Alternate operation characteristics of a solar-ground source heat pump system

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Abstract: In order to investigate the alternate operation characteristics of a solar-ground source heat pump system (SGSHPS), various alternate operation modes are put forward and defined. A two-dimensional mathematical model with freezing/melting phase changes is developed for the heat transfer analysis of the soil. Based on the numerical solution of the model, the variation trends of underground soil temperature of the SGSHPS operated in various alternate operation modes are discussed. The results indicate that, for the day-night and short-time interval alternate operation modes without solar energy, the operation time fraction of a solar heat source should be confined to from 50% to 58% when operated in an alternate period of 24 h. Meanwhile, the disadvantages of a natural resumption of soil temperature can be overcome effectively by solar energy filling, and an optimal operation effect can be achieved by integrating the mode of solar energy filling with other alternate modes. In addition, the accuracy of the presented model is verified by the experimental data of borehole wall temperatures. The conclusions can provide a reference for the optimization operation of the SGSHPS.

Key words: solar-ground source heat pump; alternate operation characteristics; numerical simulation; experimental validation

In recent years, ground coupled heat pumps (GCHP) have been recognized as being among the cleanest, most energy efficient and cost effective systems for space heating and cooling in residential and commercial buildings. The main advantage of using the ground as the system's source or sink is that this environment benefits from a relatively constant mean temperature when compared with that of ambient air[1−2]. This can comprehensively improve the thermal performance of the system and, therefore, reduce operating costs.

However, there are some disadvantages for the application of the GCHP in heating-dominated districts. 1) The temperature of the soil around ground heat exchangers (GHE) increasingly drops with the continuous heat-extraction of the GHE from the soil. This results in the decrease in the evaporating temperature of heat pumps and thus inevitably deteriorate the operation performance of the GCHP[3]. 2) The heat extracted from and released to the soil are imbalanced during a year; that is, the heat extracted from the soil greatly exceeds that released to the soil[4], which also results in the drop of soil temperature year after year over a long time of operation, such as 10 years.

In order to overcome the disadvantages of the GCHP operated in heating-dominated districts, solar energy is added as a supplemental heat source of the GCHP and a solar-ground source heat pump system (SGSHPS) is proposed. Alternate operation modes, which alternately utilize solar energy or geothermal energy as the heat source of heat pumps, are first put forward and defined for improving the operation performance of the GCHP. A two-dimensional mathematical model with freezing/melting phase changes is developed to discuss the alternate operation characteristics of the SGSHPS. Based on the numerical solution of the model, the soil temperature variation tendencies of the SGSHPS operated in various alternate modes are investigated. The validation of the developed model is performed and some conclusions are also obtained.

1 Definition and Classification of Alternate Operation Modes

The alternate mode is defined as an operation state that solar and geothermal energy are used alternately as the heat source of a heat pump[5]. The aim of the mode is to overcome the problem that the soil temperature around the GHE drops very quickly with the continuous heat-extraction of the GHE from the soil. Integrating solar energy to the GCHP makes it possible that the GCHP may be operated intermittently and the resumption of soil temperature can be achieved during the day when a solar-assisted heat pump (SAHP) is started. At the same time, integrating geothermal energy to the SAHP makes it possible that the system can still work in the evening or rainy day when the GCHP is operated. Furthermore, the redundant energy collected by solar collectors during the day may be stored in the soil partly by a U-tube GHE to use for the evening, so other energy storage equipment can be omitted. According to different time combinations of solar and geothermal energy used as heat sources during an alternate operation period, the alternate mode can be further classified into the following three categories:

1) Day and night alternate mode The GCHP is started in the evening and the SAHP is operated during the day. At the same time, the soil temperature can be resumed partly. The mode is fit for the building requiring heating during the day and night.

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2) Short time interval alternate mode The GCHP and the SAHP are operated alternately in a short time interval during an alternate operation period. The mode can make the temperature drop velocity become low and is also fit for the building requiring heating during the day and the night.

