1 **A Study on Pipe-embedded Wall Integrated with Ground**
2 **Source-coupled Heat Exchanger for Enhanced Building Energy**
3 **Efficiency in Diverse Climate Regions**

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12 **Abstract:** The study proposes a new low-grade energy utilization system, i.e. a
13 pipe-embedded wall integrated with ground source-coupled heat exchanger, and
14 investigates its energy saving potentials in five typical climate regions of China. The
15 cool/hot water produced by the ground source-coupled heat exchanger is supplied to the
16 pipe-embedded wall to intercept the heat gain/loss through the wall. A real-scale building
17 energy simulation platform has been developed for estimating the energy saving
18 potentials. The study results show that the energy saving potential of the proposed system
19 varies with the climate regions. With the same sized pipe-embedded wall system, the
20 building in warm climate regions achieves the largest energy saving percentage. It is
21 followed by the buildings in the hot summer and cold winter climate region, the severe
22 cold climate region, the cold climate region, and the hot summer and warm winter
23 climate region in the declining sequence of energy saving. Meanwhile, a multi-criteria
24 performance evaluation has been conducted to search for the optimal size of the
25 low-grade-energy system in each climate region. The proposed system can be utilized in
26 practice for energy saving, and the study results are helpful in guiding the practical
27 applications of the pipe-embedded wall system in different climate regions.

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29 **Keyword:** Pipe-embedded wall; Ground source-coupled heat exchanger; Enhanced
30 energy efficiency; Multi-criteria system design; Diverse climate regions

1. Introduction

Energy and environmental problems have gained an increasing concern around the world in recent years. Buildings account for a significant part of the total energy consumption. The percentage of total energy consumption occupied by buildings reaches up to 30% and 40% in China and America respectively [1,2]. Thus, improvement of building energy efficiency plays an important role in solving the increasing energy and environmental problems. Many efforts have been made for improving building energy efficiency. These efforts mainly include enhancing thermal-insulation of building exterior facade, improving energy efficiency of building system, and utilizing low-grade or renewable energy sources etc. [3-5].

With the improvement of living standard, much more energy has been consumed for building heating and cooling to provide a comfortable indoor environment. Given that building cooling and heating demand is largely caused by the heat gain/loss through the opaque building envelope, improving the thermal-insulation performance of building envelope may be a good approach for reducing building energy demand. Existing techniques for improving the thermal-insulation performance of the opaque building envelope mainly focus on installing high R-value insulation material inside or outside of the traditional exterior building wall. The energy saving potential of this technology is limited because the high R-value insulation is not necessarily beneficial for all the seasons of a year [6]. Moreover, increasing the insulation thickness may not be economical since the energy saving benefit may be completely compromised by the increased initial cost [7]. Some other technologies have also been used to improve the thermal-insulation performance of building envelope. For instance, dynamic insulation using ventilated wall structure [6] and embedding thermoelectric cooling module inside the exterior wall [8] have been adopted.

To further reduce the primary energy consumption in buildings, low-grade energy sources such as favorable ambient air and geothermal energy have been directly utilized for building cooling or heating. The low-grade energy can be collected from cooling tower ~~or ground source coupled heat exchanger with circulating fluid medium. The fluid medium may be air or water etc. These technologies may replace or at least reduce the usage of conventional mechanical air conditioning systems for reducing building energy consumption.~~ Vangtook and Chirarattananon [9] investigated the application of a passive radiant cooling system which utilized the cooling tower to provide cool water in hot

humid climate. The results show that the application of this passive cooling system can help achieve better indoor thermal comfort while substantial energy saving can be achieved when compared with the conventional air-conditioning system. Ma et al. [10] studied the possibility of a thermally homeostatic building with natural cooling provided by cooling tower alone. It was found from their studies that the possibility of natural cooling by cooling tower alone was largely limited by the climate, and the building thermal homeostasis can only be achieved partially in climate regions of moderate diurnal temperature variation. ~~Earth air heat exchanger is one of the utilizing styles of the geothermal energy source. An earth air heat exchanger is usually designed for summer precooling and winter preheating of ambient air supplied to the buildings for reduction of cooling load and heating load [Gan et al. 2015, Xamán et al. 2015]. Building integrated~~In addition, solar thermal collection is another type of low-grade energy utilization for reducing building heating energy [11]. Albanese et al. [12] proposed a heat pipe wall system which was used to transfer heat from a solar absorber to the indoor thermal mass through an insulated wall for building heating. The heat pipe wall system could provide significantly higher heat gains than the conventional passive solar systems especially for the cold or cloudy weather.

Meanwhile, ground source-coupled heat exchanger is another import technology for low-grade energy utilization since the underground soil temperature below 10~15m depth can be kept at a relatively constant level [13]. According to the heat carrier media, the ground source-coupled heat exchangers can be separated into two types which are earth-air heat exchanger (EAHE) and ground source heat pump (GSHP) systems [14]. EAHEs are usually designed for summer precooling and winter preheating of ambient air supplied to the buildings for reduction of cooling load and heating load [15,16]. EAHE system can be adopted alone or in combination with conventional heating ventilation and air conditioning (HVAC) system [17,18]. To improve the energy saving potentials, EAHE systems have also been integrated with phase change material (PCM), solar chimney and other renewable technologies. [19,20]. Compared with EAHE system, GSHP system is more energy efficient but more expensive [14]. Driven by electricity, GSHP systems exchange heat with the earth through circulating fluid inside the buried loops. In this regard, one popular application is the earth-buried high density plastic tube through which water or anti-freezing liquid or mixture of them flows to exchange heat with the earth [21,22]. In addition, earth-buried heat exchangers can also be used as the evaporators or condensers in which refrigerant flows to exchange heat with the earth

[\[23,24\].](#)

Pipe-embedded building envelope (i.e., wall or roof) is a new building structure which has pipe embedded inside and utilizes the hot/cool water flow in the pipe to intercept the heat/cold loss through the building envelope [25]. Few studies were concerned about pipe-embedded building exterior wall while a large amount of research were concerned about the pipe-embedded structures such as floor [26] or ceiling [27]. Zhu et al. [28, 29] developed some dynamic heat transfer models to predict the heat transfer of the pipe-embedded building envelope. The thermal performance of this structure was evaluated alone while thermal-interaction with other room parts is not involved. Ibrahim et al. [30] investigated the energy-saving potential of a pipe-embedded exterior wall system which utilized the water circulating in the embedded pipe to transfer the solar energy absorbed by the south outer wall surface to the north wall in winter season. With the application of this system, the annual heating energy could be reduced by 28% at least for new houses and 15% at least for old houses in Mediterranean climate.

