Modeling of Space Cooling System Coupled with Underground Energy Storage

Guoxiang Zhao1,  ·  Kewen Li 1,2,  Yu Jiang1,  Lin Jia1,  B.M. Mahlalela1

1 China University of Geosciences (Beijing), China
2 Stanford University, USA

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ABSTRACT

There are many indoor space temperature adjusting systems that are widely used in heating, ventilation and air conditioning engineering, such as ground source heat pumps, water source heat pumps, and building cooling heating and power systems. However, all of these indoor temperature control systems have some advantages and disadvantages. We previously reported on a heating system coupled with underground energy storage. Here, we propose a new space cooling system coupled with underground energy storage. The practicality and the possibility of meeting the indoor temperature demand in winter by using this newly coupled system has been verified and it is possible to maintain the indoor temperature in a certain temperature range. In this paper, whether the indoor space cooling demand could be met through the application of this newly coupled system is verified by simulation. Related simulations were carried out, and sensitivity analysis of possible influencing factors such as cold storage temperature, cold storage volume, flow rate and circulation fluid were also conducted. Finally, the simulation results proved that it is possible to meet human indoor space cooling demand by using the novel coupled system.

1. Introduction

There are many indoor space temperature adjusting systems that are widely used in Heating, Ventilation and Air Conditioning (HVAC) engineering, such as ground source heat pumps, water source heat pumps, and building cooling heating and power systems. However, all of these indoor temperature control systems have some advantages and disadvantages. For example,
phase change materials, such as freon, are always used in heat pump systems, although the application of phase change materials increases the coefficient of performance to some extent and reduces energy consumption, it also causes environmental pollution. Ground source heat pump systems need boreholes to extract heat from underground soil and geothermal resources, but the vertical borehole drill costs are high and their maintenance is difficult; the horizontal trenches are more easily affected by ambient air temperature fluctuations since they are proximal to the ground surface (Yang, et al., 2010).

Many previously conducted studies focused on building new heating and cooling systems and improving the current indoor temperature adjusting systems. Pérez et al. (2011) analyzed the development of building energy codes concerning HVAC energy efficiency, and pointed out that the heating and cooling systems use the major portion of the energy consumed by buildings, and HVAC equipment alone uses around 15%. Hu and Niu (2017) explored the operation dynamic of radiant systems through on-site measurement and simulation. The results of on-site measurement indicated that the capacity of heat extraction at a cooling surface can be improved by altering the operational strategy of the radiant system based on Beijing weather. Satrio et al. (2016) estimated the energy savings potential of radiant cooling system installed in an institutional building in Indonesia. The result is the radiant cooling integrated with a Dedicated Outside Air System (DOAS) could result in a 41.84% energy savings compared to the installed cooling system. The Computational Fluid Dynamics (CFD) simulation showed that a radiant system integrated with DOAS provides superior human comfort compared to the radiant system integrated with Variable Air Volume (VAV). Ren et al. (2016) took the district heating and cooling (DHC) system as the research object. The load analysis model was developed while taking the building mixing ratio as the parameter, and the supply-side analysis model was formed considering prat-load performance. Ioli et al. (2016) designed a cooling system that comprises a building composed of multiple thermally conditioned zones, a chiller plant, and a thermal storage unit. Alternative solutions for cooling and ventilation of buildings have appeared in practice as a counterweight to energy wasting conventional systems (Uroš and Vincenc, 2011). Hasan et al. (2009) created a map of internal greenhouse temperature distribution by determining the system efficiency. The results indicated that because relative humidity in the air tends to decrease during summer, temperatures in the greenhouse can be consequently be decreased to 10-12 oC by using an evaporative cooling system.

