Research and Application of Construction Technology for Key Nodes of Zero-energy and Zero-carbon Buildings

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Abstract. Promoting energy conservation for buildings towards a state of ultra-low energy consumption and near-zero energy consumption has evolved into a top priority in the process of achieving the goal of "carbon dioxide peaking and carbon neutrality" in the building field. Conceptually, the goal of near-zero energy consumption building is defined as reducing the building energy consumption by 60% to 75% based on the current energy-saving design standards for public buildings. In this regard, this paper relies on the implementation and construction process of a project of the Beijing Municipal Administrative Center to conduct systematic research on the construction technology of key nodes of zero-energy and zero-carbon buildings. After implementing the technical plan, experimental testing and calculation were conducted on the heat transfer coefficient of the building envelope structure. Through effectiveness evaluation, the building achieved a good ultra-low energy consumption effect, laying a good foundation for achieving zero energy consumption and zero carbon buildings.

Keywords: Zero Energy Consumption; Zero Carbon; Thermal Bridge Blocking up; Air Tightness; Vapor Insulation; Heat-transfer coefficient

1 Introduction

China is the country with the largest number of existing buildings and annual new construction in the world. According to the "China Building Energy Consumption and Carbon Emissions Research Report (2021)", the total carbon emissions from the entire construction process in 2019 accounted for approximately 50.6% of the total carbon emissions in the country. Building carbon emissions are mainly concentrated in five links: building material production, transportation, construction, operation, and demolition[1]. Among them, the operation stage accounts for the highest proportion. Therefore, optimizing key nodes to reduce the energy consumption of the building itself is crucial for the green development of the construction industry[2].

The guidance documents concerning energy conservation for buildings have been issued intensively in numerous places in China since this year. In this context, vigorously advancing energy conservation for buildings has been accepted as the main

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content of the “14th Five-Year Plan” of various provinces and cities[3]. Likewise, promoting energy conservation for buildings towards a state of ultra-low energy consumption and near-zero energy consumption has evolved into a top priority in the process of achieving the goal of “carbon dioxide peaking and carbon neutrality” in the building field[4]. As mentioned above, the goal of near-zero energy consumption building refers to reducing the building energy consumption by 60% to 75% based on the current energy-saving design standards for public buildings. As a whole, this paper relies on the implementation and construction process of a project of the Beijing Municipal Administrative Center to conduct systematic research on the construction technology of key nodes of zero-energy and zero-carbon buildings[5]. The project is located in the Beijing Municipal Administrative Center, among which 2# Office Supporting Building(Fig. 1) is relatively independent and mainly undertakes the function of an exhibition hall. The project involved in this research, in a broad sense, is not only a direct embodiment of the green development vision advocated by General Secretary during the construction initiated by the Beijing Municipal Administrative Center, but also is of great reference, demonstration, and guiding significance for increasing the utilization of renewable energy and fully implementing zero-energy and zero-carbon building technology in the whole city[6].

Fig. 1. Effect Diagram of Project 2# Office Supporting Building

2 Research on Construction Technology for Key Nodes of Zero-energy and Zero-carbon Buildings

2.1 Construction Technology of Roofing Vapor Barrier, Insulation Layer, and Waterproof Layer

The roofing vapor barrier, insulation layer, and waterproof layer of this project adopt a “sandwich-shaped structure”, which consists of hot-melt polyester base (type II) SBS modified asphalt waterproof membranes with a thickness of 4 mm, self-adhesive glass-fiber reinforced base modified asphalt waterproof membranes with a thickness of 3 mm, staggered assembling of double-layer graphite polystyrene boards with a thickness of 250 mm（Fig. 2）, and self-adhesive acid and alkali-resistant aluminum foil glass fiber tire vapor-insulation membranes（Fig. 3） with a thickness of 1.2 mm from top to bottom[7]. Dry construction is completely realized by the closed-loop wrapping of the insulation layer formed by the roofing waterproofing membrane and the vapor-insulation membrane. Simply put, this technology not only effectively avoids the phenomenon that multi-layer insulation materials are difficult to eliminate due to water inflow but also avoids a series of hidden dangers, such as weakening of roofing insulation effect, bulging or freeze-thaw damage as well as chemical corrosion of waterproof layer[8].

