Analysis of Factors Affecting Heat Transfer and Ablation of Glass Wool in Silo Launching

Ji-jun ZHANG¹,*, Jian XIE¹, Liang LI¹ and Hui Quan¹
¹Rocket Force University of Engineering, Xi’an Shaanxi 710025, China
*Corresponding author

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Abstract. For rocket silo launching, the heat transfer and ablation problem of glass wool, the main material of silencer layer. The glass wool with severely ablated area was selected as research object, and a unidirectional fluid-structure coupled heat transfer ablation model was established. Through the secondary development of abaqus subroutine, the influence of silo diameter and initial impact height of jets flow on the ablation of glass wool was studied using factor decoupling control method. The simulation results show that reducing diameter of silo can aggravate the ablation damage of glass wool in the process of rocketing out of silo. During the tempering phase of jets flow field, the smaller silo diameter is, the higher the peak value of average ablation rate is, and the sooner the peak value appears; Increasing initial impact height of jets flow can mitigate the ablation damage of glass wool in the process of rocketing out of silo. During the tempering phase of jets flow field, the greater initial impact height of jets flow is, the smaller the peak value of average ablation rate is, and the later the peak appears. Changing silo diameter and initial impact height of jets flow have less effect on the ablation damage of glass wool during the drainage stage and subsequent stages of jets flow field.

Introduction

When rocket launches in silo, high temperature and high speed jet flow mixes with the air in silo quickly to form strong turbulent pulsation, which produces great noise [1-3]. In order to eliminate the influence on the safety of silo, the silencer layer is built on the wall of silo. However, the environment in silo is very bad in the process of rocket discharge. Under the action of high temperature, glass wool, the main material of the silencer layer is generally melted and ablated, and the ablation is more serious within 5h from the support device [4-6]. According to the relevant data, there are many factors affecting the ablation damage of glass wool. Therefore, it is necessary to establish ablation damage model of glass wool and study the ablation damage of glass wool under different working conditions.

In order to solve the problem of material ablation in high temperature and high speed flow field, many scholars at home and abroad have done a lot of research. Daniele Bianchi [7], a foreign scholar, used the finite element method to simulate the ablation of the engine insulation, and studied the influence of the chamber pressure on the ablation. The results show that the ablation rate increases linearly with chamber pressure, and the calculated results are in good agreement with the experimental values. Piyush Thakre [8] et al. studied the ablation law of graphite/carbon-carbon nozzle by combining theoretical research with numerical simulation. The results show that the ablation of the nozzle throat region is the most serious. Yang Feng [9], a domestic scholar, used advanced ALE mesh adaptive technology to simulate the ablation of graphite and carbide materials, solved and calculated the transient temperature field, the depth of ablation retreat and the rate of temperature change of thermal protective materials during the reentry of high-speed aircraft into the atmosphere, and analyzed the effect of material properties on ablation rate.

At present, scholars at home and abroad mainly focus on the influence of flow field pressure, temperature and material properties on material ablation, but there are few studies on the influence of structure size, impact height and other factors on material ablation [10]. Therefore, this paper
neglects the influence of glass wool ablation retrogression on jet flow field, establishes a one-way fluid-solid coupled heat transfer and ablation model, and uses factor decoupling control method to study the influence of borehole diameter and initial impact height of jet flow on glass wool ablation. Firstly, the glass wool at the height of 0.25h and 2.5h is selected as the calculation sub-models A1 and A2 respectively, and the sub-model size is 5l0*5l0*2l0. Then, through the secondary development of *abaqus* user subroutine, the numerical results of flow field near the inner wall of glass wool are interpolated into the structure by the interpolation program to realize the finite element simulation of heat transfer and ablation of glass wool under different working conditions. In order to hide the specific parameters of rocket and silo, the dimensionless processing of relevant values is carried out by using t0, h0, d0, l0, h, T0, D0 and H0.

**Mathematical Model of Melting Ablation**

Glass wool belongs to inorganic non-metallic materials, and its ablation mechanism is melting type [11,12]. Glass wool melts when it reaches the melting point temperature and absorbs a lot of heat. At the same time, it forms a high viscous liquid layer with molten SiO2 as the main component and can further absorb heat. The liquid layer attached to the surface of the material hinders the heat transfer to the inside of the material. As the temperature continues to rise, the viscosity of the liquid layer decreases. When the adhesive force of the liquid layer is less than the aerodynamic shear force, the liquid layer will be blown away continuously in the form of glass beads, resulting in the ablation and retrogression of glass wool material.

