Simulation study on performance optimization factors of inflatable cushion based on rigidity theory

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Abstract

In this study, we present the influencing factors and the specific degree of cushioning performance of the air column bag. We analyze and summarize the theory of air column bag rigidity and determine that the initial inflation pressure is the most important factor affecting the performance of the pad. Select an energy-saving lamp as the package, wrap it with an air column bag with different unique initial inflation pressure, and carry out drop simulation analysis and drop test on the package. It is found that the air pressure gradient defined in the test can effectively play a protective role; smaller initial inflation pressure can effectively prolong the buffer action time, and larger initial inflation pressure can effectively improve the cushion's absorption capacity of impact energy, but if the air pressure exceeds a certain range, it is counterproductive. A comprehensive comparison shows that taking 40 kPa as the initial inflation pressure may be the best cushioning effect. Finally, it provides reference suggestions for further accurate use and simulation research on air column bags.

Article highlights

- Based on the rigidity theory, the initial inflation pressure is the largest factor affecting the performance of an inflatable cushion.
- The gas–solid coupling of the pressure vessel is used to simulate the air column bag model.
- The energy absorption capacity of air column bag liner with different initial inflation pressure was studied.
- To achieve the best cushioning effect, the appropriate initial inflation pressure should be selected, and the larger the value, the better.

Keywords Initial inflation pressure · Air column bag · Drop simulation · Cushioning performance

1 Introduction

Air column bag, otherwise known as column inflatable cushion, inflatable cushion, and inflatable bag, is a completely transparent and environmentally friendly buffer material. At present, the manufacturing materials of the air column bag mainly include PE/PE (polyethylene/

polyethylene) co-extruded film, PE/PA (polyethylene/Polyamide) co-extruded film, PU/PE (polyurethane/polyethylene) co-extruded film, etc. The basic material for the production of the air column bag has good tensile and wear-resistance properties, making the air column bag

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Fig. 1 Air column bag structure diagram

have its complete properties, so as to meet the requirements of transportation and packaging. The inflated air column bag can be deemed to be composed of 99% air and 1% film. From the perspective of structural compositions, the air column bag is mainly composed of an air inlet, check valve, airway, air chamber, and heat-sealing parts. The specific structure diagram is shown in Fig. 1.

Researching the air column bag primarily analyses three aspects: the preparation phase of the air column bag, the preparation phase of the air column bag use, and the practical application effect of the air column bag. The preparation stage mainly focuses on the material and structural characteristics of the air column bag. Research of actual application effect usually takes the air column bag as the cushioning packaging material of a specific product to carry out the corresponding test that simulates the actual transportation environment. The initial air column bag used polyvinyl chloride as the raw material [1], and then gradually developed into a composite of PA (Polyamide) and multi-layer PE (polyethylene). Hao et al. [2] used high-strength kraft paper/water-soluble PVA composite to prepare air column bags, and Wang et al. [3] used LLDPE (Linear low-density polyethylene) grafted Maleic anhydride to regenerate waste air column bag films and all obtained air column bag film materials with better performance and meeting demand. Gong and Liu [4] studied the relationship between air column bag size and compressive strength and found that compared with the width, the change in length has a greater impact on the performance of the air column bag, and the compressive strength increases with the increase of length. Sasaki et al. [5] conducted a dynamic and static compression test on a dual-cell air cushion and explored the relationship between the cushioning coefficient and the size of the air chamber. Chen et al. [6] analyzed the hyperelastic constitutive model of the airbag column and found that the loading capacity of the airbag column increased with the increase in inflation pressure, but this is limited to a certain range. Numerous studies have reached the same conclusion with similar methods. Considering the influence of

internal gas on the performance of the cushion, Gu et al. [7], and Wang et al. [8] concluded that increasing the initial inflation pressure can effectively reduce the load borne by the cushion and improve the cushion protection performance of the cushion. Combined with the research of simulation analysis, Zhang et al. [9] established the simulation model of air column bags based on the fluid–structure coupling principle in ABAQUS and discussed the influence of different film thicknesses on the performance of the air column bag from the perspective of simulation. Fang-Ying et al. [10] studied the large-size air column bag by using the static compression simulation analysis of the air column bag and concluded that the performance of the liner in a specified range was affected by the initial inflation pressure.

