Correlation between parameters of support and thermal conductivity of tempered vacuum insulated glass based on grey system theory

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Abstract. In order to further reduce the thermal conductivity, the correlation between the parameters of support and the thermal conductivity of tempered vacuum insulated glasses was investigated based on grey system theory, and the grey relational values of the parameters of support and the thermal conductivity were obtained. The results show that the grey relational degree between the thermal conductivity and the arrangement of supports is greater than that between the thermal conductivity and the other parameters of support when the samples are produced with the same process and other components, which can provide evidences for further improving the properties of tempered vacuum insulated glass.

1. Introduction

The ordinary vacuum glass has the advantages of low heat transfer coefficient and good sound insulation, but its bearing capacity is poor [1]. Replacing two pieces of ordinary glasses in the vacuum glass with tempered glass is called the tempered vacuum insulated glass [2]. As a new generation of energy-saving glass, the tempered vacuum insulated glass has been application in construction field, appliances field, agriculture sector and BIPV field because of its advantages of avoiding condensation, energy-saving, sound insulation, high strength, wind load resistance and so on [3]. With the pressure on energy conservation and emission reduction has increasing, the structure and properties of tempered vacuum insulated glass have attracted more attention.

Support is an important component of the tempered vacuum insulated glass, its design is the key to the production of tempered vacuum insulated glass [4]. In the research of the supports of vacuum glass, many scholars had studied the mechanical theory in the design process of supports [5], and analyzed the mechanical properties of supports in practical application [6], a few studies had analyzed the influence of supports on the thermal conductivity of vacuum glass [7]. However, few studies have been reported on the correlation between the parameters of support and the thermal conductivity of tempered vacuum insulated glasses. It is an urgent problem to research the relationship between the thermal conductivity and the parameters of support of the tempered vacuum insulated glasses, determine which is the primary factor and which is the secondary factor among the parameters of support, and design the parameters of support reasonably for preparing the high-energy-saving tempered vacuum insulated glasses.

Grey system theory provides a way to solve the above problems [8-9], and builds a bridge between the parameters of support and the macroscopic properties of tempered vacuum insulated glass. In view of the complex relationship between many things and factors, the randomicity of a large number of experimental data and the numerous factors which are difficult to control, the theory found out the main
influencing factors from the various factors by the analysis of the development trend. In this paper, the parameters of support (material, shape, size, spacing and arrangement) of tempered vacuum insulated glass were regarded as grey system. The correlation between the thermal conductivity and the parameters of support of tempered vacuum insulated glass was studied by the calculation method of grey system correlation.

2. Experiment

2.1 Sample
The raw materials are substrates of tempered glass with a length of 300 mm, a width of 300 mm and a thickness of 4 mm. And the samples of tempered vacuum insulated glass had prepared for experiments by advanced preparation technology of LandVac. As shown in figure 1, one side is tempered Low-E glass, the other side is tempered float glass. There is a micro-air-pumping hole on tempered float glass. The edge is sealed by glass solder through the low temperature technology. There is an air absorbent between the two glass, and the vacuum degree reached the ideal state. The parameters of support are shown in table 1.

![Figure 1. Samples for testing the thermal conductivity.](image)

| Sample | Material      | Size/mm | Shape  | Arrangement     | Spacing/mm |
|--------|---------------|---------|--------|-----------------|------------|
| A1     | Stainless steel | Dia. 0.5 | Ball   | Regular triangle | 50         |
| A2     | Alumina       | Dia. 0.6, H 0.5 | Cylinder | Square      | 60         |
| A3     | Ni-based alloy | OD 0.6, ID 0.3, H 0.5 | Ring | Regular hexagon | 70         |

2.2 Characterization of Samples
According to JC/T 1079-2008 standard, the thermal conductivity of samples were measured by vacuum glass thermal conductometer. The test requires that the ambient temperature should be kept at 22±2°C and the ambient relative humidity should be kept at 20%–75%. Air-conditioning was used to control the temperature, humidifier and dehumidifier were used to control the humidity. Meanwhile, the measuring instrument for environmental temperature and relative humidity were used to detect the temperature and humidity in real time. The micro-morphology of pillars were observed by SRL-7045 stereomicroscope.
3. Results and discussion

3.1 Structural analysis of supports

Figure 2. Microscopic photographs of different positions of spherical supports.

Figure 2 are microscopic photographs of A1 with the supports at the middle and edge. It can be seen that the indentation depth of the support in the middle position is larger than that in the edge position from figure 2, which indicates that the support in the middle position is more stressed than that in the edge position. The contact zone between two supports at different positions and glass is approximately circular, so the contact area between the spherical supports and glass is not point contact at the atmospheric pressure, its contact area can be approximately equal to the contact area between the cylindrical supports with the same radius and glasses, thus improving the thermal conductivity of spherical supports, i.e. the thermal conductivity of tempered vacuum insulated glasses are increased.

