Study on Energy Consumption of Rural Household Heating Mode in Winter

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Abstract. Although rural household heating systems provide comfortable living environment in winter, household energy consumption increases year by year. The best household heating system has become a concerned issue in rural areas. Two main types of heating, a wall panel heating system and a radiant floor-heating system, are modelled and simulated according to some regulatory documents. The annual cost method and Value Engineering are used to compare the economy of two systems. The simulation results show that the rural household energy consumption of the radiant floor-heating system is lower than that of the wall panel heating system under the same comfortable condition. The final economic conclusion is that the radiant floor-heating system is more suitable in northern China.

1. Introduction
Now wall panel heating systems are widely accepted in rural areas because of their simplicity, convenience and comfort. The cast-iron heaters with large heat dissipation can normally satisfy the needs of farmers [1]. There are more and more radiant floor-heating systems used in the countryside for beautiful environment and higher comfort. Rural household energy consumption accounts for about 6% of household income [2], which is a burden and an anxiety to these households. Therefore, the rural household energy consumption of different heating systems has become the focus of attention.

In an indoor environment, the surface of the human body is radianly heat-exchanging with indoor objects at all times. The average radiant temperature is the comprehensive average of the radiant temperatures of the objects [3]. The perceived temperature of the human body should be the average indoor temperature. Thermal energy consumption should be compared at the same level of comfort [4].

The difference between the radiant floor-heating system and the radiator heating system is analysed with low-temperature hot water in literature [5]. Reference [6] provides some technical measures to achieve good heating effect with both low-temperature floor heating and radiator heating. In literature [7], the single-story building of a small railway station is used as the research object in a cold and arid region, and the indoor thermal comfort is evaluated. The temperature field simulation analysis is done for different heating pipe spacing and materials in reference [8]. Sat [9] analyzes the impact factors of the thermal performance in a radiant floor-heating system, such as pipe diameter, pipe material, floor material and thickness, and finds that the maximum factors affecting the thermal performance are the floor material and the floor thickness. Gook-Sup[10] studies the thickness effect of the floor structure layer on the indicated floor temperature through experimental tests. Olesen [11] compares the thermal comfort of different heating systems, and concludes that the energy saving effect of floor heating is...
better under the condition of the same thermal comfort. However energy saving and comfort of home heating systems have not been deeply analyzed.

The heating systems of rural single-family buildings are mainly considered in winter in this article. The corresponding models are established for the wall panel heating system and the radiant floor-heating system according to their specifications, and some cases are studied. The energy consumption of these heating systems is obtained under the same comfort condition, which provides a basis for rural residents to choose a suitable heating system. And at the same time, Value Engineering is compared for the heating systems with an annual cost method.

2. Calculation of Room Heat Consumption

2.1. Heat Dissipation of Envelope Structure

The heat consumption of the envelope structure, \( Q_1 \) in W, should include basic heat consumption and additional heat consumption. The basic heat consumption of the envelope should be calculated as following equation [12]:

\[
Q_1 = \alpha FK(t_n - t_{\text{wn}}) \tag{1}
\]

where \( \alpha \)—the correction coefficient of the temperature difference of the envelope structure; \( F \)—the area of the envelope structure (m²); \( K \)—the heat transfer coefficient of the envelope structure [W/(m²·K)]; \( t_n \) and \( t_{\text{wn}} \)—the design temperature and the calculated temperature of the heating room (°C), respectively.

The additional heat consumption of the envelope structure shall be determined according to its additional percentage, which should be selected by the specified value [12].

2.2. Heat Consumption for Heating the Cold Air from the Gaps of Doors and Windows

The heat consumption of the cold air that penetrates into a room through the gaps of the doors and the windows of the room, \( Q_2 \) in W, can be calculated by [12]

\[
Q_2 = 0.28c_pP_{\text{wn}}L(t_n - t_{\text{wn}}) \tag{2}
\]

where \( c_p \)—the specific heat capacity of air at constant pressure, \( c_p=1.01\text{kJ/(kg·°C)} \); \( L \)—the permeable cold air volume (m³/h); \( P_{\text{wn}} \)—the air density at the calculated temperature (kg/m³).