According to previous studies, the cushioning effect of the air column bag is mainly based on the action of the film and the internal gas. Aiming at the research on the influencing factors of the performance of traditional cushioning materials, the conventional experimental research mainly focuses on the use of static compression test, dynamic impact test, drop test and film-related performance test, supplemented by simulation analysis method, combined with stress under different loads–Strain analysis, system energy curve, acceleration response curve [11, 12] and other data to determine the vulnerable area [13–15], impact characteristics [16], and the gap between different packaging forms [17] of different products, and at the same time determine the reliability of the simulation model, to optimize the packaging structure and design and realize the purpose of ideal packaging, which is the method [18–21], and finally optimize the design and structure of the packaging to achieve the ideal packaging state [22–27].

In this paper, we study the factors affecting the performance of an air column bag under the drop. To facilitate the analysis, we choose the fragile spiral energy-saving lamp as the product to be packaged, because this type of product has higher requirements for cushioning packaging and can better reflect the performance of the air column bag. At the same time, according to the size of the energy-saving lamp and market habits, an air column bag with a gas chamber width of 3 cm is selected to pack the energy-saving lamp. The continuous improvement of the finite element analysis method makes it widely used in various fields. Its visualization of stress distribution and good simulation of energy conversion is very important for packaging performance tests. Therefore, we choose finite element technology as the main method to study the performance of the air column bag.

In this paper, we take the air column bag as the research object to analyze the effect of initial inflation pressure on its cushioning performance. Firstly, we determine the

influence and action of the initial inflation pressure on the pad stiffness according to the theoretical point of view. Then, we use ANSYS Workbench for drop simulation analysis to analyze the data such as speed, acceleration, stress, and energy. Finally, we carry out the corresponding drop test and compare it with the simulation data to further verify the test conclusion. The conclusions, shortcomings, and research status of the article are discussed and analyzed, to provide a reference basis for the standardized use of air column bags.

2 Air column bag drop impact theory and model establishment

In the packaging mechanical model, buffer materials are usually regarded as ideal elastomers. According to their force–deformation curves, they are usually divided into linear elastic materials, tangent elastic materials, hyperbolic tangent elastic materials, cubic function elastic materials, and irregular elastic materials. The air column bag is usually regarded as a tangential elastic material, and its force–deformation curve can be approximated as a tangent function, as shown in Fig. 2. Therefore, the compression force F and the deformation amount x of the air column bag can be expressed as the formula (1)

$$F = 2k_0 \frac{d_b}{\pi} \tan \frac{\pi x}{2d_b} \quad (1)$$

In the formula, k_0 is the slope of the curve when x tends to 0, called the initial elastic coefficient, in N/mm; d_b is the deformation limit of the air column bag film material,

Fig. 2 Air column bags force–deformation curve

when x tends to d_b , the compression force F tends to Infinity, the unit is mm.

2.1 Air column bag drop impact stiffness models

The mechanical properties of the air column bag are greatly related to the gas in the cavity. When a fall occurs, the external impact will be transmitted to the internal gas, causing the gas to move irregularly in this space. In the process of falling, the air column bag will be impacted and vibrated in a very short time. In this process, the gas in the air column bag cannot exchange heat with the outside air. According to the properties of the specific thermodynamic energy of an ideal gas, for the same ideal gas, as long as it has the same initial state temperature and final state temperature, follow the first law of thermodynamics, that is, the energy balance relationship. Even if the volume and pressure of the gas change, this process can also be equivalent to the adiabatic process. Introducing the ideal gas theory of air thermodynamics, the equation of state is:

$$(p + p_a)V^m = (p_0 + p_a)V_0^m \quad (2)$$

Among them, p the relative pressure of the air column pocket during the impact; p_a a standard atmospheric pressure; p_0 the relative air pressure of the air column bag in the initial state; V the real-time volume of the air column pocket during the impact; V_0 The initial volume of the air column bag; m variability index, adiabatic process, takes $m = 1.4$.

From the formula (2):

$$p = (p_0 + p_a) \left(\frac{V_0}{V} \right)^m - p_a \quad (3)$$

The bearing capacity of the air column bag is:

$$F_k = p \times A^k \quad (4)$$

Among them, A^k is the effective bearing area.

Substituting formulas (3) into formula (4) can get formula (5):

$$F_k = \left[(p_0 + p_a) \left(\frac{V_0}{V} \right)^m - p_a \right] A_k \quad (5)$$

Calculate the first derivative of Eq. (5) for the displacement of the air column bag to obtain the mechanical calculation formula of the air column bag stiffness:

$$K = \frac{dF_k}{dx} = \left[(p_0 + p_a) \left(\frac{V_0}{V} \right)^m - p_a \right] \frac{dA_k}{dx} - m(p_0 + p_a) A_k \frac{V_0^m}{V^{m+1}} \frac{dV}{dx} \quad (6)$$

Considering that the action time of the drop impact stage is relatively short, $\frac{v_0}{V} \approx 1$, and at the same time, $A_k = -\frac{dV}{dx}$, then the formula (6) can be simplified as:

$$K = m(p_0 + p_a) \left(\frac{A_k^2}{V_0} \right) + p_0 \frac{dA_k}{dx} \quad (7)$$

It can be seen from formula (7) that the air column bag can be equivalent to two parallel springs when it is impacted by a drop.