In addition to the study of traditional building heating and cooling systems, many scholars have also carried out studies of indoor temperature-adjusting systems coupled with the energy storage and the Solar Energy Heat Utilization System. Dovrtel and Medved (2011) explored the optimization of a weather-prediction free cooling system combined with heat storage and presented a method of incorporating weather forecasts into the control system. Rabani et al. (2014) numerically simulated passive cooling of a room in Yazd, Iran using a solar chimney and water spraying system in the room inlet vents. Ayadi et al. (2014) designed a solar heating and cooling system for an office building in Italy and the results proved that highly integrated solar thermal heating and cooling systems can achieve a high solar fraction both for the heating and cooling seasons. Hang and Qu (2010) explored the impact of thermal storage on the energy performance of the solar absorption cooling system for a benchmark medium-sized office building located in Los Angeles, California. Fong and Lee (2014) proposed a hybrid renewable cooling system (HRCS) for office building applications by utilizing both solar energy and geothermal energy. Marc et al. (2012) presented the modeling of the solar cooling installation
within the Energy Plus environment at the Technology University Institute (IUT) of Saint Pierre in La Reunion. The model was used to propose a solution to improve the seasonal performance of the installation. Boonnasa and Namprakai (2010) put forward a method to determine the optimal chilled water storage (CWS) capacity and corresponding operating strategy for the air conditioning loads for different electricity tariffs. Vignali et al. (2015) designed an energy management system for a building cooling system that includes a chiller plant (with two or more chiller units), a thermal storage unit, and a cooling load. Fong et al. (2010) proposed a six-hybrid solar desiccant cooling system, three for full fresh air design while another three for return air design for the building zone. Kalogirou (2005) concluded that the annual solar contribution is about 55% and the economic analysis performed show the system is viable as positive life cycle savings are obtained (5100 Euro). Vishwakarma et al. (2012) studied a space cooling application for approximately 100 tons of refrigeration and hourly variation in sunlight, as well as seasonal changes for temperate climate conditions. Jiang and Wang (2011) designed a prototype of a Multifunctional Solar Assisted Heat Pump (MSAHP) system. The results indicated that the combined energy efficiency ratio (CEER) of the system fluctuated between 3.39 and 6.20 in their design.

From the above evidence, one can see that lots of papers have been published in the area of building heating and cooling, but from the view of environmental protection and energy-saving, it is necessary to develop an advanced indoor space temperature adjusting system, which should be featured with multi-energy complementary and zero carbon-emission. A new space heating system coupled with energy storage system has been proposed, but only the space heating effect is simulated. In this paper, building cooling by the application of the coupled system is simulated using the COMSOL MUTIPHYSICS; and the final simulation results proved that it is indeed possible to achieve optimal space temperature adjusting goals in summer by using this newly proposed coupled space cooling system.

2. The Proposed Space Heating and Cooling System

The new space heating system that has been published in the journal of Mathematical Geosciences (Zhao and Li, 2018) has proved that it is possible to meet human indoor temperature demand in winter by using the coupled system, but it did not verify the possibility of indoor space cooling. The space heating and cooling system coupled with underground energy storage is shown in Figure 1. To illustrate the whole system completely, both the heat storage tank and cold storage tank are included in the sketched map, and that is the only difference between this paper and the original sketched map. Other systems such as floor radiant pipes, pumps, solar collector devices, photovoltaic systems and some possible controller devices remain the same.

The heat storage tank and cold storage tank will be used according to changing ambient temperature and the indoor temperature demand conditions. Heat energy is accumulated by a solar collector system and then stored in the heat storage tank in summer, but unlike that of heat energy storing, cold energy is accumulated by the cold collector devices, such as a heat pipe, in winter. During summer, heat transfer fluid that circulates in heat exchanger pipes and floor radiant pipes can cool the target space. The photovoltaic system provides all the electricity demand of the whole coupled heating and cooling system.
Figure 1: Conceptual model of heating and cooling system coupled with energy storage and floor radiant heating pipes.

3. Mathematics

COMSOL MULTIPHYSICS modules of the heat transfer in solids module and the heat transfer in pipes module were applied to simulate the proposed space heating and cooling system. The heat transfer in pipes module which is provided by COMSOL MULTIPHYSICS was used to model the heat transfer by conduction and convection in pipes and channels of different shapes, where the fluid velocity and the pressure fields are known a priori. The heat transfer in pipes module provides a 1D model to define the pipe flow profile and the temperature profiles on curve segments or lines. These lines can be drawn in 2D or 3D and represent the simplification of the hollow pipes. The temperature equation corresponds to the 1D convection-diffusion equation which contains additional contributions like heat sources, and that is why the COMSOL MULTIPHYSICS was used in this study. The circulation pipes composed of the heat exchanger pipes and the floor radiant pipes are used to transfer the energy from the energy storage tanks to the target temperature adjusting space area by the fluid circulating in these pipes.

