Stress Characteristics and Structural Optimization of Spacecraft Multilayer Insulation Components

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Abstract: Multilayer insulation (MLI) components are important parts of spacecraft, in which thin films are the core elements. The film thicknesses are generally small, between 10 and 30 µm, to reduce the weight of the spacecraft. During the launch of a spacecraft, there is a rapid drop in the internal pressure, which causes the internal gas to flow out rapidly through the component. The resulting fluid force may cause film damage and failure, thereby directly affecting the normal operation of the spacecraft. Therefore, the mechanical characteristics of the thin films under rapid decompression conditions were investigated during this study. Considering the effects of the flow field stress distributions on the films during the rapid decompression, a fluid–structure interaction (FSI) model for a component was first constructed. The results show that the stress is largest in the outlet film, which is the part of the overall structure most vulnerable to failure. Furthermore, the effects of the structural parameters of the component on the stresses in the different film layers were analyzed using the orthogonal experimental method. The results show that the film thickness had the largest influence, followed by the film hole diameter, the number of component layers, and finally the staggered hole distance. Finally, a structurally optimized design scheme for the component is proposed based on a parameter range analysis with respect to the maximum film stress. After optimization, the maximum stress of the thin film decreased by 97.6%. This research has practical engineering value for the structural design and optimization of MLI components.

Keywords: multilayer insulation components; fluid–structure interaction model; mechanical characteristics; orthogonal experimental method; structurally optimized design

1. Introduction

Multilayer insulation (MLI) components are the key pieces of equipment installed on the outer surfaces of spacecraft. They are used for heat insulation and rapid decompression. Failure of these components can seriously affect the normal operation of the spacecraft [1–4]. These components are subjected to gas friction during spacecraft launching. Additionally, the external pressure of a spacecraft rapidly drops during launching, which causes the internal gas to rapidly flow out through the component due to the rapid drop in the external ambient pressure. These components are also simultaneously affected by random spacecraft vibrations, resulting in the vibration of their structures [5–7]. The components are composed of nylon nets and stacks of thin insulation films. The material properties, film density, and other structural parameters of the components can affect the thermal performance of the components, and improving the thermal insulation properties of...
the components is an important research focus in this field [8–11]. Therefore, the structural design of components operating in complex conditions is particularly important.

Bapat et al. [12] conducted an experimental investigation using different combinations of spacer and shield materials and compared the results with those of a numerical model. The results showed that the combination of an aluminized 12 μm thick Mylar layer and a 76.2 μm thick glass fabric layer was the best for MLI applications. Wei et al. [13] experimentally investigated the structural and shape effects of a perforated MLI blanket. A new calorimeter with spherical top and bottom surfaces was compared with a cylindrical calorimeter; the results indicated that 13% excess heat flux was transferred in the new calorimeter. This occurred because of the “edge effect” formed by the MLI deformation. Thus, it was concluded that the shape and structure affect MLI performance. Zhou et al. [14] studied the effects of the interlayer vacuum degree, the interlayer compaction pressure, and the layer density on the performance of a high-vacuum multilayer insulation component.

However, the structural parameters of a component impact not only its thermal performance but also its internal flow field. Emphasizing the thermal performance of a component while ignoring its mechanical properties is not conducive to obtaining an integral optimized design for the component. The first automated transfer vehicle (ATV), which was named Jules Verne after the French writer, was launched on 9 March 2008. Immediately after the launch, direct observations of the Jules Verne ATV using cameras onboard the international space station (ISS) indicated that some of its MLI components (primarily those located on the pressurized cylinder) appeared to have partially detached from the structure, as shown in Figure 1.

Figure 1. A problem with the multilayer insulation (MLI) components on the automated transfer vehicle [15].