Among them, $K_1 = m(p_0 + p_a) \left(\frac{A_k^2}{V_0} \right)$, subject to adiabatic coefficient, initial inflation pressure of the air column bag, shock deformation of the air column bag and structural parameters (Effective bearing area of air column); $K_2 = p_0 \frac{dA_k}{dx}$, affected by the initial inflation pressure of the air column bag. Among them, the adiabatic coefficient is fixed in the falling state, and the impact deformation of the air column bag is an external impact factor. When the size of the air column bag is fixed, the drop impact stiffness of the air column bag are mainly affected by the initial inflation pressure. According to the formula (7), the initial inflation pressure is proportional to K_1 and K_2 . It can be preliminaries considered that changing the initial inflation pressure of the air column bag can change the stiffness of the air column bag. The stiffness, increases with the increase of initial inflation pressure and decreases with the decrease of initial inflation pressure.

2.2 Theoretical models of energy conversion

When the package is in a free-fall motion at a specified height, a certain amount of energy conversion and loss will occur during the process of contacting the ground and being impacted and deformed. Generally, the kinetic energy and internal elastic potential energy will change after the package is impacted. Specifically, the kinetic energy is converted into elastic potential energy and stored in the packaged material and the cushioning liner. Ignoring the energy consumed by air damping and various external friction factors, the elastic potential energy absorbed by the cushion pad is all the kinetic energy reduction of the package, which can be expressed by the following formula:

$$E_1 = mgh = \frac{1}{2}mv^2 = \int_0^x F(x)dx \quad (8)$$

Expressed the energy absorbed per unit volume, the strain energy is the area under the stress-strain line, and the elastic potential energy absorbed by the air column bag liner can be expressed as:

$$\mu = \int_0^\varepsilon \sigma(\varepsilon)d\varepsilon \quad (9)$$

$$E_1 = \int_0^\varepsilon \sigma(\varepsilon)d\varepsilon = \frac{1}{2}Kx^2 \quad (10)$$

Usually, there will be multiple rebounding during the actual fall, which will cause secondary damage to the product. The main reason is that the original kinetic energy is removed from the E_1 which is converted into the elastic potential energy of the cushion during the rebound, there will be another part of the potential energy that penetrates the air column bag in the form of a shock wave and acts on the inner packaging. This part of the energy is named E_2 . At the same time, the energy loss caused by the influence of external factors such as air damping during the actual fall is defined as E_3 , so the energy during the actual fall The change can be expressed as:

$$mgh = \frac{1}{2}mv^2 = E_1 + E_2 + E_3 \quad (11)$$

After the first rebound, the speed will rise from 0 to another value and will reach a certain drop height. The package will still fall under this height, resulting in a secondary impact. The secondary impact process is almost similar to the first impact, but the actual Under the circumstances, due to the different cushioning materials, the package will rebound several times and produce several shocks when it is dropped. Due to the continuous energy loss, the speed and height that can be reached after each rebound are less than the previous one, Until all the kinetic energy reaches the end.

According to the change of energy in the above-mentioned falling situation, in order to keep the inner packaging well protected, multiple impacts should be avoided, so that the cushioning packaging liner can absorb as much energy as possible when impacted. Therefore, we can increase E_1 with increasing rigidity K , so as to reduce the impact energy transmitted to the inner packaging. According to the formula (7) when the size of the air column bag is constant, the initial inflation pressure p_0 can be increased to achieve the purpose; but the rigidity K is increased. It will also lead to an increase in the energy of the subsequent rebound action, so the appropriate initial inflation pressure should be selected to achieve the best cushioning protection effect. At the same time, according to the analysis of the rigidity theory, we can think that when the size of the package is fixed, the initial inflation pressure is the biggest factor affecting the performance of the cylindrical inflation cushion, so the follow-up research is carried out with this variable.