According to Lurie (2008), the energy equation for an incompressible fluid flowing in pipes is:

$$\rho A C_p \frac{\partial T}{\partial t} + \rho A C_p \cdot \nabla T = \nabla \cdot (A k \nabla T) + Q + Q_{wall}$$

(1)

where $\rho$ is the fluid density, $A$ is the pipe cross sectional area available for flow, $C_p$ is the heat capacity at constant pressure, $T$ is the temperature, and $u$ is the velocity field. Further, $k$ is the thermal conductivity. $Q$ represents a general heat source and $Q_{wall}$ represents external heat exchange through the pipe wall. Note that the $Q_{wall}$ term is detailed below.

For a single layer pipe, the radial heat transfer from the surroundings into the pipe ($Q_{wall}$) is given by:
\[ Q_{\text{wall}} = (h \cdot Z)_{\text{eff}} \cdot (T_{\text{ext}} - T) \]  
(2)

Whereas \((h \cdot Z)_{\text{eff}}\) is the effective value of the heat transfer coefficient, \(T_{\text{ext}}\) is the external temperature outside of the pipe.

Based on the solutions from the heat transfer in the pipes module, the following equation is applied to calculate the solid temperature field (Poinsot and Veynante, 2001).

\[ ρC_p \left( \frac{∂T}{∂t} + \mathbf{u}_{\text{trans}} \cdot \nabla T \right) + \nabla (q + q_r) = Q \]  
(3)

Where \(ρ\) is the density, \(C_p\) is the specific heat capacity at constant stress, \(T\) is the absolute temperature, \(\mathbf{u}_{\text{trans}}\) is the velocity vector of translational motion, \(q\) is the heat flux by conduction, \(q_r\) is the heat flux by radiation, and \(Q\) contains additional heat sources. Heat transfer from pipes to the target heating and cooling space can be calculated by Eq. 1 and Eq. 2. The temperature field of geometry can be calculated by the combination of Eq. 1, Eq. 2 and Eq. 3.

To control space temperature changes accurately, a control pattern with a temperature range has been set. There are two indicators, \(Turn_{\text{on}}\) and \(Turn_{\text{off}}\):

\[ Turn_{\text{on}} = T_{\text{low}} - T_{\text{aver}} \]  
(4)

\[ Turn_{\text{off}} = T_{\text{aver}} - T_{\text{up}} \]  
(5)

\[ T_{\text{aver}} = \frac{\iiint T \, dx \, dy \, dz}{V} \]  
(6)

\(T_{\text{low}}\) is the lower limit of average space temperature, \(T_{\text{aver}}\) is the average space temperature, and \(T_{\text{up}}\) is the upper limit of average space temperature. In the case that \(Turn_{\text{on}}\) is larger than zero, flow rate is the set-value, and if \(Turn_{\text{off}}\) is larger than zero, flow rate is zero. Thus, control of space temperature with a temperature range can be achieved.

4. Geometry, Meshing and Parameters

The geometry model used to simulate the space cooling effect is the same as that used in space heating, in most cases. The geometry model consists of the target space (room space), the insulating layer, the heat exchanger pipes and the floor radiant pipes (Figure 2). The only difference is that the heat storage tank is switched to a cold storage tank.

All parts of the geometry model are cubes, except for the floor radiant pipes and the heat exchanger pipes. Compared with the conceptual model shown in Figure 1, the geometry model does not include the solar collector system, the photovoltaic system and the cold accumulation system, and the process of cooling the cold storage to a lower temperature is omitted. During the
simulation process, it was assumed that the cold storage tank temperature had been cooled to a certain temperature. To simplify the calculation process, the pipes were simplified into 1D lines. The basic theories of the pipes flow module in COMSOL are clarified in the mathematics chapter above. Table 1 shows the parameters discussed in modeling processes.

