Research on Key Technologies of Small House Type Ultra-Low Energy Consumption Residential Buildings

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Abstract: For ultra-low energy consumption buildings, passive mode is emphasized to realize ultra-low energy consumption and provide comfortable indoor environment. It mainly relies on the high-performance building enclosure, new air heat recovery, air tightness, adjustable sunshade and other building technologies, but the difficulty of realizing passive ultra-low energy consumption mainly lies in the technical suitability. How to meet the energy demand of heating and cooling under the condition of non mechanical, non energy consumption or less energy consumption through the reasonable design of key technologies. Based on the climate characteristics of Beijing, this paper studies the key technologies of ultra-low energy consumption buildings, and tries to make a positive exploration on the technology promotion of ultra-low energy consumption buildings.

1. Introduction
The ultra-low energy consumption building is a kind of building which takes the ultra-low building energy consumption as the constraint goal, has the high thermal insulation performance, high air tightness external enclosure structure and high efficiency heat recovery new air system, and can guarantee the indoor comfortable environment at the same time.

The basic principle of ultra-low energy consumption building is to reduce heating demand significantly by minimizing heat loss and maximizing sunlight in winter, and to reduce cooling energy consumption by minimizing the heat energy through passive window, sunshade and orientation optimization in summer. In order to achieve a good balance of heating and cooling energy consumption and achieve the goal of ultra-low energy consumption, the technical measures of passive priority and active optimization are taken for ultra-low energy consumption buildings.

The basic regulation of ultra-low energy consumption buildings is to take a reasonable orientation by making full use of the natural resources of the site; the buildings should meet the requirements of natural ventilation and natural lighting, while reducing the energy consumption of ventilation and lighting; the energy-using equipment such as electrical appliances of the buildings should be energy-saving equipment that meet the relevant national standards; the shape coefficient of the building should not be greater than 0.4; at the same time, the external window should be set with sunshade [1].

Based on the climate characteristics of Beijing, this paper studies the key technologies of ultra-low energy consumption buildings. Through the integration and demonstration application of new materials, new products and new technologies, such as new insulation wallboard, high-efficiency heat recovery new air system and renewable energy utilization technology, this paper establishes an
ultra-low energy consumption building technology system suitable for Beijing, trying to make a positive exploration on the technical promotion of ultra-low energy consumption buildings.

2. Excellent External Insulation System
From the perspective of the thermal design zoning of buildings in China, Beijing belongs to a cold area, which is characterized by cold and dry climate in winter as well as high temperature and rainy climate in summer. The building shall meet the requirements of heat preservation in winter and heat prevention in summer.

The excellent external thermal insulation system of ultra-low energy consumption building should not only have a good insulation performance, but also meet the fire protection requirements of the current codes. Because the heat loss of opaque building enclosure accounts for more than 70% of the building heat loss, strengthening the thermal insulation performance of opaque building enclosure and reducing its K value can effectively reduce the building energy consumption; at the same time, the combustion performance of external thermal insulation materials should meet the requirements of GB50016-2014 Code for Fire Protection Design of Buildings; the thermal insulation treatment of heat bridge of the external thermal insulation system and detail nodes should be constructed in a refined way[2].

Through the investigation of the demonstration project, the research group has developed the rock wool grade A external thermal insulation system, modified graphite polyphenyl board grade B1 external thermal insulation system and assembly type prefabricated sandwich wall panel system that meet the requirements of ultra-low energy consumption buildings.

2.1. Rock Wool Strip External Thermal Insulation System
The rock wool strip external thermal insulation system uses the rock wool strip with heat transfer coefficient $\lambda \leq 0.045 \text{ W/(m·K)}$, tensile strength $\geq 130\text{kpa}$, acidity coefficient $\geq 1.9$ and thickness of 250mm, and it is composed of a double net system with interlayer bays which mainly adopts the method of "pasting combined with anchoring, and pasting priority".