Because the velocity of flow field is very high during thermal launching of rocket silo, dynamic scouring effect on the surface of glass wool is very strong. Therefore, it is assumed that the aerodynamic shear force on the surface of glass wool under the action of high temperature and high speed jet flow is large enough, and the glass wool will be blown away immediately after melting. And the glass wool thermal conductivity is small, so glass wool can be regarded as a one-dimensional semi-infinite object [13,14].

The ablation process of glass wool is a phase change heat transfer process with moving boundary, so the moving coordinate transformation is used to calculate the velocity of ablation interface [15].

The differential equation of thermal conductivity for melting ablation of glass wool in dynamic coordinate system is as follows:

\[
\frac{\partial^2T(x,t)}{\partial x^2} + \frac{u}{a} \frac{\partial T(x,t)}{\partial x} = 0
\]

In the formula, \( T \) is glass wool temperature, \( ^\circ C \); \( a \) is thermal conductivity, \( m^2\cdot s^{-1} \); \( u \) is ablation regression rate, \( m\cdot s^{-1} \).

Boundary condition is:

\[
\begin{align*}
T(x,t)_{|_{x=0}} &= T_p \\
T(x,t)_{|_{x=\infty}} &= T_i
\end{align*}
\]

In the formula, \( T_p \) is the phase transition temperature, \( ^\circ C \); \( T_i \) is the initial temperature, \( ^\circ C \).

The temperature field distribution function of glass wool obtained from formula (1) and formula (2) is as follows:

\[
\frac{T-T_i}{T_p-T_i} = e^{-\frac{u}{a}x}
\]

Therefore, according to the basic law of heat conduction, the heat flux at the ablation interface of glass wool is as follows:

\[
q(t)_{|_{x=0}} = -\lambda \left. \frac{\partial T(x,t)}{\partial x} \right|_{x=0} = \rho c \lambda (t_p - t_i)
\]
In the formula, \( q(t)_0 \) is the heat flux transferred from the ablation interface to the interior of the structure, J·m\(^{-2}\)·s\(^{-1}\); \( \rho \) is the density, Kg·m\(^{-3}\); \( \lambda \) is the heat conductivity, W·m\(^{-1}\)·C\(^{-1}\).

Jet flow at ablation interface transfers heat to glass wool through forced convection heat transfer. Part of the heat is heated to the surface of glass wool, which makes the surface temperature rise to the melting point and causes melting ablation. Part of the heat is transferred to the non-ablated part of glass wool through heat conduction. According to the law of conservation of energy:

\[
q(t) = -\lambda \frac{dT(x,t)}{dx} \bigg|_{x=0} + \rho \rho \nu \nu L
\]

In the formula, \( L \) is the latent heat of glass wool melting J·g\(^{-1}\).

The results of simultaneous formula (4) and formula (5) show that the melting and ablation velocity of glass wool is as follows:

\[
u = \frac{q(t)}{\rho L \left( c_s (t_p - t) + 1 \right)}
\]

The heat flux \( q(t) \) at the ablation interface can be calculated by Newton's cooling formula.

Therefore, the melting ablation thickness of glass wool, the position of the phase interface, can be calculated by the following formula:

\[
s(t) = \int_{t_{p1}}^{t_{p2}} u dt
\]

In the formula, \( t_{p1} \) is the time when the inner wall temperature of glass wool reaches the melting point of the material, \( s \); \( t_{p2} \) is the time when the inner wall temperature of glass wool falls below the melting point of the material, \( s \).

**Subprogram Development**

In this paper, the *film* and *umeshmotion* subroutines in *abaqus* are redeveloped, which effectively solves the acquisition of convective heat transfer coefficient on the inner wall of glass wool, the application of inflow temperature and the control of ablation rate in the process of rocket exit.

*film* subroutine is mainly used to specify non-uniform convective heat transfer coefficient and inflow temperature in heat transfer analysis. In this paper, *film* subroutine is used to specify the convective heat transfer coefficient and inflow temperature of coupled wall. The convective heat transfer coefficients are obtained by calculating the correlation of high-speed turbulence test for scouring plate [16], and the inflow temperature is obtained from literature [11] by interpolation algorithm.