Ren et al. [16] conducted research on the failure mode of an MLI component in a low-altitude environment. The results showed that a strong gas flow shearing force in the powered phase during the launch and a bulging force caused by decompression after entering the vacuum state were the primary factors that led to component damage. The results also indicated that considering the thermal performance of the component while ignoring the breathability could easily cause damage to the component. Woodward et al. [17] designed
and tested a multilayer thermal insulation system that also provides debris and micrometeorite damage detection. Li et al. [18] studied the transient pressure on each film of a spacecraft during rapid decompression by establishing a computational fluid dynamics (CFD) model of the MLI component. The environmental adaptability and reliability of the component were evaluated, and it was revealed that the component and brush seal structures had some common points. Huang et al. [19–21] adopted a three-dimensional slice model to solve for the complex structures associated with multiple brush wires using CFD calculations. These studies provided important reference values for the study discussed in this paper. To date, relatively little research has been performed regarding stress analyses of MLI components, but other fluid–structure interaction (FSI) calculation methods adopted under similar working conditions were used as references when conducting this research. Boustani et al. [22] simulated the descent process of the ASPIRE SR01 supersonic parachute using an FSI model. Yang et al. [23] also solved for the flow process of a flexible buffer liquid inside a solid rocket motor using an FSI model.

With the rapid development of the finite element technique, the FSI calculation method has been applied in an increasing number of fields [24–26]. The FSI method can capture the impact of flow field stresses on solid deformation more accurately than can the CFD method, and it can perform the complex calculations associated with the impact of a solid deformation on the flow field.

The MLI component of a spacecraft deforms due to the gas flow during the rapid decompression process. However, to reduce the weight of the spacecraft, the MLI film thickness is usually only a few microns to tens of microns, thereby causing the films to be prone to damage and failure when they are subjected to strong forces. To prevent damage to the MLI component during rapid liftoff, a combination of nylon nets and thin films is used in the structural design of the MLI component, where the nylon nets prevent the film from producing large deformations and thus being destroyed, and the hole design in the film quickly releases the internal fluid pressure to prevent the film from producing large deformations. However, most existing studies focus on the thermal resistance effect of MLI components, while neglecting to explore the mechanical properties, especially the size of the holes, the distribution of the holes, and the thickness of the thin film. Therefore, the structural design of this component is a problem that cannot be ignored. The stress problem associated with spacecraft MLI components was investigated during this study. The internal flow field and film stress were first studied using an FSI model under different structural parameter values. Then, the internal film stress characteristics were further explored. The results of this study provide a basis for spacecraft MLI component structural designs.

2. FSI Model of an MLI Component

2.1. FSI Model

An MLI component of a spacecraft has a three-dimensional structure similar to that of a plane, and it has a large developed area. It has a multilayer structure formed by stacking nylon nets and thin films. The films are made of aluminized polyimide materials with good thermal insulation properties. The film thicknesses are only 10–30 µm and their lengths and widths are generally a few hundred millimeters. The films have holes to allow gas to flow through them. The space between two film layers is filled with a nylon net with a thickness of approximately 200 µm, and gas can flow through the nylon net. The component is composed of nylon nets and thin films, and the gas flow through the nylon nets cannot be ignored. Therefore, significant mesh generation and calculation challenges arise when modeling an MLI component.

To solve these problems, a typically sized FSI model was established for the component during this study so FSI calculations could be conducted. The five-unit MLI component (which included five nylon nets and six films) shown in Figure 2 was taken as an example.
The FSI component model developed during this study consists of a fluid model and a solid model. The solid model was formed by stacking nylon nets and thin films, while the gaps between the nylon nets and the thin films represent the fluid domain. The nylon nets were modeled using a single strand of nylon rope, and circular nodes were adopted at the intersections to facilitate mesh division and improve the mesh quality. The holes in the films are the key channels that connect the fluid domains of the adjacent nylon nets. The holes in adjacent film layers are staggered, which means that the holes in adjacent film layers have different positions.

During the process of assembling the nylon nets and films, there was randomness in the placement of the film holes and the nylon nets. Therefore, some reasonable simplifying assumptions were made for this model when analyzing the impacts of different structural parameters on the film stress [19–21]:

1. There is only one film hole in each diamond-shaped hole of a nylon net, and it is positioned in the middle of the diamond structure. This assumption was made to study the effect of the distance between the staggered holes of two adjacent film layers on the flow field.

2. Each film layer has only one film hole. There is a certain distance between the staggered holes in two adjacent film layers, and the holes are arranged periodically. This means that the hole position in each odd film is the same and that the hole position in each even film is also the same.

