Research on Key Technology of Ultra-Low Energy Consumption Buildings in Beijing

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Abstract. Ultra-low energy buildings focus on realizing ultra-low energy consumption mainly by virtue of passive mode and providing a comfortable indoor environment. Such buildings mainly rely on high-performance envelope, fresh air heat recovery, air tightness, adjustable shade and other building technologies to enable ultra-low energy consumption. However, the difficulty mainly lies in technical suitability. That is, how to meet the energy requirements of heating and cooling under the conditions of non-mechanical, no energy or less energy consumption through reasonable design of key technologies. Combining with the climate characteristics of Beijing, this paper studies the key technologies of ultra-low energy buildings and attempts to make active exploration on the technical advance of ultra-low energy buildings.

1. Introduction

To realize ultra-low building energy consumption, ultra-low energy buildings are equipped with envelope with good performance in thermal insulation property and air tightness, and with efficient heat recovery air system, thus enabling a comfortable indoor environment.

The basic design principle of ultra-low energy buildings is to significantly reduce heating demand by minimizing heat loss and maximizing sunshine capturing in winter, and to reduce energy consumption of refrigeration by minimizing consumption of heat energy in summer through such measures as installation of passive window, shade and orientation optimization. It is appropriate to adopt passive priority and active optimization technology to well balance heating and cooling energy consumption and realize the goal of ultra-low energy consumption.

The basic regulations of ultra-low energy buildings include: fully utilizing natural resources available on the site, selecting reasonable orientation, following natural ventilation and natural lighting requirements, lowering energy consumption in terms of ventilation and lighting, selecting energy-saving electrical equipment satisfying relevant Chinese standard, controlling shape coefficient of building within 0.4, and mounting external window shading device.

This paper studies key technologies of ultra-low energy buildings based on the climatic characteristics of Beijing, establishes an ultra-low energy building technical system applicable to Beijing through integration and pilot application of such new materials, products and technologies as new type insulation wall board, efficient heat recovery air system and renewable energy utilization technology, and make active exploration on technical improvement of ultra-low energy buildings.
2. Excellent rock wool thermal insulation system

Based on the thermal performance design zoning of China, Beijing belongs to cold area, which is characterized by cold and dry winter and hot and rainy summer. Hence buildings in the city shall meet both insulation requirement in winter and heat shielding requirement in summer.

An excellent external insulation system of ultra-low energy buildings not only has good insulation performance, but also conforms to current fireproof codes. Given that thermal loss of opaque building enclosure accounts for over 70% of total thermal loss of building, energy consumption of building will be effectively reduced by improving insulation performance of opaque enclosure and lowering K value; meanwhile, combustion performance of external insulation material shall satisfy the stipulation of the Code of Design on Building Fire Protection and Prevention (GB50016-2014); external insulation system and detail node broken heat bridge insulation treatment shall be finely constructed.

Based on the survey on the demonstration project, the research group has developed Grade-A rock wool external insulation system meeting requirement for ultra-low energy buildings.

2.1. Structure of rock wool external insulation system

Rock wool external insulation system is composed of 250mm-thick rock wool bars with heat transfer coefficient $\lambda \leq 0.045$ W/(m·K), tensile strength $\geq$130kpa and acidity coefficient $\geq$1.9. The system is of a double-grid type, mainly adhered and supplemented by anchoring, with bay set between layers, as shown in Figure 1.

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

After the rock wool insulation system composition and construction technology are determined, a model is established and simulated calculation is conducted to analyze the impact of the insulation layer thickness on building energy consumption; weathering test is carried out to test the system durability, and anti-wind pressure test and anti-hanging test are made to test the system safety, taking into consideration the influence of installation (interlayer bay) and construction method on energy consumption.

2.1.1. Influence of insulation thickness on energy consumption. Comparative analysis on cooling and heating demands of external insulation system (composed of rock wool bars with thicknesses of 200mm, 250mm, 300mm and 330mm respectively) are conducted, as shown in Table 1; cooling demand of the external insulation system is almost unaffected when external shade and heat transfer coefficient are different. When insulation layer thickness is increased to 300mm and above, the influence of rock wool bar thickness on heating demand is low. Based on the overall consideration, the external insulation system is adopted with 250mm thick rock wool bar.
Table 1. Influence of different insulation thickness on energy consumption

| Rock wool thickness (mm) | With external shade or not | Heat transfer coefficient | Heating demand (kWh/m²) | Cooling demand (kWh/m²) |
|--------------------------|----------------------------|---------------------------|-------------------------|-------------------------|
|                          | No                         | 0.23                      | 7.01                    | 27.25                   |
|                          | Yes                        | 0.19                      | 8.02                    | 20.63                   |
|                          | No                         | 0.15                      | 6.30                    | 27.11                   |
|                          | Yes                        | 0.15                      | 7.15                    | 20.48                   |
|                          | No                         | 0.14                      | 5.65                    | 26.99                   |
|                          | Yes                        | 0.14                      | 6.36                    | 20.35                   |
|                          | No                         | 0.14                      | 5.41                    | 26.94                   |
|                          | Yes                        | 0.14                      | 6.07                    | 20.30                   |

The curve in Figure 2 shows the relation between annual heating energy consumption and external insulation rock wool board thickness. If rock wool thickness is increased from 200mm to 300mm, heat transfer coefficient will be lowered to 0.12 W/(m²*K) from 0.2W/(m²*K), while annual heating energy consumption of building only drops by 0.08kW•h/(m²•a). Hence rock wool bar thickness is set at 250mm after considering building energy consumption and economic factor.

