Numerical Analysis of Indoor Thermal Environment with Solar Heating Collector and Skirting Radiator

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Abstract. In view of the current heating situation in countryside, a new heating method is proposed, which is using solar to store thermal energy and using skirting radiator to dissipate. This article first calculates the heat supply of solar energy, and then analyzes the indoor temperature distribution of the skirting radiator by numerical methods. Numerical analysis shows that method has certain feasibility. In areas with abundant solar energy, the thermal energy supplied by solar collectors can support the skirting radiator for more than hours of continuous heating. The heat dissipation effect of the skirting radiator is great, the temperature distribution in the room is evenly, and there is no obvious cold feeling near the wall.

1. Introduction
Rural buildings are dominated by old houses. At the beginning of the design, the house ignored the issue of heat preservation and energy saving. Such as the house has no insulation layer, heat preservation paint, and the location of the heat preservation pipes is unreasonable, which leads to the poor heat preservation effect of the room. From a resource point of view, energy-saving renovation of rural buildings is a top priority. However, due to the deep-rooted residential habits of rural residents, the resistance to this plan will be very large. Therefore, under the premise that energy-saving renovation of buildings cannot be implemented, reducing heating energy consumption in winter requires optimization in terms of changing heat sources, innovating heat dissipation equipment and improving thermal efficiency. Based on the huge advantages of solar energy, that are universal, harmless, and long-lasting, combined with the advantages of skirting radiator’s high heat transfer efficiency, rapid heating, easy installation, and low maintenance cost. This paper proposes a new heating method of rural, is named "solar energy + skirting heating". First the solar heating is caculated, and then the numerical analysis of the indoor thermal environment temperature changes during the heating process is conducted.

2. Numerical calculation of solar heating
According to the total amount of solar radiation received by various regions, researchers divided the country into five types of regions. Shandong Province belongs to the third type of regions, which is the solar energy richer belt[1]. Dezhou City is located in the northwest of Shandong Province. The annual average total radiation is about 1426-1474 kwh/m², and the total radiation in winter is about 215-
235 kwh/m². Table 1 list the average daily maximum temperature, minimum temperature and average sunshine duration of each month in the city in winter (January, February, November, December).

Table 1. Statistics of temperature and sunshine duration in winter in Dezhou.

|                      | January | February | November | December |
|----------------------|---------|----------|----------|----------|
| Daily maximum temp  | 4       | 7        | 12       | 6        |
| Daily minimum temp  | -5      | -3       | 3        | -3       |
| Daily sunshine duration | 3.3    | 3.9      | 6.9      | 5.9      |

The area formula of Collector:

$$A_c = \frac{Q_w}{\rho c_p(\eta_{\text{col}} t_{\text{end}} - t_i)f}$$

In the formula: $J_T$ is average daily solar radiation, $KJ/m^2$; $\eta_{\text{col}}$ is the heat collection efficiency of the collector; $\eta_L$ is heat loss rate; $A_c$ is the total area of the collector; $f$ is the guarantee rate of solar energy; $Q_w$ is average daily hot water volume.

The heat formula provided by the heat collector:

$$Q_z = \frac{k f Q_w c_p(\eta_{\text{col}} t_{\text{end}} - t_i)}{3600 S_y}$$

There, $S_y$ is the sunshine time of a single day; $k$ is the time-varying coefficient of solar irradiance.

The temperature of cold water in winter is 5°C, the temperature of required hot water is 55°C, the guarantee rate of solar energy is 45%, the collector efficiency is 48%, and the heat loss rate is 20%. The average daily solar radiation in winter is about 6450-7050 KJ/m². Assuming that the total area of the collector is 4 m², according to the calculation formula (1), the average daily amount of hot water is about 105 L, and the average daily heat provided by the solar collector is about 907 W.

The calculation formula of heat dissipation[2]:

$$Q = 1.163 G (t_g - t_h)$$

Where, $G$ is the amount of circulating water in the corrugated board skirting radiator, Kg/h; $t_g$ is the inlet temperature of the heat medium, °C; $t_h$ is the outlet temperature of the heat medium, °C.

Supposed that the inlet water temperature of the indoor skirting radiator is 55°C, the outlet water temperature is 40°C, and the water flow rate of the water circulation system is 20 Kg/h. According to formula (2), the heat dissipation of the skirting radiator is 349 W per hour.

