Research on Influencing Factors of Fire Resistance of Curtain Wall in High-rise Buildings

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Abstract. With the continuous improvement of China's economic development level, the construction industry has developed significantly, and as urban high-rise buildings have become the mainstream of today's building forms. In high-rise buildings, the most important safety issue is fire prevention. The application of fire-resistant glass in the curtain wall of high-rise buildings has become the focus of attention. Fire-resistant glass can play a role in controlling fire, smoke and high temperature diffusion for a long time when a fire occurs. As well as the requirements for design materials, this article discusses the precautions for the design of curtain walls of high-rise buildings and the promotion and use of fire-resistant glass in China.

1. Introduction

With the continuous development of China's economy and construction industry in recent years, more and more high-rise building exterior walls have adopted glass curtain wall construction in the design of high-rise building exterior walls in order to pursue a certain artistic quality, but this design style exists. There is a great fire safety hazard, and there must be a fire. Due to the difficulty of fire suppression and the rapid spread of fire in high-rise buildings, serious problems and loss of life and property can occur. After a series of catastrophic fires have been reported all over the country, there has been widespread concern about the fire protection of glass on the outer walls of high-rise buildings. Many experts have successively proposed that a high-rise building exterior wall should be used with ordinary glass, which can be used to control fire, smoke and high-temperature diffusion. This article discusses the specific application measures and feasibility of fire glass in high-rise building curtain walls.

2. The concept of fire-resistant glass curtain wall

Fire glass curtain wall, we generally call it fire glass curtain wall system or fire glass partition system. Fire-resistant glass curtain wall system shall be composed of steel frame, fire-resistant glass, flame-resistant sealant strip, flame-resistant sealant, steel connectors and hardware. The anchors connecting steel frames shall not use modified epoxy resin as the anchoring agent [1]. Chemical bolts shall be connected by mechanical anchors. The steel pillars of the fire-resistant glass curtain wall shall be set to be suspended and tensioned, and a seated pressure-bearing type shall be avoided to avoid pressure instability during a fire, which may cause collapse and damage [2]. Fire-resistant glass curtain wall systems using hanging tensile steel columns generally do not need to be treated with fire-resistant
coatings for steel profiles [3]. However, the fire resistance of the entire fire-resistant curtain wall system should have relevant test reports, and the results of the tests shall prevail. The surface protection of the steel structure, such as galvanized layer or fluorocarbon topcoat, does not affect the fire resistance of the steel structure [4]. It should be noted that the aluminum alloy keel is not fire-resistant, and the fire resistance limit of fire-resistant glass curtain wall is generally not less than 1.00 hour. Spraying the fire-resistant coating on the surface of the aluminum alloy keel cannot meet the fire protection requirements. In some countries' fire-resistant glass curtain walls, aluminum alloy profiles are directly used as the supporting framework of the fire-resistant curtain wall [5]. Special materials are filled in the aluminum alloy keel, but the process is complicated and the cost is high [6]. It is rarely used in China. In general, the smaller the area of the fire-resistant glass plate, the easier it is to meet the fire resistance limit requirements for a certain period of time. Similarly, the larger the area of the fire-resistant glass plate, the more difficult it is to meet the fire resistance requirements of a certain period of time [7].

3. Glass types of fire-resistant glass curtain wall

Fire-resistant glass curtain wall uses fire-resistant glass. Fire-resistant glass is divided into Class A and Class C. Class A fire-resistant glass has relevant requirements for fire insulation and fire integrity, and class C fire-resistant glass has only relevant requirements for fire integrity. Fireproof glass mainly includes composite fireproof glass, grout fireproof glass, and single-piece fireproof glass [8]. Among them, Class A fireproof glass includes composite fireproof glass, grouting fireproof glass, and single-piece fireproof glass such as cesium potassium fireproof glass, which belongs to Class C fireproof glass. The composite fire-resistant glass is shown in the following figure. Special attention should be paid to the fact that the heat insulation of fire-resistant glass is different from the heat insulation in energy-saving standards. To the back surface space, also known as heat radiation resistance. The energy-saving thermal insulation performance of the curtain wall refers to the effective control of the heat conduction speed to achieve energy saving when there is a temperature difference between indoor and outdoor. It is also called the thermal conductivity K value.