3.2 Grey relational analysis of parameters of support and thermal conductivity of samples.

In order to analyze the importance of the parameters of support on the thermal conductivity of tempered vacuum insulated glasses, the qualitative factors should be quantified firstly, and the system behavior should be indirectly represented by the mapping quantity. Therefore, the thermal conductivity of supports are used to reflect the influence of the material of supports on the thermal conductivity of glasses, the volume of supports are used to express the influence of the size of supports on the thermal conductivity of glasses, and the contact areas between the supports and glasses are used to express the influence of the shape of supports on the thermal conductivity of glasses, the number of supports per unit area (per square metre) are used to express the arrangement of supports. The quantitative parameters of support and the data of thermal conductivities obtained from the test are listed in table 2, and then it carries on the grey correlation analysis to them.

| Sample | Thermal conductivity of supports/ (W·m⁻¹K⁻¹) | Volume/mm³ | Contact area/mm² | Quantity of per square metre | Spacing/mm | Thermal conductivity of samples/ (W·m⁻²K⁻¹) |
|--------|---------------------------------------------|------------|------------------|-----------------------------|------------|---------------------------------------------|
| A1     | 13                                          | 0.065      | 0.393            | 449                         | 50         | 0.443                                       |
| A2     | 16                                          | 0.141      | 0.565            | 289                         | 60         | 0.548                                       |
| A3     | 12                                          | 0.106      | 0.424            | 215                         | 70         | 0.392                                       |

Step 1: Assuming that the thermal conductivity of samples are listed as the parent sequence $Y_i(k)$, and the parameters of support are listed as the sub-sequence $X_i(k)$ ($j$ is 1, $i$ is 1~3, $k$ is the number of columns), the initial values of each sequence is obtained by dividing the values of each row by the values of the first row, which are shown in table 3.

| Initial values | $k$ |
|----------------|-----|
| $X_i(k)$       | 1   | 1.231 | 0.923 |
Step 2: Find the differences between the main sequence and the sequence. The values are shown in table 4.

\[
\Delta_i(k) = |y_i(k) - x_i(k)| (k \text{ is the number of columns})
\]

Step 3: Find the maximum and minimum differences between the poles.

\[
M = \max \Delta_i(k), m = \min \Delta_i(k)
\]

Table 4 shows that: \(M=1.256\), \(m=0\).

Step 4: Find the correlation coefficients.

\[
y_i(k) = \frac{m + \xi M}{\Delta_i(k) + \xi M}
\]

Among them, \(\xi\) is the resolution coefficient, it is generally 0.5 [10]. The calculation results are shown in table 5.

Step 5: Calculate the correlation degree \((p = 3)\), the values of which are shown in table 6.

\[
R_i(k) = \frac{1}{p} \sum_{i=1}^{p} y_i(k)
\]

Table 6 shows that the contribution of different parameters of support to the thermal conductivity is distinct. According to the values of correlation degree, the order of correlation coefficients between the parameters of support and the thermal conductivity of tempered vacuum insulated glasses are as follows: the arrangement of supports, the thermal conductivity of material of supports, the shape of supports, the spacing of supports and the size of supports. The results show that the grey relational degree between the thermal conductivity of tempered vacuum insulated glasses and the arrangement of supports is greater than that between the thermal conductivity of tempered vacuum insulated glasses and the other parameters of support. It can be inferred that the arrangement of supports contributes mostly to the thermal conductivity of glasses, followed by the material of supports, i.e. the thermal conductivity of supports also has a greater impact on the thermal conductivity of glasses. Therefore, the number of supports on per unit area should be reduced in the design process of the supports of tempered vacuum insulated glass which will greatly reduce the thermal conductivity of tempered vacuum insulated glasses.

### Table 4. Difference values between main sequence and sequences.

| Difference values | \(k\) | 1  | 2  | 3  |
|------------------|------|----|----|----|
| \(|y_i(k) - x_i(k)|\) | 0    | 0.318 | 0.164 |
| \(|y_i(k) - x_i(k)|\) | 0    | 1.256 | 0.872 |
| \(|y_i(k) - x_i(k)|\) | 0    | 0.525 | 0.320 |
| \(|y_i(k) - x_i(k)|\) | 0    | 0.256 | 0.280 |
| \(|y_i(k) - x_i(k)|\) | 0    | 0.287 | 0.641 |

### Table 5. Correlation coefficients of each sequence.

| Correlation coefficients | \(k\) | 1  | 2  | 3  |
|--------------------------|------|----|----|----|
| \(y_i(k)\)              | 1    | 0.664 | 0.793 |
| \(y_i(k)\)              | 1    | 0.333 | 0.419 |
| \(y_i(k)\)              | 1    | 0.545 | 0.662 |
Table 6. Correlation of parameters of support and thermal conductivity.

| Parameters of support | Correlation coefficients |
|-----------------------|--------------------------|
| Material              | 0.819                    |
| Size                  | 0.584                    |
| Shape                 | 0.735                    |
| Arrangement           | 0.872                    |
| Spacing               | 0.727                    |

4. Conclusion
1) The grey relational degree between the thermal conductivity of tempered vacuum insulated glasses and the arrangement of supports is the greatest when the samples are produced with the same parameters of production process and other components. It is inferred that the arrangement of supports contributes mostly to the thermal conductivity of tempered vacuum insulated glasses. Therefore, in the design process of tempered vacuum insulated glass, the number of supports on per unit area should be reduced as much as possible, which can help to minimize the thermal conductivity of glasses.

2) The grey relational degrees between the other parameters of support with the thermal conductivity of tempered vacuum insulated glasses are sorted by size as follows: the thermal conductivity of material of supports, the shape of supports, the spacing of supports and the size of supports.

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