However, very few studies have been conducted on the energy-saving potential of the pipe-embedded wall integrated with low-grade energy sources (e.g. ground source-coupled heat exchanger or ground aquifer etc.). This study proposes a new low-grade energy utilizing system, i.e. the pipe-embedded wall integrated with ground source-coupled heat exchanger, and investigates its energy-saving potentials in five typical climate regions of China. Energy-saving potential assessment of such system is helpful for guiding its practical applications.

2. Pipe-embedded Wall System Description

Figure 1 shows the schematics of the building system which utilizes the pipe-embedded wall integrated with a ground source-coupled heat exchanger (called as pipe-embedded wall system). The pipe-embedded wall system mainly consists of two parts which are the pipe-embedded wall and the ground source-coupled heat exchanger (GSHE). Such a system utilizes the low-grade geothermal energy provided by the ground source-coupled heat exchanger to intercept the heat gains/loss in the wall.

The pipe-embedded wall system is used for reducing the energy consumption of building system, and operates with the HVAC system simultaneously. In summer daytime, the heat absorbed from the outdoor environment is firstly stored within the concrete mass of the exterior wall. Subsequently, the low temperature water circulating in the pipes

takes away the stored heat, and the heat transfer through the exterior wall is thus intercepted. When the temperature of the cool water provided by the ground source-coupled heat exchanger is even lower than the indoor air temperature, extra space cooling can be provided by the pipe-embedded wall system. In winter daytime, when both the solar radiation and the outdoor air temperature are very low, a certain amount of heat loss may occur through the building exterior wall although the high R-value insulation is installed inside or outside. The high temperature water circulating in the pipe-embedded wall system can compensate the heat loss and even provide extra space heating to some degree.

<Figure 1 Schematics of the pipe-embedded wall system>

<Figure 2 Structure of the pipe-embedded wall>

Figure 2 shows the structure of the pipe-embedded wall. The pipe-embedded wall basically consists of an inner plaster layer, a pipe-embedded concrete layer, an insulation layer and an outer plaster layer from inside to outside. The embedded pipe is fixed at the reinforcing mesh before the concrete pouring process. The embedded pipe can be made from various materials such as high-density polyethylene or polybutylene and metal etc. [31]. A certain amount of ethanol can be added into the circulating water inside the embedded pipe considering antifreeze.

The ground soil temperature below 10~15 m depth is not obviously affected by the over-ground thermal disturbances (i.e., the intensified solar radiation and elevated air temperature etc.), and it is almost constant at a value close to the annual average air temperature [13]. The ground source-coupled heat exchanger is connected to the pipe-embedded wall through a simple water distribution system as shown in Figure 1. In the whole closed water loop, extra energy is only consumed by the circulating water pump.

Thermal responses of the pipe-embedded wall system are affected by many factors, e.g. the location and spacing of the embedded pipe, the water flow rate in the pipe, and the depth of the ground source-coupled heat exchanger etc. For instance, the water flow rate and the pipe location influence the heat transfer of the building exterior wall in terms of delay and attenuation. Since the study focuses on investigating the energy saving potentials of the pipe-embedded wall system in typical climates, impact analysis of these

factors on system thermal response will not be performed. In the study, the parameters are exactly the same as the proposed system is applied in different climates including the location and spacing of the embedded pipe, the water flow rate in the pipe, and the depth of the ground source-coupled heat exchanger.

3. Methodology

3.1 Overview of the methodology

<Figure 3 Flow chart of the study on the pipe-embedded wall system>

The aim of this study is to investigate the energy-saving potentials of the pipe-embedded wall system in different climate regions of China. The flow chart of this study is shown in Figure 3. For each climate region, one representative city is chosen for investigation. Energy simulation of a real-scale building which utilizes the pipe-embedded wall system will be conducted on a dynamic simulation platform developed in TRNSYS [32]. A building without utilizing the pipe-embedded wall system will be used as the baseline case in this study. Cooling and heating load profiles of the building with different numbers of GSHEs are firstly obtained through the simulation. Then, the HVAC system can be sized based on the building peak load [33]. Then the energy consumption of the building system is obtained with the selected HVAC system size, and the corresponding cooling and heating load profile. The energy consumption includes the energy consumption of HVAC system and the extra energy consumption of the water pump in the pipe-embedded wall system. Energy savings of the pipe-embedded wall system are calculated by comparing with the energy consumption in the baseline case. With regard to its practical application issue, a multi-criterion evaluation considering both energy saving and initial cost increase is performed to search for the optimal number of GSHEs based on the users' actual preference.

3.2 HVAC system sizing and initial cost estimation

Cooling and heating load profiles of these buildings are estimated using the associated weather data. The HVAC system size can be determined based on the larger value between the peak cooling load and the peak heating load as Equation (1). With the given HVAC system size and the pipe-embedded wall system size, the total initial cost of the building system is calculated by Equation (2).

$$CAP = \max[Q_{C,peak}, Q_{H,peak}] \quad (1)$$

$$P_{cost} = P_{cost,base} \times \frac{CAP}{CAP_{base}} + \beta_{GHE} \times N + \beta_{pipewall} \times A_{pipewall} \quad (2)$$

where, $Q_{C,peak}$ and $Q_{H,peak}$ are the peak cooling load and the peak heating load respectively, CAP is the capacity of HVAC system in the buildings with the pipe-embedded wall systems, CAP_{base} is the capacity of HVAC system in the baseline case, $P_{cost,base}$ is the initial cost of HVAC system in the baseline case, N and β_{GHE} are the number of GSHEs and the corresponding unit price respectively, $A_{pipewall}$ and $\beta_{pipewall}$ are the area of the pipe-embedded wall and its price per unit area for the embedded pipe, and P_{cost} is the associated total initial cost.