2.3. Heat Dissipation of Wall Panel Heating System

The wall panel heating system is designed for continuous heating at 75 or 50 °C, and the water supply temperature should not be more than 85 °C. The temperature difference between the supply and return water should not be less than 20 °C. Under standard atmospheric pressure, the heat dissipation of the panel radiator, \( Q_3 \) in W, can be calculated according to the following formula [12]

\[
Q_3 = G_m \times (h_1 - h_2) \tag{3}
\]

\[
G_m = \frac{m}{t}
\]

where \( G_m \)—the water mass flow through the radiator (kg/s); \( h_1 \) and \( h_2 \)—the specific enthalpy of the inlet and the outlet of the radiator (J/kg), respectively; \( m \)—the water mass in the water collecting container (kg); \( t \)—the sampling time to collect water by the container (s).

2.4. Heat Transfer of Radiant Floor-Heating System

The water supply temperature of the radiant floor-heating system should be 35–45 °C and not be greater than 60 °C. The temperature difference between the supply and return water should not be greater than 10 °C and not be less than 5 °C. The heat transfer per unit area of radiation surface, \( q \) in W/m², can be given by [13]:

\[
q = \frac{Q_{\text{dis}}}{A}
\]
where $q_t$ and $q_d$—the radiant heat transfer and the convective heat transfer per unit area of radiation surface (W/m²), respectively; $t_{nj}$—the average temperature of the radiating surface (°C); $t_n$—the weighted area average temperature of the indoor non-radiated surface (°C).

3. Case Study and Benefit Analysis

3.1. Energy Calculation

It is set up as a single-story room facing south in the rural area of northern China, which is 6 meters long, 4 meters wide and 3 meters high. There are sufficient sunshine and strong wind in the area.

From Eq. (1), the basic heat dissipation of the room can be calculated, i.e. $Q_1 = 1270.08$ W, when $K$ is taken as 0.3 W/(m²·K), $t_n$ as 20°C and $t_{an}$ as -13.6°C according to the regulations [12]. And then the correction rate is set to 20%, the wind additional rate is 0, and the external door additional rate is 65%, the additional heat dissipation is gotten, $Q_{add} = 1079.568$ W. From Eq. (2), the heat consumption of the cold air that penetrates into the room from the gaps of the doors and the windows can be calculated, i.e. $Q_2 = 13.68$ W, when $L$ is taken as 1.2 and $P_{wn}$ as 1.2. In summary, the room heat load is: $Q = Q_1 + Q_{add} + Q_2 = 2365.328$ W.

The mass flow of water flowing through the radiator can be obtained from Eq. (3), i.e. $G_m = 28.212$ kg/s, and the energy consumption of water in the pipeline per unit length and time can be calculated in the wall panel heating system, i.e. $Q_{EC·WP} = 566.147$ kJ/s.

In the radiant floor-heating system, if the floor area is 24 square meters and all the floor heating is provided, the heat supply required for a single area is 98.472 W/m². When a PE-X tube is used with a thermal conductivity of 0.38 W/(m·K), the upward effective heat dissipation and downward heat loss per unit floor area can be viewed with the average water temperature 40°C and the distance between the heating tubes 100 mm, then the heat dissipation per unit area is 106.3 W/m², which meets the demand. The velocity of the floor heating water pipe may be set as 0.4 m/s, $G_m·RF$ can be gotten, $G_m·RF = 12.56$ kg/s. Energy consumption of water in the pipeline per unit length and time can be calculated in the radiant floor-heating system, i.e. $Q_{EC·RF} = 126.024$ kJ/s.

