

Investigation on performance of solar-driven floor heating system

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ABSTRACT: Performance of a solar-powered floor heating system was studied. This system utilized a 96m² solar collector array as heat source and serves an office area of 170 m². Experiments have been carried out for a whole winter under various conditions, and the result showed that this system goes well during the experimental period with average room temperature maintained above 16°C except for continuous overcast days.

A computer program was developed to simulate system performance under variant conditions, and it showed that solar radiation and initial hot water temperature had significant influences on system performance. A great thermal lag was also observed in this system, which seriously reduced indoor temperature. By adjusting system control strategy, the negative influence of the thermal lag was eliminated with indoor temperature 1~2°C higher.

Keywords: solar energy, floor heating, system performance

1. INTRODUCTION

Solar energy is receiving more attention recently, for its safety, cleanliness and energy saving potential. There are several ways to utilize solar energy, and using solar energy for low temperature radiant floor heating in winter is a popular one of which, because the temperature need in radiant floor heating has a good consistency with that of the hot water produced from solar collectors. Characterizes of low temperature radiant floor heating has been under research for a long time. Part of these efforts was given to the dynamic behavior of floor

heating system ^[1], because floor heating itself is an unsteady system, and is more unsteady when combined with a solar powered heat source within which solar radiation varied almost all the time. Besides, control strategy of radiation floor heating system also has a significant influence to energy consumption as described by S.H. Cho et al. ^[2] who applied a new control strategy to a radiant floor heating system and got more than 10% energy saving.

Combination technique of solar energy with floor heating has developed a lot in recent years. M. T. Alkhalaileh et al. ^[3]

developed a computer program to analyze a solar pond floor heating system, and found this kind of combination could meet heating demand for at least 2 months in local district. Ali A. Badran et al. [4] set up an experiment to compare energy consumption of the floor heating system using solar pond or solar collector, and found that floor heating using solar collector was 6% more efficient than the other. However, these studies mainly focused on the energy performance, and the system operation feature was not investigated.

In the presented study, a solar-powered floor heating system was experimentally studied and modeled, and then the performance and sensibility was analyzed based on this model.

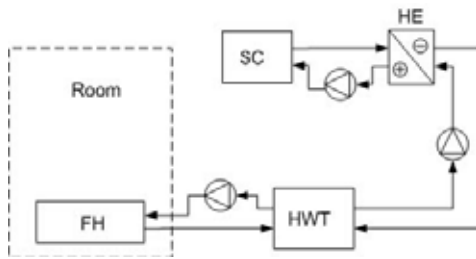


Figure 1: System Schematics

2. SYSTEM DESCRIPTION

The solar-powered floor heating system was built in Shanghai, with 96m² U-type evacuated tubular solar collectors with CPC on the roof as heat source. The floor heating area is 170m².

Hot water from the solar collector (SC) is pumped to a plate heat exchanger (HE), where it heats water from a hot water storage tank (HWT). The volume of hot water tank is 3m³, and it is well thermally isolated on the surface. When heating is needed, hot water is pumped from hot water tank into a radiant floor heating system (FH). The floor heating system consists of coil pipes embedded in concrete slabs with a homogeneous distribution to decrease ununiformity of floor temperature. An automatic controlling and data logging program was applied to this system. With

temperature values provided by PT-1000 RTS embedded in key nodes of water loop, this program controls system operation by turning pumps on or off. Solar radiation intensity at surface of solar collector was measured via a radiometer.

