A Brief analysis of the sealing design of plastic bottle caps under pasteurization conditions

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Abstract: Plastic bottle caps, as the core components ensuring sealing in Baijiu packaging, have developed mature design schemes under normal temperature conditions. However, there is a lack of systematic reference for sealing design under high-temperature conditions for pasteurization. This paper analyzes the mechanism of how high-temperature environments affect the sealing performance of plastic bottle caps, employs a single-variable experimental method, and systematically investigates the influence of sealing structure parameters and material formulations on high-temperature sealing performance, providing a reference for the sealing design of plastic bottle caps under pasteurization conditions.

Key words: sealing design; structural parameters; material formulation; high-temperature sealing performance

Classification number: TQ330.63 **Article number:** 1009-797X(2026)10-0027-05

Document code: B **DOI:** 10.13520/j.cnki.rpte.2026.10.012

In recent years, low-alcohol beverages such as fruit wine, rice wine, and pre-mixed drinks have become an important direction for the transformation of liquor enterprises due to their rich taste and diverse application scenarios. Unlike traditional high-alcohol Baijiu, which does not require sterilization, low-alcohol beverages contain sugar and are prone to microbial contamination and deterioration after bottling. Therefore, pasteurization is widely introduced into the bottling process. While ensuring biological safety, this process poses severe challenges to the plastic cap sealing system, and improper design of structure or materials may lead to leakage. This article systematically explores the high-temperature sealing rules from multiple levels, providing a reference for the sealing design under high-temperature pasteurization.

1 Operating conditions of bottle cap usage

The bottle cap needs to undergo pasteurization with high-temperature spraying, and its sealing integrity remains unaffected. According to the commonly used process standards in the wine industry, the specific steps are as follows: heating stage, 60~70℃, spraying for 10 minutes; sterilization stage, 70~80℃, spraying for 30 minutes; and cooling stage, 40~50℃, spraying for 10 minutes.

2 Introduction to bottle cap structural design

2.1 Sealing principle

The bottle cap relies on the interference fit between the inner wall of the inner plug and the inner wall of the glass bottle mouth to generate uniform radial pressure. At the same time, the inner plug material deforms under pressure to fill the gap in the sealing interface, blocking liquid leakage. Under pasteurization conditions, the core of sealing lies in the ability of the structure to retain sufficient and effective interference fit after high-temperature treatment, maintaining stable radial sealing pressure.

Biography: Liu Baozhou (1993-), is an engineer, primarily engaged in research and design of plastic bottle caps.

2.2 Selection of structural form

The bottle cap adopts a single-piece inner plug structure. This structure features a single inner plug design, retaining only the sealing interface between the inner plug and the glass bottle mouth. It possesses the characteristics of a single component and a unique failure path, offering strong structural stability and better suitability for pasteurization high-temperature conditions.

2.3 Structural scheme design

2.3.1 Option 1 - Lower-end open type internal plug

The sealing ring is closed at the top and open at the bottom, with a locally designed bulge surface. This bulge surface possesses sufficient rigidity, forming a strong radial pressure with the glass bottle mouth, as shown in Figure 1. Taking into account the capping force during bottle loading and the comfort level during cap screwing, the interference fit is selected to be 0.4~0.5 mm.

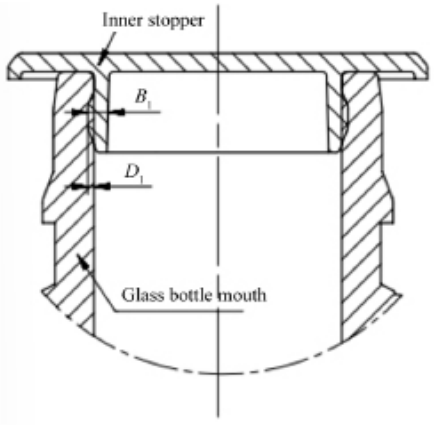


Figure 1 Structural scheme 1

2.3.2 Option 2 - Lower-end sealed inner plug

The lower end of the sealing ring is sealed, while the upper end is open. This structure has uniform overall rigidity, and the sealing surface forms a more uniform radial pressure distribution with the glass bottle mouth, as shown in Figure 2. The interference fit is also set at 0.4~0.5 mm.