2.2. Calculation Method

FSI calculations were performed for the five-unit MLI component described above. The FSI simulation method fully considers the interactions between the fluid and the solid in complex models. The FSI model can apply the internal fluid pressure to the solid surface to obtain solid deformation and stress results that are more accurate than those produced by CFD calculations.

Due to the rapid drop in the external pressure and the rapid outflow of the internal gas, the films of the component deform as a result of the gas flow during launching. Based on this process, the calculation method shown in Figure 3 was used to determine the flow field changes and the film stresses in the component. The fluid model and the solid model were first established and their meshes were generated. The interface between the fluid model and the solid model was set as the FSI surface, which forms the key data transmission bridge for the FSI process. Next, the pressure distribution on the FSI surface was obtained from finite element calculations of the fluid model. Finally, static calculations were
performed for the solid model. During the calculation process, the stress distribution and magnitude on each side of each film layer were imported from the CFD model results to obtain the deformation and stress results for the films subjected to the fluid pressure.

Figure 3. Schematic of the FSI model calculation method. Different colors represent the result value, with red being the largest value and blue the smallest. The specific result values are shown in the following section 2.3. CFD Mathematical Model.

The controlling equation for the internal flow field of the MLI component is described next. The gas volume force was ignored, and the fluid was considered to be a compressible gas. The continuity equation, the momentum equation, and the energy equation can be respectively expressed as follows:

\[
\begin{align*}
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) &= 0, \\
\frac{\partial (\rho \vec{v})}{\partial t} + \nabla \cdot (\rho \vec{v} \vec{v}) &= -\nabla p + \nabla (\tau) + S_M, \\
\frac{\partial (\rho h_{\text{tot}})}{\partial t} - \frac{\partial \rho p}{\partial t} + \nabla \cdot (\rho \vec{v} h_{\text{tot}}) &= \nabla \left( \lambda \nabla T + \vec{v} (\tau) \right) + \vec{v} \cdot S_M + S_E,
\end{align*}
\]

where \( \rho \) represents the gas density, \( t \) is the time, \( \vec{v} \) is the velocity vector, \( p \) is the pressure, \( \lambda \) is the effective thermal conductivity, \( \tau \) represents the stress tensor, \( T \) is the temperature, \( h_{\text{tot}} \) is the total enthalpy, and \( S_M \) and \( S_E \) are the generalized source terms for the mass and thermal energy (internal energy), respectively.

\( \tau \) can be expressed as follows:

\[
\tau = \mu (\nabla \vec{v} + (\nabla \vec{v})^T) - \frac{2}{3} \delta \nabla \cdot \vec{v}.
\]

\( \delta \), which represents the Kronecker Delta function, can be defined as follows:

\[
\delta = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}
\]

The relationship between \( h_{\text{tot}} \) and the static enthalpy, \( h_{\text{stat}} \), can be expressed as follows:

\[
h_{\text{stat}} = h_{\text{tot}} + \frac{1}{2} \vec{v} \cdot \vec{v}, \quad h_{\text{stat}} = h_{\text{stat}}(p, T).
\]

The equation of state for an ideal gas can be expressed as follows:

\[
\rho = p/(RT_{\text{mo}}/M_w).
\]
where $M_w$ represents the molar mass constant of the gas, $R$ is the ideal gas constant, and $T_{em}$ is the room temperature, which is equal to 300 K.

The gas accelerates in each film hole of the component, and the entire flow process is an entropy increment process. The maximum Reynolds number of the gas exceeds 9000. Therefore, the $k-\varepsilon$ turbulence model, the turbulent kinetic energy equation, $k$, and the energy dissipation equation, $\varepsilon$, can be used together as follows:

$$\frac{\partial}{\partial t}(\rho k) + \nabla \cdot (\rho \overline{kk}) = \nabla \left( \left( \frac{\mu + \frac{\mu_t}{\sigma_k}}{\sigma_k} \right) \nabla k \right) + G_k + G_b - \rho \varepsilon - Y_M + S_k,$$

(8)