Ordinary glass will explode when exposed to fire, and the fire resistance limit is very low. It is difficult to meet the fire resistance requirements of glass curtain walls. For this reason, ordinary glass must be fire-treated. As a member of safety glass, fire-resistant glass, in addition to some properties of ordinary glass, but also its ability to retard the spread of fire, heat insulation, and gradually get people's green. On important occasions with special requirements, it plays a pivotal role. After more than ten years of development, fire-resistant glass has undergone great changes in all aspects of its performance (fire resistance, optical properties, mechanical properties, etc.), and the materials used have also undergone considerable changes. Depending on the material used, fire-resistant glass can be divided into the following types:

3.1. Wire fire-resistant glass

Wire-laminated fire-resistant glass is a composite formed by adding a metal wire mesh to the interlayer of an organic film or an inorganic adhesive in the middle of two layers of glass. After the wire mesh is added, not only the overall impact strength of the fireproof glass is improved, but also it can be connected with electric heating and safety alarm systems to play a variety of functions. The two-layer glass of wine-laminated fire-resistant glass is inorganic glass, the organic film is PVB glue or PVC glue, the inorganic adhesive is a hydrated metal salt such as sodium silicate, phosphate, aluminate, etc., and the metal wire is stainless steel wire. The only drawback of this fire-resistant glass is its poor light transmission.

3.1.1. Borosilicate fire-resistant glass. Chemical composition of borosilicate fire-resistant glass: $\text{SiO}_2$ content is between 70% to 80%, $\text{B}_2\text{O}_3$ content is 8% to 13%, $\text{Al}_2\text{O}_3$ content is 2% to 4%, and $\text{R}_2\text{O}$ content is 4% to 10%. The characteristics of this glass are High softening point, low thermal expansion
Coefficient and stable chemical properties. The softening point is about 850°C, and the thermal expansion coefficient is $3 \times 10^{-7} / {\degree C} - 4 \times 10^{-7} / {\degree C}$ at 0°C-300°C;

3.1.2. Aluminosilicate glass. The chemical composition of aluminosilicate glass is: SiO$_2$ content is between 55% to 60%, B$_2$O$_3$ 5% to 8%, Al$_2$O$_3$ 18% to 25%, R$_2$O 0.5% to 1.0%, CaO 4.5% to 8.0%, MgO 6% to 9%. This glass is characterized by a low Al$_2$O$_3$ content and a high softening point, and it is generally not cracked or deformed when directly placed on the flame and heated. The softening point is between 900°C and 920 °C, and the thermal expansion coefficient is about $5 \times 10^{-6} / ^\circ{C}$ to $7 \times 10^{-6} / ^\circ{C}$;

| Frame | Glass Type         | Thickness (mm) | Overall Size (m x m) | Max Glass (mm x mm) | FRL    |
|-------|--------------------|----------------|----------------------|---------------------|--------|
| AW60  | Contraflam 120-6   | 65             | 3 x unlimited width  | 3000 x 1500         | -120/120 |
|       | Contraflam 120-6 & Climplus | 65         | 3 x unlimited width  | 3000 x 1500         | -120/120 |
|       | Contraflam 120/5 & Climplus | 54       | 3 x unlimited width  | 3000 x 1500         | -120/120 |
|       | Contraflam 90      | 40             | 3 x unlimited width  | 3000 x 1800         | -90/90  |
|       | Contraflam 90 Climplus | 40         | 3 x unlimited width  | 3000 x 1800         | -90/90  |
|       | Contraflam 30      | 16             | 3 x 1.5              | 3000 x 1240         | -120/30 |
|       | Contraflam 30 Climplus | 16       | 3 x 1.5              | 3000 x 1240         | -60/30  |
|       | Contraflam Lite 120 | 16             | 3 x unlimited width  | 3000 x 1400         | -120/30 |
|       | Contraflam Lite 120 Climplus | 14        | 3 x unlimited width  | 3000 x 1400         | -120/30 |
|       | Fireblock 60       | 35             | 3 x unlimited width  | 3000 x 900          | -60/60  |
|       | Fireblock 60 Climplus | 14         | 3 x unlimited width  | 3000 x 1200         | -60/30  |