3) Solar-U tube feeding heat alternate mode The GCHP is operated in the evening and is off in the daytime. At the same time, solar energy is fed to the soil by a U-tube during the daytime. The mode is fit for the building that needs heating only during the day such as residential buildings during workdays.

2 Calculation Models

2.1 Physical model

Heat transfer between the GHE and its surrounding soil is rather complicated. This includes the influence of the thermal and geometrical properties of the GHE, the soil temperature distribution, the soil moisture content and its thermal properties, groundwater movement, and possible freezing and thawing in the soil. In order to facilitate the analysis, the following assumptions are made to simplify the problem:

1) The soil is viewed as a homogeneous hydrous porous medium, and the hole is full of water.

2) The influences of heat-moisture transfer and natural convection are negligible.

3) The volume change is ignored during the phase change process of the water, and thus the density of the water is constant.

4) The thermal properties of the soil in the regions of freezing and unfreezing are constant.

5) A two-dimensional transient heat transfer process in the radius and depth directions is assumed for the heat exchange between the GHE and its surrounding soil.

6) The freezing-thawing phase change process for the soil is assumed to be completed over a small temperature range, and according to the temperature, the control places around the GHE can be divided into three phase regions along the radius and depth directions, that is, the freezing region, the mushy two-phase region and the unfreezing region.

7) The GHE is assumed to be a cylindrical heat source/sink with an equivalent diameter.

8) The soil temperature is constant if the depth $z > 15$ m and the radius $r > 2$ m.

With the above assumptions, the heat transfer process between the GHE and its surrounding soil can be regarded as a two-dimensional axial symmetrical cylindrical heat source/sink with an equivalent diameter, and there are three phase regions in the radius and depth directions, respectively. As shown in Fig. 1, T is freezing phase change temperature semi-interval across. $S_1(\tau)$ and $S_2(\tau)$ are up and down phase change interfaces, respectively. R and H are the calculation boundaries in the radius and depth directions, respectively.

2.2 Mathematical model

According to the above physical model, the following control equations can be derived for various phase regions as shown in Fig. 1.

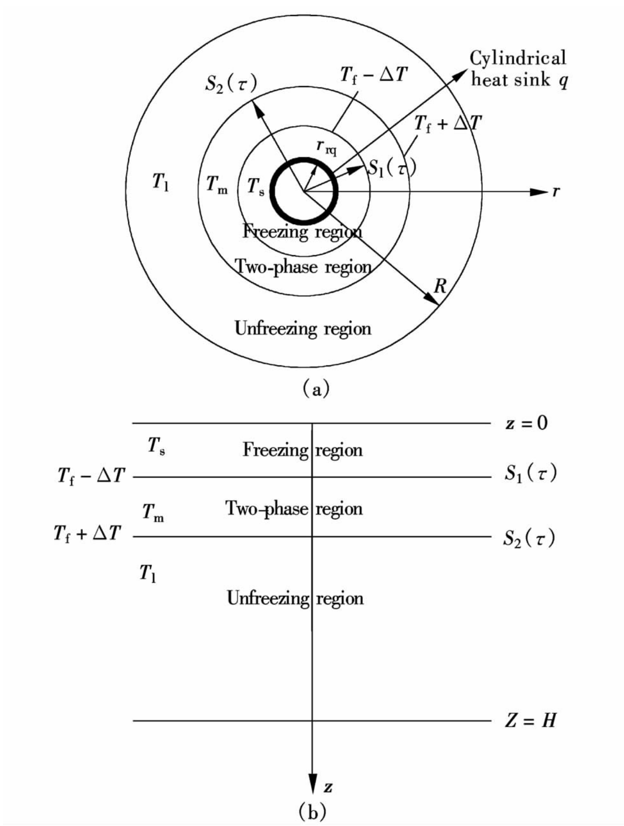

Fig. 1 Physical model of soil freezing process around the GHE. (a) Phase region division in radius direction; (b) Phase region division in depth direction