![Figure 1. Rock wool insulation structure](image)

After determining the composition and construction technology of the rock wool strip external thermal insulation system, the impact of the thickness of the insulation layer on the building energy consumption is analyzed by establishing a model for simulation calculation, the durability of the system is tested by the weathering test, and the safety of the system is tested by the wind pressure resistance test and vertical anti-hanging test. Meanwhile, the impact of the installation (interlayer bay) and construction method on the energy consumption is considered.

2.1.1. Influence of insulation thickness on energy consumption.
The external wall insulation system formed by 4 kinds of rock wool strips with thickness of 200 mm, 250 mm, 300 mm and 330 mm is used to compare and analyze the cooling and heating demand of the system; considering the influence of external shading and different heat transfer coefficients, the
external wall insulation system of 4 kinds of thickness has little impact on the cooling demand. When the thickness of the thermal insulation layer increases to 300 mm or more, the influence of the rock wool strip thickness of the outer wall thermal insulation layer on the heating demand is relatively low. Therefore, for comprehensive consideration, the external insulation system adopts 250 mm thick rock wool strip.

Table 1. Influence of different insulation thickness on energy consumption

| Thickness of rock wool strip (mm) | Whether there is external sunshade | Heat transfer coefficient | Heating demand kWh/m² | Cooling demand kWh/m² |
|----------------------------------|-----------------------------------|--------------------------|-----------------------|-----------------------|
|                                  | No | Yes | No | Yes | No | Yes | No | Yes |
| 200                              | 0.23 | 0.19 | 0.15 | 0.14 | 7.01 | 8.02 | 6.30 | 7.15 | 27.25 | 20.63 | 27.11 | 20.48 | 26.99 | 20.35 | 26.94 | 20.30 |
| 300                              | 0.25 | 0.16 | 0.17 | 0.14 | 7.56 | 8.57 | 6.80 | 7.65 | 27.99 | 21.41 | 27.88 | 21.29 | 27.66 | 21.18 | 27.63 | 21.15 |
| 330                              | 0.27 | 0.17 | 0.18 | 0.15 | 8.15 | 9.16 | 7.20 | 8.05 | 28.64 | 22.06 | 28.60 | 22.00 | 28.56 | 22.00 | 28.53 | 22.00 |

The following diagram shows the relationship curve between the annual heating energy consumption of the building and the thickness of the external insulation rock wool board. When the thickness of rock wool increases from 200mm to 330mm, the heat transfer coefficient decreases from 0.2W/(m²·K) to 0.12W/(m²·K), while the annual heating energy consumption of buildings only decreases by 0.08kW·h/(m²·a). Therefore, from the perspective of building energy consumption and economy, it is more reasonable to choose the thickness of rock wool as 250 mm.

2.1.2. Durability
In order to verify the durability of 250mm thick rock wool strip external insulation system under simulated natural conditions, a large-scale weathering test was carried out according to the standard. In the test, the weathering test of the outer insulation system of rock wool strip was tested for 80 hot rain cycles and 5 cold and hot cycles.
The test results show that the external insulation system of 250mm thick rock wool strip meets the requirements of JGJ144 *Technical Specification for External Thermal Insulation on Walls*. After the test, the color of the thermal imaging photos is relatively uniform. When the temperature difference between the inside and outside is large (50 °C), there is no heat bridge phenomenon between the rock wool strips, and the rock wool strip has a good heat preservation and heat insulation as well as good weather resistance.

![Figure 3. Durability test of rock wool insulation system](image)

**Figure 3.** Durability test of rock wool insulation system

### 2.1.3. Safety

The safety of 250mm thick rock wool strip external insulation system under simulated negative wind pressure is verified by wind load test. For the rock wool strip used in the test, the tensile strength of the vertical plate is greater than 130 kpa, so the theoretical calculation is safe; the test wall has passed the large-scale wind pressure test, which proves that it is safe.