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \nabla \cdot (\rho \overline{ke}) = \nabla \left( \left( \frac{\mu + \frac{\mu_t}{\sigma_\varepsilon}}{\sigma_\varepsilon} \right) \nabla \varepsilon \right) + C_1 \varepsilon \left( \frac{G_k + C_3 \varepsilon}{k} \right) - C_2 \rho \frac{\varepsilon^2}{k} + S_\varepsilon,$$

(9)

where $G_k$ represents the turbulent kinetic energy generated by the average velocity gradient, $G_b$ represents the turbulent kinetic energy generated by the buoyancy, $Y_M$ represents the turbulence dissipation rate generated by the turbulent expansion in the compressible turbulence, and $\mu_t = \rho C_1 k^2 / \varepsilon$ is the turbulent viscosity. $C_1$, $C_2$, $C_3$, and $C_\varepsilon$ are empirical constants with values as listed in Table 1, $\sigma_k$ and $\sigma_\varepsilon$ are the Prandtl constants of the turbulent kinetic energy equation, $k$, and the energy dissipation equation, $\varepsilon$, respectively, with values as listed in Table 1, and $S_k$ and $S_\varepsilon$ are the source terms.

**Table 1.** Empirical constants and Prandtl constants.

<table>
<thead>
<tr>
<th>$C_1$</th>
<th>$C_2$</th>
<th>$C_3$</th>
<th>$C_\varepsilon$</th>
<th>$\sigma_k$</th>
<th>$\sigma_\varepsilon$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.44</td>
<td>1.92</td>
<td>1.3</td>
<td>0.09</td>
<td>1</td>
<td>1.3</td>
</tr>
</tbody>
</table>

A transient solver and a compressible ideal gas were used in the numerical solution process. The SIMPLEC algorithm, which is based on the SIMPLE algorithm but adds a pressure correction relaxation factor, was adopted to achieve better convergence during the calculation process. In the numerical solution process, the convergence accuracy was set to $1 \times 10^{-6}$ to ensure the stability of the results and the accuracy of the calculations.

### 2.4. Mesh Generation

The mesh generation was challenging because the fluid model structure had a small thickness value but large length and width values. To solve this problem, a polygonal mesh was used to mesh all the fluid domains, as shown in Figure 4; this polygonal mesh produced a better mesh quality with fewer cells. Establishing circular nodes at the nylon net intersection points enables a smoother fluid mesh transition, which improves the mesh quality and the computational accuracy.
Mesh independence verification was conducted for the fluid model, and mesh refinement was performed in some regions to reduce the computational error in key regions of the model. The mesh independence verification results are shown in Figure 5. The results show that the mesh quality tended to stabilize when there were more than 8 million cells (the minimum cell size was 0.02 mm), thereby indicating that the CFD model calculations had reached mesh independence. Based on this result, a minimum cell size of 0.02 mm was used for the CFD calculations in this study.
The relationship between the external pressure (the outlet pressure of the fluid model) and time during launching is shown in Figure 7. The outlet pressure gradually decreases with time, and the stress on each surface in the fluid model reaches a maximum value when the pressure decreases most rapidly. Therefore, the moment when the films are subjected to the maximum pressure was selected for the FSI analysis. This was completed to obtain the stress characteristics of the films under maximum fluid pressure conditions.

By solving the CFD model, an outlet leakage–time curve was obtained, as shown in Figure 8. Figure 8 shows that the outlet leakage reaches a maximum near the 58th second. Based on this result, it was assumed that the films in the CFD model experience the maximum fluid pressure at the 58th second. Therefore, the fluid pressure results of the FSI model were extracted at the 58th second for the subsequent solid finite element analyses.
In practice, buckles are used to fasten the MLI components to the exterior of a spacecraft. Therefore, fixed supports were added around the films and at the end points of the nylon nets in the solid model, as shown in Figure 9.

3. Results and Discussion

3.1. Fluid Model Result Analysis

The structural parameters of the MLI component, as well as the corresponding symbols used to represent them in this paper, include the film hole diameter \( D \), the staggered hole distance \( L \), the number of component layers \( N \), and the film thickness \( c \). The five-unit MLI component used as an example in this study had the following structural parameters: \( D = 1 \text{ mm}, \ L = 4 \text{ mm}, \ N = 5, \text{ and } c = 0.01 \text{ mm} \). The structural model shows that a fluid domain existed between every two film layers. Due to the small fluid domain thickness, the drop in the fluid pressure in the thickness direction could be ignored; therefore, the pressure in the fluid domain between two films was the same throughout that domain.