1) For the freezing and unfreezing region

$$(\rho c_p)_j \frac{\partial T_j}{\partial \tau} = \frac{1}{r}\frac{\partial}{\partial r}\left(\lambda_j r \frac{\partial T_j}{\partial r}\right) + \frac{\partial}{\partial z}\left(\lambda_j \frac{\partial T_j}{\partial z}\right) \tag{1}$$

2) For the two-phase region

$$(\rho c_p)_m \frac{\partial T_m}{\partial \tau} = \frac{1}{r}\frac{\partial}{\partial r}\left(\lambda_m r \frac{\partial T_m}{\partial r}\right) + \frac{\partial}{\partial z}\left(\lambda_m \frac{\partial T_m}{\partial z}\right) + L\frac{\partial f_s}{\partial \tau} \tag{2}$$

3) On the phase change interface

For $r = S_1(\tau)$,

$$\left.\begin{aligned} &T_s(r, z, \tau) = T_m(r, z, \tau) \\ &\lambda_s \frac{\partial T_s(r, z, \tau)}{\partial r} - \lambda_m \frac{\partial T_m(r, z, \tau)}{\partial r} = L\frac{\partial f_s}{\partial \tau} \end{aligned}\right\} \tag{3}$$

For $r = S_2(\tau)$,

$$\left.\begin{aligned} &T_m(r, z, \tau) = T_l(r, z, \tau) \\ &\lambda_m \frac{\partial T_m(r, z, \tau)}{\partial r} = \lambda_l \frac{\partial T_l(r, z, \tau)}{\partial r} \end{aligned}\right\} \tag{4}$$

For $z = S_1(\tau)$,

$$\left.\begin{aligned} &T_s(r, z, \tau) = T_m(r, z, \tau) \\ &\lambda_s \frac{\partial T_s(r, z, \tau)}{\partial z} - \lambda_m \frac{\partial T_m(r, z, \tau)}{\partial z} = L\frac{\partial f_s}{\partial \tau} \end{aligned}\right\} \tag{5}$$

For $z = S_2(\tau)$,

$$\left.\begin{aligned} &T_m(r, z, \tau) = T_l(r, z, \tau) \\ &\lambda_m \frac{\partial T_m(r, z, \tau)}{\partial z} = \lambda_l \frac{\partial T_l(r, z, \tau)}{\partial z} \end{aligned}\right\} \tag{6}$$

4) Initial conditions

$$T_1(r, z, \tau)\big|_{\tau=0} = T_m(r, z, \tau)\big|_{\tau=0} = T_s(r, z, \tau)\big|_{\tau=0} = T_0(z, \tau) \tag{7}$$

5) Boundary conditions

$$-\lambda_j \frac{\partial T_j}{\partial z}\bigg|_{z=0} = \alpha_w (T_a - T_j(z, r, \tau)\big|_{z=0}) - \tag{8}$$

$$\pi d_{eq} \lambda_j \frac{\partial T_j}{\partial r}\bigg|_{r=d_{eq}/2} = q(\tau) \tag{9}$$

$$\frac{\partial T_j(z, r, \tau)}{\partial z}\bigg|_{z=H} = 0 \tag{10}$$

$$\frac{\partial T_j(z, r, \tau)}{\partial r}\bigg|_{r=R} = 0 \tag{11}$$

where α_w is the overall convection heat transfer coefficient between the ground surface and the ambient air; T_a is the ambient air temperature; q is the heat flux of the GHE per unit length (A positive q value implies heating, i. e., heat transfer from the soil to the fluid; while $q = 0$ for intermittent time). d_{eq} is the equivalent diameter of the U-tube, and it can be calculated as[6]

$$d_{eq} = \sqrt{2 d_{po} D_U} \tag{12}$$

where d_{po} is the outside diameter of the U-tube, and D_U is the spacing between the two legs of the U-tube. $T_0(z, \tau)$ is the initial soil temperature and it can be calculated as[7]

$$T_0(z, \tau) = T_M + A_s \exp\left(-z\sqrt{\frac{\omega}{2a_s}}\right)\cos\left(\omega\tau - z\sqrt{\frac{\omega}{2a_s}}\right) \tag{13}$$

where T_M is the mean soil temperature; a_s is the soil thermal diffusivity; A_s is the annual amplitude or swing of the soil surface temperature.