3.3 Energy saving estimation

With the selected HVAC system size and the associated cooling and heating load profile, the energy consumption of the HVAC system can be obtained using the HVAC system simulation platform. The energy consumption of the building system utilizing the proposed system is the sum of the HVAC system energy consumption and the water pump energy in the pipe-embedded wall system. Energy-saving percentage of the pipe-embedded wall system is calculated by comparing with the building energy consumption in the baseline case, as expressed by Equation (3).

$$P_{es} = \left| \frac{E - E_{base}}{E_{base}} \right| \times 100\% \quad (3)$$

where, E is the energy consumption of the building system which utilizes the pipe-embedded wall system, and E_{base} is the energy consumption of the building system in the baseline case.

3.4 Multi-criteria performance evaluation

The optimal design of the pipe-embedded wall system needs to consider the tradeoff between the energy saving and the initial cost increase. For instance, a larger sized pipe-embedded wall system (i.e. with a larger number of GSHEs) leads to larger energy saving but with more initial cost. A multi-criteria system design method is thus used to select the optimal number of GSHEs in the pipe-embedded wall system. The multi-criteria function is established as Equation (4). It consists of two performance

scores, i.e. initial cost score G_{cost} and energy-saving score G_{es} . The performance score G is quantified using the linear interpolation between the least preferred performance P_{least} and the most preferred performance P_{most} , as expressed in Equation (5). For one performance criteria, the most preferred performance is assigned the score of 100, and the least preferred option is assigned the score of 0.

$$J = \alpha_{\text{cost}} \times G_{\text{cost}} + \alpha_{\text{es}} \times G_{\text{es}}, \quad \alpha_{\text{es}} = 1 - \alpha_{\text{cost}} \quad (4)$$

$$G = \frac{P - P_{\text{least}}}{P_{\text{most}} - P_{\text{least}}} \times 100 \quad (5)$$

where, α_{cost} is the weighting factor assigned to the initial cost performance by users according to their actual preference, G represents the performance score corresponding to a certain criteria, J represents the overall performance score of the building system with user-defined weighting factors, P is the initial cost performance or energy saving performance and can be calculated by Equation (2) or (3), and the subscripts *cost* and *es* refer to system initial cost and energy saving respectively.

4. Simulation platform

4.1 Classification of climate regions in China

The climate regions in China are classified into five typical categories which are hot summer and warm winter climate region, warm climate region, hot summer and cold winter climate region, cold climate region, and severe cold climate region [34]. For each climate region, one representative city is chosen for energy saving investigation in this study. The chosen cities from these five climate regions respectively are Hong Kong, Kunming, Wuhan, Tikanlik, and Shenyang. In terms of the accumulated frequency distribution of ambient air temperature and horizontal solar radiation, the climatic characteristics in these five cities are different, as shown in Figure 4. The weather data used in the study are from the TRNSYS weather database. The soil temperature below 15m depth, denoted as *undisturbed soil temperature*, is determined by the annual average air temperature [35]. Due to different climate regions in these five cities, their undisturbed soil temperatures are different. More specifically, the undisturbed soil temperatures are 24°C, 17.5°C, 16°C, 13°C and 10.5°C in Hong Kong, Wuhan, Kunming, Tikanlik and Shenyang.

<Figure 4 Accumulated frequency distribution of the weather condition, (a) Outdoor air

temperature; (b) Horizontal solar radiation>

4.2 Building model

The multi-zone building component (i.e. Type 56) in TRNSYS is used to simulate the heat transfer process of the baseline building. A three-story office building with the floor area of 220m² (22m long and 10m wide) is used. The building exterior walls of these buildings in these selected five cities respectively are shown in Table 1. In Hong Kong, the exterior building wall is configured with referring to [36]. Installing insulation layer to exterior wall of the building is not preferable in practice in Hong Kong because cooling is always needed in a whole year [36]. In other four cities, the configurations of the exterior walls are selected based on the overall heat transfer requirements of the design standards GB 50189-2015 [37]. In all these five cities, the window-wall ratios of the north wall and south wall are 25% and 30% respectively. Double glazing window with U-value of 1.4 W/m² is installed. The occupant density is set as 8m²/people and the ventilation rate is 30m³/h for each person [37]. The lighting load is set as 13W/m². A computer with power of 140W is equipped for each person and it is on-off controlled based on the regular occupancy schedule in an office building (i.e. from 9:00 am to 5:00 pm). In Hong Kong, heating is not needed while both cooling and heating are needed in the other four cities.

<Table 1 Configurations of building exterior walls for different cities>

4.3 Pipe-embedded wall system

4.3.1 Pipe-embedded wall

The pipe-embedded wall is simulated by the existing thermo-active building construction element inside the building component Type 56 of TRNSYS. The heat transfer model of this thermo-active building construction element was developed by Koschenz and Dorer [38], and it can be used to simulate the heat transfer of the pipe-embedded wall. The heat transfer model of the pipe-embedded wall is comprised of two parts. The first part is to estimate the two-dimensional heat transfer within the cross section of the pipe-embedded wall in x - y direction, as shown as Figure 5 (a). The total heat transfer $\dot{q}$ from the water pipe to both sides of the wall is calculated by a one-dimensional heat conduction analysis within the building construction material under the effect of the pipe, as described as Equation (6). The other part is to estimate the heat

transfer along the water loop, as shown as Figure 5 (b). The water loop is divided into finite elements along z direction (i.e. the water flow direction) and the heat transfer balance equation of each element is established as Equation (7). Both parts are connected with the average fluid temperature T_w inside the pipe, which can be calculated by Equation (8). Then, with the given environmental conditions and the inlet water temperature, the outlet water temperature and the surface temperatures on both sides of the pipe embedded wall can be obtained by solving these equations. More details about the heat transfer model of the thermo active building element can be found in Refs [Koschenz and Dorer 1999, Klein et al. 2004]. directions, as shown as Figure 5 (a). The other part is to estimate the heat transfer along the water loop, as shown as Figure 5 (b).