3 Selection of internal sealing material

The pasteurization process maintains high temperature conditions for a long period of time, requiring the internal plug material to possess both heat resistance and dimensional resilience. It should not soften or collapse at high temperatures,

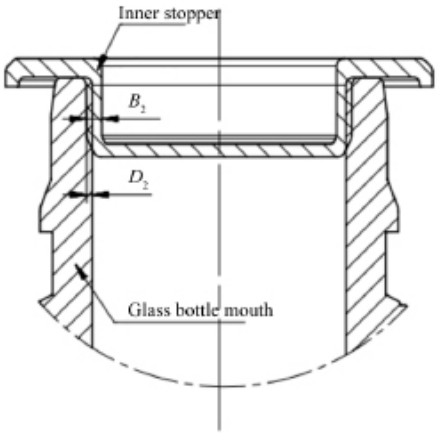


Figure 2 Structural scheme 2

and should be able to autonomously rebound and recover after being deformed under high temperature compression, maintaining an effective interference fit.

3.1 PP substrate

PP (polypropylene) is a highly crystalline polyolefin material with excellent temperature resistance and high flexural modulus,

It will not soften or collapse as a whole under high temperatures. However, PP has strong rigidity and lacks flexible elastic structure, so after being squeezed under high temperatures for a long time and then cooled, it has no resilience to recover, resulting in severe loss of interference fit; furthermore, due to its hard material and small deformation, it cannot fill the fine concave and convex surfaces of the glass bottle mouth, and cannot be used alone for pasteurization sealing.

3.2 TPE elastomer

Styrene-based thermoplastic elastomer (TPE) with SEBS as the base material exhibits excellent compression resilience. The material is soft and can deform to fill the fine concave and convex surfaces of the glass bottle mouth, forming a continuous sealing interface. Moreover, the internal elastic network can store pressure potential energy, which is released after cooling, driving the material to recover its size. However, pure TPE material has poor temperature resistance and is prone to softening and collapse at high temperatures. The elastic energy storage continues to dissipate, losing its resilience, making it unsuitable for use alone in pasteurization high-temperature conditions.

3.3 PP+TPE composite material

PP+TPE composite materials can achieve complementary performance advantages. PP, as the substrate, provides a high-temperature resistant rigid skeleton support, while TPE offers high resilience and high conformity flexible characteristics. After mixing and modifying the two materials in a reasonable ratio, a balance point between structural rigidity and resilience performance is found, overcoming the defects of single materials. It is an ideal sealing material suitable for pasteurization.

4 Material degradation mechanism under temperature effect

4.1 Molecular motion characteristics at room temperature

At room temperature, the long polymer chains are in a stable entangled and coiled state. Upon compression, the molecular chains undergo only minor adjustments, with no significant slippage or disentanglement. After the force is removed, small deformations occur.

4.2 Molecular motion characteristics at high temperature

At high temperatures, the activation energy of molecular chains is significantly reduced, and the segmental mobility is greatly enhanced. Upon compression, the molecular chains undergo disentanglement and conformational rearrangement, causing the originally coiled segments to unfurl and slide. After the force is removed, significant or even permanent plastic deformation occurs.

5 Analysis of the sealing mechanism throughout the pasteurization process

5.1 Temperature rising stage

As the overall temperature of the inner plug continues to rise, the molecular segmental motion ability is enhanced, the intermolecular forces are slightly weakened, the rigidity is temporarily reduced, and the flexibility is improved. The macroscopic manifestation is the uniform thermal expansion of the inner plug sealing ring, accompanied by a slight increase in radial contact pressure.

5.2 Sterilization stage

This stage is the main process where the sealing performance undergoes irreversible degradation. Prolonged exposure to high temperatures causes the molecular chains to gradually transition from being curled to being uncurled and sliding, with elastic energy storage continuously dissipating. Reversible elasticity gradually transforms into irreversible plastic components, and this part of the deformation cannot be restored with temperature reduction. The macroscopic manifestation is the gradual creep of the sealing ring and the slow decrease in radial contact pressure.

5.3 Cooling stage

Cooling gradually freezes the movement of molecular chains, and the dislocation and slip states are fixed within the material, making the existing molecular structural damage irreparable. The macroscopic manifestation is permanent deformation of the sealing ring, significant reduction in interference, and radial contact pressure significantly lower than the initial state.

6 Sealing experiment

6.1 Experimental variables

6.1.1 PP substrate

Three commonly available PP raw materials on the market were selected, and their heat distortion temperature and flexural modulus showed a positive correlation trend, as shown in Table 1.

Table 1 Relevant performance parameters of three PP substrates

PP raw material types	Heat distortion temperature/°C	Flexural modulus/MPa
PP1	70~75	400~500
PP2	90~95	600~700
PP3	105~110	900~1000

6.1.2 PP/TPE ratio

The PP/TPE ratio is set at four gradients: 8:2, 7:3, 6:4, and 5:5.

