RESEARCH ON THE INTEGRATED DESIGN OF SOLAR THERMAL ENERGY SYSTEMS AND EXISTING MULTI-STOREY RESIDENTIAL BUILDINGS

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To save energy and commit to the environmental protection and sustainable development of green ecological buildings, how to integrate solar energy systems with the reconstruction of multi-storey residential buildings has become a key area of growth in the current construction market. Fully integrating solar thermal energy systems with such reconstruction is a major problem. In this paper, the integration of solar thermal energy systems, roof design, and elevation design were studied systematically. Various effective schemes were presented, laying a foundation for the integrated design of existing multi-storey buildings and solar thermal energy systems during reconstruction.

Key words: *solar thermal energy, existing buildings, multi-storey residential reconstruction, integration, design*

1. Introduction

The use of solar thermal energy in residential buildings is mainly reflected in the application of solar water heaters. Solar water heaters are not originally installed on building roofs; instead, they are often installed later on and without adherence to any specific plan, which has a great impact on the whole urban landscape. To commit to energy-saving, environmental protection and the sustainable development of green ecological buildings, the number of green building projects has increased gradually in recent years. How to fully integrate the renewable energy of solar energy with the renovation design of existing buildings is a major challenge [1]. The problems of self-installed solar water heaters in existing multi-storey residential buildings are mainly reflected in several aspects: disorderly placement and unstable installation of solar water heaters on the roof; lack of effective management; technical problems in the installation, etc.

Installing integrated solar water heaters on a sloping roof makes the construction and later maintenance more difficult, and protective measures must be taken during installation. The original roof slope of the house must be used as much as possible, and personnel facilities must be left for convenient future maintenance [2, 3]. We can see that although some multi-storey buildings are installed with solar water heaters, there are obvious shortcomings in these heaters. Some buildings do not reserve a space for solar water heaters at the beginning of its design [4]. Moreover, the roof can only be used by residents living on the top floor. If residents living on a middle floor want to use solar water heaters, they can only install them on the elevation, which will lead to the destruction of the building elevation and also damage the urban landscape. In winter, north-facing balconies are the most likely to freeze [5]. If solar collectors are hung outside the balcony and the ice outside the balcony is not removed in time, the collectors will be damaged. In the case of extreme weather such as rain, snow, and strong wind, not only will the collectors be affected but the safety of traffic and pedestrians on the ground becomes an area for concern. Since south-facing balconies are major areas to introduce light into the house [6], the installation of solar collectors is likely to affect the lighting of lower-storey balconies, resulting in neighborhood disputes. In short, installing solar water heaters on the balcony does more harm than good, and thus the best place to install collectors in a south-facing apartment is between the upper-storey window and the lower-storey balcony (on the sill wall) or on the wall between two windows [7].

Therefore, how to effectively realize the integrated design of solar water heaters in the reconstruction scheme for a building is the aim of the present paper. This paper focuses on the integrated design of solar water heaters, the sloping roof, and elevation design.

1.1 Integrated design of integral solar water heaters on a sloping roof

Solar water heaters can be installed on multi-storey buildings with sloping roofs. This paper puts forward reasonable and effective design schemes for such installations.

Scheme 1: The platform above the balcony can be used to install solar water heaters. Methods such as concession and cutting can be used to properly join the sloping roof and the flat roof of the balcony, which can reduce the risk of force majeure. The flat roof and cornice of the balcony can also be combined. In this scheme, the roof is designed as a combination of a flat roof and a sloping roof. That is, a flat section parallel to the lower-storey balconies is designed to cut halfway into the sloping roof to accommodate the solar water heaters (Fig. 1 and Fig. 2).

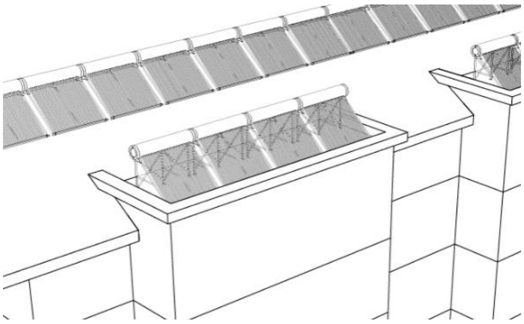

Fig. 1. Placement of integral solar water heaters on a sloping roof

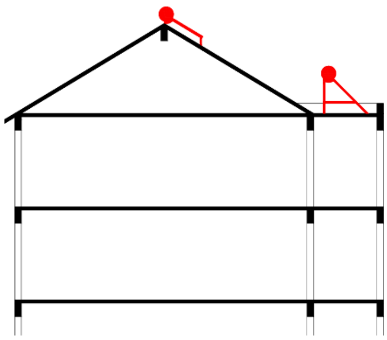

Fig. 2. Section sketch for placement of integral solar water heaters on a sloping roof

Scheme 2: The water heaters can be installed on the top of the roof ridge if the ridge is wide enough. This scheme enables full integration of the water heaters with the building, as shown in Fig. 3 and Fig. 4.