<Figure 5 Schematics of the heat transfer model of the pipe-embedded building wall [32], (a) two-dimensional heat transfer within the cross section; (b) heat transfer along the water loop>

With regard to the first part heat transfer, the total stationary heat transfer $\dot{q}$ from the water pipe to both sides of the wall can be calculated as Equation (6).

$$\dot{q} = \Phi \cdot [U_1(T_p - T_{a1}) + U_2(T_p - T_{a2})] \quad (6)$$

where, U is the heat transfer coefficient from the pipe level to outside or inside air, which includes heat conduction through the solid part of the wall and heat convection from the wall surface to the surrounding environment; Φ is a correction factor considering the effect of the pipe inside the wall; T_{a1} and T_{a2} are outside or inside air temperature respectively; T_p is the temperature of the outer pipe surface.

With regard to the second part heat transfer, (i.e. heat transfer along water pipe), the water loop, s_p is the pipe spacing, is divided into a series of elements along z -direction (i.e. the water flow direction), as shown in Figure 5(b), and the heat balance equation of each element is established as Equation (7).

$$-\dot{m} \cdot c_p \cdot dT_w(z) = \frac{T_w(z) - T_p}{R_w + R_r} \cdot dz \cdot S_p \quad (7)$$

where R_w is the heat convection resistance between the water flow and the inner pipe surface, and R_r is the heat conduction resistance of the pipe shell; T_w is the water temperature of the water loop; c_p is the specific heat of water; $\dot{m}$ is the mass flow rate of the water flow; T_{air} is outside or inside air temperature, ΔT_{lg} is the logarithmic average

Field Code Changed

temperature difference between the inlet water temperature and the outlet water temperature S_p is the pipe spacing.

In TRNSYS, the above model is used in integration with the multi-zone building model. The internal surface of the pipe-embedded building wall interfaces with the room air and other room surfaces through convective and radiant heat exchange respectively. The exterior surface of the pipe-embedded building wall interfaces with the outdoor climatic conditions. More details about the heat transfer model of the thermo-active building element and its implementation in TRNSYS can be found in Refs. [32, 38].

In the operation periods of the HVAC system, the water pump of the pipe-embedded wall system is on-off controlled based on the temperature difference between the outlet water of the embedded pipe $T_{out,wall}$ and the average soil temperature of GSHE T_{soil} , as expressed by Equation (98) and (409). In cooling period, when the temperature difference is larger than a user-defined threshold δ_C , the water pump is switched on (i.e. $SIG_{pump}=1$), otherwise, it is switched off (i.e. $SIG_{pump}=0$). In heating period, when the temperature difference is smaller than another user-defined threshold δ_H (a negative value), the control signal is set to 1, otherwise, it is set to 0.

$$\text{Cooling: } SIG_{pump} = \begin{cases} 1, & T_{out,wall} - T_{soil} \geq \delta_C \\ 0, & T_{out,wall} - T_{soil} < \delta_C \end{cases} \quad (98)$$

$$\text{Heating: } SIG_{pump} = \begin{cases} 1, & T_{out,wall} - T_{soil} \leq \delta_H \\ 0, & T_{out,wall} - T_{soil} > \delta_H \end{cases} \quad (409)$$

4.3.2 Ground source-coupled heat exchanger

The existing Type 557a in TRNSYS, i.e. the model of Duct Ground Heat Storage (DST), can be used to simulate the vertical ground source-coupled heat exchanger. The temperature field of the ground is calculated from three parts, i.e. the global temperature T_{global} , the local temperature T_{local} , and the steady-flux temperature $T_{steadyflux}$. The global and local temperatures are solved by using the finite difference method. The steady-flux temperature is obtained analytically. The temperature field of the ground is then calculated based on superposition principle, as described as Equation (410). More details about the DST model can be found in Refs [32,39]. The effectiveness of DST model has been validated by Thornton et al. [40], and it has been widely used to estimate the heat transfer of the ground source-coupled heat exchanger [41, 42].

$$T = T_{global} + T_{local} + T_{steadyflux} \quad (410)$$

4.4 HVAC system

In Hong Kong, since only cooling is needed all around the year, chiller and cooling tower system is adopted. In the other four cities (i.e. Wuhan, Kunming, Tikanlik, Shenyang), both cooling and heating are needed, and thus ground source heat pump systems are adopted. The schematics of the water system are described in Figure 6. A constant-speed water pump (i.e. Type 3 in TRNSYS) is equipped in the cooling water loop (or ground side water loop). In the supply water side, the primary water pump (i.e. Type 3 in TRNSYS) is constant-speed while the secondary water pump (i.e. Type 110 in TRNSYS) is variable-speed which delivers changeable flow rate to meet the varying cooling/heating demand. The air-conditioning terminal used in the system is AHU (i.e. Type 673 in TRNSYS), and its air flow rate can also be changed to meet varying air-conditioning demand.

