shape have been tried with limited success in the returnable/refillable mode but they have not become popular because PET’s temperature limitations do not allow it to survive repeated hot washing, nor prolonged storage outdoors or in trucks parked in heat of the sun.

This paper presents the design and development of a collapsible, disposable single trip 15 litre PET bottle with...
innovative bottle geometry specifically suited for manual crushing of the bottle after single use. Such single trip bottles could be produced in-line at the bottling plant and would eliminate the need for bottle washing and disinfecting equipment, which is estimated to be the highest cost of the filling line in traditional PC bottles.

Figure 1. A typical refillable PC Water Bottle (shaded and wireframe models)

2. Research and Development

Extensive research is presently being carried out in many countries around the globe to effectively introduce 15-litre PET containers into the market and gradually replace PC bottles. In 1999, Sterling Containers, a company in the USA has produced the largest stretch-blow moulded 5-gallon (18 litres) PET bottle for home delivery [2]. PET is a felt to be a better choice by designers when there are complex shapes to be considered. It was observed that a company in the UK was distributing PET bottles in an unusual triangular shape [3]. Due to low cost, better aesthetic appearance and savings in transport and handling, PET is being preferred over PC. Also, areas where the collection and recycling system is not so well organised, the latter too do not live out the number of cycles. It has been estimated that the market for 5-gallon water containers is increasing at an annual rate of 20% to 25% and research has showed that Europe alone will need 5 to 7 million units by the year 2007 [4].

Optimum designs of large plastic bottles, which are collapsible and recyclable, call for advanced design approaches. Reduction of weight and easily collapsibility after use are desirable characteristics but must not be at the cost of stability, strength and normal handling. Several studies have been made to study the deformation behaviour and material reduction in plastic bottles mostly related to small to medium size bottles. Karalekas et. al. [5] have carried out numerical and experimental investigation of the deformation behaviour of PET plastic bottles using ABAQUS finite element program with bottles subject to columnar crush conditions. Van Dijk et. al. [6] have investigated lateral deformation of round and square sectioned PET bottles of 1 litre sizes for top load testing and vacuum resistance testing. Oliveira et. al. [7] have studied the effects of weight reduction on the mechanical performance for PET bottles of 900 ml sizes. Huang and Huang [8] have used FEM and artificial neural network model for thickness optimisation of blow moulded HDPE bottle of 810 ml volume. It appears that very little work has been done on the optimum design and development of large 15 litre water cooler bottles, which requires specific design considerations for its shape for collapsibility, lighter weight, and structural stability of large water weight for one way recyclable application.

3. Water Bottle Design

In the design of water bottles, many CAD softwares are used. In particular, parametric CAD systems can design general objects that represent a family of different objects that share the same topological constraints but have different geometry. Parametric design is becoming a useful methodology for conceptual design, tolerance analysis, and the efficient design of families of parts, the representation of standard parts and features in libraries, kinematic simulations and assemblies’ design.

Some of the factors affecting the design of the blow-moulded bottles are as follows:

1. Exaggerated size relationships such as extremely narrow or extremely wide tops, bottoms, or midpoints should be avoided as they are difficult to blow.
2. Square or flat surfaces with sharp corners are undesirable.
3. Wall thickness can vary considerably from side panels to corners. Flat panels are not uniform and flat shoulders offer little strength.
4. Blow moulded product should be designed with generous radii corners and edges.
5. Fillets and rounds should be employed wherever possible in corners, ribs and edges. Such parts should possess more uniform wall thickness.
6. The entire bottle design should be as elastic as possible so that impact energy can be absorbed.
7. The design can include aesthetic features that have structural benefits. Decorative ribs, vertical or circumferential, can rigidify a container.

Figure 1 shows a typical 15-litre Polycarbonate (PC) bottle consisting of neck, shoulder, body with handle and base. The bottle is approximately 250 mm in diameter and 465 mm long. The thickness is about 1.5 mm with bottom portion being the thicker of about 2.0 mm. The PC bottle as shown in Figure 1 weighs about 830 g.

The PC bottle normally has a neck diameter of 55 mm approximately and forms an important potion of the bottle because it has to withstand water pressure when placed upside down on the water coolers. Next is the shoulder, which takes a major portion of weight of a fully filled 15-litre bottle when placed upside down on a cooler. The shoulder is a critical portion of the bottle, which supports the whole bottle upside down. The body of the bottle is the one that contains the handle and ribs like features, which provide toughness and rough texture providing...
rigidity of the body. The bottom part of the bottle is the base, which is really strong and slightly concave in shape because the concave shape of the bottle acts as a shock absorber and also improves impact strength. In order to improve resistance to stress cracking agents, it is important to have round bottom edges in the bottle.