3 Simulation experiment and analysis of air column bag packaging

3.1 Finite element model establishments and simulation parameter setting

3.1.1 Establishment of the finite element model

3.1.1.1 The establishment of energy-saving lamp model In this paper, the three-dimensional modeling software UG-NX was used to establish the model. The model of the energy-saving lamp was E27, which was composed of a lamp cap, spiral lamp tube, connecting part I, connecting part II and internal chip. Considering the problem of the simulation operation time, the structure of the energy-saving lamp was simplified as follows: replaced the internal chip with a regular body of the same quality; ignored partial fillets.

3.1.1.2 The establishment of air column bag model According to the specific size of the energy-saving lamp, the number of gas columns of the inflatable buffer pad is 12. The film thickness is 55 microns and the width of a single gas column is 3 cm. Ignoring the sealing part between each gas column, 12 closely connected columns are established; At the same time, due to better airtightness of the cylindrical inflatable buffer liner, the check valve structure is simplified form a sealed shell.

The combined finite element model was shown in Fig. 3.

3.1.2 Simulation material parameters, grid division, contact mode, and inflation pressure

Each part of the E27 energy-saving lamp is mainly made of PBT, aluminum, and lead-free glass. The material of the air column bag liner is PE/PA co-extrusion composite film. The film material is the Hyperplastic model in ANSYS Workbench. The stress–strain curve of the film material was obtained from the previous film tensile test, as shown in Fig. 4, which will be used as an important parameter of the film simulation material. See Table 1 for specific material parameter settings.

After repeating attempts, “Body sizing” was selected to mesh the model. A total of 20,000 meshes and 8894 nodes were divided. The grid division is shown in Fig. 5. The contact mode of each part was set as bonded, and the contact

Fig. 4 PE/PA stress–strain curve

Fig. 3 Geometric model diagram of spiral energy-saving lamp package

Table 1 Material parameters

Material	Density (kg mm ⁻³)	Young's modulus (Mpa)	Poisson's ratio	Yield strength (Mpa)	Tangent modulus (Mpa)	shear modulus
Glass	2.5×10^{-6}	70,200	0.22	380	29,200	–
PBT	1.6×10^{-6}	1930	0.3902	–	–	–
AL	2.707×10^{-6}	–	–	–	–	27,100
Structural steel	7.85×10^{-6}	20,000	0.3	–	–	–
PE/PA co-extrusion film	9.3×10^{-7}	8400	0.38	–	–	3043

Fig. 5 Meshing diagram

between the falling process and the rigid surface was set as no friction.

Four gradients of 20 kPa, 30 kPa, 40 kPa, and 50 kPa are set according to the previous test of a pressure bearing range of air column bag liner. The gas–solid coupling principle of the pressure vessel is used to set the initial inflation pressure value. Specifically, set the pressure value from inside to outside by the pressure in ANSYS Workbench.

3.1.3 Drop simulation condition parameter setting

Using the display dynamics module in ANSYS Workbench, the drop simulation condition was completed by the Drop Test Wizard. The corresponding equivalent drop parameters were automatically generated by inputting the initial drop height. The specific settings were as follows: set the drop height to 80 cm (automatically equivalent to the initial speed of -3.96 m/s and the drop height of 0 cm); The drop angle was 180° , and the drop direction of the package horizontal to the rigid surface was Y-; The gravitational acceleration of the rigid surface, the rigid surface support,

and the falling direction were automatically generated by the plug-in according to the falling height, angle, and direction. The specific drop diagram is shown in Fig. 6.

3.2 Analysis of the simulation speed of air column bags with different air pressure

As shown in Fig. 7, the changing trend of the Total Mass Average Velocity of air column bag packaging with different initial inflation pressure with time is the same. First, the speed gradually decreases, indicating that the package has entered the buffer deceleration stage. Until the speed drops to 0 m/s for the first time, the speed begins to increase in the opposite direction, indicating that the package enters the rebound stage. Take the stage when the collision speed of each package drops to 0 m/s for the first time in comparison. At $t = 7.6 \times 10^{-3}$ s, the speed of the air column bag (20 kPa) decreases to zero; At $t = 7.1 \times 10^{-3}$ s, the speed of the air column bag (30 kPa) drops to zero; At $t = 6.63 \times 10^{-3}$ s, the speed of the air column bag (40 kPa) decreases to zero. At $t = 6.08 \times 10^{-3}$ s, the

Fig. 6 Drop diagram **Fig. 7** Velocity change curve in Y-axis direction of package

speed of the air column bag (50 kPa) decreases to zero. If this stage is defined as the buffer action time, reducing the initial air pressure can effectively prolong the buffer action time, which is due to the reduction of the initial inflation pressure, resulting in the reduction of the stiffness, so that the cylindrical inflation buffer liner has the better deformation ability.