The pressure contours in the flow field on one side of each of the six film layers are shown in Figure 10, where \( N \) represents the film layer number as counted from the inlet. Figure 10 shows that the nylon net forms a barrier to the gas flow and that the fluid pressure exhibits significant stratification at the nylon net. Meanwhile, the gas is not evenly distributed throughout the fluid domain of the nylon net; this result is primarily reflected in the relatively high pressure at the inlet side of the film hole, as well as in the observation that

![Figure 8](image-url)  
*Figure 8. Outlet leakage–time curve. The leakage reaches a maximum at the 58th second.*

![Figure 9](image-url)  
*Figure 9. Solid model boundary conditions: (a) film boundary and (b) nylon net boundary.*
the fluid pressure gradually decreases from the inlet side to the outlet side of the hole in each film layer.

![Figure 10. Pressure contours in the flow field: (a) N₁, (b) N₂, (c) N₃, (d) N₄, (e) N₅, and (f) N₆. Different shapes represent different pressure distribution.](image)

The pressure distribution on each film layer can be obtained from Figure 10. The fluid pressure differences between the films can be obtained by calculating the differences between the average fluid pressures on the surfaces of both sides of each film. To further study the effects of the structural parameters on the flow field pressure differences between the films, the flow field pressure differences calculated by CFD models with different structural parameter values were obtained by the single-factor variable method, as shown in Figure 11. The figure shows that the fluid pressures on the different films are not equal and that the fluid pressure gradually increases from the first layer to the last layer. This phenomenon occurs because the gas inside the component can only be discharged through the outlet. A film that is closer to the outlet experiences less gas resistance, and thus, it has a larger internal pressure difference.
Figure 11. Effects of the structural parameters on the flow field pressure difference: (a) film hole diameter effect, (b) staggered hole distance effect, (c) film layer sequence effect, and (d) film thickness effect.

Figure 11 shows that the pressure difference of the last film layer is always the largest. The effects of the structural parameters on the flow field pressure difference are described in the following six points:

1. The film hole diameter, the staggered hole distance, and the film layer sequence are all inversely proportional to the maximum pressure difference. The film thickness, however, is positively correlated with the maximum pressure difference.

2. The parameters that affect the maximum film stress, in descending order according to their degrees of influence, are the film hole diameter, the number of film layers, the staggered hole distance, and the film thickness.

3. Of all the parameters investigated, the film hole diameter has the greatest impact on the maximum pressure difference. In the component, the hole diameter directly affects the flow of the internal gas, and the throttling effect of the thin film hole is crucial to prevent leakage. A smaller hole diameter causes a greater resistance to the gas flowing through the film hole, and gas that flows more fully into the nylon net fluid domain between the films causes more fluid kinetic energy to be converted into pressure energy in the fluid domain.

4. As the number of the film layers increases, the number of film-layer nylon net sequences increases. This increase results in an increase in the internal gas resistance and a decrease in the flow velocity, which enables better conversion of gas kinetic energy into pressure energy in the nylon net fluid domain. Therefore, the influence of the number of film layers on the maximum pressure difference is also significant.

5. The staggered hole distance changes the pressure difference by changing the gas resistance in each nylon net layer, which has a limited impact on the pressure distribution.

6. The influence of the film thickness on the maximum pressure difference is minimal. Because the film thickness is very small, the time it takes for the gas to flow through the film hole is short; therefore, there is not enough time for energy conversion or dissipation.

Therefore, through finite element analyses of components with different structural parameters, the impacts of the structural parameters on the pressure difference of each film layer were obtained. These results lay a foundation for the structural design of MLI components. The pressure difference acting on a film can intuitively reflect the mechanical characteristics of the film. However, the component is composed of stacked films and nylon nets, and the nylon nets also impact the mechanical characteristics of the films. Therefore, finite element calculations were also performed for the solid component model to further analyze the film stresses and deformations, as discussed in the following section.