3. Heat dissipation analysis

3.1. Geometric model and assumptions

Figure 1. Model schematic
Select a residential bedroom as the research object of the heating room, as shown in Fig.1. The room size is 4m×3m×3m, and the door opening size is 0.8m×2m, located in the middle of the west wall. The initial temperature of the inner wall is $T_c=5^\circ C$; the height and thickness of skirting radiator are 0.1m and 0.03m respectively. The skirting radiator installed in a ring close to the ground, except for the door opening. Where the surface temperature of the heater is $T_h=47^\circ C$. The model adopts a rectangular coordinate system, with the corner of the northwest wall as the coordinate origin, the positive direction of the X axis is south, and the positive direction of Y axis is east.

The physical model needs to be simplified to a certain extent. It is assumed that the indoor gas is an ideal gas, incompressible, constant physical properties, and steady-state laminar flow; the room is a confined space, and the walls are isothermal and steady-state heat transfer; radiation heat transfer effects are not considered; the Boussinesq density assumption is satisfied[3]. The Boussinesq density assumption is a measure to simplify the calculation to deal with the buoyancy term caused by the temperature difference. It is assumed that the influence of density on the pressure difference term, the inertial force term and the viscous force term is negligible, and only the density of the mass-related term in the momentum equation is considered, and the rest are regarded as constants. That is, the buoyancy term (gravity term) in the momentum equation adopts the Boussinesq density assumption, and the density values in the other equations are all the average of the fluid area. The density in the buoyancy term is expressed as:

$$\rho = \rho_0 [1 - \beta(T - T_0)]$$

In the formula: $T_0$ is reference temperature; $\rho_0$ is the fluid density corresponding to $T_0$; $\beta$ is thermal expansion coefficient of ideal gas.

### 3.2. Mathematical model

When is no ventilation in the room, for the heating room, the natural convection caused by the temperature difference in the dominant airflow in the room, using the assumption in 3.1, the governing equations of the steady-state natural convection problem are[4]:

$$\begin{align*}
\frac{\partial \rho u}{\partial x} + \frac{\partial \rho v}{\partial y} &= 0 \\
\frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho v)}{\partial y} &= -\frac{1}{\rho} \frac{\partial p}{\partial x} + \nu \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) \\
\frac{\partial (\rho v)}{\partial x} + \frac{\partial (\rho v)}{\partial y} &= -\frac{1}{\rho} \frac{\partial p}{\partial y} + \nu \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right) - \rho g \\
\frac{\partial (\rho u T)}{\partial x} + \frac{\partial (\rho v T)}{\partial y} &= \alpha \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right)
\end{align*}$$

In the formula: $u$, $v$ is the velocity component of the coordinate $x$ and $y$, $p$ is the pressure, $T$ is the temperature, $\alpha$ is the thermal diffusion coefficient, $\rho$ is the fluid density. There, $u$, $v$, $p$, $\rho$ are all functions of the coordinates and time[4].

The solution idea is to make dimensionless definitions of some parameters in the above differential control equations firstly, then obtain a new set of differential control equations. Then the barycentric interpolation method[5] is used to discretize the differential equations into algebraic equations, and numerically solve the algebraic equations.

Dimensionless parameters[6]:

1. $x$, $y$ are dimensionless space coordinates.
2. $u$, $v$ are dimensionless velocity components.
3. $p$ is dimensionless pressure.
4. $\rho$ is dimensionless fluid density.
5. $T$ is dimensionless temperature.
6. $g$ is dimensionless gravitational acceleration.
7. $\alpha$ is thermal diffusion coefficient.
8. $\beta$ is thermal expansion coefficient.

Dimensionless parameters are defined as:

$$\begin{align*}
x' &= \frac{x - x_0}{L} \\
y' &= \frac{y - y_0}{L} \\
u' &= \frac{\nu}{v} \\
p' &= \frac{p}{p_0} \\
\rho' &= \frac{\rho}{\rho_0} \\
T' &= \frac{T - T_0}{T_h - T_0} \\
g' &= \frac{g}{g_0}
\end{align*}$$

In the above formulas, $x_0$, $y_0$, $L$, $v$, $p_0$, $\rho_0$, $T_h$, $T_0$, $g_0$ are the corresponding reference values.
\[
U = \frac{u}{U_R}, \quad V = \frac{v}{U_R}, \quad Y = \frac{y}{H}, \quad X = \frac{x}{H}, \quad P = \frac{p}{\rho U_R}, \quad \Theta = \frac{T - T_c}{T_h - T_c}, \quad U_R = \frac{\alpha}{H} \sqrt{R \times Pr},
\]

\[
Pr = \frac{\nu}{\alpha}, \quad R = \frac{g \beta H^3 (T_h - T_c)}{\alpha \nu}.
\]

In the formula: \(H\) is the height of the room, \(T_h\) is the surface temperature of the skirting line radiator, \(T_c\) is the indoor cold wall temperature, \(\nu\) is the viscous diffusion coefficient, \(g\) is the acceleration of gravity, and \(\beta\) is the volume expansion coefficient.