For the design of the bottle, one of the most commonly used software called DUCT5 is used, which allows hundreds of shapes and templates for easy design [9]. The bottle model is divided into three main parts; namely the base, the body and the shoulder. Each part has its own library. The design for each part is done separately. For the design of bottle, the body has more variations than the base and the shoulder. Hence, more libraries are developed for the design of the body.

To prepare the bottle for manufacturing, an automatic parting line generation programme is included. The programme will split the bottle into half and orient it properly for mould NC generation.

4. Design of Collapsible PET Bottles

The aim of this research was to design an innovative one-way recyclable, collapsible 15-litre PET bottle. This means that after the first use, the bottle has to be simply crushed and disposed. In conjunction with the objective, there were several other requirements that have to be met, such as optimum wall thickness, less weight, easily collapsible, identical neck dimensions to existing ones and finally the designed bottle should be produced by injection stretch blow molding. Some of the challenges faced were firstly, to have thickness of bottle enough to withstand handling forces, stable enough to be placed on the cooler and finally thin enough to be crushed. Secondly, it was desired to have a reduced weight of the bottle probably lesser than the existing PC bottle weight of approximately 830 g.

An attempt has been made to use new and innovative concept in this work to design and optimize the 15-litre PET water bottle. The main idea of design is generated from the concept of bellows-style collapsible containers, such as bottles and pumps that are foldable. The series of bellows overlap and fold to retain their folded condition without external assistance, thus providing a self-latching feature. This latching is the result of bringing together under self-pressure two adjacent conical sections of unequal proportions and different angulations to the bottle axis. One type of collapsible PET bottle, designed like a bellows can be easily crushed into a compact size and sent for recycling. Moreover, the bottle can be shipped in its crushed state, thus greatly saving space and costs.

For the design of the bottle, critical dimensions of the existing PC bottle like the diameter of the neck, shoulder and height of the bottle are recorded. Even thickness of the bottle is noted down for reference. To incorporate the above design concept into the geometry, the most important factor that has to be taken into account was that the neck and the shoulder portions has to be of identical dimensions as of the existing design of the PC bottle. The dimensions recorded for modelling of proposed design is as follows.

- The length of the body from base to the shoulder was 350 mm, similar to existing design.
- The length of the shoulder vertically was determined to be 70 mm and it has to be maintained for proposed design.
- The length of the neck being the critical part was 45 mm and it has to be maintained for proposed design to fit the water coolers.
- The diameter of the body of the bottle was 250 mm in which case the proposed design for round bottle has similar diameter.
- Initially thickness of 0.5 mm for the entire bottle was assigned and the bottle was modelled. The bottle with different wall thickness to neck, shoulder and body cannot be designed because the bottle has to be first stretched and blown sideways which means that the bottle should have uniform thickness through out.

The parametric modelling software Pro/Engineer was used to design the bottle. Figure 2 shows the shaded CAD model of the proposed collapsible PET bottle.

![Figure 2. Model of the PET Bottle Design](image)

In Pro/Engineer system, first the entire bottle is created as a solid using the Revolve option since the bottle is of round shape. The required sketch is drawn using the drawing tools and the sketch is revolved along the centre line, which completes the full bottle profile. All the sharp corners are rounded off to required radius using the Round option, which gives the model of rounded solid bottle. The round feature also provide the designs with aesthetic looks and especially if the parts are to be moulded. Then the solid bottle is made hollow using the command “Shell” feature. The shelled bottle is thus created to the required wall thickness. The difference between the volumes of the solid bottle material and shelled bottle material gave the volume occupied by the water, which is 15 litres.
5. Finite Element Analysis

Pro/Mechanica is powerful finite element analysis software, which makes use of the geometric model created by the Pro/Engineer system. The model type used is the solid model. The required properties of Young’s Modulus, Poisson’s ratio and density are entered. Then the constraints on the solution are specified. In stress analysis, these could be fixed points, points of specified displacement, or points free to move in specified directions only. The applied loads on the model are specified (such as point loads, uniform edge loads, pressure on surfaces, etc.). Once the model is defined, a processor is setup that actually performs the solution to the posed FEA problem. This starts with the automatic creation of the finite element mesh from the geometric model by a subprogram called AutoGEM, which creates triangular and Quad Shell elements. The processor will produce a summary file of output messages which can be consulted if something goes wrong - for example, a model that is not sufficiently constrained by boundary conditions. Pro/Mechanica has very powerful graphics capabilities to examine the results of the FEA - displaced shape, stress distributions, mode shapes, etc. These results must be reviewed critically. In the first instance, the results should agree with the modeling intent. For example, if an animated view of the deformation is looked, it can be easily seen if the boundary constraints have been implemented properly. The results should also satisfy the intuition about the solution (stress concentration around a hole, for example). If there is any cause for concern, it may be advisable to revisit some aspects of the model and perform the analysis again.