Its function interface is as follows:

*Subroutine film*

\[
h, \text{sink}, \text{temp}, jstep, jinc, time, noel, npt, coords, jltyp, field, nfield, sname, jusernode, aera)
\]

*umeshmotion* subroutine is mainly used to control the movement of grid nodes in ALE mesh adaptive process. This paper mainly uses *umeshmotion* subroutine to control the ablation law of glass wool muffler. The ablation rate is calculated by formula (6).

Its function interface is as follows:

*Subroutine umeshmotion*

\[
uref, ulocal, node, nndof, londetype, allocal, ndim, time, dtime, pnewdt, kstep, kinc, kmeshsweep, jmatyp, j gwblock, lsmooth)
\]

The specific simulation process is as follows:

Firstly, the gas flow field data near the inner wall of glass wool were extracted by *fluent* and pretreated.
Then, the temperature data extracted are interpolated to the integral point of the unit surface load of the glass wool inner wall by the inverse distance weighting method. Simple linear interpolation method is used to interpolate time. The flow chart of interpolation program is shown in Figure 1.

Finally, the real-time acquisition of convective heat transfer coefficient and inflow temperature and the control of ablation law are realized by calling *film* and *umeshmotion* subroutines.

![Flow chart of interpolation program.](image)

### Calculation Results and Analysis

Using factor decoupling control method, the influence of two factors, the diameter of wellbore and the initial impact height of jet flow, on the ablation of glass wool was analyzed. Under each working condition, the parameters of the influencing factors are set as shown in Table 1. In the table, Ds denotes the borehole diameter and H denotes the initial impact height of jet flow.

| Influence factor | \( D_s \) (m)   | \( H \) (m)         |
|------------------|----------------|---------------------|
| 1                | \( D_0 \)     | \( H_0 \)           |
| 2                | \( D_0 - 0.2d_0 \) | \( H_0 \)           |
| 3                | \( D_0 - d_0 \) | \( H_0 \)           |
| 4                | \( D_0 - 0.2d_0 \) | \( H_0 + 1.3h_0 \) |
| 5                | \( D_0 - 0.2d_0 \) | \( H_0 + 2.7h_0 \) |
Effect of Diameter on Ablation of Glass Wool

Figure 2 and 3 show the glass wool ablation depth nephogram at A₁ and A₂ positions at 5T₀ under different diameter conditions. From Figure 2 and 3, it can be seen that when the diameter of silo is D₀ m and (D₀-0.2d₀) m respectively, the distribution of ablation depth of glass wool is less different. The ablation depth at A₁ position is [2.5, 2.7] mm in both cases, and at A₂ position is [2.0, 2.5] mm in both cases. However, when the diameter of silo is reduced to (D₀-d₀) m, the ablation depth of glass wool is obviously increased, and at A₁ position is deeper. At [2.6, 2.8] mm, the ablation depth at position A₂ is [2.3, 2.6] mm.

Figure 2. Ablation depth nephogram of glass wool at position A₁.

Figure 3. Ablation depth nephogram of glass wool at position A₂.
Figure 4 shows the average ablation rate curves of glass wool at positions A1 and A2, respectively. It can be seen from the curves that when the diameter of the wellbore is \( D_0 \) m and \( (D_0-0.2d_0) \) m respectively, the ablation rates of glass wool at A1 and A2 positions are basically the same with time; when the diameter of the wellbore is reduced to \( (D_0-d_0) \) m, the peak value of the ablation rate curve appears obviously earlier than the other two conditions before 1 s time, and the peak value of the ablation rate also increases significantly. However, after 1 s, the amplitude difference of glass wool ablation rate curve is small under three working conditions. The results show that the ablation rate of glass wool in tempering stage can be affected by changing the diameter of wellbore. Reducing the diameter of the wellbore leads to an increase in the ablation rate of glass wool in tempering stage, and the peak occurs earlier, while reducing the diameter of the wellbore has less influence on the ablation rate of glass wool in the drainage stage and instability stage of gas flow field. This also further proves the phenomena shown in cloud 2 and cloud 3 of ablation depth. When the diameter of wellbore is reduced to \( (D_0-d_0) \) m, the ablation degree of glass wool at A1 and A2 positions is significantly increased.