Substituting dimensionless parameters into equation (5) to obtain the governing equations are as follows:

\[
\begin{align*}
\frac{\partial U}{\partial X} + \frac{\partial V}{\partial Y} &= 0 \\
\frac{\partial (UU)}{\partial X} + \frac{\partial (VV)}{\partial Y} &= -\frac{\partial P}{\partial X} + \sqrt{Pr} \left( \frac{\partial^2 U}{\partial X^2} + \frac{\partial^2 U}{\partial Y^2} \right) \\
\frac{\partial (VU)}{\partial X} + \frac{\partial (VV)}{\partial Y} &= -\frac{\partial P}{\partial Y} + \sqrt{Pr} \left( \frac{\partial^2 V}{\partial X^2} + \frac{\partial^2 V}{\partial Y^2} \right) + \Theta \\
\frac{\partial (U \Theta)}{\partial X} + \frac{\partial (V \Theta)}{\partial Y} &= \frac{1}{Pr} \left( \frac{\partial^2 \Theta}{\partial X^2} + \frac{\partial^2 \Theta}{\partial Y^2} \right)
\end{align*}
\]

3.3. Result analysis

Fig.2 shows the cross-sectional temperature distribution at \(X=0\)m and \(X=2\)m in the room with the skirting radiator. It can be seen in fig.a that the temperature near the skirting radiator is higher, and the temperature gradient from the top of the radiator to \(Z=1.8\)m is larger, and the temperature gradually decreases. Affected by the adjacent wall skirting line radiator, the overall temperature isotherm of this surface is U-shaped. As can be seen in fig.b, affected by the door, the temperature is low on the left side and high on the right side, and the temperature decreases gradually around the skirting line radiator.

![Figure 2. The temperature distribution diagram on YOZ inside the room with skirting radiator](image)

Fig.3 shows the cross-sectional temperature distribution at \(Y=0\)m and \(Y=1.5\)m in the room with the skirting radiator. As can be seen in fig.a, the temperature curve is not continuous because the skirting line radiator is not installed at the door. The overall temperature distribution is high on both sides, low in the middle, and high in the bottom and low in the middle. As can be seen in fig.b, the indoor temperature is approximately evenly distributed. Except for the high temperature in the area...
near the skirting radiator, the temperature in most of the cross-section is between 18-21 ℃, and there is obvious downdraft.

![Temperature distribution diagrams](image)

Figure 3. The temperature distribution diagram on XOZ inside the room with skirting radiator

Fig.4 shows the cross-sectional temperature distribution at Z=0m and Z=1.5m in the room with the skirting radiator. As can be seen in fig.a, the temperature of the section decreases from the periphery to the center ring, and the temperature drops significantly. As can be seen in fig.b, the overall temperature is still distributed in a ring, and the temperature gradient is not obvious. Except for the lower central temperature and the temperature near the door, the temperature in most areas is above 18°C.

![Temperature distribution diagrams](image)

Figure 4. The temperature distribution diagram on XOY inside the room with skirting radiator

4. Conclusion

This paper analyzes the indoor temperature distribution in the case of solar heat collection and skirting heat dissipation, and draws the following conclusions:

(1) Under certain conditions in areas with abundant solar energy, the heat collector can provide about 907W of heat per day, the heat dissipation capacity of the skirting radiator is 349W per hour. From the average result, the heat provided by the solar collector can support the skirting heater for continuous heating for many hours.

(2) The skirting radiator has good heat dissipation effect, the temperature distribution in the room is even, and there is no obvious cold feeling near the wall.

(3) The heating method has certain feasibility. Not only for rural houses, but also for schools, offices and other occasions.
Acknowledgments
Thanks for the help from Zhang Yu and Wang Xue, and thanks for the support from Dezhou’s Key Laboratory of High-efficiency Heat Pump Air Conditioning Equipment and System Energy Saving Technology (Shandong Huayu University of Technology, Item Number: 26).

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