The vapor barrier at the bottom of the ultra-thick insulation layer aims to prevent indoor water vapor from entering the insulation layer through upward movement, which may further cause various quality hidden dangers such as the failure of insulation layer performance as well as the bulging and destruction of the waterproof layer. Therefore, the self-adhesive acid and al-kali-resistant aluminum foil glass fiber tire vapor-insulation membranes with a thickness of 1.2 mm are used to construct the vapor barrier. In addition, it is necessary to make the vapor barrier form a fully-enclosed structural layer on the roof, which turns over to the top of the parapet along the surrounding parapet. Meanwhile, the subsequent construction of the waterproof layer is required to form an integral wrapping of the intermediate insulation layer jointly with the vapor barrier to prevent air leakage and water seepage[9].

The insulation board between the upper and lower layers is effectively bonded with polyurethane foam adhesive. During construction, the adhesive is directly applied to the insulation board, which is then quickly pressed on the base or bottom insulation board. In this regard, coiled waterproof membranes or other temporary heavy objects can be evenly pressed on the newly-bonded insulation board for at least 15 minutes to prevent the insulation board from shifting and falling off under the action of roofing wind load[10]. People are not allowed to walk on the surface of the insulation board until 2 hours after the bonding is completed.

In addition, the isolation membrane of self-adhesive waterproof membranes（Fig. 4） should be torn off evenly from one end of them during construction. While tearing off the isolation membrane, it is necessary to roll membranes slowly forward to exhaust the air inside and make them tightly bonded together. The bottom membrane shall be rolled up on the parapet to achieve bonding and sealing with the vapor-insulation membrane, thus ensuring the complete encapsulation of the flat insulation layer of the roof.

Upon the completion of the paving and acceptance of the bottom self-adhesive waterproofing membrane, the construction of the waterproofing membrane for the upper surface layer shall be started. The waterproofing membrane of the upper surface layer is rolled up to the top of the parapet to complete the closure with the vapor-insulation membrane. By completely wrapping the insulation layer on the side of the parapet, it can realize the complete drying and sealing of the system of the whole roof, encompassing the vapor barrier, insulation layer, and waterproof layer.

Fig. 2. Paving Diagram of the Staggered Assembling of Graphite Polystyrene Board

Fig. 3. Paving Diagram of the Vapor-insulation Membrane

Fig. 4. Paving Diagram of the Waterproof Membrane

2.2 Air-tightness Construction Technology of Peripheral Protection Structure

The air-tight layer typically refers to a continuous and seamless envelope that is located inside the outer envelope and made of air-tight material and can prevent gas leakage. Likewise, air tightness is usually defined as the ability of a building to prevent air leakage in the closed state. Air tightness is directly related to the indoor heat loss caused by cold air or hot air infiltration, namely, indoor energy loss. The higher the air tightness, the smaller the heat loss. In other words, the quality of air-tightness construction for the peripheral protection structure of buildings directly affects the energy-saving insulation and overall energy-saving effect of buildings. In particular, some buildings that emphasize the comfort of human settlements put forward more stringent requirements for air tightness. In this connection, the adoption of steel structures in these buildings generally leads to unsatisfactory air tightness. The reason is that the steel structure showcases assembly-type characteristics and has more gaps between components. Therefore, the expected air tightness effect is not easy to achieve.

Fig. 5. Construction Drawing of Bonded Waterproof and Vapor-insulation Membranes

Galvanized angle steel is welded at the fixed position of the main steel beam based on the setting out of the main steel structure. Furthermore, self-tapping self-drilling screws are used to fix cement pressure plates and galvanized steel sheets on galvanized angle steel respectively. The waterproof and vapor-insulation membranes should be aligned with the gap between the cement pressure plate as well as the gap between the cement pressure plate and the galvanized steel plate for bonding respectively. In addition, air-tightness treatment should be conducted for all easily identifiable gaps. More precisely, waterproof and vapor-insulation membranes (Fig. 5) should be bonded at the gap to form a barrier to ensure air tightness, which is beneficial to keep the air-tight layer continuous and penetrating to ensure the overall air tightness and prevent the air leakage of the building's peripheral protection structure, thus significantly improving the energy-saving efficiency of the building by reducing the heat loss and energy consumption of the building[11].

2.3 Construction Technology of Thermal Bridge Blocking up through Curtain Wall Connector

Regarding the external wall with metal curtain wall and steel structure frame, the direct fixation of curtain wall keel on steel column and steel beam will inevitably form a thermal bridge pas-sage composed of keel, connector, rear-positioned ground plate, steel column, and steel beam (secondary structure), which will lead to a higher thermal rate than similar concrete structures and seriously affect the indoor thermal insulation effect. Hence, the technology of thermal bridge blocking up, as a key technology suitable for ultra-low energy consumption buildings, is particularly important in terms of steel structure buildings[12].