Figure 2. Changes of heating energy consumptions as the thickness of external thermal insulation rock wool board changes

2.1.2. Influence of interlayer bay on energy consumption. One layer of bay is added every other two floors, with lateral clearance being 800~1000mm. The bay dimension is L (length) x50mm (width) x5mm (material thickness) and heat transfer coefficient is 50W/(m²*K); insulation spacer (composite material) is 5mm thick and heat transfer coefficient is 0.024W/(m²*K).

Based on the simulated calculation on the influence of interlayer bay on heat transfer property of the insulation system, if protruding length of bay is around 2/3 of the insulation layer thickness, the system heat transfer coefficient will be less influenced by the bay; meanwhile, heat insulation block shall be set to avoid thermal bridge effect.

3. Energy-efficient window system

Building energy consumption is taken as the target in the design, construction and operation of ultra-low energy buildings, so external window system shall be energy-saving, of higher thermal insulation, shading and air tightness performance while meeting no thermal bridge design and construction requirement.

On the whole, external door and window applicable to ultra-low energy buildings include al-alloy door & window, plastic-steel door and window, aluminum-clad wood door and window, etc. Efficient
energy-saving window system is developed mainly based on aluminum composite energy-saving window.

3.1. Aluminum composite energy-saving window

Aluminum composite energy-saving window sash is adopted with 78mm thick finger joint laminated larch as section material, coefficient of thermal conductivity of pine type laminated timber is 0.13 W/(m·K); 20mm aluminum sash is attached outside and fire-retardant and efficient insulation material is filled inside to lower coefficient of thermal conductivity to 1.3 W/(m²·K) from 1.8 W/(m²·K).

Aluminum composite energy-saving window is equipped with three-layer glass and two-cavity-hollow-vacuum+Low-e compound glass, 5+18A (thermally improved +5V5). Main performance indexes include: heat transfer coefficient: 0.516 W/(m²·K); light to solar gain ratio: 1.41; total solar energy transmittance: 0.522.

Aluminum composite energy-saving window is set with SWISSPACER ADBANCE ordinary thermally improved spacer, λ: 0.290 W/(m·K).

Energy-saving window sash overlaps are sealed by four courses of sealing joint strips to form three sealed cavities, which reduces convection of air and greatly improves air tightness of window. Energy-saving window with four courses of sealing joint strips performs better than three courses of sealing joint strips in terms of air tightness, and is one grade higher in terms of water tightness and anti-wind pressure performance. Six lock point design improves anti-wind pressure performance of passive aluminum composite window.

In summary, the following aspects are considered in energy-efficient window design: section material type and structure, configuration of compound glass, sealing and lock point arrangement, etc. Main structure is made of wooden section material, aluminum alloy section is fixed with plastic connection buckle, efficient and fire retardant insulation material is filled in between wooden section material and aluminum sash, thus effectively lowering heat transfer coefficient of window section material. Window glass system is adopted with three-layer glass and two-cavity-hollow-vacuum+Low-e compound glass with thermally improved spacer so as to improve insulation performance. Four courses of sealing joint strips improves air tightness performance; six lock point design improves overall anti-wind pressure performance.

Based on test, heat transfer coefficient of aluminium composite energy-saving window is 1.3 W/(m²·K) while that of window as a whole is 0.8 W/(m²·K), air tightness grade is 8, water tightness grade is 6, anti-wind pressure level is 9 (currently the highest level for window), anti-condensation factor is 10 and air sound insulation level is 4. The product has obtained German Passive House Institute (PHI) certification and Kang-Ju Construction Parts Certification of the Technology & industrialization Development Center, the Ministry of Housing and Urban-Rural Development.

3.2. Energy-saving window installation

Exposure to sun is a factor to be considered in the design for east-west direction rooms in ultra-low energy buildings. In order to reduce energy consumption of refrigeration in summer, movable overhang external shading system is required, windows are mounted in insulation layer and pasted with water and vapor separating membrane on the inner side and waterproof & air-permeable membrane on the outer side.

Different installation methods will lead to large differences in linear heat transfer coefficients of thermal bridge and heat transfer coefficients of windows installed. Upon simulated calculation, if insulation layer is disconnected by window mounted in masonry, linearity of the whole window will be increased to 0.15 W/(m·K) from 0.005 W/(m·K). Figure 3 shows installation detail of energy-saving window.
4. Efficient heat recovery air system

Fresh air supply is indispensable in ultra-low energy buildings of high air tightness. By filtering particles in air, occupants are provided with clean and fresh air in a comfortable manner through rational air flow organization; efficient heat recovery air system is installed to pre-heat (in winter)/pre-cool (in summer) fresh air utilizing exhaust air energy, thus reducing energy consumption. The system may be of centralized, semi-centralized or household type.