3. SYSTEM MODELING

With solar radiation on solar collector known, heat transfer in U-type evacuated tube solar collectors with CPC is calculated as follows:

$$m_{sc} C_p (T_{sc,out} - T_{sc,in}) = I * A_{sc} * eff_{sc}$$

Where m_{sc} is circulating water volume in solar collector (kg/s), C_p the specific heat of water (J/kg°C), $T_{sc,out}$ the outlet temperature of solar collector (°C), $T_{sc,in}$ the inlet temperature of solar collector (°C), I the solar radiation on solar collector (W/m²), A_{sc} the area of solar collector array (m²), and eff_{sc} the collector efficient factor which has a relationship with solar radiation I and ambient air temperature T_a as follows:

$$eff_{sc} = a - b \frac{T_{sc,in} - T_a}{I}$$

Where a and b are coefficient varied with special solar collector.

Hot water tank acts as connection between solar collector and floor heating system. In this system the inlets and outlets are designed at a reasonable position to avoid large temperature difference between upper layer and lower layer during operating. So water temperature in hot water tank is considered as uniform, and the energy balance is as follows:

$$m_{hwt} C_p \frac{dT_{hwt}}{d\tau} = m_{wh} C_p (T_{hwt,in} - T_{hwt,out}) + m_{fh} C_p (T_{fh,out} - T_{fh,in}) + Q_{hwt,loss}$$

Where m_{hwt} is water capability of tank (kg), m_{wh} volume of water heating loop

between hot water tank and (kg/s), m_{fh} volume of floor heating loop (kg/s), T_{hwt} hot water temperature in the tank ($^{\circ}C$), $T_{hwt,in}$ inlet temperature of hot water tank coming from heat exchanger ($^{\circ}C$), $T_{fh,out}$ and $T_{fh,in}$ temperature of floor heating inlet and outlet ($^{\circ}C$), and $Q_{hwt,loss}$ is heat loss of water tank which is calculated from hot water temperature, tank geometry, thermal isolation and outdoor temperature (W).

In the floor heating system, hot coil pipes are embedded into concrete floor construction. In the continuously running system the hot coil layer could be considered as a heat source panel with uniform temperature. With such assumption heat transfer in floor can be assumed as one dimension with the following governing equation:

$$\frac{\partial T_f}{\partial \tau} = \alpha \frac{\partial^2 T_f}{\partial x^2}$$

Where T_f is the floor temperature ($^{\circ}C$) which variants with floor depth x (m), α thermal diffusivity (m^2/s).

Temperature at outer surface of hot coil is assumed the same as the concrete temperature at the same depth. Heat transfer through the pips follows these equations:

$$m_{fh} C_p (T_{fh,out} - T_{fh,in}) = K_p L_p \Delta t_m$$

Heat transfer in exterior-protected construction of the office is also considered as one dimension. The governing equation is as follows:

$$\frac{\partial T_{w,i}}{\partial \tau} = \alpha_{w,i} \frac{\partial^2 T_{w,i}}{\partial x^2}$$

Where $T_{w,i}$ and $\alpha_{w,i}$ are temperature ($^{\circ}C$) and thermal diffusion constant (m^2/s) of wall i.

Energy equation for indoor air is as follows:

$$V_r \rho_a C_{p,a} \frac{\partial T_{ia}}{\partial \tau} = \sum_{j=1}^N h_j A_{s,j} (T_{s,j} - T_{ia}) + Q_{gen} + Q_{le}$$

A computer simulation program was developed. When solving the equations,

space discretisation and variable time step was applied. A simulation for system operation as made to compare the simulated data with experiment data, as shown in Fig. 2. The three groups of data are temperatures of hot water tank, floor surface and indoor air, respectively. In that day system started to operate at 6:00, then hot water was pumped to floor heating system and temperature of hot water tank dropped rapidly meanwhile floor and indoor air was heated. After sunrise when solar collector was able to supply sufficient heat, the temperature of hot water tank started to rise rapidly, then the temperature of floor surface and indoor air. In late afternoon solar energy received by solar collector was not large enough to maintain the indoor environment at that high temperature so temperatures of the system began to drop. The comparison shows that this simulation program is able to illustrate the dynamic characterize of this system, with acceptable accuracy.