3.2. Solid Model Result Analysis

The solid model was formed by stacking films and nylon nets while leaving gaps between each layer of films and nets during the initial assembly. When a film deforms due
to the influence of the fluid pressure, it may come into contact with a nylon net. Therefore, the films and the nylon nets were set as frictional contacts in the finite element model. The five-unit MLI component model, which was used as an example, had solid model structural parameters of \( D = 1 \) mm, \( L = 4 \) mm, \( N = 5 \), and \( c = 0.01 \) mm. Deformation nephograms for the films were obtained by introducing the fluid pressure onto both sides of the films, as shown in Figure 12.

![Figure 12. Deformation nephograms of the films: (a) N1, (b) N2, (c) N3, (d) N4, (e) N5, and (f) N6. Different shapes represent different deformation distribution. The maximum deformation areas are marked.](image)

The results show that the maximum film deformations occur in the middle regions of the films due to the fixed constraints around the film edges. Additionally, the overall maximum deformation occurs in the sixth film layer. It can also be concluded that the deformations of the first three film layers are relatively small and that these films do not come into contact with the nylon nets; therefore, the nylon nets do not significantly deform. The fourth and fifth film layers, however, come into contact with the nylon nets, and the nylon nets do significantly deform; their deformation nephograms are shown in Figure 13. The maximum nylon net deformations occur in the middle regions of the nets (the reverse direction of the Z-axis in Figure 13 is the direction of the gas flow). Due to the small nylon net deformation values, the deformation results are amplified 50 times in Figure 13 for better observation. They indicate that the nylon nets experience Z-direction deformations in their middle regions, which are caused by the Z-direction deformations of the films and the contact between the films and the nets.
Figure 13. Deformation nephograms for the nylon nets (unit: mm): (a) primary deformation of M₄, (b) deformation of M₄ in the Z-direction, (c) deformation of M₄ in the X-direction, (d) primary deformation of M₅, (e) deformation of M₅ in the Z-direction, and (f) deformation of M₅ in the X-direction. Different shapes represent different deformation distribution. The maximum areas are marked.

Simultaneous lateral displacements also occur inside the nylon nets; these are primarily reflected in the X-direction motion in Figure 13. This occurs because the gas enters a nylon net through the hole in the upper film layer and flows out through the hole in the next film layer. This flow process generates lateral gas pressure on the nylon nets, resulting in deformations. Because the contact stress is greater than the internal stress, the deformations of the nylon nets in the Z-direction are greater than those in the X-direction.

Figures 12 and 13 show the solid deformation trends for the FSI model. However, the research presented above is still limited for systematic analyses of structural parameters. To further study the effects of the structural parameters on the maximum deformation of each film layer, the single-factor variable method was used with the FSI model to calculate the deformation for different structural parameter values. The maximum deformation of each film layer was thus obtained, as shown in Figure 14.
Figure 14. Effects of the structural parameters on the film deformations: (a) film hole diameter effect, (b) staggered hole distance effect, (c) film layer sequence effect, and (d) film thickness effect.

Figure 14a,b shows the effects of different film hole diameters and different staggered hole distances on the maximum deformation of each film layer, respectively. The results show that the deformations of the fifth film layer are the same despite changes in the parameter values. This result indicates that the film has come into contact with the nylon net, which limits further deformation of the film and reduces the risks of film damage and failure caused by excessive deformation. The sixth film layer exhibits the largest deformation because it is subjected to the maximum fluid pressure and there is no nylon net to limit its deformation. Figure 14c,d depicts the effects of the different numbers of film layers and different thicknesses on the film deformation, respectively. The results show that the largest deformation occurs in the film at the outlet. As the film thickness increases, the film strength significantly increases and the maximum film deformation significantly decreases.

The fluid pressure was introduced onto both sides of the solid film models to obtain the film stress distributions, and the results are shown in Figure 15. The maximum film stresses are generated at the edges of the films, indicating that the fluid pressure generated by the gas flowing out from between the films is the key cause of film failure.
Figure 15. Stress distributions of the films (unit: MPa): (a) N₁, (b) N₂, (c) N₃, (d) N₄, (e) N₅, and (f) N₆. Different shapes represent different stress distribution. The maximum stress areas are marked.