![Wall body for wind load resistance experiment](image)

**Figure 4.** External insulation system wind load experiment

The anti-hanging ability of 250mm thick rock wool strip external thermal insulation system under natural conditions is verified by shear resistance experiment. The experimental results show that the bay can effectively reduce the longitudinal displacement of the rock wool strip external thermal insulation system, and improve the shear resistance and stability of the system.
2.1.4. **Influence of interlayer bay on energy consumption**

The bay scheme is to add one layer of bay in every two floors, with the transverse bay spacing of 800 - 1000mm. The bay size is L (length) × 50mm (width) × 5mm (material thickness), and the heat transfer coefficient is 50W/(m·K); the heat insulation gasket (composite material) has a thickness of 5mm and heat transfer coefficient of 0.024W/(m·K).

The influence of installing interlayer bay on the heat transfer performance of the thermal insulation system is simulated and calculated. It can be seen from the simulation results that when the projection length of bay is about 2/3 of the thickness of the insulation layer, the influence on the heat transfer coefficient of the system is very small; at the same time, heat insulation block shall be used for the bay to block the heat bridge.

2.2. **External Thermal Insulation System of Modified Graphite Polystyrene Board + Rock Wool Fire Protection Strip**

The research group has developed the modified graphite polystyrene board for ultra-low energy consumption buildings, which has good heat preservation performance, low heat conductivity coefficient λ ≤ 0.032 W/(m·K), combustion performance of flame retardant grade B1, low smoke production, no ignitability of molten droplets, no toxic gas after combustion, and high oxygen index. It has excellent physical and mechanical properties, and its tensile strength perpendicular to the plate surface reaches 0.24Mpa.
The system adopts the traditional thin plastering system, and the fire barrier zone is set according to the requirements of GB50016-2014 *Code for Fire Protection Design of Buildings*. The modified graphite polystyrene board should be pasted in double layers, and the board with notches can be single-layer pasted. The following diagram shows the construction details of the external thermal insulation system.

3. High efficiency energy-saving window system

The design, construction and operation of ultra-low energy consumption buildings take the building energy consumption value as the constraint goal. For the energy-saving window, the external window system with higher heat insulation performance, sunshade performance and air tightness performance should be adopted, and the design and construction of the no heat bridge should also be satisfied.

Generally speaking, the external windows used in ultra-low energy consumption buildings include aluminum alloy doors and windows, plastic steel doors and windows, aluminum clad wood doors and windows, etc. Based on the aluminum wood composite energy-saving window, an efficient energy-saving window system is developed.

3.1 Aluminum Wood Composite Energy Saving Window

The frame profile of aluminum wood composite energy-saving window is made of 78m thick Larch finger jointed composite material, and the thermal conductivity coefficient of pine type composite material is 0.13W/(m·K); the heat transfer coefficient can be reduced from 1.8W/(m²·K) to 1.3W/(m²·K) by attaching 20mm aluminum frame and filling with flame-retardant and efficient thermal insulation material.

The glass part of the aluminum wood composite energy-saving window adopts the composite glass of three glass and two cavities - hollow - vacuum + Low-e. The configuration of the glass is $5 + 18A$ (warm side) + $5V5$. The main performance indexes are: the heat transfer coefficient is $0.516W/(m^2·K)$,
the light heat ratio is 1.41, and the total solar energy transmission ratio is 0.522.

The aluminum wood composite energy-saving window glass interval adopts warm-edge interval strip, which is SWISSPACER ADBANCE ordinary warm-edge interval strip, with the thermal conductivity \( \lambda \) value of 0.290\( \text{W/(m·K)} \).

![Figure 9. Passive aluminum composite window node diagram](image)

The sealing of energy-saving window frames and sashes adopts the design of four sealing strips. The three sealing chambers formed are conducive to reducing the convection of gas and greatly improving the air tightness of the whole window. The four seal windows have better sealing performance than the three seal windows, and the water tightness and wind pressure resistance are improved by one level respectively. The six lock points increase the wind pressure resistance of the passive aluminum wood composite windows.