3.3 Analysis of drop stresses distribution of air column bags with different air pressure

The stress distribution of different initial inflatable pressure packages is shown in Figs. 8 and 9. The function of cushioning packaging is mainly to effectively protect the inner packaged product. From the stress point of view, it

is mainly reflected as the maximum stress borne by the internal packaging products. Whether the stress value is within the allowable range, and whether the cushion packaging reduces the maximum stress distribution range.

Under the same drop environment, the drop simulation analysis of four air column bag packaging with different initial inflation pressure is carried out. The stress borne by the cushion is mainly distributed on the air column below to contact the ground. The maximum stress borne by the spiral energy-saving lamp is mainly located at the spiral transition of the lamp tube, and the specific position is shown in the figure. According to the figure, under the initial inflation pressure of 20–50 kPa, the maximum stress values borne by the package are 259.61 Mpa, 249.87 Mpa, 236.88 Mpa, and 228.19 Mpa in turn, which shows that by the increase of the initial inflation pressure, some external stresses are effectively offset and the stress acting on the package is reduced. At the same time, the maximum stress transmitted to the energy-saving lamp is 25.8 Mpa, 26.6 Mpa, 23.4 Mpa, and 39.6 Mpa in turn, among which the maximum stress borne by the energy-saving lamp wrapped by air column bag is similar under the initial inflation pressure of 20–30 kPa, and 40 kPa is slightly smaller than the other two. However, the stress of energy-saving lamps under 50 kPa increased sharply, exceeding the others by about 60%. To sum up, the increase of air pressure in a certain range can effectively reduce the stress borne by the package, but when the air pressure is too high, the stress borne by the inner package will increase. Compared with the four, the initial inflation pressure of 40 kPa is better than the other three, which can reduce the maximum stress of the package and protect the internal products.

(1)

(1)

(2)

(2)

(3)

(3)

(4)

(4)

Fig. 8 Maximum stress distribution diagram of air column bags with different inflation pressures

Fig. 9 Maximum stress distribution diagram of energy-saving lamps with different inflation pressures

3.4 Analysis of energy change of air column bags with different initial pressures

Based on the analysis of energy theory, the energy transformation will occur after the packaging system falls at a specified height, which starts from the impact caused by contact with the ground. When an impact occurs, there is the conversion between kinetic energy and elastic potential energy and the consumption of friction energy, which follows the conservation of energy. In this simulation analysis, we take the collision between the package and the ground as the beginning, and the speed of the package drops to 0 m/s for the first time as the end (i.e. falling to the critical point of the buffer and rebound) for energy analysis, and define this stage as the buffer action time; At the same time, combined with the comprehensive comparison of energy conversion specific gravity, it can be used as an important index of the influence of different initial inflation pressure on the performance of the air column bag.

3.4.1 Analysis of energy change of cushion pad

3.4.1.1 Kinetic energy The kinetic energy of the cushion pad changes with time as shown in Fig. 10. The initial kinetic energy of the air column bag under different initial inflation pressure is the same. As the impact time of the drop increases, the kinetic energy decreases, and the amount of decrease is similar. In the initial stage, the trend of kinetic energy changes occurred rapid and continuous fluctuations and gradually decreased. Combined with the above analysis of the time required for the speed to drop to 0 for the first time, the increase of kinetic energy after the speed of each package drops to 0 should be the rebound stage. The simulation time is only slightly longer

than that of this stage, and the subsequent energy is not the final static energy. The buffering time of each package is introduced to quantitatively compare the energy changes. At 20 kPa pressure, the initial kinetic energy of the air column bag is 84.18 mJ, and when $t = 7.6 \times 10^{-3}$ s, the kinetic energy decreases to 54.6 mJ. At 30 kPa pressure, the initial kinetic energy of the air column bag is 84.18 mJ, and when $t = 7.1 \times 10^{-3}$ s, the kinetic energy decreases to 51.67 mJ. At 40 kPa pressure, the initial kinetic energy of the air column bag is 84.18 mJ, and when $t = 6.63 \times 10^{-3}$ s, the kinetic energy decreases to 65.02 mJ. At 50 kPa pressure, the initial kinetic energy of the air column bag is 84.18 mJ, and when $t = 6.08 \times 10^{-3}$ s, the kinetic energy decreases to 57.64 mJ.