Traditional curtain wall connectors are welded by embedded steel plates and square steel, and the same method is used for primary and secondary keels and connectors. As a result, the low thermal resistance of steel leads to the high thermal conductivity of connectors, which greatly affects the energy-saving effect of buildings. Nowadays, it is composed of adapters, stainless steel bolts, moisture-proof and heat-insulating gaskets (Fig. 6), and keel bolting. By effectively adding heat-insulating gaskets to cut off the transmission path of the thermal bridge from the keel, connector, and rear-positioned ground plate to the steel column and steel beam (secondary structure), a very good effect of reducing energy loss can thus be realized. The thermal resistance of the integral curtain wall connector is further improved by upgrading and reforming the connector and increasing the application of the treatment technology concerning thermal bridge blocking up for 10mm polyurethane moisture-proof and heat-insulating gaskets with high thermal resistance. Meanwhile, by changing the "surface-based" connection mode of connectors into a "point-based" connection mode (i.e., changing welding to hinge) and increasing heat-insulating gaskets to reduce the cross-sectional area of thermal transmission, the maxi-mum blocking up of thermal bridge is ultimately realized.

Fig. 6. Construction Drawing of Moisture-proof and Heat-insulating Gaskets

Except that the curtain wall connector and keel are fixed in the form of bolting, nylon gaskets with high thermal resistance are added to reduce the cross-sectional area of thermal trans-mission at the conversion connection and block the thermal bridge to the maximum extent, thereby reducing the thermal transmission of the curtain wall system. On the whole, the above construction technology is beneficial to greatly reduce the building energy consumption com-pared with the energy-saving design standard of public buildings, thus actively promoting environmental protection, energy conservation, and emission reduction, and reducing the energy loss of buildings. From a long-term perspective, the above construction technology is helpful to reduce carbon emissions, and more importantly, to achieve good environmental benefits.

2.4 Construction Technology of Air-tightness Treatment for Electromechanical Pipelines

To fulfill the air-tightness requirements of the project, great attention must be paid to the treat-ment of external walls, windows, roofs, and pipeline parts through the wall during the con-struction stage. To this end, special component connection and sealing materials should be adopted to implement the treatment concerning thermal bridge blocking up, thereby reducing the loss of energy transmission. In the meantime, the energy-saving goal of ultra-low energy-consumption buildings can only be achieved by reducing the damage to air tightness caused by pipeline parts through the wall and reducing the leakage points of air tightness to form a good air tightness whole.

After installing the pipeline according to the design requirements of the drawings, the air-tight adhesive tape should be used to bond the gaps. Meanwhile, the special thermal-insulation rock wool for the pipeline should be stuffed to realize the thermal bridge blocking up. In addi-tion, it is necessary to make another plastering air-tight layer on the outside of rock wool and the wall surface, with alkali-resistant glass fiber mesh attached to it to achieve crack resistance. In the case that the pipeline is round, the air-tight adhesive tape should be cut into small pieces for bonding. Each section of air-tight adhesive tape should be bonded to the pipeline and com-pacted first, then bonded to the wall and compacted, leaving no gap at the corner. On the other hand, In the case that the pipeline is rectangular, the air-tight adhesive tape should be wrapped around the pipeline, and the four corners of the pipeline should be overlapped with the air-tight adhesive tape.

3 Calculation of heat transfer coefficient of envelope structure

Through the implementation of the above key node construction technical scheme, the heat transfer coefficient of the building envelope has been greatly improved. Through experimental detection and theoretical calculation, the heat transfer coefficient of each part of the envelope is as follows:

3.1 Enclosure Structure 1-External Wall (Table 1)

Inner surface heat transfer coefficient α n [w/(MK)]: 8.7
External surface heat transfer coefficient α w [w/(MK)]: 23
Thermal resistance of enclosed air interlayer rk [MK/w]: 0

Table 1. Test and test parameters of various envelope materials involved in external walls.

