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Feasibility Investigation of the Low Energy Consumption Cooling Mode with Ground Heat Exchanger and Terminal Radiator

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Abstract

Due to its huge heat capacity, ground can provide heat source in winter and heat sink in summer as the so called shallow geothermal energy, which is mainly utilized by the ground coupled heat pump system. In fact, free cooling can be provided by circulating water between the ground heat exchanger (GHE) and the indoor terminal directly. Recently, radiator for cooling developed rapidly due to it possesses high energy efficiency and comfortable level, however, condensation arises if entering water temperature is lower than dew point of the ambient air. Therefore, this study proposes a low energy consumption cooling mode by combining the GHE and the terminal radiator to utilize the ground cooling directly and to prevent the condensation problem of terminal radiator. The simulation model of this novel mode is established, and the feasibility of this low energy consumption cooling mode is analyzed based on simulation results.

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Keywords: Low energy consumption; cooling mode; ground heat exchanger; terminal radiator

1. Introduction

Since its huge heat capacity, the ground obtains a nearly constant temperature equals to the annual average dry bulb air temperature just below the surface around the whole year. Compared with ambient air, the ground is warmer

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in winter and cooler in summer with temperature usually below 20℃ [1]. Ground can provide free heat source in winter and free heat sink in summer as the so called shallow geothermal energy, which is mainly utilized by the ground coupled heat pump (GCHP) air conditioning system [2]. For cooling provision of the GCHP system, the condenser of heat pump unit will reject heat into ground by circulating cooling water between the condenser and the ground heat exchanger (GHE). Then the cold water with low temperature is produced by evaporator and sent to fan coil units inside air conditioning room. In fact, the ground temperature is lower than the required indoor air temperature. Free cooling can be provided by circulating water between the GHE and the indoor terminal directly.

Recently, floor radiator for cooling which consisted with an embedded cooling pipe system integrated with the building floor construction developed rapidly due to it possesses high energy efficiency and comfortable level with entering water in relative high temperature. [3-5] Radiant cooling system directly transfer heat in order to condition a space to a specific temperature, and can also be used to directly provide heat to humans as well as to spaces. For radiant cooling mode, the same comfort level can be maintained with a higher air temperature compared with convective cooling. But disadvantage of this technology is the condensation problem for entering water temperature lower than dew point of the ambient air [6].

Therefore, this study proposes a low energy consumption cooling mode by combining the GHE and the floor radiator to utilize the ground cooling directly and to prevent the floor condensation. The simulation model of this novel mode is established, and the feasibility of this low energy consumption cooling mode is analyzed based on simulation results. The proposed cooling mode can maintain the comfortable temperature circumstance with low energy consumption for buildings located in regions hot in summer and cold in winter. It should be noticed that, the independent dehumidification equipments should be included for buildings with high dehumidification requirement.

2. System of low energy consumption cooling mode

For utilizing the ground cooling directly to obtain the low energy consumption cooling, the proposed cooling mode circulates water between the outdoor GHE and the indoor floor radiator by a low-power circulating pump. In order to diminish the effect of surrounding air, the vertical borehole GHE is selected. Besides, a heat pump unit is installed to ensure the cooling provision of system in extreme hot weathers. As shown in Fig. 1, valves 1 and 1’ are open and valves 2, 2’, 3, 3’ are close for normal low energy consumption operation to circulate water between GHE and floor radiator. In extreme hot weathers, valves 2, 2’, 3, 3’ are open, valves 1 and 1’ are close, and heat pump unit is activated to handle the cooling load. Data acquisition system consists of the temperature, the flow rate and the power consumption acquisition systems are installed. The temperature of water entering the floor radiator should be monitored for guaranteeing the cooling effect and for preventing the floor condensation.