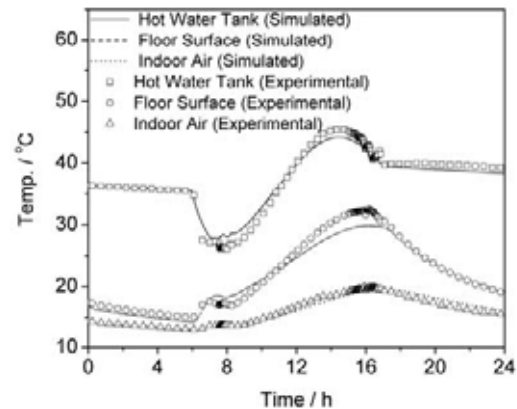


Figure 2: Comparison between simulation and experiment

4. DISCUSSIONS

Solar-powered floor heating system faces an object with great variability. In a heating season solar radiation and ambient temperature changes a lot and initial temperatures of hot water tank or floor construction are also not the same in different days. These variations would

change performance of the system to different extent. Simulation on Feb 1st, 2007 was made to illustrate these influences. Base on the experimental data, it was sunny that day with an average solar radiation of 625W/m^2 on solar collector surface during daytime was, and ambient temperature fluctuates around 2°C . Initial temperatures of hot water tank, floor surface and indoor air at 0:00 was 36°C , 17°C and 14.2°C , respectively. In the simulation, system performance was checked under different conditions, and average temperatures of hot water tank, floor surface and indoor air for each condition were calculated. The result was shown in Fig. 3 and 4.

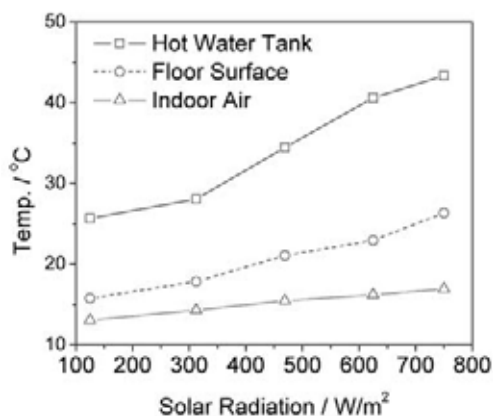


Figure 3: Influence of solar radiation

Fig. 3 shows that solar radiation had great impact on system performance. In sunny days, average hot water temperature could reach 43°C , and average indoor air temperature reaches 17°C during office hours. While in overcast days the performance was reduced badly with average indoor temperature of 13°C .

Initial temperature of hot water tank is another parameter that has great impact on system performance. It was observed from Fig. 4 that average indoor temperature could be as high as 18°C if initial hot water temperature reaches 60°C due to continuous sunny day. While if hot water had been used too much in the previous day and initial hot water temperature was only 25°C , the average indoor temperature could just reach

14°C , although it was still sunny that day and solar radiation was strong.

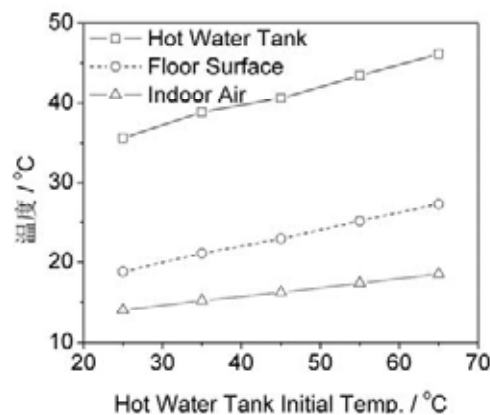


Figure 4: Influence of HWT initial temperature

Besides solar radiation and HWT initial temperature, several other conditions like initial floor temperature and ambient temperature were also considered, however they show much less impact on system performance.

