Case analysis of thermal defect detection of near-zero energy building envelope based on infrared thermography

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Abstract. The thermal performance of the envelope structure is one of the important components of the performance design of near-zero energy buildings. Minimizing envelope heat loss is the key to improving building energy efficiency. A necessary first step in the building envelope optimization process is the assessment of its actual thermal performance. This paper summarizes the application status of infrared thermography in thermal defect detection of building envelopes and common forms of thermal defects in near-zero energy buildings. Taking a near zero energy building in Shenyang area as the target object, an efficient and non-destructive infrared thermal image measurement method is applied to determine the thermal defect rating of the building from both qualitative and quantitative aspects. The results show that the building has high thermal performance. The temperature field distribution of the building envelope could be quickly obtained by using the infrared thermal imaging instrument. In this way, it can accurately identify the location of thermal bridges and air tightness defects, and provide an efficient and accurate detection method for building energy-saving diagnosis and evaluation.

1 Introduction

Building energy efficiency is an important part of achieving carbon peaking and carbon neutrality goals. With the transformation and upgrading of the building energy conservation industry, the concepts of "ultra-low energy building", "near zero energy building" and "zero energy and zero carbon building" have been gradually promoted. The work on building energy efficiency design standards and green evaluation standards is particularly important. As a non-destructive testing technology, infrared thermography has the advantages of fast detection speed, high precision and real-time observation, which is widely used in building diagnosis and thermal performance testing, and has become one of the research hotspots in the field of non-contact testing. It is clearly pointed out in China's "Energy Conservation Testing Standard for Public Buildings" that the detection of thermal defects should be given priority before the in-depth detection of building envelope, so as to understand the changes in thermal characteristics of building envelope and air-tight components. Z. Li [1] discussed the infrared images of post-earthquake building frame structures and brick-concrete structures by means of image processing and mathematical statistics, and qualitatively analysed the relationship between infrared images and physical properties of materials, humidity, solar radiation and other factors. F. Asdrubali [2] introduced a quantitative factor: the incidence factor of the thermal bridge, at the aim of evaluating in a simple and effective manner the effect of thermal bridges on the global dispersions of buildings. In the follow-up research [3], their research team develop a procedure for the detection of the contours of thermal bridges from thermographic images, in order to study the energy performance of buildings. An improvement of the parameter defining the thermal bridge is obtained. M. O'Grady[4] introduced a window thermal transmittance or M-value to quantify the total additional heat loss through the building element due to the presence of the window. Research results demonstrated the suitability of the indoor quantitative infrared thermography technique for the heat loss assessment of multiple thermal bridges and windows in building components. B. Tejedor [5]. evaluated the influence of operating conditions and thermophysical properties on the accuracy of in-situ measured U-values, using the quantitative internal IRT method. D. González-Aguilera [6] described a new approach for image-based modeling based on thermographic images and applied to efficiency energy studies of building facades.

The researchers determine the thermal defects of the envelope structure by using infrared thermography, combined with image processing, computer vision and other technologies, and extended to the whole life cycle diagnosis of the building. Finally, a completed building inspection and evaluation system will be formed. This will become one of the important research directions in the field of building energy efficiency in the future.

2 Methodology

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2.1 Test object

The test object is a near zero energy building in Shenyang, which is divided into two floors. The first floor is 3.3m high and the second floor is 3.6m high. The construction area is 302.4m², and the appearance is shown in Figure 1. The exterior wall structure is mainly composed of polymer anti-crack mortar, SEPS insulation board (300mm), self-insulation wall and calcium silicate board, etc. The comprehensive heat transfer coefficient is 0.099 W/(m²·k). The roof shape is flat roof whose structure is mainly composed of waterproof roll-roofing material, cement mortar, XPS insulation board (280mm), autoclaved lightweight concrete slab. The comprehensive heat transfer coefficient is 0.090 W/(m²·k). The external window adopts insulated aluminum alloy window frame. The comprehensive heat transfer coefficient is 1.0 W/(m²·k).

![Fig. 1. Appearance drawing of near-zero energy building](image1.jpg)

2.2 Test method

The field test content is the diagnosis of thermal defects of building envelope, including building thermal bridge, external wall insulation system, air tightness of doors and windows, etc.

The test time was in February 2022. The maximum wind speed on that day was North wind force 3 and the relative humidity was 36%. In order to avoid the influence of solar radiation on the diagnostic results of infrared thermal imaging, the evening period was selected as the test period. During the detection period, the hourly change of outdoor air temperature is no more than 5°C, and the hourly change of indoor air temperature is no more than 2°C, which is in line with the environmental conditions stipulated by the standard.

The test instrument is FLUKE brand classic Ti series infrared thermal imager. Infrared wavelength range: 7.5~14.0 μm. Measuring temperature range: -20 ~ +250°C. Measurement accuracy: ±2°C or ±2%. Spatial Resolution: 3.39 mRad. The equipment meets the requirements of the technical parameters of building diagnostic infrared thermal imaging cameras stipulated by relevant national standards.

3 Test results and analysis

3.1 Infrared thermography test results

3.1.1 The external door

The external door is an important part of the heat loss in the building envelope, which is easy to generate thermal bridges and air leakage gaps at the connection. As can be seen from Figure 2, there is a significant temperature difference between the external door and the surrounding wall insulation because of the different materials. The two obvious high temperature areas in the infrared thermal image are caused by the reflection of the electronic lock of the external door and the detection instrument, which are not considered. The temperature distribution of the external door glass and the joints is relatively uniform, but there is a significant temperature increase at the joints between the door frame and the wall. Therefore, this part of the area is determined as the suspected location of thermal defects.