3.4.1.2 Internal energy Figure 11 shows the curve of the internal energy of the pad with time, and the elastic potential energy of the pad shows an upward trend. The initial change state is rapid fluctuation and rise, and the fluctuation and rise amplitude increase with the increase of initial inflation pressure. In this process, the impact energy makes the thin film compressed gas and gas move and react to the thin film to achieve the fluctuation of energy. When it reaches a certain stable state, it starts to rise steadily. In the whole process of falling, the internal energy of the air column bag with 50 kPa air pressure is the largest, which is kept at the top layer, and the other three kinds are sorted according to the air pressure. When $V = 0$ mm/s, the initial elastic potential energy of 20 kPa air pressure is 0 mJ, and when $t = 7.6 \times 10^{-3}$ s, the elastic potential energy increases to 861.7 mJ. At 30 kPa, the initial internal energy is 0 mJ, and when $t = 7.1 \times 10^{-3}$ s, internal energy increases to 824.34 mJ. At 40 kPa, the initial internal energy is 0 mJ, and when $t = 6.63 \times 10^{-3}$ s, internal

Fig. 10 Cushion pad kinetic energy-time change curve

Fig. 11 Cushion pad internal energy-time change curve

energy increases to 869.6 mJ. At 50 kPa, the initial elastic potential energy is 0 mJ, and the internal energy increases to 781.99 mJ at $t = 6.08 \times 10^{-3}$ s.

3.4.2 Analysis of Energy Change of Energy Saving Lamp

3.4.2.1 Kinetic energy The kinetic energy of the energy-saving lamp changes with time as shown in Fig. 12. The initial kinetic energy is 1530.5 mJ. With the increase of the initial inflation pressure, the downward trend of the kinetic energy of the energy-saving lamp gradually accelerates. The kinetic energy of 50 kPa tends to be stable first, followed by 40 kPa; 30 kPa and 20 kPa showed a downward trend in the calculation time. It can be considered that the 50 kPa and 40 kPa air column bags have better kinetic energy absorption of energy-saving lamps, and have a better braking effect in the case of falling. When the speed of the energy-saving lamp under the air column bag with 20 kPa air pressure drops to 0, that is, when $t = 7.6 \times 10^{-3}$ s, the kinetic energy is reduced to 427.6 mJ. The kinetic energy of the energy-saving lamp wrapped in the air column bag under 30 kPa air pressure is reduced to 505.94 mJ when $t = 7.1 \times 10^{-3}$ s. The kinetic energy of the energy-saving lamp wrapped in the air column bag under the air pressure of 40 kPa is reduced to 520.18 mJ at $t = 6.63 \times 10^{-3}$ s. The kinetic energy of the energy-saving lamp wrapped in the air column bag under 50 kPa pressure is reduced to 607.87 mJ at $t = 6.08 \times 10^{-3}$ s.

3.4.2.2 Internal energy The curve of internal energy of energy-saving lamps with time is shown in Fig. 13. Under different initial inflation pressure conditions, the internal energy received by the energy-saving lamps showed an upward trend, and the overall changes were similar, with

Fig. 12 Energy Saving Lamp kinetic energy-time change curve

Fig. 13 Energy Saving Lamp internal energy-time change curve

multiple peak fluctuations. Among them, the peak value of 50 kPa is much larger than the other three pressures, that is, the internal energy transferred to the energy-saving lamp is the largest, which is disadvantageous for cushioning pads. And 40 kPa, 30 kPa, 20 kPa are not much different. Under initial inflation pressure of 20 kPa, when $t = 7.6 \times 10^{-3}$ s, the internal energy of the energy-saving lamp rises from 0 mJ to 14.3 mJ. Under initial inflation pressure of 30 kPa, when $t = 7.6 \times 10^{-3}$ s, the internal energy of the energy-saving lamp rises from 0 mJ to 15.95 mJ. Under initial inflation pressure of 40 kPa, when $t = 6.63 \times 10^{-3}$ s, the internal energy of the energy-saving lamp rises from 0 to 20.47 mJ. Under initial inflation pressure of 50 kPa, when $t = 6.08 \times 10^{-3}$ s, the internal energy of the energy-saving lamp rises from 0 to 48.67 mJ. As the initial inflation pressure increases, the internal energy transferred to the energy-saving lamp shows upward. The initial air pressure changes a little from 20 to 40 kPa, and when the air pressure reaches 50 kPa, a big change occurs.