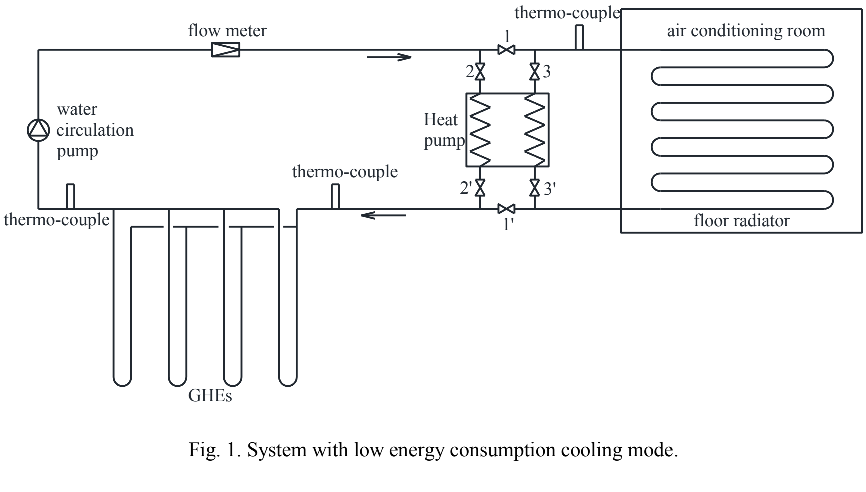

Fig. 1. System with low energy consumption cooling mode.

2.1. Model of GHE

The GHE is the key component to utilize the shallow geothermal energy as the free cooling source, as shown in Fig. 2, it is important to establish the model of GHE to simulate the operation performance of system with low energy consumption cooling mode. Due to its complications and long term effect, the heat transfer process is usually separated into two parts: the heat transfer inside the borehole, which is considered as a steady process; and the heat transfer outside the borehole, which is treated as a transient process.

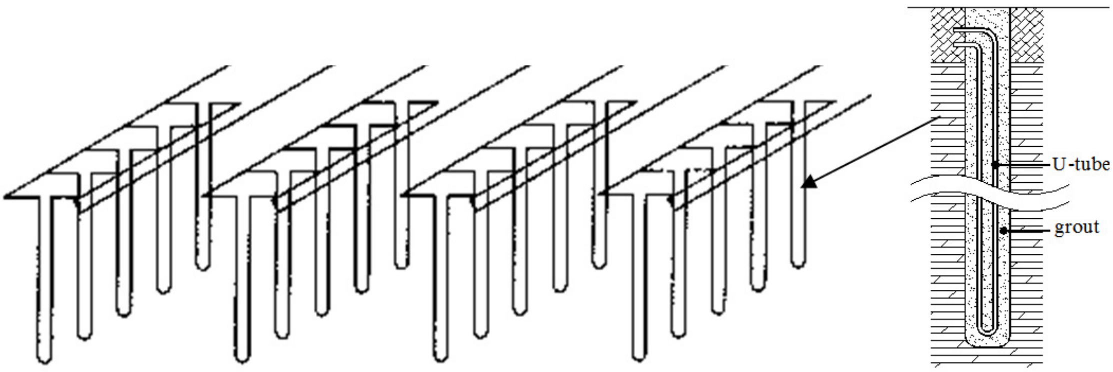

Fig. 2. Ground heat exchanger and one vertical borehole with single U-tube.

Taking the fluid axial convective heat transfer and thermal "short-circuiting" among the U-tube legs into account, a quasi-3-D model for the heat transfer inside the boreholes of the GHE has been obtained by Zeng et al. [7]. The transient heat transfer outside the boreholes is analyzed by a 2-D model, and the analytical solution has been obtained by Zeng et al. [8]. Generally, the GHE contains more than one borehole which has its own temperature responses based on the location. In order to ensure the effective heat transfer capacity of the GHE, the most unfavorable temperature as shown in equation (1) is employed to represent the temperature response of the whole GHE:

$$\theta_e = \frac{q_l}{4k\pi}\int_0^1 \left\{ \frac{erfc\left(\frac{\sqrt{\left(\frac{r_b}{H}\right)^2+(0.5-H')^2}}{2\sqrt{\frac{a\tau}{H^2}}}\right)}{\sqrt{\left(\frac{r_b}{H}\right)^2+(0.5-H')^2}} - \frac{erfc\left(\frac{\sqrt{\left(\frac{r_b}{H}\right)^2+(0.5+H')^2}}{2\sqrt{\frac{a\tau}{H^2}}}\right)}{\sqrt{\left(\frac{r_b}{H}\right)^2+(0.5+H')^2}} + \sum_{j=1\, j\neq i}^{N} \frac{erfc\left(\frac{\sqrt{\left(\frac{\rho_j}{H}\right)^2+(0.5-H')^2}}{2\sqrt{\frac{a\tau}{H^2}}}\right)}{\sqrt{\left(\frac{\rho_j}{H}\right)^2+(0.5-H')^2}} - \sum_{j=1\, j\neq i}^{N} \frac{erfc\left(\frac{\sqrt{\left(\frac{\rho_j}{H}\right)^2+(0.5+H')^2}}{2\sqrt{\frac{a\tau}{H^2}}}\right)}{\sqrt{\left(\frac{\rho_j}{H}\right)^2+(0.5+H')^2}} \right\} dH' \tag{1}$$