3.1.3. Microcrystalline fireproof glass. Microcrystalline fire-resistant glass is a polycrystalline formed by adding crystal nucleating agents such as Li$_2$O, TiO$_2$, and ZrO$_2$ to the chemical composition of the glass. After the glass is melted, heat treatment is performed to precipitate and grow uniformly. The characteristics of this glass are good chemical stability and physical and mechanical properties, high mechanical strength, high flexural and compressive strength, high softening temperature, and low thermal expansion coefficient.

3.1.4. Composite fire-resistant glass. Due to the poor transmittance of wire-laminated fire-resistant glass and fire-resistant glass made of special materials, it is difficult for people to accept its high price. Currently, the market is mainly transparent laminated composite fire-resistant glass. Laminated composite fire-resistant glass is composed of two or more layers of ordinary flat glass sandwiched with transparent fire-resistant expanded fire-resistant adhesive. For this type of fire-resistant glass, the focus of research is on transparent fire-resistant adhesives between two layers of inorganic glass. The reason is that the performance of fire-resistant glass mainly depends on the performance of fire-resistant adhesives.

3.1.5. High-strength single-piece cesium-potassium fire-resistant glass. A high-strength single-piece cesium-potassium fire-resistant glass, which is successfully developed by new technology and new technology and put into industrial production, is a curtain wall or door and window glass for building interior walls with fire-resistant function. It is obtained by processing float glass using physical and
chemical methods. It can keep 84min-183min from bursting under the flame impact of 1000 °C, which can effectively prevent the spread of flame and smoke, so that people have enough time to evacuate the site and carry out disaster relief work. Its appearance solves the fatal weakness of poor fire safety of ordinary glass exterior walls and greatly improves the safety factor of glass exterior walls.

High-strength single-piece cesium-potassium fire-resistant glass not only has excellent fire-proof function, but also excels in strength. At the same thickness, its strength is 6 to 12 times that of float glass; 1.5 times that of tempered glass-3 times. Therefore, under the same wind pressure, it can adopt a thinner thickness or a larger area design, thereby increasing the sense of transparency and reducing the cost.

**Figure 1.** Principle analysis of fire resistance of high-rise building curtain wall

3.2. Relevant points of thermal insulation and fire-resistant glass curtain wall

Fire-resistant glass curtain wall systems with fire insulation and fire integrity requirements are generally divided into Grade A, Grade B, and Grade C. The fire insulation and fire integrity are not less than 1.50h, 1.00h, and 0.50h, respectively. The supporting form of full-frame glass curtain wall shall be adopted, and its steel columns shall be suspended and tensioned. The glass uses composite fire-resistant glass. Composite fire-resistant glass is composed of float glass (or semi-tempered glass, tempered glass) and fire-resistant rubber interlayer. In a fire situation, because the fire-resistant glass bursts quickly after encountering high temperatures, the fireproof rubber interlayer slowly foams and expands, and the maximum can be expanded about ten times. The composite fire-resistant glass is fixed in the slot of the steel frame open frame support structure. Although the fire-resistant rubber interlayer of the glass expands due to heat, the fire-resistant glass will quickly burst after encountering high temperatures.

**Figure 2.** Actual performance of fire-resistant glass
Expansion in the unconstrained direction of broken panels, etc. Although the fireproof glass interlayer in the slot will also expand slightly in the direction of entry and exit, the steel structure is exposed to high temperatures and the temperature of the steel structure is high. The weaker rigidity is beneficial to meet the micro-expansion requirements of composite fire-resistant glass, thereby achieving the requirements of fire-resistant integrity. The fireproof rubber interlayer foams and expands, absorbs the high heat brought by the flame burning, forms an opaque fireproof rubber sheet, and effectively plays a role in blocking heat conduction. After the fire reaches a certain time, the fire-resistant adhesive expands and expands due to heat, and finally falls off, which in turn causes the next piece of glass to break, and the next piece of fire-resistant adhesive expands and expands due to heat, effectively blocking heat conduction.