![Figure 10. Passive structure of aluminum-wood composite window](image)

To sum up, the design of high-efficiency energy-saving window mainly considers profile type and structure, composite glass configuration, sealing and lock point setting, etc. The main structure is made of wood profiles, the aluminum alloy profiles are fixed by plastic connecting clips, and the middle area between the window frame wood profiles and aluminum frames are filled with high-efficiency flame-retardant insulation materials, which effectively reduces the heat transfer coefficient of window profiles. The window glass system adopts three glasses and two cavities - hollow - vacuum + Low-E glass with warm edge spacer strip, which improves the thermal insulation performance of the window glass. Four sealing strips are used to improve the airtightness of
energy-saving windows, and six locking points are set to improve the wind pressure resistance of the whole window.

After testing, the aluminum wood composite window frame has a heat transfer coefficient of 1.3 W/(m²·K), and the whole window has a heat transfer coefficient of 0.8 W/(m²·K), air tightness of grade 8, water tightness of grade 6 and wind pressure resistance of grade 9, which is the highest level at present; the anti-dewing factor is grade 10, and the air sound insulation performance is grade 4. The product has been granted the PHI certification of German Passive Housing Research Institute and the certification of healthy dwelling product of Technology and Industrialization Center of Ministry of Housing and Urban Rural Development.

3.2. Installation of Energy Saving Windows

The east-west rooms of ultra-low energy consumption buildings should consider the sun light. In order to reduce the cooling energy consumption in summer, the movable external sunshade system should be used. The sunshade shall be installed in the way of external suspension, and the window shall be installed in the insulation layer. The waterproof vapor barrier film shall be pasted inside the window, and the waterproof air permeable film shall be pasted outside the window.

The linear heat transfer coefficient of the heat bridge and the installation heat transfer coefficient of the window are quite different with different installation methods. According to the simulation calculation, when the window is installed on the masonry and the insulation layer is interrupted, the linearity of the whole window will increase from 0.005 W/(m·K) to 0.15 W/(m·K). The installation details of the energy-saving window are as follows.

![Energy-saving window installation](image)

**Figure 11. Energy-saving window installation**

4. High Efficiency Heat Recovery New Air System

In the ultra-low energy consumption building with high air tightness, it is not allowed to neglect to provide fresh air for users. Filtering the particles in the air can provide clean fresh air for the residents, and reasonable air distribution ensures the comfort of the air supply; the new air system installed with efficient heat recovery device can preheat (winter)/precool (summer) the new air of exhaust energy, so as to reduce energy consumption. High efficiency heat recovery new air system includes the centralized, semi-centralized and household type.

The ultra-low energy consumption buildings have no radiator heating, so the outlet temperature of
the new air system must meet the minimum requirements in order to prevent the indoor temperature from being too low in winter; in order to ensure the indoor temperature comfort of the ultra-low energy consumption building, the outlet temperature of the new air should always be above 17°C. For the fan energy consumption, it is required that the value of fan power consumption $W_s$ is not higher than 0.45W/m$^3 \cdot$h when conveying unit volume of air. In consideration of safety, anti-freezing measures must be taken for the new air heat exchanger. Especially when the temperature of the new air is lower than 0 °C, the condensed water vapor may freeze due to the high moisture content in the exhaust side of the heat recovery device, so anti-freezing measures such as preheating, etc shall be taken.

4.1. System Layout
At present, the layout of high-efficiency heat recovery new air system has centralized, semi-centralized and household type.

Centralized new air system: one or more sets of cooling and heating sources are arranged in a centralized way, and new air is delivered to each room through pipes. The centralized new air system is usually composed of new air unit and auxiliary energy system, and it usually adopts the centralized new air unit + centralized auxiliary cooling and heating source system.

It is commonly used in the central air conditioning system of large-scale public buildings. The air duct occupies part of the floor height, and the fan has a long conveying distance and high energy consumption. This way is convenient for centralized management and control.