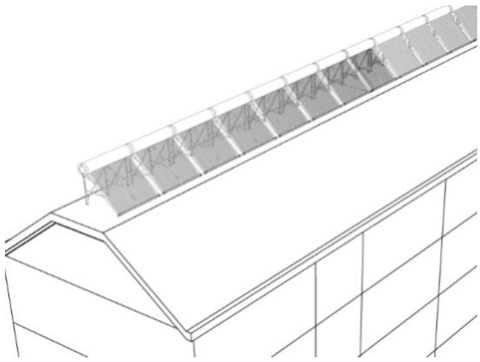

Fig. 3. Placement of integral solar water heaters on the roof ridge

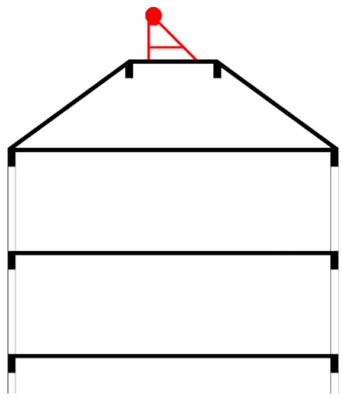

Fig. 4. Section sketch of the integral solar water heaters on the roof ridge

1.2 Integrated design of integral solar water heaters on a flat roof

There are a few restrictions on the installation of integral water heaters on a flat roof. Flat roofs must have access for inspection and maintenance. It is also necessary to consider the bearing capacity of the roof, and verify this with the original design of the building [8]. The installation of solar water heaters on a flat roof also has some of the same problems as that on a sloping roof. These are related to safety, and include the disorderly placement of water heaters, inconsistent models and specifications of these water heaters, and exposed storage tank pipelines [9]. In view of these problems, the integrated design scheme of integral solar water heaters on a flat roof is proposed.

Scheme 1: The array layout method can be adopted for overhead installation, which can increase the heat collection area to a certain extent. Besides, its shading effect can reduce the air conditioning energy consumption of top-floor rooms. Moreover, it can even play a role in beautifying the space. However, it is necessary to pay attention to the stability of the solar collectors and the convenience of maintenance.

$$N = M/A \tag{1}$$

Here, N represents the per unit load on the roof; *M* represents the load of the solar collector; and

A represents the projected area of the solar collector.

Based on an existing multi-storey residential building with 6 floors and 18 units, we input the specifications provided by the solar water heater manufacturer into the formula and obtain the following:

$$A = 1.082 \times \cos 45° \times 1.98 \times 18 = 27.36 m^2;$$

$$N = \frac{M}{A} = \frac{756}{27.36} = 27.36\, kg/m^2 .$$

The unit area load of a solar collector is far less than the bearing capacity of the existing multi-storey residential roof, and therefore the collector provided by the solar water heater manufacturer has no impact on the bearing capacity of the roof. However, in green housing projects, the existing multi-storey buildings are calculated according to 6 floors with a total of 18 units (three on each floor), and a roof area of about 122 m^2. According to calculations, the roof area required by each household is about 13-15 m^2, and only 60% of these areas can be counted as effective areas. If we assume all the areas are fully used and hence are effective areas, each household will need an area of 8-9 m^2 on the roof. In this case, a roof of at least 144 m^2 is needed for installation of the heaters. Thus, there is not enough roof area for the installation of water heaters in this example. This illustrates that having enough load capacity on the roof does not necessarily mean that solar water heaters can be installed.

2. Research on the integrated design of solar water heaters and elevation

A decentralized water storage system should be adopted for the solar water heaters placed on the elevation of multi-storey residential buildings. The system can be based on mechanical circulation or natural circulation, with mechanical circulation and indirect systems preferred. In a decentralized system, a small water storage system is mounted to each household and thus the original structure of the building will not be changed. The solar collectors can be placed uniformly on the elevation, and the water storage tanks can be hidden indoors; this is very appropriate for integrated design.

2.1. Integrated design of solar water heaters and sill walls

2.1.1 Design of solar collectors on sill walls

In green-building projects, solar collectors can be installed on the wall between the upper-storey window and the lower-storey balcony. Since the height of this wall in the existing multi-storey building is about 1300 mm, there is enough space to install collectors. The wall body can also provide support for the collectors, strengthening the horizontal line in the exterior wall and improving the elevation.