For the new PET bottle design, appropriate shell thickness was assigned for the sections of the bottle and the following analyses were carried out:

1. Structural Stability Analysis in Upright, Horizontal and Inverted Positions for water load of 16 kg
2. Crushing Analysis

For the bottle in upright position, Figure 3 (a) shows the constraint set to the bottom portion of the bottle and load is set for the top and circum surface of the bottle i.e., uniform load on the body portion of the bottle acting downwards towards the bottom of the bottle.

For the bottle in horizontal position, Figure 3 (b) shows the constraint set to the bottle when it is lying horizontally and load is set for the circum surface of the bottle i.e., uniform load on the body portion of the bottle acting downwards towards the other half of circum surface of the bottle.

For the bottle in inverted position, Figure 3 (c) shows the constraint set to the shoulder portion of the bottle and load is set for the circum surface of the bottle i.e. uniform load on the body portion of the bottle acting downwards towards the neck of the bottle. For all the three positions, the simulation results for this analysis were obtained and are discussed in Section 6.

Figure 3. Load and Constraint conditions for PET Bottle in (a) Upright, (b) Horizontal, (c) Inverted Positions

For the top crushing analysis of the PET bottle, the constraint was set to the base surface of the bottle and load was set on the top surface of the bottle i.e., uniform load on the neck and shoulder portion of the bottle acting downwards towards the base of the bottle. The simulation results for this analysis have are shown in Section 6.

Figure 4. FE displacements (left) and stresses (right) of the PET Bottle in Inverted Position

6. Results of Structural Analysis

The Figure 4 shows the pictorial representation of “Single-Pass Adaptive” analysis for proposed PET Bottle Design with a wall thickness of 2.0 mm in Inverted position under water load of 16 kg. The maximum displacement obtained is 0.892 mm, which is negligible and the maximum stress developed is 6.46 MPa, which is very less compared to the maximum allowable stress for the PET of 48.3 MPa. This stress is mainly concentrated on the rim of the bottle and has less significant effect on the full bottle. This is mainly because the displacement is from the bottom of the bottle (as shown when inverted on
the water cooler), since the water pressure is vertically downward, the sidewalls are pulled downward acting as a bellow. Similar results were obtained for analysis of bottle in upright and horizontal positions.

6.1 Sensitivity Design Study

A sensitivity study is used to determine, for example, which design variables will have the most effect on a particular measure of performance of the design like the maximum stress or total mass of the thickness of the bottle. Here the total mass of the bottle, maximum displacement and maximum von mises stress are analysed by generating plots of graphs. The design parameter is chosen as the thickness of the bottle, which is varied from 0.5 mm to 2.0 mm with an interval of 0.1 mm thickness.

Figure 5 shows the graph of maximum displacement versus thickness for proposed PET bottle design in different positions. The inverted position shows a curve of high values of maximum displacement, the reason simply being the design is based on the functionality of bellows and the side walls pull the bottom portion of bottle downwards (when bottle is inverted on cooler).

Figure 6 shows the graph of maximum stress versus thickness for proposed PET bottle design in different positions. The curve of inverted position shows high values of maximum stress, but well below the maximum allowable stress of 48.3 MPa. The curves of upright and horizontal positions show that the stress induced is very less and this shows that the bottle is safe during handling, storage and transportation.

Considering the displacement developed and the stress induced, the PET Bottle of thickness 1.5 mm to 2.0 mm would be good enough to withstand the water load of 16 kg and also satisfy the requirement of manufacturing of the PET Bottle by Injection Stretch Blow Moulding. The weight of the PET bottle was calculated to be 630 g, which is about three quarter of the existing PC bottle weight of about 830 g.

7. Crushing Load Analysis

The Quick check analysis is carried out to find out the correctness of model under given constraints and loading conditions. In Figure 7, it is clearly seen that the designed bottle follows the pattern of collapsibility as seen in bellows. The height of the bottle designed is about 450 mm from top to the bottom of the bottle and already it can be seen that for a load of 45 kg, there is a displacement of 94.12 mm in height for the thickness of 1.5 mm. This shows that as the load increases, the displacement also increases thus crushing the bottle. It is important to note that the load starts the crushing pattern of the bottle and finally the crushed bottle ends up in any pattern but should be flattened.