4. Fire-resistant characteristics and application technology of fire-resistant glass

4.1. Fire resistance characteristics of fire-resistant glass
Fire-resistant glass can be divided into heat-resistant fire-resistant glass and non-insulated fire-resistant glass according to fire resistance. Insulated fire-resistant glass is a fire-resistant glass that meets both fire-resistant integrity and fire-resistant insulation, namely Class A fire-resistant glass; non-insulated fire-resistant glass is a fire-resistant glass whose fire-resistant performance can only meet the requirements of fire-resistant integrity, that is, ℃ Class fire-resistant glass. According to GB15763.1—2009 "Safety Glass for Buildings Part 1: Fireproof Glass", the fire resistance limits of Class A and Class C fireproof glass are divided into 0.5h, 1.0h, 1.5h, 2.0h, and 3.0h.

![Figure 3](image_url) Analysis of the actual situation of fire resistance of fire-resistant glass

Fire-resistant glass should be heated by open flames during the fire resistance test, so that the test piece is exposed to a flame similar to the actual fire. The temperature in the test furnace changes with time, and the change rule should satisfy the following functional relationship:

\[
T_i = K \pi \sum_{j=1}^{n} m \pi j \pi S
\]

In the formula: \(T_i\) — the average furnace temperature rising to \(t\)℃;
It should be pointed out that when fire-resistant glass is used for smoke vertical walls, it is mainly affected by hot flue gas, and its fire resistance requirements are different from the standard fire test. Generally, it is required to heat up according to GB / T9978 "Fire Test Method for Building Components" When the temperature is raised to 620°C, and the temperature is maintained at 620°C±20°C for 30 minutes, the fire-proof glass smoke-retaining vertical wall should be kept intact.

![Figure 4. Analysis of fire resistance performance of fire-resistant glass](image)

Fire-resistant glass can be divided into composite fire-resistant glass and single-piece fire-resistant glass according to the structure. At present, there are two main technical routes for single-piece fire-resistant glass in China: first, high-strength single-piece fire-resistant glass and special fire-resistant glass (mainly borosilicate fire-resistant glass) with integrated strengthening treatment; and second, composite fire-resistant glass. Composite fire-resistant glass is a kind of transparent and flame-retardant gel that is condensed between two pieces of glass. This gel undergoes an endothermic decomposition reaction when it encounters high temperature, becomes opaque, and has the function of blocking flame. The production methods of composite fire-resistant glass are divided into two methods: sandwich method and grouting method. Its advantages are heat insulation, but its disadvantages are that it cannot be used directly on external walls and is difficult to further process. Compared with fire-resistant glass, monolithic fire-resistant glass has the advantages of good weather resistance, high strength, easy deep processing and convenient installation, but it is not insulated. Due to the difference in performance between single-piece fire-resistant glass and composite fire-resistant glass, they are complementary in architectural applications.

\[
T - T_0 = 345 \lg (8t + 1)
\]  
(2)

\[
C_2H_4O_2 + kO_2 \rightarrow kCO_2 + kH_2O + kCO
\]  
(3)

\(X, y, z\): represent the respective component coefficients  
\(K\): represents the burning coefficient of refractory glass  
Borosilicate glass has good chemical stability, high softening point about 850°C, and low thermal expansion coefficient. It can be used as heat-resistant and fire-resistant glass. The thickness of this
glass as fire-resistant glass is generally 6-8mm is suitable, it is widely used in some developed countries abroad. However, borosilicate fire-resistant glass has technical difficulties such as high melting temperature, high forming temperature, volatilization of boron during melting, prone to borosilicate-separated phase, and fast erosion of refractory materials in the furnace. The technical threshold and cost are very high high. In addition to borosilicate fire-resistant glass, special fire-resistant glass also includes aluminosilicate fire-resistant glass, microcrystalline fire-resistant glass, and soda-lime float glass with a softening temperature higher than 800℃. Its common characteristics are: the glass has a higher softening point, generally above 800℃, and a low thermal expansion coefficient, and will not generally burst or deform due to high temperature under strong flames, especially crocrystalline fire-resistant glass. In addition to the above characteristics, it also has It has high mechanical strength, high flexural and compressive strength, and good chemical stability and physical and mechanical properties. However, special materials of fire-resistant glass are expensive and difficult to accept in the market. At present, China's single-piece fire-resistant glass technology basically uses flat glass physical or chemical strengthening technology to improve the glass. The strength makes the glass able to withstand the stress generated during rapid heating, and thus has the function of fire prevention.