(1) Daylighting analysis

In order to ensure that the solar collector does not affect the indoor lighting of the residents, a daylighting analysis of the collector installed on the elevation is carried out. Taking the Chinese city of Changchun as an example, the optimal installation angle of the collector is 48.72°, which can be calculated according to the solar height angle. The formula for calculating the elevation angle of the noon sun is

$$h = 90° - |\phi_1 - \phi_2| \qquad (2)$$

where h represents the elevation angle of the sun; φ_1 represents the local geographic latitude; and φ_2 represents the latitude of direct sunlight.

The formula for calculating the installation angle of collectors is as follows:

$$\theta = \phi + \delta \tag{3}$$

q represents the installation angle of the solar collector, which is generally calculated by $q=f \pm d$; when it is used in spring, autumn, and summer, the formula is $q=f - d$; and when it is used in winter, the formula is $q=f + d$.

$$L_1 = L_0 \cos\theta \tag{4}$$

$$L_2 = L_1 \tan H_1 \tag{5}$$

Here, L_0 represents the width of the solar collector; L_1 represents the projection length of the solar collector on the horizontal plane; L_2 represents the projection length of the solar collector on the wall; and H_1 represents the distance from the bottom of the solar collector to the top of the window eave, which is 300 mm.

In winter, in order to ensure that the building can be exposed to sunlight for at least 2 hours, the solar collector should not affect the daylighting of the windows. Therefore, the projection length of the collector on the winter solstice should be less than the distance from the top of the window eave to the bottom of the collector, that is, $L_2 \leq 300$ mm. The local elevation angle of the sun on the winter solstice is 22.85 °. According to Eq. (4) and Eq. (5), L2=278 mm. It can be seen that $L_2 < H_1$; therefore, at noon on the winter solstice, the solar collector will not affect the daylighting of the window.

In summer, the solar elevation angle on the summer solstice is 69.72°, the height of the existing multi-storey building is 2800 mm, and the height of the windowsill is 900 mm. Inputting the above data into the formulas above, we obtain L_3 =1785.42 mm and H_2=2048.51 mm. Since $L_3 < H_2$, the maximum projection distance of the solar collector on the upper part of the building does not affect the heat collection effect of the collector on the lower part of the building. At noon on the summer solstice, the sun does not shine directly into the apartment units.

(2) Plane layout

In Jilin Province, the multi-storey buildings undergoing reconstruction for green housing projects generally belong to a kind of old-fashioned layout that we call Model 52. On each floor of Model 52, there are five bays and two kinds of depth. This old-fashioned layout is selected as the research object in this study and the specifics are shown in Tab. 1.

Tab. 1 Layout analysis of Model 52

	Layout	Floor space	Depth	Width	Number of bays
Type A	two rooms, one hall, and one bathroom	43.97 m^2	9600 mm	3000 mm	1
Type B		41.76 m^2	4800 mm	8700 mm	3
Type C		43.97 m^2	9600 mm	3000 mm	1

As can be seen from Tab. 1, there is only one south-facing bedroom in Type A and Type C units. Since the collector is installed on the sill wall, the water storage tank should be set in the bedroom according to the principle of proximity. The pipe should be arranged along the architraves or against the wall to minimize structural damages. The Type B unit has three bays, all facing south. Because the toilet is located to the west, the water storage tank should be installed in the west bedroom, thus shortening the length of the pipe and reducing heat loss.

(3) Design of the elevation

The size of the vacuum tube collector used at the sill wall is 2213 × 725 × 92 mm, and the size of the flat plate collector is 200 × 1000 × 80 mm. Two designs are available to select from.

Scheme 1: The collectors are all placed horizontally. The collectors are not placed on the first floor, but are instead installed on the sill wall of the second to fifth floors, and the collectors are only installed on one side of the sixth floors. The collectors that should have been installed on the sill wall of the first floor and the sixth floor are all centrally placed on the second to fifth floors. Since 36 solar collectors are needed, and only 32 collectors can be placed on the second to fifth floor, the remaining four collectors are placed on the sill wall of the sixth floor.

Scheme 2: All collectors are placed horizontally. The collectors are not placed on the first floor; instead, they are installed on the sill wall of the second to sixth floors and on the parapet wall of the top floor. The 36 collectors are divided into three groups of 12 collectors each, and are respectively installed on the left, middle, and right parts of the building; this design choice strengthens the vertical line and balance of the elevation.