Where r_b denotes the radius of the borehole, H denotes the depth of the borehole, p_j denotes the distance from other boreholes to the concerned borehole.

In order to integrate the analytical solution into our computer program, the *f*-function is used to represent the non-dimensional temperature response of the GHE, shown as equation (2).

$$\mathrm{f}\left(\tau-\tau_{i-1}\right)=g\left(\tau-\tau_{i-1}\right)-g\left(\tau-\tau_{\mathrm{i}}\right), \text{ or, } \mathrm{f}\left(\tau-(\mathrm{i}-1)\Delta\tau\right)=g\left(\tau-(\mathrm{i}-1)\Delta\tau\right)-g\left(\tau-\mathrm{i}\Delta\tau\right) \tag{2}$$

Where $g(\tau)=\frac{2\pi \mathrm{k}\theta_{\mathrm{e}}}{\mathrm{q}_{\mathrm{l}}}$, and q_l denotes the heat releases rate of the line-source per length; θ_{e} can be calculated by equation (1). Since the *f*-function represents the non-dimensional temperature response of the GHE to the pulse heat input, the temperature response of the borehole wall can be deduced using the superimposing theory by equation (3):

$$\theta=\frac{1}{2\pi k}\sum_{i=1}^{\infty}q_{l_i}\cdot \mathrm{f}\left(\tau-\tau_{i-1}\right) \tag{3}$$

Taking the fluid axial convective heat transfer and thermal "short-circuiting" among U-tube legs into account, a quasi-3-D model for boreholes in the GHE has been established, and its analytical solutions of the fluid temperature profiles along the borehole depth have been obtained for single U-tube boreholes [7]. The temperature of water entering and effusing the GHE can be derived by the heat transfer resistance:

Entering fluid temperature: $T_f^{'}=T_b+\frac{q_l\times H}{M\,C_p}\left(\frac{1}{1\text{-}Q''}\right)$ (4)

Effusing fluid temperature: $T_f^{''}=T_b+\frac{q_l\cdot H}{M\,C_p}\left(\frac{\Theta''}{1-\Theta''}\right)$ (5)

Where T_b denotes the temperature of borehole wall, which can be calculated by the heat conduction outside boreholes; Θ'' denotes the non-dimensional effusing fluid temperature.

2.2. Model of floor radiator

In many building system simulation using dynamic simulation models, the heat transfer of floor radiator is often split up in a convective part and a radiant part. As shown in Fig. 3, the structure of common utilized floor radiator consisted of floor covering, weight bearing and thermal diffusion layer, thermal insulation, and structural bearing.

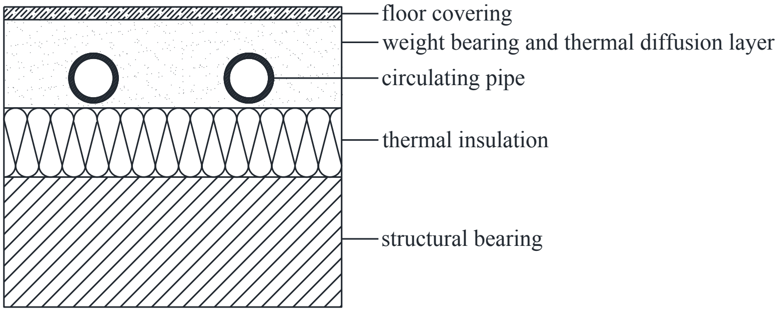

Fig. 3. Structure of floor radiator.