![Figure 2: The Geometry of coupled system](image)

<table>
<thead>
<tr>
<th>Variables</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient temperature, °C</td>
<td>49.6</td>
</tr>
<tr>
<td>Target space volume, m³</td>
<td>20*10³</td>
</tr>
<tr>
<td>Initial temperature of target cooling space volume, °C</td>
<td>35.6</td>
</tr>
<tr>
<td>Insulating layer height, m</td>
<td>6</td>
</tr>
<tr>
<td>Cold storage tank temperature, °C</td>
<td>10,-10,-30,-50</td>
</tr>
<tr>
<td>Heat and cold storage tank volume, m³</td>
<td>240,180,120, 60</td>
</tr>
<tr>
<td>Initial pipe diameter in cooling, mm</td>
<td>10,20,30,40</td>
</tr>
<tr>
<td>Flow velocity, m/s</td>
<td>0.0001,0.0005,0.01,0.025,0.05,0.2,0.8</td>
</tr>
<tr>
<td>Circulation fluid</td>
<td>Brine, antifreeze, heat conducting oil</td>
</tr>
</tbody>
</table>

High thermal conductivity of the soil layer covering the energy storage tank will result in huge amounts of energy escaping through the soil layer, making it difficult to control the whole system. Insulation of the energy storage tank was applied to prevent energy loss. The insulating layers are composed of one soil layer, two polyurethane layers, one concrete layer and one granite layer.

The modeling was conducted using different values of flow rate, temperature of cold storage tank, cold storage tank volume, pipe diameters and other critical parameters, as shown in Table 1. All of the effects of these parameters are discussed in the following section.
The geometry was discretized on a finite element model consisting of 17,294 triangular elements. Mesh density of the target space (room, building, etc), the floor radiant pipes and the heat storage tank were increased to obtain high-accuracy solutions. The mesh is shown in Figure 3.

![Mesh for coupled heating system and insulating layer](image)

**Figure 3:** Mesh for coupled heating system and insulating layer

### 5. Results

The effect of temperatures of the cold storage tank, cold storage tank volumes, flow rates, and circulation fluid on space cooling effect were investigated. The parameters studied in space cooling simulation can be found in Table 1. According to the China National Radiant Floor Cooling Standard, the appropriate range of space temperature is 21°C-27°C.

#### 5.1 Flow Rates and Temperatures of The Cold Storage Tank

The flow rates and temperatures of the cold storage tank are two important influencing factors in the changes of space temperature. As it can be seen in Figure 4, the space temperature increases with the decrease in flow rate and the increase in cold storage tank temperature.

As it is shown in Figure 4(b), (c) and (d), the changes in cooling at lower flow rates are larger than those at higher flow rates. Flow rates also affect space temperature fluctuation and fluctuation frequency. All three figures in Figure 4 show similar trends that the cooling effect becomes lower and lower as the cold storage temperatures increase and the flow rates decrease, meanwhile, the time requirements of space cooling (the time that the space temperature reaches 21°C for the first time) becomes longer. In a case where the energy storage tank temperature is 10°C (Figure 4(a)), none can meet the cooling standard.

#### 5.2 Cold Storage Tank Volumes

As one can see from Figure 5, it is only when the cold storage volume is greater than 120m³ and cold storage temperature is below -30°C that the cooling effect can be met. All of the results from the cases where the cold energy storage volume is larger than 120m³ and the temperatures
are below -50°C show great space cooling effect. In other words, the cold energy capacity must be higher than a certain value to acquire a reasonable space cooling effect.

Figure 4: Relationship between time and space temperatures at different flow rates (cold storage tank volume of 180m³) - (a) cold storage temperature of 10°C; (b) cold storage temperature of -10°C; (c) cold storage temperature of -30°C; (d) cold storage temperature of -50°C

5.3 Pipe Diameters

Figure 6 shows the relationship between time and temperature at different pipe diameters (flow rate = 0.2m/s). It can be seen from the figure that it is only when the pipe diameter is larger than 1cm that the space cooling effect can be satisfied. The space cooling performance obviously increases with increased pipe diameter. These results illustrate that the circulating flow rate must meet a certain minimum value (such as pipe diameter of 1cm, flow rate of 0.2m/s) so that the cooling demand can be satisfied. The cold energy capacity (cold energy storage volume, temperature) of cold energy storage also needs to be considered.
Figure 5: Relationship between time and temperature at different cold storage tank volumes (flow rate = 0.2m/s) - (a) cold storage temperature of 10°C; (b) cold storage temperature of -10°C; (c) cold storage temperature of -30°C; (d) cold storage temperature of -50°C