Given that no radiator for heating purpose is set in ultra-low energy buildings, outlet air temperature of the fresh air system must meet the minimum requirement to prevent excessive low indoor temperature in winter; to guarantee comfort level of indoor temperature in such kind of buildings, fresh air outlet temperature must be above 17°C. Power consumption of fan supplying unit volume of air is no greater than 0.45W/m³·h. For safety reason, fresh air heat exchanger must be anti-frozen, in particular, when fresh air temperature is lower than 0°C, water vapor might be condensed at exhaust side of the heat recovery device as a result of high moisture content, so fresh air shall be pre-heated to prevent freezing.

4.1. System layout

Currently, the efficient heat recovery air system layout includes centralized, semi-centralized and household types.

Centralized fresh air system is centrally arranged with one or several cold and heat sources, supplying fresh air to all rooms through pipes. The system is generally composed of MAU and supporting auxiliary energy system and centralized MAU+ centralized auxiliary cold and heat source system is commonly adopted.

The system is applicable for central air-conditioning system in large-sized public buildings where air ducts occupying part of floor height, long conveying distance of fan and high energy consumption, thus facilitating centralized management and control.
Semi-centralized fresh air system: each floor is arranged with one MAU to supply fresh air to each household, and each household is arranged with one cold and heat source all-in-one machine to meet temperature requirements for different households, supplement heat loss of fresh air system and satisfy cooling and heating demand during summer and winter. The all-in-one machine supplies fresh air to each household through public pipeline, with air returned uniformly through toilet in household and heat recovered by means of heat exchanger.

The semi-centralized fresh air system is applicable for public rental housing and some public buildings under centralized management.

Household fresh air system: the system integrates fresh air and cooling & heating functions, usually adopting air source heat pump as auxiliary energy. The system is composed of fresh air cold and heat source all-in-one machine, outdoor unit, etc. Ultra-low energy residential buildings are mostly equipped with household fresh air system for its advantages like compact equipment, simple arrangement, short conveying distance and low noise.

4.2. Auxiliary energy sources
Due to ultra-low energy demand, many types of auxiliary cooling/heating energy sources can be adopted in ultra-low energy buildings, of which, commonly adopted auxiliary sources include air source heat pump auxiliary cooling/heating, tunnel air auxiliary pre-cooling/pre-heating fresh air, etc.

Air source heat pump has cooling/heating function, and is compact, simple in layout, so it is widely applied in ultra-low energy buildings.

Tunnel air may be used as auxiliary energy for fresh air pre-cooling/pre-heating in project equipped with soil heat exchanger.

5. Complete and continuous airtight layer
Airtight layer refers to a seamless envelope layer designed to prevent gas leakage. Ultra-low energy buildings have excellent air tightness performance, which can effectively reduce heating load, improve living comfort level, avoid indoor condensation and mold, and reduce noise and air pollution. Hence, a complete and continuous airtight layer is set in the envelope to control in-organized flow of air inside and outside of buildings.

As shown in Figure 4, a continuous and complete line can be drawn by a pencil along the airtight layer on all the plans and sections.

![Figure 4. Schematic of airtight layer](image)

Cast-in-place concrete or masonry with a plastering layer of over 20mm may be used as airtight layer. Sockets mounted at door & window and at positions where pipes penetrating through external wall and airtight layer shall be specially treated (as shown in Figure 5 and node detail shall be drawn.
6. No-thermal bridge design method

Common thermal bridge design methods adopted in building construction include structural thermal bridge, systematic thermal bridge and geometric thermal bridge.

Structural thermal bridge: structural members, beams, columns and slabs penetrating through insulation layer will dis-connect or thin insulation layer and lead to thermal bridge, which shall be removed as much as possible.

Systematic thermal bridge: anchor bolt and metal adapting pieces used to fix external insulation system, and supports used to fix various devices and sewer pipes. The systematic thermal bridge is generally unavoidable, but measure shall be taken to settle this problem.

Geometric thermal bridge: it is caused by increasing local heat transfer coefficient due to change of geometrical structure. For instance, the thermal insulation treatment made at the internal & external corners and roof parapet wall.

7. Conclusions

In ultra-low energy building development, technology and design serve as foundation, material the key and construction the guarantee. Ultra-low energy buildings mainly rely on high-performance envelope, fresh air heat recovery, air tightness, adjustable shade and other building technologies. However, the difficulty of achieving passive ultra-low energy consumption mainly lies in technical suitability. This paper summarizes key technologies for developing ultra-low energy buildings based on the study on key technologies for ultra-low energy buildings in Beijing, and makes active exploration on improvement of technologies applicable to ultra-low energy buildings.

8. References

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