Material name	Thickness δ[mm]	λ[W/(mK)]	Correction factorα_λ	Thermal resistance R =$\delta/(\alpha_\lambda \times \lambda)$ [m^2K/W]
Cement fiber pressure plate	24	0.930	1.00	0.026
Rock wool board	80	0.040	1.10	1.818
Cement fiber pressure plate	24	0.930	1.00	0.026
Rock wool board	130	0.040	1.10	2.955
Total	258	--	--	4.824

Heat-transfer coefficient $K=1/(1/\alpha_n+\sum R+R_k+1/\alpha_w)$ =0.201 [W/(m^2K)]

3.2 Enclosure Structure 2- External wall (underground) (Table 2)

Inner surface heat transfer coefficient α n [w/(MK)]: 8.7
External surface heat transfer coefficient α w [w/(MK)]:12
Thermal resistance of enclosed air interlayer rk [MK/w]: 0

Table 2. Test and test parameters of various envelope materials involved in external walls (underground).

Material name	Thickness δ[mm]	λ[W/(mK)]	Correction factorα_λ	Thermal resistance R =δ/(α_λ×λ) [m²K/W]
Reinforced concrete exterior wall	200	1.740	1.00	0.115
3mm waterproof membrane	3	0.170	1.00	0.018
4mm waterproof membrane	4	0.170	1.00	0.024
Extruded polystyrene Board	150	0.030	1.15	4.348
Additional waterproof layer	3	0.170	1.00	0.018
Brick wall protective layer	100	1.280	1.00	0.078
Total	460	--	--	4.600

Heat-transfer coefficient $K=1/(1/\alpha_n+\sum R+R_k+1/\alpha_w)=0.208$ [W/(m²K)]

3.3 Enclosure Structure 3- Roof covering (Table 3)

Inner surface heat transfer coefficient α n [w/(MK)]: 8.7

External surface heat transfer coefficient α w [w/(MK)]:23

Thermal resistance of enclosed air interlayer rk [MK/w]: 0

Table 3. Test and test parameters of various envelope materials involved in roof covering.

Material name	Thickness δ[mm]	λ[W/(mK)]	Correction factorα_λ	Thermal resistance R =δ/(α_λ×λ) [m²K/W]
Reinforced concrete roof slab	120	1.740	1.00	0.069
Fine aggregate concrete sloping layer	50	1.280	1.00	0.039
Waterproof and vapor proof membrane	1	0.170	1.00	0.007
High capacity and heavy weight graphite polystyrene board	250.0	0.033	1.05	7.215
Bottom waterproof membrane	3	0.170	1.00	0.018
Surface waterproof membrane	4	0.170	1.00	0.024
Fine aggregate concrete protective layer	50	1.280	1.00	0.039
Total	478	--	--	7.410

Heat-transfer coefficient $K=1/(1/\alpha_n+\sum R+R_k+1/\alpha_w)=0.132$ [W/(m²K)]

3.4 Enclosure Structure 4- Unheated basement roof (Table 4)

Inner surface heat transfer coefficient α n [w/(MK)]: 8.7
External surface heat transfer coefficient α w [w/(MK)]:12
Thermal resistance of enclosed air interlayer rk [MK/w]: 0

Table 4. Test and test parameters of various envelope materials involved in unheated basement roof.

Material name	Thickness δ[mm]	λ[W/(mK)]	Correction factorα_λ	Thermal resistance R =$\delta/(\alpha_\lambda\times\lambda)$ [m^2K/W]
Cement mortar plastering layer	15	0.930	1.00	0.016
Reinforced concrete roof slab	120	1.740	1.00	0.069
Cement mortar leveling layer	20	0.930	1.00	0.022
Rock wool board	200	0.040	1.10	4.545
Cement mortar plastering layer	15.0	0.930	1.00	0.016
Total	370	--	--	4.668

Heat-transfer coefficient $K=1/(1/\alpha_n+\sum R+R_k+1/\alpha_w)=0.205$ [$W/(m^2K)$]

4 Conclusion

This article combines the construction and implementation process of a certain project in the Beijing Municipal Administrative Center, and through research on the construction technology of key nodes in the building, summarizes and forms mature and operable technical solutions such as construction technologies of the roofing vapor barrier, insulation layer, and waterproof layer, air tightness of peripheral protection structure, thermal bridge blocking up through curtain wall connector, and air-tightness treatment for electromechanical pipelines. After the implementation of the technical plan, the heat transfer coefficients of the building's various parts of the enclosure structure were tested and tested, effectively verifying that the technical plan proposed in this study can effectively improve the heat transfer coefficient of the building's enclosure structure, reduce local energy consumption to a certain extent, improve the overall energy-saving effect of the building, and is of great significance for achieving zero energy consumption and zero carbon in the building. At the same time, it has accumulated rich experience and provided reference for the construction of similar projects in the future, which has good economic and social economic benefits and is worthy of widespread use and promotion.

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