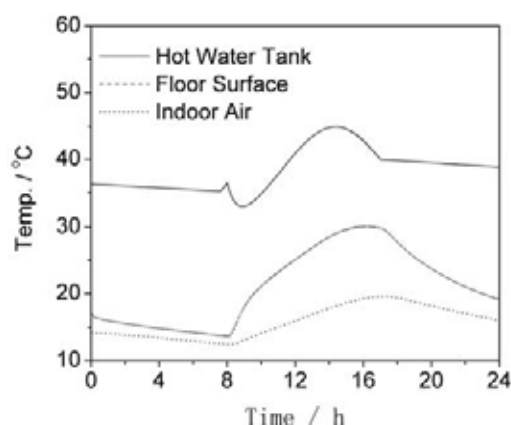


Figure 5: Thermal lag within system

Besides these characterize, it was observed that the system operated with great thermal lag, as shown in Fig. 5. When system operated under the same schedule as office an hour, that is 8:00~17:00, room peak temperature arrived 8 hours later at 16:00. After system started to operate, temperatures rose slowly due to the thermal lag, so in a long time the indoor air temperature was too low to supply a comfortable environment. Statistic showed that in this operation mode, indoor air temperature was below 15°C in 33% of the

office hours, and such thermal lag had badly reduced indoor thermal comfort. There are two reasons for the thermal lag:

a) Great heat capacity in the system, including hot water tank, concrete floor construction and thick exterior-protected construction;

b) Characterize of solar energy which reaches its peak value in noon while supplied less energy in the early morning.

These characterize mentioned above showed that a suitable control strategy should be applied to improve system performance. This could be achieved by adjusting system operation schedule. In the adjusted schedule, system started to operate 2.5 hours earlier at 5:30 to preheat the system and reduce the thermal lag. Operation stopped also a little earlier at 15:00 to save enough heat for the preheating of next day. A continuous simulation of 5 days was made, and calculated data was shown in Fig. 6. The result showed that the indoor environment had been significantly improved.

Average indoor air temperature reached 19°C, which was 1°C higher than the former case. And indoor air temperature was kept above 15°C during the whole office hours, compared to 33% dissatisfaction rate in the former case.

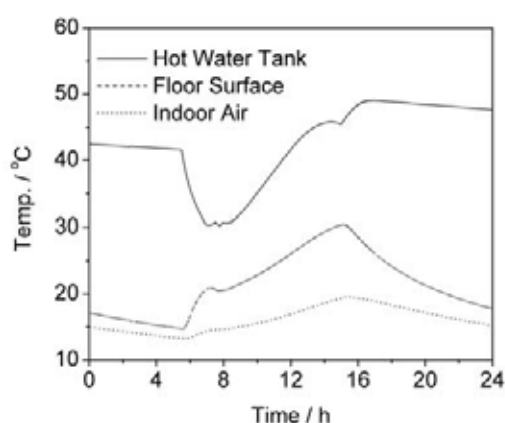


Figure 6: System performance with adjusted control

System started at 5:30 to preheat the system, and hot water was cooled at the same time. At 6:50 hot water temperature

had dropped too low to supply efficient preheating, then the floor circulation is cut off. By this time floor surface temperature had been heated from 15°C to 22°C, and the warmer floor kept on heating indoor environment through radiation and convection, and maintained the indoor air temperature at about 15°C at 8:00. The floor heating circulation started again around 8:20, when hot water temperature had been raised high enough by solar energy. Then system operated continuously until 15:00, after that indoor air temperature was maintained about 19°C for the thermal lag until the end of office hours.

4. CONCLUSION

In this paper performance of a solar-powered floor heating system was studied, result showed that it operated well in winter, supplying an average indoor air temperature above 16°C in normal days. Computer simulation was applied to this system, and it showed that solar radiation and initial hot water tank temperature had significant influence on system performance. Also a thermal lag was observed in this system which greatly reduced system performance. By adjusting system control, the thermal lag could be greatly weakened with average air temperature 1~2°C higher and dissatisfaction rate significantly reduced.

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