Figure 5. Structural analysis of fire-resistant glass curtain wall in high-rise buildings

The refractory mechanism of high-strength single-piece fire-resistant glass is to increase the strength of soda-lime-silica glass to counteract thermal stress and avoid cracks caused by cracks on the glass surface. During the fire, the glass expands due to heat, and the whole glass is deformed. The micro-cracks on the fire-receiving surface of the glass are subject to thermal stress and gradually expand and cause the glass to crack. To improve the thermal stress resistance of the glass, when the glass is thermally expanded, the high prestress on the surface will offset the thermal stress generated, so that the micro cracks no longer propagate and cause the glass to crack, thereby ensuring the fire resistance under flame impact or high temperature. When the heat received by the glass as a whole is greater than the heat lost from the back surface, the overall temperature of the glass gradually rises, and along the height direction, it gradually enters the softening zone from the fire surface until the viscosity of the glass back surface is not sufficient to support the weight of the glass itself. As a result, the glass as a whole collapses and loses its integrity.
Although single-piece fire-resistant glass has incomparable advantages compared with traditional fire-resistant glass, in the event of a fire, because the single-piece fire-resistant glass is not insulated, its heat radiation prevents fire the flammable, flammable materials and people's safe passage outside the zone will affect the safety. How to make the single piece of fire-resistant glass have a transparent appearance and ensure good fire resistance while having heat insulation has become a concern of designers. Studies have shown that the application of an automatic spray protection system to a single-piece fire-resistant glass partition can solve the problem of the single-piece fire-resistant glass insulation. By setting an automatic water spraying system at the upper edge of the fire-proof glass partition, when the air temperature of the glass backfire surface reaches the operating temperature of the sprinkler head after the fire, the automatic spraying system of the backfire surface starts, and the glass backfire surface forms a continuous water curtain. Takes away the heat absorbed by the glass due to heat transfer, so that the fire-resistant glass can maintain a low temperature even under a high fire load. Relevant tests show that under the protection of automatic spraying, the thermal insulation performance of the single-piece fire-resistant glass system is significantly improved, heat radiation is effectively blocked, and the fire resistance time of the glass is greatly extended. The temperature of the back surface below 40°C can be completely replaced Fireproof Shutter.

At present, the technology of fire-resistant glass is very mature. For example, the fire-resistant glass produced by Gravibao of Belgium, Saint-Gobain of France, and Guangdong King Kong Glass Technology Co., Ltd. is of very good quality and can meet the needs of curtain wall fire protection.

4.2. Requirements of fire-resistant glass in high-rise curtain wall application

In the design of a building, the fire protection function is an important content that cannot be ignored. There must be a clear fire rating in each area of the building. When using exposed materials, the fire rating must be equal to or higher than the area. In this way, it can play a good fire prevention role, the greatest possible loss of life and property and provide sufficient time for disaster relief work. Combined with the specific application of fire-resistant glass in the curtain wall of high-rise buildings in China, its design requirements should meet the following requirements:

4.2.1. In the selection of the main keel of fire-resistant glass curtain wall. When designing the fire protection function of the curtain wall of high-rise buildings, no matter how advanced and effective the fireproof glass used is, once the main keel material of the surrounding hidden frame is unqualified, the bearing capacity appears at high temperature, and it cannot achieve good fire protection. At present, the maximum temperature of aluminum alloy structural materials and silicone glue used in the design
of glass curtain walls in China is not more than 300°C, which has a serious impact on the current stability of fire-resistant glass. As a non-flammable building material, even if the keel is not coated with any fireproof material on the surface, it can be maintained at a high temperature of 1200°C for 180 minutes, even if it is slightly deformed, it will not affect the overall integrity. Can be used in large quantities in fire-resistant glass curtain walls.