<Figure 6 Schematics of the HVAC system simulation platform. (a) system configuration in Hong Kong; (b) system configuration in other four cities, i.e. Wuhan, Kunming, Tikanlik and Shenyang.>

4.4.1 Chiller and cooling tower

Chiller is the main energy consumption component in the HVAC system of the building in Hong Kong. A simplified water-cooled chiller model ~~based on user profile is used. The power consumption of the chiller can be calculated by using Equation (12), i.e. Type 666 in TRNSYS, is used in this study to simulate the chiller's performance. This chiller model relies on a catalog data lookup method. To set the model, two data files must be provided by users. The first file contains the chiller's capacity ratio and COP ratio as a function of the chilled water set point temperature and the entering cooling water temperature. The second file contains the chiller's fraction of full load power (FFLP) as a function of part load ratio (PLR). The power consumption of the chiller can be calculated by using Equation (11).~~

$$W_c = FFLP \times \frac{Q_{nom}}{COP_{nom}} \quad (11)$$

~~where, $FFLP$ and COP_{nom} represent the fraction of full load power and the coefficient of performance of the chiller respectively. Both these two parameters can be interpolated from the performance data in the user profile based on the outlet temperatures in the evaporation side and the inlet water temperature in the condensation side respectively.~~

~~Q_c is the rated cooling capacity of the chiller.~~

~~where, $FFLP$, Q_{nom} and COP_{nom} represent fraction of full load power, cooling capacity at current conditions and coefficient of performance of the chiller at current conditions respectively. All the three parameters can be obtained from the user provided profiles through interpolation.~~

With regard to the cooling tower, the cooling capacity is defined by the entering and leaving water temperatures, the entering air wet bulb temperature and the water flow rate [43]. The rated air flow rate of the cooling tower fan is determined according to the water-air ratio L/G based on Equation (4312). In this study, the water-air ratio L/G is set as 1.3. The associated fan power is estimated using Equation (4413).

$$L/G = \frac{\dot{m}_{r,cow}}{\dot{m}_{r,tow,a}} \quad (4312)$$

$$W_f = \frac{\dot{m}_{r,tow,a} \cdot \Delta p}{1000 \cdot \rho_{air} \cdot \eta_f} \quad (4413)$$

where, $\dot{m}_{r,cow}$ is the rated mass flow rate of the cooling water based on a traditional design method for HVAC system [33]; $\dot{m}_{r,tow,a}$ is the mass flow rate of the ambient air through the cooling tower; Δp is the static pressure difference; ρ_{air} is the density of the ambient air; η_f is the overall efficiency of the fan.

4.4.2 Ground source heat pump

A simplified water-to-water heat pump model based on user profile is also used in the HVAC system in each of the other four cities (i.e. Kunming, Wuhan, Tikanlik, Shenyang). The power consumptions of the water-to-water heat pump for cooling and heating can be calculated by using Equation (4514) and Equation (4615) respectively.

$$\text{Cooling: } W_{HP} = FFLP_{C,HP} \times \frac{Q_{C,HP}}{EER_{nom,HP}} \quad (4514)$$

$$\text{Heating: } W_{HP} = FFLP_{H,HP} \times \frac{Q_{H,HP}}{COP_{nom,HP}} \quad (4615)$$

where, $EER_{nom,HP}$ and $COP_{nom,HP}$ represent the energy efficiency ratio and the coefficient of performance of the heat pump unit respectively; $FFLP_{C,HP}$ and $FFLP_{H,HP}$ represent the fractions of the full load power of the heat pump unit in cooling mode and heating mode respectively. These four parameters can be interpolated from the

performance data in the user profile based on the input and outlet water temperatures in the load side and the inlet water temperature in the source side respectively, $Q_{C,HP}$ and $Q_{H,HP}$ represent the rated cooling capacity and the rated heating capacity of the heat pump unit respectively.

With regard to the ground source-coupled heat exchanger of the ground source heat pump system, its size can be selected using a traditional design method based on the peak cooling load or the peak heating load [41, 44]. The component Type 557a based on DST model in TRNSYS is also used to estimate the heat transfer of the ground source-coupled heat exchanger.

4.5 Simulation process

Figure 7 shows the schematic of the simulation process in TRNSYS. In the simulation, the time interval is 1 hour. The simulation process is mainly comprised of two steps. The first step is to obtain the cooling and heating load profiles by conducting building thermal simulation with the given climate data. The second step is to estimate associated HVAC system energy consumption using the obtained cooling and heating load profiles. Note that the HVAC system has been sized based on the peak cooling or heating load before the system energy estimation.

<Figure 7 Schematic of the simulation process in TRNSYS>

5. Case studies

This section mainly investigated the energy-saving potentials of the pipe-embedded wall system in these five cities. All the exterior walls of the building had pipe embedded. The pipe was positioned in the middle of the concrete layer of exterior wall and arranged in serpentine pattern [45]. With referring to [46], the pipe spacing was selected to 150 mm and the pipe inner diameter was selected to be 16 mm. The pipe shell thickness was 2 mm and the pipe shell conductivity was $0.22 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$. The water flow rate inside the embedded pipe was set as 300 kg/h. The ground-coupled heat exchangers were equipped in parallel with a depth of 100 m. For each climate, the number of the ground-coupled heat exchangers varied from 1 to 12. The control thresholds (i.e., δ_C and δ_H in Equation (98) and (409)) for the water pump of the pipe-embedded wall system were set to 0.

5.1 Building load analysis in the baseline cases

Figure 78 shows the accumulated and peak building loads (including both cooling load and heating load) of the buildings in the baseline cases for climate regions. The

characteristics of the building loads in these five cities had a strong relation with their climates. In Hong Kong, a city in hot summer and warm winter climate region, the cooling load was dominant and heating load wasn't needed at all. In cold climate region (i.e. Tikanlik) and severe cold climate region (i.e. Shenyang), the heating loads were larger the associated cooling loads in terms of the accumulated value and the peak value. In hot summer and cold winter climate region (i.e. Wuhan) or warm climate region (i.e. Kunming), the cooling load was much larger in comparison with the heating load. The energy savings of the pipe-embedded wall systems were influenced by both peak building load reduction and accumulated building load reduction. With the reduction of the accumulated building load, the building energy consumption was reduced accordingly. The peak load determined the size of the HVAC system which also influenced the energy consumption of the building system.