8. Comparison of PET and PC Bottles

For comparison of results, the existing PC water bottle shown in Figure 1 was also modelled on Pro/Engineer and analysed using the Pro/Mechanica FE system. Manufacturing 15-litre PET bottles in a two step injection blow moulding process offers significant advantages over the extrusion-blow PC process. Stretch blow moulded PET bottles have a sparkling clarity and more uniform material distribution than can be achieved with extrusion blow moulding. While 15-litre PET bottles can also be designed for refillable applications, the greatest benefits are realized by moving to one-way recyclable bottles. Blowing recyclable bottles in-line with the filling equipment results in a number of advantages, including:
• Elimination of bottle washing and disinfection equipment.
• Reduction in storage space requirements.
• Better hygiene.
• Lower transportation costs
• Compact size of preforms
• Simplification of distribution logistics.
• Lighter bottles since they don’t need to survive multiple trips.
• More flexibility in the filling process.

Table 1 Comparison of New 15 Litre PET Water Bottle and 15 Litre PC Water Bottle

<table>
<thead>
<tr>
<th>Criterion</th>
<th>PET Bottle</th>
<th>PC Bottle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of Production</td>
<td>Injection</td>
<td>Extrusion</td>
</tr>
<tr>
<td></td>
<td>Stretch Blow</td>
<td>Blow moulding</td>
</tr>
<tr>
<td>Type of Processes</td>
<td>Single step</td>
<td>Multi steps</td>
</tr>
<tr>
<td></td>
<td>or two steps</td>
<td></td>
</tr>
<tr>
<td>Collapsible</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Weight</td>
<td>630 g</td>
<td>830 g</td>
</tr>
<tr>
<td>Price of Material</td>
<td>Lower</td>
<td>Higher</td>
</tr>
<tr>
<td>Recycle fraction</td>
<td>0.45</td>
<td>0.45</td>
</tr>
<tr>
<td>Cost of Recycling</td>
<td>A$ 68/Kg</td>
<td>A$75/Kg</td>
</tr>
<tr>
<td></td>
<td>(Approx.)</td>
<td>(Approx.)</td>
</tr>
<tr>
<td>Market opportunity</td>
<td>Rising</td>
<td>Stagnant</td>
</tr>
<tr>
<td>Drop testing</td>
<td>High</td>
<td>Less than PC</td>
</tr>
<tr>
<td>performance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Availability in</td>
<td>Light Blue,</td>
<td>Light Blue</td>
</tr>
<tr>
<td>Colours</td>
<td>Yellow, Pink, Green</td>
<td></td>
</tr>
<tr>
<td>Refilling</td>
<td>Not necessary</td>
<td>Necessary</td>
</tr>
<tr>
<td>Washing and Cleaning</td>
<td>Not necessary</td>
<td>Necessary</td>
</tr>
</tbody>
</table>

Bottles produced in a two-step system also have better closure seals because the neck finishes are formed during injection and are not subject to subsequent reshaping. In addition to the economic benefits, PET has better physical properties than PC making it a better choice for bottle manufacture. Compared to PC extrusion-blow, PET two-step injection-blow produces bottles with:
• Better dimensional stability
• Lower oxygen and CO2 permeability
• More consistent wall thickness distribution
• Better appearance
• Lower resin cost (45-50% less)

PET preform moulding equipment is also highly flexible and can be easily re-tooled to meet changing production demands. PC extrusion-blow equipment is highly specialized and may have limited potential for reconfiguration. Table 1 summarises the criteria, which can be used to compare the new PET water bottle design with the existing PC water bottle design of the same capacity.

9. Conclusions

While this paper presents numerous aspects, considerations, and suggestions for the design and development of the 15-litre collapsible, recyclable PET bottle for one-way applications to overcome the problems with existing PC water cooler bottle, no guidebook, publication or suggestion can provide the exact solution to such problems. Trial-and-error is a must and if a few suggestions in this paper are followed then experimentation will quickly provide the desired results. Here the objectives were to reduce the weight of the bottle to cater for efficient material usage and be effective in terms of collapsibility and lower costs. To satisfy these objectives of the research, finite element structural analysis was also conducted on the new design as well as the existing design. From the results obtained, it could well be seen that the proposed design satisfies all the critical requirements of an economical and recyclable 15-litre water cooler bottle.

References