4.2.2. Selection of glass for fire-resistant glass curtain wall. In addition to controlling the fire, smoke, and high-temperature diffusion, the glass selection of urban high-rise curtain walls should also meet the requirements of light transmission, high weather resistance, aesthetics, and consistency with the surrounding environment. Therefore, when selecting the glass for the curtain wall of high-rise buildings, under the long-term ultraviolet radiation and high temperature, the laminated fire-resistant glass will have a milky white color and affect the light transmittance of the glass; the reason will also affect the light transmission and visual effects to a certain extent. Therefore, a single piece of fire-resistant glass has become the mainstream choice in the glass curtain wall of modern high-rise buildings.

Table 2. Analysis of fire-resistant glass in fire-resistant glass curtain wall structure of high-rise buildings

| Fire Test Standard | Marking | Definition of Marking |
|--------------------|---------|-----------------------|
| ASTM E119 or UL 263 | W       | Meets wall assembly criteria. |
| NFPA 257 or UL 9    | OH      | Meets fire window assembly criteria including the hose stream test. |
| NFPA 252 or UL 10B or UL 10C | D H T | Meets fire door assembly criteria. Meets fire door assembly "Hose Stream" test. Meets 450°F temperature rise criteria for 30 minutes |
| XXX                |         | The time in minutes of the fire resistance or fire protection rating of the glazing assembly |

4.2.3. Measures for fire resistance of fire-resistant glass curtain wall. According to whether the various materials used in the fire-resistant glass curtain wall meet the specific requirements of the project, the fire resistance of the materials must be comprehensively tested. When testing the fire resistance of materials, we must pay attention to two points: First, when testing fire-resistant glass curtain walls, we must grasp the integrity, that is, we must test the fire-resistant glass and frame materials used. When testing the fire resistance, even if the fireproof glass can last for a long time, and the curtain wall frame or other auxiliary materials have fired, it is also considered as unqualified. Second, the fireproof glass samples are inspected. When testing, be sure to carry out the inspection strictly according to the 1:1 size of the installation with the practical project. During the inspection, you must strictly follow the principle that the small size cannot cover the large size, the large size can cover the small size, and the fired size does not cover. Can be tested and accepted less than 1100mm × 600mm.

4.3. Structural design of fire curtain wall

The steel frame of the fire curtain wall supporting keel adopts a steel frame, and the surface is painted with fire retardant paint. Considering the need for indoor aesthetics, the outside of the steel frame is surrounded by sprayed aluminum alloy profiles. Energy-saving performance. Fire-resistant glass
should not be in direct contact with rigid materials during design. At the same time, sufficient space must be left to ensure free expansion of heat. Fire-resistant glass has a large thermal expansion 15 minutes before the fire starts. At the same time, the glass still has heat. Brittle, although its strength is high, but the glass expansion is restricted or hard contact with the supporting structure after expansion may cause burst and lose the fire protection effect; fire-resistant rubber strips and pads are used between the fire-resistant glass and the curtain wall frame, which not only has Fire resistance also ensures the air and water tightness of the curtain wall.

5. Conclusion
Fire-resistant glass and system technology are important links in building fire protection, and the ideal frame design is the key to achieving the fire-resistant performance of fire-resistant glass systems. The fire-resistant glass system with fire-resistant glass as the main body can meet the different fire-resistant requirements of building curtain walls. Building fire protection issues are becoming more and more important. Fire-resistant glass systems have begun to make breakthrough applications in China's high-rise buildings. This requires China to actively use foreign successful experiences in fire-resistant glass as the theory and application of fire-resistant glass curtain walls in high-rise buildings. Based on the practical basis and the specific conditions in China, we will continue to improve the production technology of fire-resistant glass in China, so that the curtain walls of high-rise buildings in China are more secure and reliable on the basis of the basic conditions of transparency and aesthetics. This also indicates a good development space and prospects for China's fire-resistant glass and system technology

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