<Figure 78 Accumulated (a) and peak (b) loads of the baseline building in five climate regions>

5.2 Building peak loads reduction by utilizing the proposed system

Figure 89 shows the reduction percentages of the building peak loads (i.e. the peak cooling load and the peak heating load) in these five cities by utilizing the pipe-embedded wall system. As shown in Figure 89 (a), the peak cooling load in Hong Kong was not reduced significantly. In contrast, the peak cooling loads were largely reduced in the other four cities. With the increase of the number of the GSHEs, the peak cooling load reductions increased largely in Tikanlik, Shenyang, Kunming and Wuhan. In these four cities, the peak cooling load reductions increased from 15% to 43%, 17% to 45%, 10% to 34% and 9% to 31% as the number of GSHEs varied from 1 to 12. In contrast, a relatively small increase of peak cooling load reduction (2% to 10%) was observed in Hong Kong. In comparison with the peak cooling load, the peak heating load was not reduced significantly by utilizing the pipe-embedded wall system in all these five cities, as shown in Figure 89 (b). The reduction percentages of the peak heating load were smaller than 10% in all these five cities.

With the given building peak loads, the HVAC system size was determined by Equation (1). Figure 910 shows the HVAC system size reductions in these five climate regions by utilizing the pipe-embedded wall system. The HVAC system sizes were hardly changed in Tikanlik and Shenyang. In contrast, the HVAC system sizes were largely reduced in Kunming and Wuhan. In Hong Kong, the HVAC system size reduction was

between these two extreme regions. With the increase of the number of the GSHEs, the reduction of the HVAC system size increased to various degrees corresponding to different climate regions. In Wuhan and Kunming, the HVAC system size was largely reduced by from 10% to 30% as the number of the GSHEs varied from 1 to 12. With regard to Hong Kong, a relatively small size reduction from 2% to 10% was observed. In contrast, little HVAC system size reduction (i.e. less than 1%) was observed in Tikanlik and Shenyang. Reduction of the peak building loads influenced the HVAC system size, and thus, influenced the initial cost and operation energy consumption of the building system.

<Figure 89 Reduction percentages of the peak cooling loads (a) and the peak heating loads (b) in these five climate regions>

<Figure 910 Reduction percentages of the HVAC system size in these five climate regions>

5.3 Building accumulated load reduction by utilizing the proposed system

Figure 4011 shows the reduction percentages of the building accumulated loads (i.e. the accumulated cooling loads and the accumulated heating loads) in these five climate regions by utilizing the pipe-embedded wall system. As shown in Figure 4011 (a), the accumulated cooling load was not significantly reduced in Hong Kong. In contrast, the accumulated cooling load was largely reduced in the other four cities. With the increase of the number of the GSHEs, the accumulated cooling load reductions increased largely in Tikanlik, Shenyang, Kunming and Wuhan. In these four cities, the peak cooling load reductions increased from 24% to 63%, 23% to 52%, 18% to 45%, and 13% to 38% as the number of GSHEs varied from 1 to 12. In contrast, a relatively small increase of accumulated cooling load reduction (2% to 8%) was observed in Hong Kong. In comparison with the accumulated cooling load, the accumulated heating load was not reduced significantly by utilizing the pipe-embedded wall system in all five cities, as shown in Figure 4011 (b). As the number of the GSHEs increases, the accumulated heating load reduction reached up to 13% at most in Wuhan while not exceeded 5% in the other four cities.

<Figure 4011 Reduction percentages of the accumulated cooling load (a) and the accumulated heating load (b) in these five climate regions>

5.4 Energy saving by utilizing the proposed system

Figure 4-12 shows the energy-saving percentages of the pipe-embedded wall system in these five climate regions. In Hong Kong, the energy-saving percentage about 4% was not significant. In contrast, the average energy-saving percentages were very large in Kunming (about 30%) and Wuhan (about 24%). In Tikanlik and Shneyang, the average energy-saving percentages (about 9% and 11%) were between these two extremes. With the increase of the number of the GSHEs, the energy-saving percentages were largely increased in Kunming, Wuhan, Tikanlik and Shenyang. The energy-saving percentages increased from 13% to 46%, 11% to 36%, 3% to 14% and 5% to 16% in these four cities. In contrast, a relatively small increase of the energy-saving percentage (1% to 6%) was observed in Hong Kong.

There were obvious differences in the energy-saving results of these five cities when compared with the building-load-reduction results shown in Figure 89 and 4-11. In Tikanlik and Shenyang, the heating load was dominant as shown in Figure 78. Utilizing the proposed system led to limited reductions of the heating loads in these two cities. Such limited heating load reductions eventually resulted in limited energy savings. In contrast, in Wuhan and Kunming where the cooling load was dominant, significant cooling load reductions were observed when the proposed pipe-embedded wall system was utilized. The significant cooling load reduction eventually resulted in large energy savings. It can also be found that the increase of the number of the GSHEs no longer had a significant effect on the energy saving once the number of the GSHEs reached a certain value.

<Figure 4-12 Energy-saving percentages of the pipe-embedded wall system in these five climate regions>

5.5 Energy-saving results analysis

The above results have presented the energy-saving potentials of the pipe-embedded wall system in different climate regions. The energy-saving potential of the pipe-embedded wall system varied from climate to climate. This section explains the differences of energy savings in these diverse climate regions from the point of heat transfer. The transient cooling or heating load due to the exterior wall is determined by the heat transfer between the inner wall surface and the indoor air (or the indoor surfaces). The variation of the inner wall surface temperature caused by the circulating water was considered as an indicator of building load reduction. As examples, operating data of the

east wall and the north wall were analyzed with 6 GSHEs adopted. Typical two weeks in August and January were selected to represent winter and summer respectively. In the examples, the on-off signal of the water pump in the pipe-embedded wall system was determined by Equation (98) and (499).