The energy consumption of two heating systems is shown in Table 1.

| Project                        | Wall panel heating system | Radiant floor-heating system |
|--------------------------------|----------------------------|------------------------------|
| Energy consumption             | 566.147 kJ/s               | 126.024 kJ/s                 |

3.2. Economic Analysis

The annual cost method refers to a method that converts all expenditure costs incurred at different points in the calculation period of a project into equal annual payment cost based on a benchmark rate of return and then performs a comprehensive evaluation. Its mathematical model used in the heating systems is

$$AC = C_t \left( \frac{(1+i)^n}{(1+i)^n - 1} \right) + C_k$$  \hspace{1cm} (5)

where $AC$—the equal annual payment cost (Yuan); $C_t$—the initial investment (Yuan); $C_k$—the annual operating cost (Yuan); $i$—the benchmark discount rate (%); $n$—the life of the heating system (a).
3.2.1. Wall Panel Heating System

The element cost is about 7000 Yuan, the civil construction cost is 1067 Yuan, and the equipment installation cost is about 100 Yuan. Therefore, the total initial investment cost is about 9367 Yuan, and the initial investment cost of the room, \( C_{i-WP} \), is 390.29 Yuan/m².

The annual operating cost of the system includes the gas cost in winter and the maintenance cost. Because the heating energy demand is 18374.688 * 1.2 = 22049.6 MJ and the natural gas calorific value is 35.88 MJ/m³, the natural gas required in winter is 614.54 m³. The gas cost in winter, 1843.61 Yuan, can be obtained and the unit price is 76.8 Yuan/m³ with the natural gas price, 3.08 Yuan/m³.

Assuming that the benchmark discount rate is 8%, the equal annual payment cost can be gotten in Table 2 under different operating years.

| Life of equipment(a) | AC(Yuan/m²) |
|----------------------|-------------|
| 10                   | 136.505     |
| 20                   | 118.093     |
| 30                   | 113.008     |

3.2.2. Radiant Floor-Heating System

The element cost is about 7000 Yuan, the indoor coil cost is 640 Yuan, the civil materials cost is 708 Yuan, and the equipment installation cost is about 240 Yuan. The total initial investment cost is about 10588 Yuan, and the initial investment cost of the room, \( C_{i-RF} \), is 441.16 Yuan/m².

The annual operating cost is calculated, i.e. \( C_{k-RF} = 66.72 \text{ Yuan/m}² \) with the heating cost 65.72 Yuan/m² and the maintenance fee 1 Yuan/m² when the maintenance cost rate is 1.5%.

Assuming that the benchmark discount rate is 8%, the equal annual payment cost can be calculated in Table 3 under different operating years.

| Life of equipment(a) | AC(Yuan/m²) |
|----------------------|-------------|
| 10                   | 132.466     |
| 20                   | 111.654     |
| 30                   | 105.906     |

It can be seen that the annual cost of the radiant floor-heating system is lower than that of the wall panel heating system under three equipment life conditions. And as the equipment life becomes longer, the difference in annual cost of the two heating systems becomes larger, i.e. the longer the life span is, the cheaper the radiant floor-heating system.

The above comparative result is in different operating years under a fixed benchmark discount rate. The annual cost of each system is gotten in Table 4 under a fixed operating year, 20 years, and different benchmark discount rates. \( AC \) of the radiant floor-heating system is evidently lower.

| Project                                | Benchmark discount rate | AC(Yuan/m²) |
|----------------------------------------|-------------------------|-------------|
| Wall panel heating system              | 6%                      | 112.381     |
|                                        | 8%                      | 118.093     |
|                                        | 10%                     | 124.183     |
3.3. Value Engineering Application

Value Engineering, VE, has some characteristics such as considering the cost of the entire life cycle, based on functional analysis, and relying on organized collective power. The value analysis seeks to increase system value by realizing system functions with the lowest system life cost through functional analysis, which emphasizes the functional analysis by [14]

\[ V = F_c / C \]  

where \( V \) is the system function value coefficient; \( F_c \) is the system function evaluation coefficient; \( C \) is the function coefficient. When \( V > 1 \), it means that the system has high function and low cost. When \( V = 1 \), it means that the system cost is equivalent to the function. When \( V < 1 \), it means that the system cost is relatively high compared to the function.