3 Solution of Control Equations

In order to simplify the mathematical model, the apparent heat capacity method[8-9], a classic method to solve phase change problem by transferring multiple phases into a single phase, is employed here. The main idea is that the hydrous soil is not pure substance, and, therefore, the latent heat effect can be expressed by a large heat capacity over a small temperature range, and the magnitude of the heat capacity can be determined by the phase change temperature range and the latent heat released.

Based on the idea of the apparent heat capacity method, suppose that C_s, C_1, λ_s and λ_1 do not depend on temperature T; then the following definitions can be assumed in the phase change temperature interval: $T_f - \Delta T \leqslant T \leqslant T_f + \Delta T$.

$$C_V^*(T) = \frac{\varepsilon L}{2\Delta T} + \frac{C_s + C_1}{2} \tag{14}$$

$$\lambda^*(T) = \lambda_s + \frac{\lambda_1 - \lambda_s}{2\Delta T}[T - (T_f - \Delta T)] \tag{15}$$

Thus the above phase change heat transfer problem with three phase regions can be expressed uniformly as follows:

$$C_V^* \frac{\partial T}{\partial \tau} = \frac{1}{r}\frac{\partial}{\partial r}\left(\lambda^* r \frac{\partial T}{\partial r}\right) + \frac{\partial}{\partial z}\left(\lambda^* \frac{\partial T}{\partial z}\right) + S \tag{16}$$

where

$$C_V^* = \begin{cases} C_s & T < T_f - \Delta T \\ \dfrac{\varepsilon L}{2\Delta T} + \dfrac{C_s + C_1}{2} & T_f - \Delta T \leqslant T \leqslant T_f + \Delta T \\ C_1 & T > T_f + \Delta T \end{cases} \tag{17}$$

$$\lambda^* = \begin{cases} \lambda_s & T < T_f - \Delta T \\ \lambda_s + \dfrac{\lambda_1 - \lambda_s}{2\Delta T}[T - (T_f - \Delta T)] & T_f - \Delta T \leqslant T \leqslant T_f + \Delta T \\ \lambda_1 & T > T_f + \Delta T \end{cases} \tag{18}$$

where C_V^* is the effective volumetric heat capacity, and $C_V^* = c\rho$; λ^* is the effective thermal conductivity; ε is the porosity; S is the source term. C_s, λ_s and C_1, λ_1 are the volumetric heat capacity and the thermal conductivity of the soil for freezing and unfreezing regions, respectively.

4 Results and Discussion

The partial differential Eq. (16) is discretized based on the control volume method. The TDMA algorithm[10] is used to solve the discrete matrix equations groups. The calculating conditions are as follows: A_s = 13.9 ℃, λ_s = 2.048 W/(m·℃), λ_1 = 1.712 W/(m·℃), c_s = 1 218.6 J/(kg·℃), c_1 = 1 637.8 J/(kg·℃), ρ_1 = 1 400 kg/m^3, T_M = 10 ℃, T_0 = 10 ℃, T_f = 0 ℃, L = 333.4 MJ/m^3, R = 2 m, H = 53 m, ΔT = 0.8 ℃, ε = 0.18, α_w = 23.3 W/(m^2·℃). The calculated results of the variations in middle borehole wall temperature (MBWT) at different ratios of operation time to off time are shown in Figs. 2 to 4. Where t_1, t_2 and t_3 are the operation time, the off time and the feeding heat time, respectively.