<Figure 4213 Operating data of the pipe-embedded wall system in summer (a) and winter (b) of Wuhan.>

Figure 4213 shows the operating data of the pipe-embedded wall system in Wuhan. In the typical consecutive weeks in summer as shown in Figure 4213 (a), the east inner wall surface temperature was largely lowered by about 4°C due to the utilization of the pipe-embedded wall system. The resultant east inner wall surface temperature was even 1 °C lower than the indoor room temperature set-point, i.e. 25°C [37]. In this case, the pipe-embedded wall system was able to provide extra space cooling besides intercepting the external load. The supply water temperature to the pipe-embedded wall fluctuated basically between 20°C and 21°C during the operation periods. Thus, significant energy saving was achieved in summer of Wuhan. In the typical consecutive weeks in winter as shown in Figure 4213 (b), the north inner wall surface temperature increased to a small extent due to the utilization of the pipe-embedded wall system, and the maximum increase of the north inner wall surface temperature was only about 1°C. The increased inner north wall surface (18°C~19°C) was still 1~2°C lower than the indoor air set-point 20 °C [37]. In this case, the limited temperature rise cannot significantly compensate/intercept the heat loss through the north wall in winter. Thus, the energy saving wasn't significant in winter of Wuhan. Kunming had the similar conditions to Wuhan in both summer and winter, thus it was not described here for avoiding redundancy.

<Figure 4314 Operating data of the pipe-embedded wall system in summer (a) and winter (b) of Hong Kong.>

Figure 4314 shows the operating data of the pipe-embedded wall system in Hong Kong. The east inner wall surface temperature was lowered by about 2°C at most due to utilization of the pipe-embedded wall system as shown in Figure 4314 (a). Regardless of this, the east inner wall surface temperature was still about 3°C higher than the indoor air temperature set-point 25°C. The supply water temperature to the pipe-embedded wall

basically fluctuated between 25.5°C and 27°C. With such high-temperature circulating water, the pipe-embedded wall system cannot effectively intercept the heat gains and provide extra space cooling. Thus, very limited energy saving was achieved in summer season in Hong Kong. Since cooling was still needed in winter of Hong Kong, intercepting the heat gains was still needed. The pipe-embedded wall system was almost not working in winter, as shown in Figure 4314 (b).

Figure 4415 shows the operating data of the pipe-embedded wall system in Shenyang. In comparison with the cases of Wuhan and Hong Kong, the east inner wall surface temperature was reduced more significantly, it was about 3°C below the indoor air temperature set-point 25°C in the summer season in Shenyang as shown in Figure 4415 (a). This was due to the lower soil temperature in Shenyang. However, the pipe-embedded wall system was almost not working in winter because such low average soil temperature (12°C) was not able to effectively intercept heat loss or provide extra heating, as shown in Figure 4415 (b). Thus, significant energy saving was achieved in summer of Shenyang while the energy saving in winter season was very little. Tikanlik had very similar condition with Shenyang, the analysis of energy saving in Tikanlik was not illustrated here for avoiding redundancy.

<Figure 4415 Operating data of the pipe-embedded wall system in summer (a) and winter (b) of Shenyang.>

6. Multi-criteria system design optimization

With regard to the optimal design of the pipe-embedded wall system in practice, it is necessary to consider the tradeoff between the energy saving and the initial cost increase. As shown in the above results, the energy saving of the pipe-embedded wall system largely depended on the number of the GSHEs. However, larger number of GSHEs led to more initial cost of the building system. A multi-criteria system design method was thus used to select the optimal size of the proposed system, i.e. the optimal number of the GSHEs. In this study, only two performance criteria, i.e. initial cost and energy saving, were adopted to evaluate the overall building system performance based on the actual preferences (i.e. the user-defined weighting factors).

Figure 4516 shows the overall performance score of the building system with different numbers of GSHEs calculated by using Equation (4). Two cases with $\alpha_{\text{cost}}=0.4$

(i.e. $\alpha_{es}=0.6$) and $\alpha_{cost}=0.6$ (i.e. $\alpha_{es}=0.4$) are presented in Figure 15 (a) and (b) respectively. $\alpha_{cost}=0.4$ means that energy saving is more preferable for the users. In opposite, $\alpha_{cost}=0.6$ means that less initial cost is more preferable for the users. As the number of GSHEs increased, the variation of the system performance score appeared a nonlinear characteristic, i.e. the system performance score firstly increased to a peak value and then reduced. The main reason was attributed to the performance tradeoff between the energy saving and the initial cost. When α_{cost} was equal to 0.4, as shown as Figure 15(a), the peak values of the system performance score profiles corresponding to different climate regions were obtained at 6, 7 or 8 GSHEs. In this case, continuous increase of the number of GSHEs didn't lead to a continuous increase of system overall performance score. When α_{cost} was equal to 0.6, as shown as Figure 15(b), the peak values of the system performance score profiles corresponding to different climates were obtained at 3 or 4 GSHEs and then reduced rapidly. This was because a larger weight factor has been assigned to the initial cost performance and the increase of the energy-saving score was much smaller than the reduction of the initial cost score.

In a word, the final selection of the optimal system size by using the proposed method depended on the actual preferences to a large extent. This multi-criteria system design method can give a good guideline for sizing the pipe-embedded wall system by considering a tradeoff between the initial cost increase and the energy saving. The proposed method can also be used when more than two performance criteria are considered in the system design phase.

<Figure 15 System performances of the building utilizing the pipe-embedded wall system in these five climate regions. (a) $\alpha_{cost}=0.4$; (b) $\alpha_{cost}=0.6$ >

7. Conclusions

This study has proposed a pipe-embedded wall system which utilizes the relatively cool/hot water/low-grade energy produced by the GSHEs to intercept the heat gain/loss through the exterior wall. The energy-saving potential/potentials of the proposed system has/have been investigated in five typical climate regions in China by using a real-scale building simulation platform. The results show that the energy saving percentage of the pipe-embedded wall system varied from climate to climate. Based on the study results, the following conclusions can be made.