![Figure 4. Change curve of average ablation rate of glass wool at A1 & A2 position.](image)

The average ablation depth of glass wool at A1 and A2 locations under different wellbore diameters is extracted from the simulation results as shown in Table 2. According to the data in the table, reducing the diameter of the wellbore will increase the average ablation depth of glass wool, which will aggravate the ablation damage of glass wool. However, when the borehole diameter is reduced from \( D_0 \) m to \( (D_0-0.2d_0) \) m, the change rate of average ablation depth is not more than 1.18%. When the borehole diameter is reduced from \( D_0 \) to \( (D_0-d_0) \) m, the change rate of average ablation depth is less than 4.33%.

| Parameter       | A1  | A2  |
|-----------------|-----|-----|
| \( D_0 \) m     | 2.54| 2.25|
| \( (D_0-0.2d_0) \) m | 2.57| 2.27|
| \( (D_0-d_0) \) m | 2.65| 2.33|
| \( (d_2-d_1)/d_1 \times 100\% \) | 1.18% | 0.89% |
| \( (d_3-d_1)/d_1 \times 100\% \) | 4.33% | 3.36% |

### Effect of Initial Impact Height of Jet flow on Ablation of Glass Cotton

Figure 5 and 6 show the glass wool ablation depth clouds at A1 and A2 positions at 5\( T_0 \) under different initial impact height of jet flow. From the cloud images, it can be seen that the distribution of ablation depth of glass wool at A1 and A2 locations is quite different. With the increase of the initial impact height of jet flow, the ablation degree of glass wool decreases gradually, that is, the ablation depth decreases gradually.
Figure 5. Ablation depth nephogram of glass wool at position A₁.

Figure 6. Ablation depth nephogram of glass wool at position A₂.

Figure 7 shows the average ablation rate curves of glass wool at A₁ and A₂ locations under three working conditions respectively. From the curves, it can be seen that the ablation rate curves of glass wool at A₁ and A₂ locations are similar with time. Before 1s, with the increase of the initial impact height of jet flow, the time when the peak value of ablation rate appears is delayed, and the peak value of ablation rate is also significantly reduced. The main reason for this phenomenon is that with the increase of the initial impact height of the jet flow, the free section of the high-temperature and high-speed jet flow from the tail of the engine becomes longer and develops more fully. When the jet flow strikes the diversion cone, the velocity and mass ratio of the reflected gas...
flow are smaller. However, after 1 s, the ablation rate curves of glass wool under three working conditions are in good agreement.

![Figure 7. Change curve of average ablation rate of glass wool at A1&A2 position.](image)

The average ablation depth data of glass wool at A1 and A2 locations are extracted from the simulation results under different initial impact heights of jet flows as shown in Table 3. According to the data in the table, the average ablation depth decreases with the increase of the initial impact height, which reduces the ablation damage of glass wool. When the initial impact height of jet flow increases from \(H_0\) m to \((H_0 + 2.7h_0)\) m, the average ablation depth change rate is not less than 9.61%.

| Parameter                  | A1       | A2       |
|----------------------------|----------|----------|
| \(H_0\) m                  | 2.57     | 2.29     |
| \((H_0+1.3h_0)\) m         | 2.45     | 2.18     |
| \((H_0+2.7h_0)\) m         | 2.32     | 2.07     |
| \((d_4 - d_2) / d_2\times100\%\) | -4.67\% | -4.80\% |
| \((d_5 - d_2) / d_2\times100\%\) | -9.73\% | -9.61\% |

**Conclusion**

By means of factor decoupling control method and secondary development of *abaqus* subroutine, the effects of wellbore diameter and initial impact height of jet flow on heat transfer and ablation of glass wool are studied and analyzed. Through comparative analysis, the following conclusions are drawn:

1. Reducing borehole diameter can aggravate the ablation of glass wool during rocket exit. The smaller the borehole diameter is, the larger the peak value of average ablation rate of glass wool is at the tempering stage of gas flow field, and the earlier the peak value appears.
2. Increasing the initial impact height of jet flow can alleviate the ablation of glass wool during rocket exit. The higher the initial impact height of jet flow is, the smaller the peak value of average ablation rate is at the tempering stage of gas flow field, and the later the peak value appears.
3. Changing the diameter of the wellbore and the initial impact height of the jet flow has little effect on the ablation of glass wool in the drainage stage and the subsequent stage of the gas flow field.

The results can provide a reference for the structure design of launcher. This is also the next step.

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