Analyze the conversion and transfer between the kinetic energy and internal energy of the cushion liner and the energy-saving lamp. When an impact occurs, the kinetic energy of the liner and the energy-saving lamp is reduced, and part of the reduced kinetic energy is converted into internal energy of the energy-saving lamp

Table 2 Initial inflation pressure: 20 kPa

Parts	Air column bag	Energy-saving lamps	Others	Total
Store energy (mJ)	861.7	15.2	226	1102.9
Proportion	78.1%	1.37%	20.53%	100%

and the liner, part of the energy consumed for simulation analysis. Introducing the above definition of buffer action time and analyzing the specific changes in each part of the energy. Tables 2, 3, 4 and 5 show the energy distribution and the proportion of each part of the package when the speed of the buffer package drops to 0. The specific gravity is the percentage of the increase in the internal energy of each part and the decrease in the kinetic energy of the energy-saving lamp, other items are expressed as the difference between the energy-saving lamp kinetic energy reduction and the internal energy increments of all components in the test range. This part should be friction and damping converted into internal energy in practice, and it is the energy consumed in the simulation analysis. The internal energy is absorbed by the air column bag accounts for 78.1%, 80.46%, 86.08%, and 84.8% of the energy-saving lamp kinetic energy reduction. With the increase of the initial inflation pressure, the energy absorption capacity of the air column bag increases to a certain extent, but it decreases when the pressure reaches 50 kPa; At the same time, the proportion of energy stored by energy-saving lamps is similar at 20–40 kPa, while at 50 kPa, it is more than twice higher than the other three. This is because, in the stress analysis, energy-saving lamps wrapped in a 50 kPa air column bag bear greater stress than energy-saving lamps wrapped in other air column bags.

By analyzing the relationship between initial inflation pressure and cushioning performance of the air column bag from the aspects of speed change, stress size and distribution, energy conversion, and transmission. It can be concluded that reducing air pressure can effectively prolong cushioning time, increasing air pressure may improve energy absorption, and make the product tend to a stable state earlier to avoid being impacted again. But the impact energy that may be borne by excessive air pressure will also increase, because the stiffness is too large, which indirectly causes the internal product to bear greater stress. Considering the damage of rebound to products, not recommended. Comparing the simulation data comprehensively, the initial inflation pressure of 40 kPa is better in energy absorption and stress barrier, which can be used as a reference value of inflation pressure. Under 30 kPa and above 40 kPa are not recommended.

Table 3 Initial inflation pressure: 30 kPa

Parts	Air column bag	Energy-saving lamps	Others	Total
Store energy (mJ)	824.34	15.95	184.17	1024.46
Proportion	80.46%	1.56%	17.98%	100%

Table 4 Initial inflation pressure: 40 kPa

Parts	Air column bag	Energy-saving lamps	Others	Total
Store energy (mJ)	869.6	20.47	120.05	1010.12
Proportion	86.08%	2.02%	11.9%	100%

4 Drop test and simulation verification of air column bag packaging

4.1 Test method

The E27 spiral energy-saving lamp based on the simulation analysis model is wrapped around with an air column bag (12 columns). The air pressure in the air column bag is inflated by a constant pressure air pump, and measured by a portable barometer. Four groups are set, namely 20 kPa, 30 kPa, 40 kPa, and 50 kPa. According to the test standard “GB/T4857.5 Drop Test Method for Transport Packages”, 0.8 m is selected for drop test, and the specific drop mode is the same as that simulation analysis. As shown in Fig. 14, place the sensor in the center of the energy-saving lamp, pack the energy-saving lamp with an air column bag (12 columns), and fix it at a height of 80 cm from the ground with a magnetic flux valve. During the test, the package is dropped by controlling the switch of the magnetic flux valve. See Fig. 14 for the specific drop system and Fig. 15 for the drop mode. The acceleration data of multiple drops are collected in the experiment. The first peak acceleration when colliding with the ground is taken. Its average value is calculated and compared with the simulation data.

4.2 Comparative analysis of drop test results and simulation

Drop the gas column bag package with different initial pressure repeatedly, the energy-saving lamps were not damaged, which indicated that they all played an effective role in cushioning protection. Among them, the first peak acceleration of air column bag cushion package with initial internal pressure of 20–50 kPa is 755.3 m/s², 741.23 m/

Table 5 Initial inflation pressure: 50 kPa

Parts	Air column bag	Energy-saving lamps	Others	Total
Store energy (mJ)	781.99	48.667	91.473	922.13
Proportion	84.8%	5.27%	9.93%	100%

Fig. 14 Drop test system **Fig. 15** Schematic diagram of the specific method of falling

s^2 , 643.58 m/s^2 and 763.2 m/s^2 in turn. According to the brittleness value, it can be equivalent to 75G, 74G, 64G, and 76G in turn. According to the brittleness value theory, the brittleness value of glass products is required to range from 90 to 120G, all of which are less than this range, which shows the effectiveness of cushioning packaging. At the same time, with the increase of initial inflation pressure in a certain range, the acceleration gradually decreases,

Fig. 16 Drop test acceleration and simulated acceleration under different initial inflation pressures

and when it increases to a certain value. It increases again. The results show that increasing the initial inflation pressure in a certain range helps to reduce the drop response acceleration.