Fig. 2(a) shows that the resumption effect of MBWT depends on the ratio of operation time to off time when the SGSHPS operated in the day and night alternate modes. The longer the operation time and the less the off time, the worse the resumption effect is. From Fig. 2(b), we can find that after one month, the MBWT is below 0 ℃ for various ratios of operation time to off time when the off time is less than 10 h, and it cannot naturally resume up to above 0 ℃. This means that the off time should exceed 10 h for ensuring a good resumption effect. It is obvious that the soil temperature resumption effect will become better and better with the decrease in operation time. However, a good resumption effect means a high initial cost of the solar collector because of the increase in the collector area. Meanwhile, solar energy, an unsteady energy source, needs a large energy-storage installation, and this will also increase the initial cost of the whole system. Considering the integrative effect of the energy efficient utilization, system cost, and soil temperature resumption together, the operation time of 10 to 12 h for the GCHP is preferable; that is, the proportion of the operation time of the SAHP should be confined to from 50% to 58% for the day and night alternate mode, and thus the required area of the solar collector can be obtained.

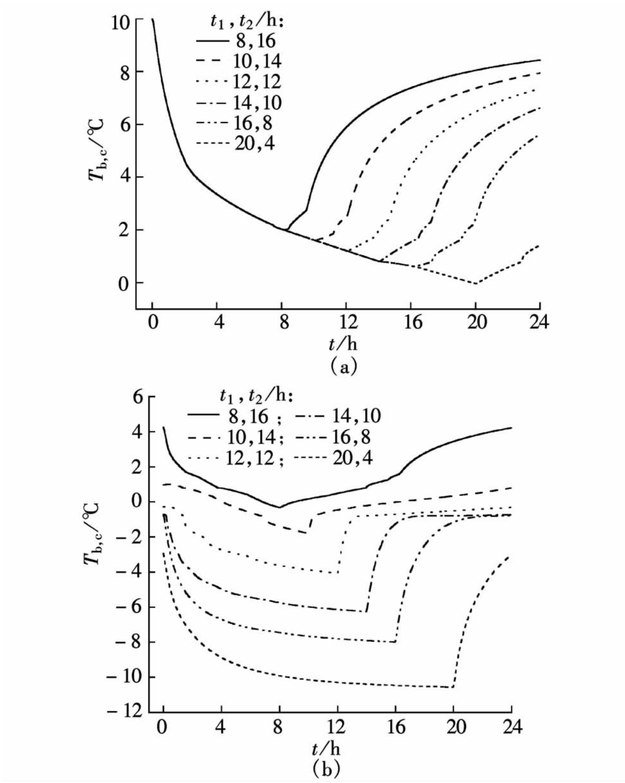

Fig. 2 Variations of MBWT at different ratios of operation time to off time for day and night alternate mode. (a) For the first day; (b) For the 30th day

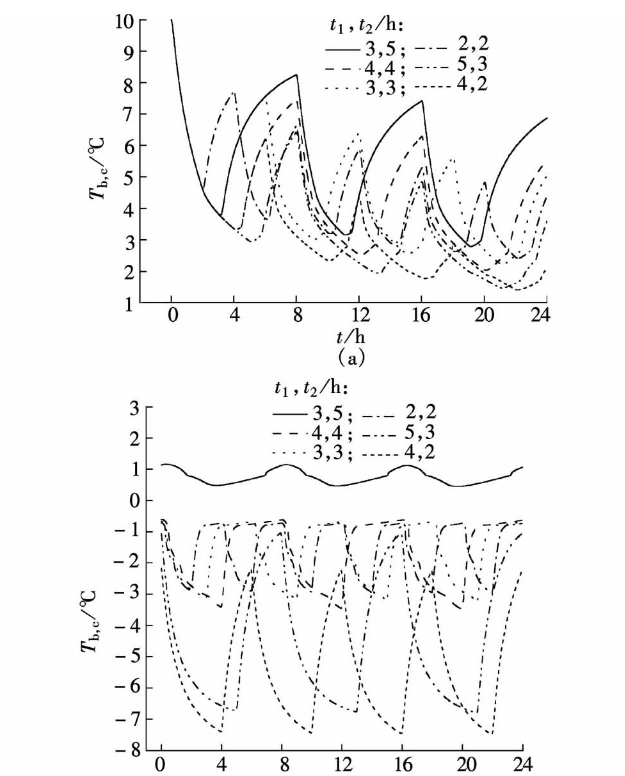

Fig. 3 Variations of MBWT at different ratios of operation time to off time for short time interval alternate mode. (a) For the first day; (b) For the 30th day