Figure 16 depicts the impacts of the different structural parameters on the maximum stress in each film layer. The results show that the film at the outlet has the maximum stress value because this is where the maximum fluid pressure occurs. Therefore, the film at the outlet is the part of the MLI component that is most vulnerable to failure. Increasing the film thickness significantly increases the film strength and reduces the maximum film stress.
The effects of the structural parameters on the deformations and stress distributions of the films were obtained by analyzing the results of the FSI model. The single-factor variable analysis method revealed that the film thickness is the most critical factor affecting the maximum film stress; it indicated that increasing the film thickness can effectively reduce the film stress. The impacts of the structural parameters on the film stress of the component are complex, and a method of applying the rules discussed above when optimizing the design of a component has great significance. Therefore, an optimal design scheme for the component is proposed next.

### 3.3. Structure Optimization Analysis

The effects of the MLI component’s structural parameters on the maximum film stress are complex, and strict restrictions are imposed on the maximum weights of components used on spacecraft. Therefore, the film thickness should be as small as possible so that the weight requirements can be met. According to the weight limitations and the actual manufacturing scenarios of components, the design limitations were obtained for a certain type of component. The parameter values were selected based on these design limitations, as shown in Table 2.

**Table 2. Orthogonal parameter scheme that includes four factors and three levels.**

<table>
<thead>
<tr>
<th>Factor</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Number of component layers</td>
<td>5</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>2 Film thickness (10⁻³ mm)</td>
<td>10</td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>3 Film hole diameter (mm)</td>
<td>0.8</td>
<td>1</td>
<td>1.2</td>
</tr>
<tr>
<td>4 Staggered hole distance (mm)</td>
<td>4</td>
<td>6</td>
<td>7.75</td>
</tr>
</tbody>
</table>

The process used to analyze the parameter effects on the maximum film stress using an orthogonal experimental method is described next. First, the correct orthogonal analysis table was selected according to the number of factors to be analyzed and the typical parameters to be calculated. Second, through a variance analysis of typical experimental data, the effects of the parameters on the maximum film stresses were obtained. Finally, the accuracy of the analysis results was verified using statistical methods. The letter $j$ is used to represent the serial number of the corresponding factor, where $j = 1, 2, 3, 4$ represent the number of component layers, the film thickness, the film hole diameter, and the staggered hole distance, respectively. The letter $k$ is used to indicate the serial number.
of the corresponding factor level, and \( k = 1, 2, \) and 3 represent the values selected for factors, as shown in Table 2. An \( L(3^4) \) orthogonal table, which has three levels and four factors, was selected, and nine corresponding numerical experiments were conducted. The results of the nine experiments are shown in Table 3.

Table 3. Results of the orthogonal experiment.

<table>
<thead>
<tr>
<th>Model</th>
<th>Number of Component Layers</th>
<th>Film Thickness ((10^{-3} \text{ mm}))</th>
<th>Film Hole Diameter (mm)</th>
<th>Staggered Hole Distance (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>10</td>
<td>0.8</td>
<td>4</td>
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<tr>
<td>2</td>
<td>5</td>
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<td>1</td>
<td>6</td>
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<td>8</td>
<td>15</td>
<td>20</td>
<td>0.8</td>
<td>7.75</td>
</tr>
<tr>
<td>9</td>
<td>15</td>
<td>30</td>
<td>1</td>
<td>4</td>
</tr>
</tbody>
</table>

\[
K_j^k = \frac{\text{max}}{\text{min}} \left\{ K_j^k \right\}, \quad j / k = 1, 2, 3, 4,
\]

The maximum film stress was the key evaluation index used to analyze the component film failure. The maximum film stress was calculated for all the numerical experiments listed in Table 3. The influence trends of the structural parameters with respect to the maximum film stress are different. A range analysis was used to analyze the influence degrees of the different structural parameters on the maximum film stress. A larger range indicated a greater impact of the corresponding structural parameter on the maximum film stress. The definition of the range, \( R_j \), of factor \( j \) is as follows:

\[
R_j = \max \left\{ \frac{\bar{K}_j^1}{\bar{K}_j^k} \right\} - \min \left\{ \frac{\bar{K}_j^1}{\bar{K}_j^k} \right\}, \quad j / k = 1, 2, 3, 4,
\]

where \( \bar{K}_j^k \) represents the mean value of all the maximum film stress values when factor \( j \) is at level \( k \), while \( k = 1, 2, \) and 3 represent the values selected for the factors in Table 2.