6.1.3 Thickness of sealing ring

The radial interference is uniformly set at 0.4~0.5 mm, and the thickness of the sealing ring is set at three gradients: 0.9 mm, 1.2 mm, and 1.5 mm.

6.2 Experimental scheme

Using the single variable control method, screening was conducted step by step in the order of "PP substrate → PP/

TPE ratio → sealing ring thickness". Each experimental group followed the pasteurization process outlined in Section 1. After completion, the wine bottles were inverted and placed in a negative pressure device, maintaining a pressure of 50 kPa for 30 minutes. Each group consisted of 200 bottles. The number of leakage incidents was counted, and the interference decay value was measured.

6.3 PP substrate screening

PP/TPE=8:2, with a sealing ring thickness of 0.9 mm and an interference fit of 0.4 mm. Both schemes were tested simultaneously, and the results are shown in Table 2.

Table 2 Experimental results of PP substrate screening

Experimental sequence	Structural scheme	PP substrate	Average interference decay value / mm	Leakage quantity
1	Option 1	PP1	0.36	86
2	Option 1	PP2	0.30	52
3	Option 1	PP3	0.33	71
4	Option 2	PP1	0.34	78
5	Option 2	PP2	0.28	43
6	Option 2	PP3	0.31	65

The results indicate that both schemes PP2 are optimal substrates.

6.4 PP/TPE ratio screening

The fixed substrate is PP2, with a sealing ring thickness of 0.9 mm. Four synchronous experiments were conducted with different PP/TPE ratios, and the results are shown in Table 3.

Table 3 Experimental results of PP/TPE ratio screening

Experimental sequence	Structural scheme	PP/TPE ratio	Average interference decay value / mm	Leakage quantity
2	Option 1	8:2	0.30	52
7	Option 1	7:3	0.23	23
8	Option 1	6:4	0.26	35
9	Option 1	5:5	0.29	37
5	Option 2	8:2	0.28	43
10	Option 2	7:3	0.25	29
11	Option 2	6:4	0.22	15
12	Option 2	5:5	0.26	27

The results indicate that the optimal ratio for Scheme 1 is 7:3, while for Scheme 2, it is 6:4.

6.5 Selection of sealing ring thickness

In Scheme 1, PP/TPE=7:3 is adopted, while in Scheme 2, PP/TPE=6:4 is used. The substrate is PP2, and three wall thicknesses are tested simultaneously. The results are shown in Table 4.

Table 4 Experimental results of sealing ring thickness screening

Experimental sequence	Structural scheme	Thickness of sealing ring / mm	Average interference decay/mm	Leakage quantity
7	Option 1	0.9	0.23	23
13	Option 1	1.2	0.21	11
14	Option 1	1.5	0.17	0
11	Option 2	0.9	0.22	15
15	Option 2	1.2	0.19	0
16	Option 2	1.5	0.15	0

The results indicate that for Scheme 1, the thickness of the sealing ring should be 1.5 mm; for Scheme 2, the thickness of the sealing ring can be either 1.2 mm or 1.5 mm. Considering the force required to place the bottle and open the lid, Scheme 2 is chosen with a thickness of 1.2 mm.

7 Conclusion

（1）Recommended parameters for Scheme 1: interference fit of 0.4~0.5 mm, sealing ring thickness of 1.5~1.6 mm, heat distortion temperature of PP raw material of 90~95 ℃, flexural modulus of 600~700 MPa, and PP/TPE ratio of 7:3.

（2）Recommended parameters for Scheme 2: interference fit of 0.4~0.5 mm, sealing ring thickness of 1.2~1.3 mm, heat distortion temperature of PP raw material of 90~95

℃, flexural modulus of 600~700 MPa, and PP/TPE ratio of 6:4.

（3）Under the same conditions, Scheme 2 exhibits superior sealing performance compared to Scheme 1. Its lower sealing structure provides rigid support at the bottom, resulting in less interference attenuation and better sealing effect.

（4）The higher the heat distortion temperature, the better is not necessarily true. A higher heat distortion temperature indicates stronger resistance to collapse at high temperatures, but the simultaneous increase in bending modulus can inhibit rebound, reducing dimensional recovery and compatibility with glass bottle fitting.

（5）The ratio of PP/TPE needs to balance rigid support and elastic recovery. A higher proportion of PP results in stronger collapse resistance but poorer rebound; a higher proportion of TPE results in better rebound but is prone to collapse at high temperatures.

（6）Increasing the wall thickness of the sealing ring can enhance the total elastic reserve, improve the dimensional recovery capability, and offset the interference loss caused by high-temperature deformation. However, it is necessary to consider both the bottle-lifting force and the lid-opening force simultaneously.