2.1.2 Design of water storage tank and pipeline

Taking scheme 2 as an example, after installing solar collectors on the sill wall, the water storage tanks should be placed indoors. Since collectors for the top-floor residents are installed on the parapet wall, the collectors of the first floor should be installed on the sill wall of the first and second floors. In this way, the position of the water storage tanks is lower than the installation position of the collectors, and hence the forced circulation mode should be adopted. This means that we have a decentralized heat collection and water storage system for each household, that is, each household has a small and independent solar water heating system. Residents can choose the capacity of the water storage tank according to the amount of hot water regularly used. The installation position of the water storage tank and the pipeline adopt the principle of proximity. Lastly, the opening in the wall needs to be well insulated, and the laying of the pipe should be concealed.

2.2 Integrated design of solar water heaters and the wall between windows

2.2.1 Design of collectors on the wall between windows

(1) Determination of collector azimuth

Daylighting analysis of walls between windows proceeds as follows. It is assumed that the solar collector installed on the window wall is a flat-type collector with a size of 2000×1000×80 mm. Because the distance between windows of a multi-story building is about 1200-1500 mm, the flat-type collector can only be placed vertically. No collector is installed on the first floor, and nine collectors are required on the second to sixth floors. The total length of the collectors is 14 m. The vertical projection length L_2 of each collector on the wall is about 1555.6 mm. According to Eq. (3), the installation angle of the collectors is about 85°. Since the collectors are placed together continuously, they may cause shading at any time. Moreover, the optimal installation angle in Changchun is 48.72°, the angled flat-plate collector cannot be installed between windows. Similarly, the vacuum tube solar collectors should not be placed horizontally on the wall between windows, but installed vertically. Furthermore, since the vacuum tube can be installed vertically, that is, the installation angle of the collector is 90°, it can be placed continuously on the elevation. To ensure that the collector gets more sunlight, the horizontal projection line of the collector and the wall must produce an appropriate angle, that is, the best azimuth. This in turn ensures heat collection efficiency.

The formula for calculating the azimuth of the sun is as follows:

$$\sin C = \frac{\cos\Phi \times \sin\omega}{\cos H} \tag{6}$$

where C represents the azimuth of the sun; *Φ* represents the latitude of direct sunlight; *ω* represents the hour angle; and *H* represents the elevation angle of the sun.

When the sinC calculated by this formula is greater than 1, or the absolute value of sinC is small, the following formula can be used:

$$\cos C = \frac{\sin h \times \sin\varphi - \sin\varphi}{\cos h \times \cos\phi} \tag{7}$$

Here, *φ* represents the local geographic latitude.

Taking Changchun, Jilin Province as an example, we first bring its geographic latitude and the elevation angle of the noon sun during winter solstice and summer solstice into Eq. (6). Then, the azimuth angle is 0°, that is to say, the best orientation for collectors at this time is due south. We select the time of 10:00 on the winter solstice and introduce it to Eq. (6); thus, we see that the azimuth angle at this time is about 29.86°. These results are consistent with the decision to orient solar collectors directly south, or 30° south by west or south by east.

Therefore, the horizontal projection line of the collector and the wall can have an appropriate angle. In order to meet the integrated design of the collector and the elevation, the azimuth angle of should be 0°, that is, the collector should be installed directly south.

(2) Estimation of collector area

The collectors installed between windows are mainly of the vacuum tube type. The area for installing collectors is estimated by calculating the area of the collector itself, which ensures enough space on the elevation for the installation. The collector area is determined by the hot water supply load and local solar radiation. To meet residents' demands for hot water, the collector area F required per square meter of the building can be calculated as follows:

$$F = Q \big/ (I \cdot \eta') \tag{8}$$

$$Q = 0.0864 Q_0 n \tag{9}$$

Here, *Q* represents hot water supply load, GJ/m^2; *I* represents the total solar radiation in one heating period, GJ/m^2; and *η'* represents the efficiency of the solar collector. The average annual efficiency of the commonly used vacuum tube collector is about 50%.

Q_0 represents the heat consumption index per unit area of the local building; and *n* represents the number of days of heating.

The standard total collector area = number of family members× 0.5 m^2. For a family of three, the required collector area is 1.5 m^2. The area of the vacuum tube collector provided by the solar water heater manufacturer is about 1.6 m^2, which can meet residents' daily needs for hot water.

(3) Plane and elevation design

The existing multi-storey residential buildings in Changchun are generally the aforementioned Number 52. In such buildings, the collectors can only be placed between window walls and next to the balcony. The building has 6 floors and 18 units, which means that the window walls to the left and right of each unit must be installed with 9 solar collectors to meet the needs of all residents.