Based on researches on radiation cooling mode, the international standard [9] provides a practical model to establish the relationship between the heat flux of floor radiator q, the average surface temperature $\theta_{s,m}$, and design indoor temperature θ_i, as shown in equation (6):

$$q=7\left(\left|\theta_{s,m}-\theta_i\right|\right) \tag{6}$$

For floor radiation cooling, there is a maximum allowable heat flux, which is determined by selected design indoor air temperature and the allowable average surface temperature. For the calculations, the centre of the floor radiation cooling surface area is used as a reference point for the maximum surface temperature.

On the other hand, the heat flux of floor radiator q is mainly determined by the pipe spacing, thickness and thermal conductivity of the layer above the pipe, thermal conduction resistance of covering, dimensions and thermal conductivity of pipe. Therefore, heat flux q can be calculated by the structure parameters of floor radiator, the design indoor temperature θ_i, the supply temperature of circulating fluid θ_V, and return temperature of circulating fluid θ_R, as shown in equation (7):

$$q = B \cdot a_B \cdot a_W^{m_W} \cdot a_U^{m_U} \cdot a_D^{m_D} \cdot \frac{\theta_R - \theta_V}{\ln \frac{\theta_i - \theta_V}{\theta_i - \theta_R}} \quad (7)$$

Where B is a system-dependent coefficient depends on the type of system, a_B is surface covering factor, a_W is the pipe spacing factor, a_U is the covering factor, a_D is the pipe external diameter factor, and m is exponents for determination of corresponding characteristic curves. For a specific floor radiator, the heat flux of floor radiator q can be calculated based on the supply temperature of circulating fluid θ_V, and return temperature of circulating fluid θ_R.

For the proposed low energy consumption cooling mode by combining the GHE and the floor radiator, the models of GHE and floor radiator can be connected with circulating fluid, i.e. the supply fluid and return fluid of floor radiator are the effusing fluid and entering fluid of GHE correspondingly. If the temperature change in the connection pipe between GHE and floor radiator can be neglected, the supply fluid temperature of floor radiator equals to the effusing fluid temperature of GHE, and the return fluid temperature of floor radiator equals to the entering fluid temperature of GHE.

Then the model of the proposed low energy consumption cooling mode can be established and compiled with FORTRAN language. Operation performance of system such as the heat flux between floor radiator and indoor surrounding, the supply and return fluid temperature of floor radiator as well as GHE can be simulated.

3. Simulation Results

3.1. Sample project information

System operated in low energy consumption cooling mode with GHE and floor radiator is designed for a sample office building located in Jinan (36°40’ in north latitude, 117°00’ in east longitude), Shandong province of China, where is hot in summer and cold in winter. The sample office building possess 6 floors above ground, its total building floor space is 5360m^2 with air-conditioning area in 4850m^2. The length of this office building is 46.9m, the width is 19.0m, and height between floors is 3.6m. The required indoor air temperature for summer is 26℃, and annual cooling degree days is 135. Working hours of this sample office building is 8:30~17:30, and the air conditioning system operated in the intermittent mode.

Then the hour-by-hour weather data are represented by the Typical Meteorological Year weather data of Jinan city. The cooling loads of sample building are calculated on an hour-by-hour basis by the DEST software. Based on calculation results, the mean cooling load of sample building is 64.5kW, and the peak cooling load appears in the 15:00 of 19th July with value of 172 kW. The initial ground temperature of Jinan is 14.7℃.

The GHE designed and installed for the sample office building is comprised of 60 vertical boreholes whose depths and diameters are 90m and 150mm, respectively. The borehole spacing is selected as 5m. Water circulates in single U-pipes buried in boreholes, and the U-pipes buried in each borehole are connected in parallel. These HDPE U-pipes’ with outside and inside diameters in 32mm and 25mm, respectively, are connected in parallel above ground. According to the common geological parameters of Jinan [10], the ground around boreholes is saturated moisture soil. The thermal conductivity, thermal diffusivity and temperature of ground at 9m depth are 1.9X10^{-3} kW/(m·K), 0.7X10^{-6}m^2/s and 14.7℃, respectively. In order to prevent the surface water penetration and potential groundwater contamination, all of boreholes were completely backfilled with the grout which was mixed with drilling mud, cement and sand soil in specific proportions. The thermal conductivity and thermal diffusivity of the grout are 2.2X10^{-3} kW/(m·K) and 0.9X10^{-6}m^2/s, respectively.