~~For the same number of GSHEs, the warm climate region achieved the best~~

energy saving potential such as Kunming, and then followed by the hot summer and cold winter climate region such as Wuhan, the severe cold climate region such as Shenyang, the cold climate region such as Tikanlik, and the hot summer and warm winter climate region such as Hong Kong in declining sequence of energy saving. In the warm climate region and the hot summer and cold winter climate region, significant energy saving (i.e. over 30%) was achieved using a medium number of GSHEs. In contrast, the energy saving potential was very limited (i.e. less than 10%) in the hot summer and warm winter climate region even if a large number of GSHEs was used. The results also indicate that the effect of the proposed system on the cooling load was much more significant than the heating load in all climate regions.

(1) Through the application of the proposed system, building cooling loads (i.e. both peak cooling loads and accumulated cooling loads) can be largely reduced in the warm climate (e.g. Kunming), the hot summer and cold winter climate (e.g. Wuhan), the severe cold climate (e.g. Shenyang) and the cold climate (e.g. Tikanlik). In contrast, much smaller reductions of building cooling load are observed in the hot summer and warm winter climate (e.g. Hong Kong). In comparison with the large reduction of building cooling load, building heating loads have not been reduced significantly in all the five climates.

(2) Through the application of the proposed system, the energy saving potentials are significantly different in the five climates. For the same number of GSHEs, the warm climate (e.g. Kunming) and the hot summer and cold winter climate (e.g. Wuhan) achieve the most energy savings. In the two climates, over 30% energy savings can be achieved using a medium number of GSHEs. The energy saving potentials of the severe cold climate (e.g. Shenyang), the cold climate region (e.g. Tikanlik) and the hot summer and warm winter climate (e.g. Hong Kong) are in a declining order. The soil temperature turns out to have important impacts on the energy saving potentials in the five climates.

(3) As for the application issue of the proposed system, a multi-criteria system design method has been adopted to select the optimal number of the GSHEs by taking account of the energy saving and the initial cost increase simultaneously. The results show that the optimal number of the GSHEs varied with the weighting factors assigned by users. With the weighting factors given, the optimal number of the GSHEs can be selected by using ~~this~~the multi-criteria design method.

Acknowledgements

The research work presented in this paper is financially supported by a Start-up grant of City University of Hong Kong (No. 7200398), and a grant (No. 51178201) of National Science Foundation of China.

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Figure 1 Schematics of the pipe-embedded wall system

Figure 2 Structure of the pipe-embedded wall

Figure 3 Flow chart of the study on the pipe-embedded wall system

(a)

(b)

Figure 4 Accumulated frequency distribution of the weather condition, (a) Outdoor air temperature; (b) Horizontal solar radiation

Figure 5 Schematics of the heat transfer model of the pipe-embedded building wall [32], (a) two-dimensional heat transfer within the cross section; (b) heat transfer along the water loop

Figure 6 Schematics of the HVAC system simulation platform. (a) system configuration in Hong Kong; (b) system configuration in other four cities, i.e. Wuhan, Kunming, Tikanlik, and Shenyang.

Building load simulation

Cooling & heating load profile

HVAC system simulation

Figure 7 Schematic of the simulation process in TRNSYS

(a)

(b)

Figure 78 Accumulated (a) and peak (b) building loads of the baseline building in five climate regions

Figure 89 Reduction percentages of the peak cooling loads (a) and the peak heating loads (b) in these five climate regions

Figure 910 Reduction percentages of the HVAC system size in these five climate regions

(a)

(b)

Figure 4 Reduction percentages of the accumulated cooling load (a) and the accumulated heating load (b) in these five climate regions

Figure 4-12 Energy-saving percentages of the pipe-embedded wall system in these five climate regions

Figure 4-13 Operating data of the pipe-embedded wall system in summer (a) and winter (b) of Wuhan.

Figure 13-14 Operating data of the pipe-embedded wall system in summer (a) and winter (b) of Hong Kong.

Figure 14-15 Operating data of the pipe-embedded wall system in summer (a) and winter (b) of Shenyang

(a)

(b)

Figure 4516 System performances of the building utilizing the pipe-embedded wall system in these five climate regions. (a) $\alpha_{\text{cost}}=0.4$; (b) $\alpha_{\text{cost}}=0.6$

Table 1 Configurations of building exterior walls for different cities

Location	Construction	Thickness (m)	Density ($\text{kg}\cdot\text{m}^{-3}$)	Thermal conductivity ($\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$)	Specific heat capacity ($\text{kJ}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$)	U-value ($\text{W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$)
Hong Kong	Internal plaster	0.01	1200	0.21	1	2.80
	Concrete	0.18	2400	2.1	0.8	
	External plaster	0.02	1200	0.37	0.84	
Kunming	Internal plaster	0.01	1200	0.21	1	1.17
	Concrete	0.18	2400	2.1	0.8	
	Insulation	0.02	40	0.04	0.8	
	External plaster	0.02	1200	0.37	0.84	
Wuhan	Internal plaster	0.01	1200	0.21	1	0.90
	Concrete	0.18	2400	2.1	0.8	
	Insulation	0.03	40	0.04	0.8	
	External plaster	0.02	1200	0.37	0.84	
Tikanlik	Internal plaster	0.01	1200	0.21	1	0.52
	Concrete	0.3	2400	2.1	0.8	
	Insulation	0.06	40	0.04	0.8	
	External plaster	0.02	1200	0.37	0.84	
Shenyang	Internal plaster	0.01	1200	0.21	1	0.46
	Concrete	0.3	2400	2.1	0.8	
	Insulation	0.07	40	0.04	0.8	
	External plaster	0.02	1200	0.37	0.84	