Semi-centralized new air system: one new air unit on each floor provides new air for each household, and one integrated cooling and heating source unit is set for each household to provide the temperature conditions of each household, and supplement the heat loss caused by the new air system and the cooling and heating demand in winter and summer. The integrated new air machine is to supply new air to each household through public pipes, return air through each household's toilet and recover heat through heat exchange.

For centrally managed public rental housing and some public buildings, semi-centralized layout can be adopted.

Household type new air system: the air source heat pump is usually used as the auxiliary energy source for the integrated new air and cooling and heating functions of the household new air unit. It is composed of integrated new air cooling and heating source unit, outdoor unit, etc. Residential buildings with ultra-low energy consumption mostly adopt the household type new air system, which has the characteristics of compact equipment, simple layout, short transportation distance and low noise.

4.2. Form of Auxiliary Energy
Due to the extremely low energy demand, there are many types of auxiliary energy for the cooling / heating of ultra-low energy building, and the more common ones are: auxiliary cooling / heating of air source heat pump, auxiliary precooling / preheating new air of air through tunnel, etc.

Air source heat pump integrates the cooling / heating functions into one unit, and it is widely used in ultra-low energy consumption buildings because of its compact equipment and simple system layout.

For projects with conditional arrangement of soil heat exchanger, air through tunnel can also be used as auxiliary energy for precooler / preheating of new air.

5. Complete and Continuous Air Tight Layer
Airtight layer refers to the seamless enclosure layer which can prevent gas leakage in the building. The excellent air tightness in ultra-low energy consumption buildings can effectively reduce the heating load, improve the living comfort of people, avoid indoor condensation and mildew, and reduce noise and air pollution. Therefore, the unorganized flow of air inside and outside the buildings can be strictly controlled by forming a complete and continuous air tight layer in the building enclosure structure.

On all the plan and section drawings of the building, the pencil can go through the air tight layer continuously and completely without interruption.
The cast-in-place concrete or the masonry external wall after plastering treatment of more than 20 mm can be regarded as the air tight layer. Special treatment measures shall be taken for the installation of doors and windows, pipe passing through the outer wall and the socket on the air tight layer, etc., and detailed node drawings shall be drawn.

**Figure 12. Building airtight schematic**

6. **Design Method of No Heat Bridge**

The common heat bridges in construction include structural heat bridge, systematic heat bridge and geometric heat bridge.

Structural heat bridge: the heat bridge resulting from the discontinuity or thinning of the thermal insulation layer caused by the penetration of structural members such as beams, columns and plates into the thermal insulation layer shall be eliminated as far as possible.

Systematic heat bridge: fix the anchor bolt and metal connector of the external thermal insulation system, and fix the bracket of various equipment and sewer pipe, etc. The systematic heat bridge is usually inevitable, but it must be blocked.

Geometric heat bridge: it is the heat bridge caused by the increase of local heat transfer coefficient due to the change of geometric structure. For example, heat preservation and insulation treatment for internal and external corners and roof parapets.
Figure 14. The first floor and wall insulation at the junction node

Figure 15. Water insulation node
7. Conclusion
To develop ultra-low energy buildings, technology and design are the foundation, materials are the key and construction is the guarantee. Ultra-low energy consumption buildings mainly rely on high-performance enclosure structure, new air heat recovery, air tightness, adjustable sunshade and other building technologies, but the difficulty of realizing passive ultra-low energy consumption mainly lies in the technical suitability. Through the research on the key technologies of ultra-low energy consumption buildings in Beijing, this paper summarizes the key technologies of ultra-low energy consumption buildings, and actively explores the technical promotion of ultra-low energy consumption buildings.

8. References
[1] Technical guidelines for passive ultra-low-energy consumption green building (Trial) (residential building) of the Ministry of Housing and Urban-rural Development of the People's Republic of China 2015
[2] Song Changyou, Ji Guangqi, et al. 2008 Fire Performance Test and Evaluation Method of External Wall Insulation System [J], Building Science 2 24-29.