![Fig. 2. Natural light and infrared thermal image of the external door](image2.jpg)

3.1.2 The exterior window opening

The exterior window opening is also a key area prone to thermal defects. As can be seen from Figures 3 and 4, due to the use of high-performance insulating glass and window frame, the temperature distribution of the glass and window frame of single-sash and double-sash windows is relatively uniform. The sealant strips work well. There is basically no thermal bridge at the edge of the glass. However, there is a significant temperature difference between the upper part of the window frame and the lower part of the window sill plate. Although the area occupied is relatively small compared with the whole window, the resulting heat loss cannot be ignored. Therefore, it was identified as a suspected thermal defect area.

![Fig. 3. Natural light and infrared thermal image of the single-sash window](image3.jpg)

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3.1.3 The exterior envelope structures

Except for some fixed parts of the lower part of the window sill, the surface temperature distribution of the exterior envelope structure of the tested target building is relatively uniform, and there is no obvious thermal bridge defect. The external wall insulation material has a high level of installation technology, and the air tightness of the riveted part of the insulation board is properly handled. It can be seen that the overall thermal performance of the exterior envelope structures of the near-zero energy consumption building is fine.

3.1.4 The pipe external wall interface

The target building is equipped with a heat recovery fresh air unit in the east room on the first floor, and its external fresh air duct is the only part through the wall in the whole building. It can be seen from Figure 6 that the temperature distribution at the connection between the component and the outer wall is uniform, and there is no obvious temperature difference. The dark blue area is caused by the reflection of the sky by the outer covering of the smooth casing, which does not cause heat loss. The test results show that this part has been well treated for thermal bridge treatment during the construction phase.

3.2 Thermal defect grade evaluation

3.2.1 The evaluation method

Infrared thermal imaging results could accurately obtain the location of thermal defects, which cannot be used as a standard to evaluate the severity. According to domestic and foreign evaluation standards, the parameters for determining thermal defects including the maximum temperature difference $\Delta T_{\text{max}}$, the relative area ratio of thermal defects $\Psi$ and the area temperature difference $\omega$. The calculation formula is:

$$\Delta T_{\text{max}} = |\bar{T} - T_{\text{m}}|$$

(1)

Where $\Delta T_{\text{max}}$ is the maximum temperature difference between the average temperature of the detection area and the maximum/minimum grid temperature ($K$), $\bar{T}$ is the average temperature of the detection area ($^\circ C$) and $T_{\text{m}}$ is the maximum/minimum grid temperature ($^\circ C$).

The relative area ratio of thermal defects $\Psi$ should be calculated according to formula (2):

$$\Psi = \frac{\sum A_i}{A_0} \times 100\%$$

(2)

Where $\Psi$ is the relative area ratio of thermal defects, $A_i$ is grid area of the $i$-th thermal detection area($m^2$) and $A_0$ is projection expanded area of detection area($m^2$).

The area temperature difference $\omega$ should be calculated according to formula (3):

$$\omega = \sum A_i \Delta T_i$$

(3)

Where $\omega$ is the area temperature difference($m^2 \cdot K$), $A_i$ is grid area of the $i$-th thermal detection area($m^2$) and $\Delta T_i$ is the temperature difference between the grid of the $i$-th thermal defect area and the average temperature of the detection area($K$).

The thermal defect performance grading of building exterior window openings and exterior envelope structures are shown in Table 1 and Table 2.

**Table 1. Thermal defect performance classification of building exterior window openings**

| Thermal defect level | The area temperature difference ($\omega$) |
|----------------------|------------------------------------------|
| Severe               | $\omega > 0.20$                          |
| Moderate             | $0.10 < \omega \leq 0.20$               |
| Mild                 | $0.03 < \omega \leq 0.10$               |
| Pass                 | $\omega \leq 0.03$                      |
Table 2. Thermal defect performance classification of exterior envelope structures

| Thermal defect level | The maximum temperature difference ($\Delta T_{\text{max}}$) | The relative area ratio of thermal defects ($\varphi$) |
|----------------------|-----------------------------------------------------------|--------------------------------------------------|
| Severe               | $\Delta T_{\text{max}} > 6$                              | $\varphi > 40$                                   |
| Moderate             | $\Delta T_{\text{max}} > 6$                              | $20 \leq \varphi < 40$                           |
| Pass                 | $\Delta T_{\text{max}} > 6$                              | $\varphi < 20$                                   |
|                      | $\Delta T_{\text{max}} \leq 6$                           | -                                                |

Table 3. Thermal Defect Calculation Results

| Defect level | $\bar{T}$ | $T_m$ | $\Delta T_{\text{max}}$ | $\varphi$ | $\omega$ | Defect levels |
|--------------|-----------|-------|----------------------|----------|---------|---------------|
| External door| 0.5       | 2.6   | 2.1                  | -        | -       | Pass          |
| Single sash window | -0.7    | 2.1   | 2.8                  | -0.01    |         | Pass          |
| Double sash window  | -1.3    | 1.8   | 3.2                  | 0.015    |         | Pass          |
| Exterior envelope structures | -2.7    | 0.4   | 3.1                  | -        | -       | Pass          |
| Pipe external wall interface | -3.2    | 3.3   | 6.5                  | 4%       | -       | Pass          |

3.2.2 The evaluation results

According to the calculation method and judgment standard of the quantitative index of thermal defects in 3.1. If the relative temperature difference between the main area and the problem area is lower than 6°C, it is considered as qualified. If the temperature exceeds 6°C, the relative area ratio of thermal defects should be considered [7]. The infrared thermal image test results of the near-zero energy consumption building were evaluated and analysed, and the calculation results are shown in Table 3.

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