Fig. 3 shows that the soil temperature drop velocity is decreased and the temperature can be partly resumed in the short time intermittent period, which is beneficial for improving the performance of heat pumps. The resumption effects have a correlation with the ratio of operation time to off time. When the total ratio of operation time to off time is constant, the longer the intermittent time is, the better the temperature resumption effect is. Fig. 3(a) shows that the resumption effect of soil temperature operated in the time ratio of 4 h operation time to 4 h off time is better than that operated in the time ratio of 3h operation time to 3 h off time, and the resumption effect operated in the time ratio of 3 h operation time to 3 h off time is better than that operated in 2 h operation time to 2 h off time. The reason is that the natural resumption velocity of soil temperature is less than the corresponding temperature drop velocity, which results in that the temperature resumption cannot be easily achieved naturally in a short intermittent time. So the intermittent time should be increased when the total ratio of operation time to off time is constant. This helps to improve the soil temperature resumption effect. From Fig. 3(b), we can further find that after one month of operation, the MBWT cannot be resumed up to 0 ℃ when the ratio of operation time to off time is more than 1; that is to say, the heat extraction time is longer than the intermittent time. This is mainly caused by the fact that a large amount of phase latent heat coming from the freezing-thawing phase change of the soil has been absorbed during the resumption period. So the ratio of operation time to off time should be less than 1; that is, the resumption time should be longer than the heat extraction time for improving the temperature resumption effect and can be determined by the load characteristics of the building load. If possible, some assistant energy sources such as solar energy should be used for decreasing the time of heat extraction of the GHE.

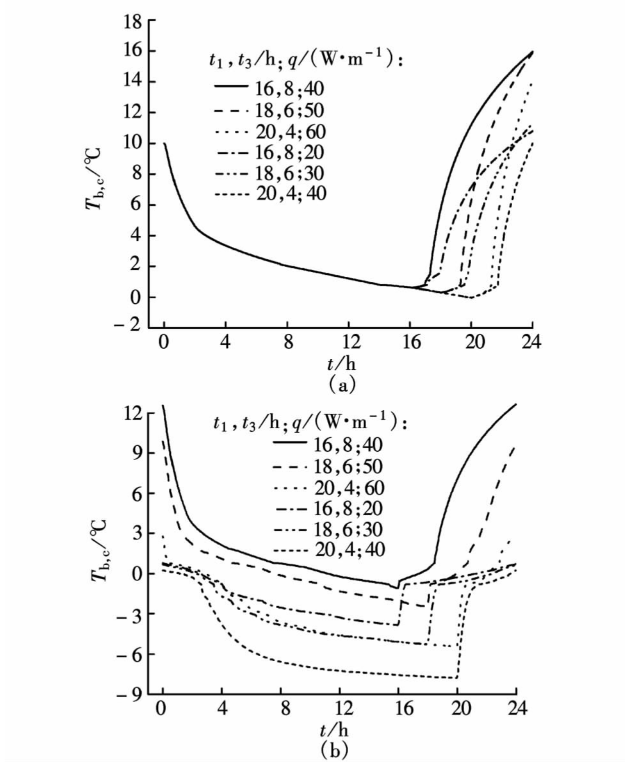

Fig. 4 Variations of MBWT at different ratios of operation time to off time for solar-U tube feeding heat alternate mode. (a) For the first day; (b) For the 30th day