Scheme 1: The collectors are only placed vertically, and are designed to be placed side by side and in a single row on the elevation. There is no collector on the first floor, and two collectors are placed vertically side by side on the second to fifth floors. Only a single row of collectors is placed on the sixth floor to ensure that there are enough collectors on the wall between windows for each household.

Scheme 2: Limited by the width of the window wall, the collectors can be installed at the joint of the sill wall and the window wall. We place the collector on the sill wall horizontally and the collectors on the window wall vertically. That is to say, there is no collector on the first floor, the collectors on the sill wall of the second to fifth floors are placed vertically, and the collectors on the window wall of the third to fifth floors are placed horizontally. Therefore, there are enough collectors on the wall for each household.

2.2.2 Design of water storage tank and pipeline

Once the solar collector is installed on the window wall, the water storage tank should be installed indoors, and the natural circulation system or forced circulation system should be determined according to the relative position of the collector. The hot water supply system can be a natural circulation single water tank system, DC single water tank system, forced circulation DC single water tank system, or forced circulation indirect single water tank system. The pipeline layout also adopts the principle of proximity, and the opening in the wall is properly insulated.

3. Conclusion

(1) In the reconstruction of existing buildings for green housing projects, the slope of the roof is not exactly the same as the optimal inclination of the solar collector, which limits the type of collector that can be used. It is necessary to select an appropriate collector and installation method, which increases the difficulty of the reconstruction. Factors such as a sloping roof structure, load bearing capacity, and area, limit the number of solar water heaters that can be installed. If the number of water heaters cannot meet the needs of all residents, solar collectors cannot be installed on the roof. Flat roofs have a similar problem. If there is not enough space to install enough solar collectors, the project cannot proceed.

(2) Compared with the roof, the elevation of the multi-storey building is undoubtedly more suitable for the installation of solar water heaters. On the elevation, the decentralized solar heating system is adopted. The residents of each floor can have their own independent heating water system, which do not interfere with each other and is convenient for management and maintenance. Besides, this results in minimal structural damage to the buildings. The most important thing to consider when installing collectors on the elevation is the placement of the collectors. A reasonable and regular arrangement of solar collectors can enhance the overall appearance of the building.

(3) Pipe installation is difficult. Since there is no retained pipe shaft for installing solar water heaters in these existing buildings, creating a shaft would compromise the structural integrity of the building. The roof, wall, and floor need to be punched through to place pipes, which will damage thermal insulation layers and waterproofing layers.

(4) The initial investment of using a solar water heater is high, with the purchase and installation cost reaching nearly 8000 yuan. Most residents cannot afford this. Moreover, solar water heaters have a limited lifespan of about 15 years. Additionally, wear and tear with everyday use increases the cost of

maintenance. For example, the antifreeze of the vacuum tube collector needs to be replaced frequently. Besides, since the buildings cannot withstand secondary damage, how to dismantle and replace the solar water heater when it has reached the end of its life is also a problem to be considered. If this issue cannot be properly solved, the building will inevitably undergo damage.

(5) The advantage of installing a solar water heater comes in its commitment to environmental protection and the saving of energy. These are of great significance to a country's implementation of a national sustainable development strategy and the use of clean energy. In a narrow sense, residents' use of clean energy reduces air pollution, haze, and other environmental issues, thus improving people's quality of life. As for the building itself, the installation of solar water heaters increases its value. At the same time, the elevation is improved, enhancing the appearance of the building and exuding a sense of science and technology; this plays a great role in improving the community's environment and the city's overall appearance.

Acknowledgment

This work is financially supported by the National Natural Science Foundation of China (51478205).

Nomenclature

N - the per unit load on the roof, [kg/m^2]
M - the load of the solar collector, [kg]
A - the projected area of the solar collector, [m^2]
h - the elevation angle of the sun, [°]
φ_1 - the local geographic latitude, [°]
φ_2 - the latitude of direct sunlight, [°]
q - the installation angle of the solar collector, [°]
L_0 - the width of the solar collector, [mm]
L_1 - the projection length of the solar collector on the horizontal plane, [mm]
L_2 - the projection length of the solar collector on the wall, [mm]
H_1 - the distance from the bottom of the solar collector to the top of the window eave, which is 300 mm, [mm]
C - the azimuth of the sun, [°]
Φ - the latitude of direct sunlight, [°]
ω - the hour angle, [°]
H - the elevation angle of the sun, [°]
φ - the local geographic latitude, [°]
Q - hot water supply load, [GJ/m^2]
I - the total solar radiation in one heating period, [GJ/m^2]
η' - the efficiency of the solar collector.
Q_0 - the heat consumption index per unit area of the local building, [%]
n - the number of days of heating, [d]

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