The effects of the different factors on the maximum film stress were obtained according to the ranges of the orthogonal experiment results. The parameter order, ranked from the largest to the smallest according to the parameter influence on the maximum film stress, is the film thickness, the film hole diameter, the number of component layers, and the staggered hole distance. To reduce the maximum stresses in the thin films, a structurally optimized design scheme for the component is proposed: \( D = 1.2 \text{ mm}, L = 7.75 \text{ mm}, N = 15, \) and \( c = 30 \, \mu\text{m} \). This scheme is illustrated in Figure 17.
According to the results presented in Section 3.2, the film at the outlet has the maximum stress and is the most prone to failure. The maximum deformation of the film at the outlet of the five-unit MLI component \((D = 1\, \text{mm}, \, L = 4\, \text{mm}, \, N = 5, \, \text{and} \, c = 0.01\, \text{mm})\) is 0.549 mm, and the maximum stress is 4.17 MPa. According to the modeling and calculations that were conducted based on the optimized design scheme, the maximum film deformation is 0.0017 mm, and the maximum stress is 0.098 MPa. Therefore, the optimized design produced significant decreases in the deformation and stress values.

4. Conclusions

The mechanical characteristics of the MLI component of a spacecraft during rapid decompression were investigated in this study. An FSI model for the component was established, and the internal flow field stress trends, the film deformation trends, and the film stress distribution trends were obtained for the component through FSI calculations and analyses. Then, a structurally optimized design scheme was proposed for the component, which provides an important basis for the design of spacecraft MLI components. This study produced five primary conclusions:

(1) An FSI model for the component was established. By reasonably simplifying the model and solving the modeling and mesh generation problems for the complex structure, simulation calculation and analysis methods were proposed for the component.

(2) Finite element calculation results for the flow field indicate that the film stress gradually increases in successive layers from the inlet to the outlet for any structural parameter values. Therefore, the film stress is the largest in the outlet film, which causes this film to be the part of the component that is most prone to damage and failure. The film hole diameter, the staggered hole distance, and the film layer sequence are all inversely proportional to the maximum film pressure difference, while the film thickness is positively correlated with the maximum film pressure difference. The structural parameter with the greatest influence on the maximum film pressure difference is the film hole diameter; it is followed by the number of component layers, the staggered hole distance, and finally the film thickness.

(3) The calculation results of the solid FSI model indicate that the film thickness is the factor that most critically affects the maximum film stress and that increasing the film
thickness can effectively reduce the film stress. It was also verified that the nylon nets can effectively limit the film deformation, thereby better protecting the films.

(4) An orthogonal experiment was used to analyze the effects of typical component structural parameter values on the maximum film stress. The results show that the parameter with the largest influence is the film thickness; it is followed by the film hole diameter, the number of component layers, and finally the staggered hole distance. Based on this result, a structurally optimized design scheme was proposed for the component, for which the deformation and stress values decreased significantly.

(5) The method presented in this paper is generally applicable to the study of the film stresses in MLI components of spacecraft. FSI model calculations can be conducted, orthogonal experiments can be used to analyze the effects of the structural parameters on the stresses, and optimal design schemes can be proposed to avoid component failure. The influence of various structural parameters on the maximum stress of the thin film presented in this paper can be directly applied to the structural design of the MLI components of spacecraft. Under the condition that the heat insulation performance of the MLI components meets the requirements, the failure risk of the film can be effectively reduced by appropriately increasing the film thickness and the film hole diameter. However, only the effect of the fluid pressure on the component films under rapid decompression conditions during spacecraft launching was investigated in this study. The interference of external factors, such as random vibrations during spacecraft launching, was not considered. The results of this study do not reflect the overall film stress situation. In the future, the mechanical characteristics of MLI component films will be investigated under combined fluid and random vibration effects.

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