Figure 6: Relationship between time and temperatures at different pipe diameters (flow rate = 0.2m/s) - (a) cold storage temperature of 10°C; (b) cold storage temperature of -10°C; (c) cold storage temperature of -30°C; (d) cold storage temperature of -50°C
5.4 Circulation Fluids

Figure 7 is a plot of room temperature versus time for different fluids with a cold storage volume of 240 m$^3$ as an example, corresponding to cold storage temperatures of 10°C, -10°C, -30°C, and -50°C, respectively. From Figure 7, it is apparent that the cooling effect of brine is higher than that of antifreeze, and that of antifreeze is higher than that of heat conducting oil, especially at higher cold storage temperatures.

Again from Figure 7, it can be seen that when the cold storage temperature is 10°C, the space cooling performance of brine is better than the heat conducting oil and the antifreeze, but the difference between the three kinds of fluid is obvious; when the cold storage temperature is equal to or lower than -10°C, the space cooling performance of brine is better than that of the antifreeze liquid and the heat conducting oil, and the difference is small. Therefore, whether it is in the cooling performance, or in the economic, environmental protection or energy conservation, brine is the most suitable circulation fluid.

Figure 7: Relationship between time and temperatures with different circulation fluids (flow rate = 0.2 m/s) - (a) cold storage temperature of 10°C; (b) cold storage temperature of -10°C; (c) cold storage temperature of -30°C; (d) cold storage temperature of -50°C
6. Discussion
Simulation results illustrate that indoor temperature demand can be satisfied by using a coupled space heating and cooling system (Figures 8-10). Figure 8 shows the temperature distribution of the final simulation result after 180 days of space cooling. Figure 8 also illustrates that the target space temperature can reach the appropriate temperature range. But, despite these results, there are still differences in the effects of energy storage tank volumes and energy storage tank temperatures on target space temperature changes. Space temperature changes in heating and cooling are shown in Figure 9 and Figure 10, illustrating that energy storage tank volume and energy storage temperature affect the space heating performance of the coupled system more than that of space cooling performance. In other words, space heating performance are more sensitive to simulation conditions such as energy capacity (mainly depending on the energy storage temperature and energy storage volume) and heat transfer efficiency (depending upon flow rate, pipe diameter and thermal conductivity of pipes). It is clear that the space temperature reaches the target temperature range for heating in less time, at the same flow rate and energy storage tank volume, than for cooling. Of course, work performance of the coupled system would be affected by many other factors, such as the changing ambient temperature, intensity of solar radiation and even wind speed. These possible influences will be explored in a future study.

Figure 8: Temperature field (flow rate = 0.2m/s) - (a) space cooling, cold storage temperature of -30°C; (b) space heating, heat storage temperature of 99°C
7. Conclusions
Simulation results proved that the space heating and cooling system can not only satisfy human indoor heating demand, but also the indoor space cooling demand. Based on our study, we concluded that:

1) The indoor temperature demand could be satisfied by using the coupled space cooling system

2) Space cooling effectiveness increases with the increase of cold storage tank volumes, decreased cold storage tank temperatures, flow rates, and pipe diameters. Among these parameters, the cold storage tank volumes and temperature are dominant. The other parameters could be optimized to increase cooling effect to a certain extent.
3) The circulating flow rate must satisfy a certain minimum value (flow rate of 0.2 m/s when pipe diameter is 1 cm) so that the cooling demand can be satisfied. The cooling capacity (cold energy storage volume, temperature) of cold energy storage should also be considered.

4) Compared to heat conducting oil and antifreeze, brine is more suitable to be used as the circulation fluid.

5) Space heating performance is more sensitive to simulation conditions such as energy capacity (mainly depending on the energy storage temperature and energy storage volume) and heat transfer efficiency (mainly affected by flow rate, pipe diameter and thermal conductivity of pipes) than space cooling.

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