Functional analysis is the key to VE. In northern China, the function of the heating systems can be considered from the high comfort, fast room heating, low cost, stable system operation and less occupy space. Of course, the priority or importance of these functions is different. The importance coefficient of each function, \( f_i \), can be given by

\[ f_i = \frac{s_i}{\sum s_i} \]  

where \( s_i \)—the score of each function.

The 0-4 evaluation method can be used to calculate the functional importance coefficient. The calculation results are shown in Table 5.

**Table 5. Functional importance coefficient.**

| Function                          | Functional importance coefficient |
|----------------------------------|----------------------------------|
| Comfort                          | 0.273                            |
| Room heating speed               | 0.182                            |
| Cost                             | 0.318                            |
| System operation stability       | 0.182                            |
| Occupy space                     | 0.045                            |

The two heating systems are scored with different functions. The highest score is 10 and the lowest score is 0. The function cumulative score of the system, \( P_i \), can be calculated from

\[ P_i = p_i \cdot f_i \]  

where \( p_i \)—the functional score of each system.

\[ F_i = \frac{P_i}{\sum P_i} \]  

where \( F_i \)—the function evaluation coefficient for each system.

The function evaluation coefficients are calculated in Table 6 for the wall panel heating system and the radiant floor-heating system.

**Table 6. The function evaluation coefficients of two systems.**

| Function                          | Wall panel heating system | Radiant floor-heating system |
|----------------------------------|---------------------------|-------------------------------|
| High comfort | 6 | 10 |
| Fast room heating | 10 | 2 |
| Low cost | 6 | 8 |
| Stable System operation | 8 | 10 |
| Less occupy space | 2 | 10 |
| Cumulative score | 6.912 | 7.908 |
| Function evaluation coefficient | 0.466 | 0.534 |

The cost coefficient of the system is calculated from its life cost with the annual value of the cost at 6% of the benchmark discount rate for 20 years. The cost factor of the system, \( C_c \), can be calculated by

\[
C_c = \frac{B_i}{\sum B_i}
\]

(10)

where \( B_i \)—the life cycle cost.

The cost factors of two systems are gotten in Table 7.

**Table 7.** The cost factors of two systems.

| Project                      | \( B_i \) (Yuan/m²) | \( C_c \) |
|------------------------------|---------------------|----------|
| Wall panel heating system    | 112.381             | 0.517    |
| Radiant floor-heating system | 105.198             | 0.483    |

Finally, the calculation results of the value coefficients for the different systems are shown in Table 8.

**Table 8.** The value coefficients of the systems.

| Project                      | Function evaluation coefficient | \( C_c \) | Value coefficient |
|------------------------------|---------------------------------|----------|-------------------|
| Wall panel heating system    | 0.466                           | 0.517    | 0.901             |
| Radiant floor-heating system | 0.534                           | 0.483    | 1.106             |

It can be seen from the above table that the value coefficient of the radiant floor-heating system in the two systems is greater than 1, which includes the high function and the low cost. The value coefficient of the wall panel heating system is less than 1, which is high in cost and low in function.

4. Conclusion

Now the best household heating system has attracted more and more attention in rural areas because of its energy consumption. The required energy per unit time and unit length of the pipeline is calculated in the radiant floor-heating system and the wall panel heating system. The result shows that the radiant floor-heating system is more energy efficient. From an economic point of view, the initial investment in the radiant floor-heating system is high, but the annual operating cost and the annual cost are low. It can come to a conclusion from Value Engineering that the value coefficient of the radiant floor-heating system is greater than 1 and the value coefficient of the wall panel heating system is less than 1, which also recommends that the radiant floor-heating system should be applied in the countryside of northern China.

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