The floor radiator designed for the sample office building is comprised of PE-X pipes with outside and inside diameters in 20mm and 16mm, respectively. These pipes are buried between the thermal insulation material and the surface floor covering, as shown in figure 3. These PE-X pipes overspread the floor of air-conditioning area with average spacing in 250mm. The ceramic tile with thickness of 0.9cm is utilized as the surface covering. The screed cement is selected as the weight bearing and thermal diffusion layer, and the thickness of cement layer between the pipe's external wall and the ceramic tile is 30cm. The whole floor radiator of each floor is separated into several circulating loops connected in parallel, and the air-conditioning floor area served by each circulating loop is no larger than $30m^2$.

3.2. Simulated operation performance of low energy consumption cooling mode

Performance of system operated in low energy consumption cooling mode designed for the sample office building is simulated by the computer program based on the established model. The temperature of circulating water entering and effusing the GHE during the low energy consumption cooling mode from June to August for the sample office building is plotted in Fig. 4.

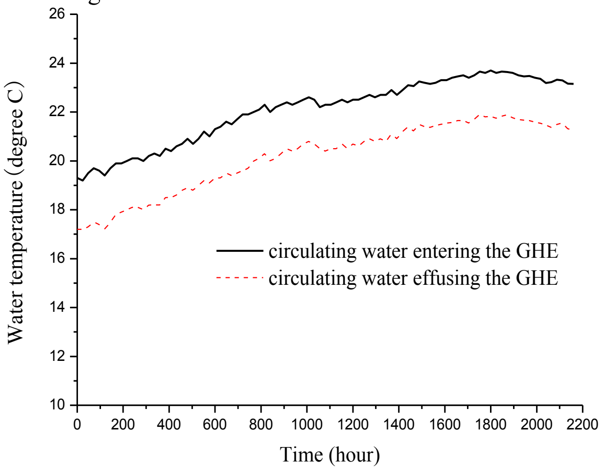

Fig. 4. Operation temperature of circulating water.

As shown, the temperature of circulating water entering the GHE ranges from 19.2℃ to 23.7℃, effusing the GHE ranges from 17.2℃ to 21.9℃. Although the circulating water experience a slight temperature raise during system operation, the indoor air temperature can be controlled below 26℃ due to the thermal energy storage of the floor construction during night operating mode. On the other hand, the temperature of water effusing the GHE is high enough to be circulated directly into the floor radiator for preventing the floor condensation.

4. Discussion

Based on the simulative operation data, the system performance during the whole cooling provision days can be summarized: the average cooling power of GHE is 30.2kW (5.60W/m), the total cooling obtained from GHE is 97.9MW·h, the total electricity consumed by floor radiator-GHE circulating pump is 3.9kW·h, and the COP of the low energy consumption cooling mode with ground heat exchanger and floor radiator can be as high as 25.1. Based on the analysis, the average cooling power of GHE in proposed system is lower than GHE in traditional ground coupled heat pump system. It is because the heat transfer difference between circulating water and the surrounding soil in proposed system is smaller than which in traditional ground coupled heat pump system. For districts executing the peak-valley electricity price, the economy of proposed low energy consumption cooling mode is even higher. It should be noticed that, if the proposed low energy consumption cooling mode serves for buildings with high dehumidification requirement, the independent dehumidification equipments should be included.

5. Conclusions

This study proposes a low energy consumption cooling mode by combining the GHE and the floor radiator to utilize the ground cooling directly and to prevent the floor condensation. The simulation model of this novel mode is established. The feasibility of this low energy consumption cooling mode is analyzed based on simulated performance of a system with proposed mode designed for a sample building. According to simulation results, the system with proposed cooling mode can maintain the indoor comfortable temperature circumstance and prevent the floor condensation of sample building with low energy consumption. The COP of proposed low energy consumption cooling mode with GHE and floor radiator can be as high as 25.1. It is found that, by utilizing the renewable shallow geothermal energy and the thermal energy storage capacity of the floor construction, the proposed cooling mode with GHE and floor radiator can provide cooling for buildings with very low energy consumption. Since the proposed cooling mode can not afford the indoor air dehumidification load, the independent dehumidification equipments should be included for buildings with high dehumidification requirement.

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