Referring to the selection method of drop test acceleration, the initial peak acceleration corresponding to each initial inflation pressure in the simulation analysis is 718.33 m/s^2 (20 kPa), 705.35 m/s^2 (30 kPa), 631.39 m/s^2 (40 kPa) and 792.69 m/s^2 (50 kPa). The drop acceleration and simulation acceleration under different initial inflation pressures are shown in Fig. 16. Based on the acceleration measured in the test, the absolute values of the absolute

Table 6 Acceleration and error data

Initial inflation pressure (kPa)	Test acceleration(m/s ²)	Simulation acceleration (m/s ²)	Absolute error	Relative error (%)
20	755.3	718.33	37.76	5.15
30	741.23	705.35	37.06	5.09
40	643.58	631.39	32.18	1.93
50	763.2	792.69	38.16	3.71

errors under each initial inflation pressure (20–50 kPa) are 37.76, 37.06, 32.18, and 38.16. The absolute values of relative errors (20–50 kPa) are 5.15%, 5.09%, 1.93% and 3.71%, as shown in Table 6. It is found that the error between the simulated acceleration and the drop test acceleration is less than 5%, which is within the allowable error range. In the simulation analysis, to reduce the operation time, some positions of the model are simplified, which should be the main source of error. At the same time, the preliminary preparation experiment found that different meshing methods and fineness will also affect the results. The results show that the meshing method selected in this paper is reasonable and the simulation results are reliable.

5 Discussion

The stress distribution and energy conversion curve obtained by ANSYS Workbench simulation analysis can effectively analyze the impact of initial inflation pressure on the performance of the air column bag, which is more intuitive and accurate; At the same time, the obtained acceleration data can also be compared and analyzed by drop experiment, which also ensures that this simulation analysis can make good simulation predictions. The conclusion of this paper is similar to that References [7, 8] and [10]: the research of some size air column bags is consistent, but the research of larger size air column bags is different.

In the research, it is found that grid division and other settings will affect the operation accuracy in the preparation of simulation. For the subjects, in terms of product specifications, energy-saving lamps are small products, which are quite different from the product specifications designed in other studies. Compared with other small products, the energy-saving lamp has a special shape, a special-shaped structure (spiral structure), various composition materials, and great performance differences between various materials, such as PBT and glass. In conclusion, the size, shape, and material type of products are the reference premise for the selection of cushioning materials, which means that the products selected from the above different points may have different choices of the best gas column bag cushioning packaging. This

paper only makes a systematic analysis and research on a certain kind of product. From this point, we lead to the shortcomings of this paper and provide a general direction for further research in this field. Whether there is a fixed relationship between product attributes and air column bag. In addition, due to the limitation of operation conditions, the model is simplified to reduce the operation time, which will inevitably lead to errors. At the same time, according to the analysis of the fluctuation curve of the energy change of the air column bag, it is preliminarily considered that it is the energy change caused by the film deformation and the repeated movement of the internal gas during the collision process. But no research on this point is found, so it is difficult to carry out the comparative analysis. Future research should be carried out from the above angles, to provide a more powerful reference basis for the standardized use of air column bags.

6 Conclusion

In this paper, the maximum influencing factors of the performance of the air column bag liner were determined based on the rigidity theory, and its specific influence on the cushion performance was determined through drop simulation and drop test. The results showed that with the increase of the initial inflation pressure, the stiffness of the cylindrical inflation buffer liner increased, which enhanced the energy absorption capacity of the cylindrical inflation buffer liner and reduced the cushioning time; That was, a smaller initial inflation pressure could get a longer buffer action time, and a larger initial inflation pressure could get a better energy absorption capacity, but this needed to be within a certain range, not the larger the better, otherwise it would be counterproductive.

Based on the size and rigidity theory of the packaged product, the impact of the initial inflation pressure on the cushioning performance of the cushion was mainly considered in this test, and the impact of the size of the cylindrical inflation cushion on its performance was not analyzed; At the same time, the deformation of the film and the pressure changed in the air column bag during the instantaneous impact were idealized, so it had some

limitations. However, this does not affect the study of the initial inflation pressure and will be studied later.

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Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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