Fig. 4 describes the variation trend of MBWT for the first and 30th day when the SGSHPS operates in the solar-U tube feeding heat alternate mode. From Fig. 4, we can find that the resumption of soil temperature around the GHE can be achieved by solar heat, and the resumption effect becomes better with the increase in feeding heat flux when the time of feeding heat is constant. As shown in Fig. 4(b), the MBWT can be resumed to above 0 ℃ even after one month. If the value of feeding heat flux is enough to thaw the freezing soil, the soil temperature resumption can also be enhanced even though the feeding heat time is very little. Thus, the operation mode of forced resumption of soil temperature by solar feeding using a U-tube is advisable, and can be used combined with the above other two modes for obtaining an optimal effect.

5 Experimental Validation on the Model

In order to validate the presented model, an experimental test is performed in a solar-geothermal heat pump experimental system[11]. The test heat flow value is input as a boundary condition of the model. The experimental data and the calculated value of borehole wall temperature (BWT) at 6.5 m depth are compared, and the comparison results are shown in Fig. 5.

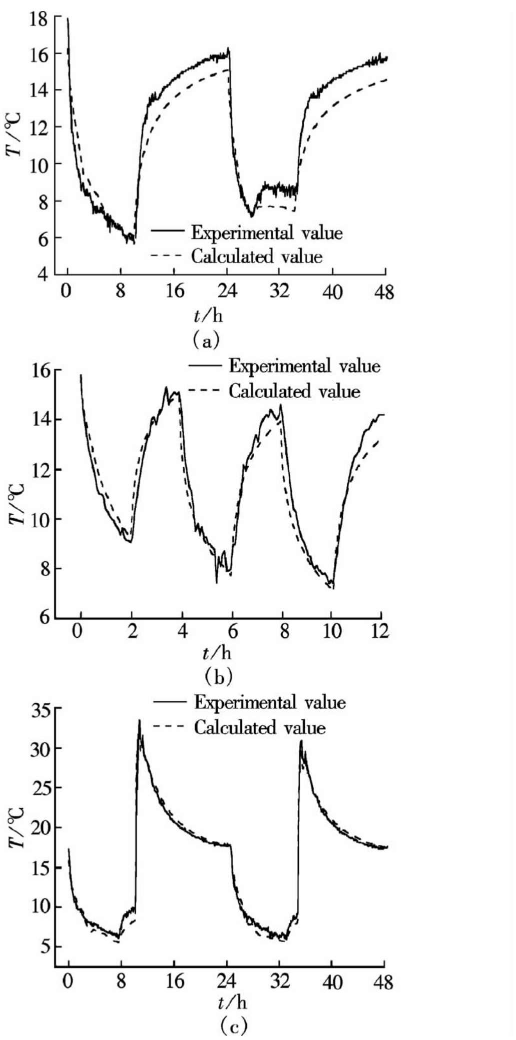

Fig. 5 Comparison between the experimental and calculated values of BWT for various alternate modes. (a) For day and night alternate mode; (b) For short time interval alternate mode; (c) For solar-U tube feeding heat alternate mode

We can see from Fig. 5 that the calculated temperatures using the model agree well with the corresponding test data for various alternate operation modes. This means that the model developed above is feasible and can be used to investigate the resumption characteristics of soil temperature in various alternate modes for the SGSHP.

6 Conclusions

1) Various alternate modes can all make the temperature drop velocity become low and improve the resumption effect of soil temperature.

2) For the day and night alternate mode, the operation time of the SAHP should be confined to from 50% to 58% for the conditions used in this paper.

3) For the short time interval alternate mode, when the total ratio of operation time to off time is constant, the longer the intermittent time is, the better the temperature resumption effect is. The ratio of operation time to off time should be less than 1 for obtaining a good resumption effect.

4) The operation mode of forced resumption of soil temperature by solar-U tube feeding heat is advisable, and can be used combined with the other two modes for obtaining an optimal effect.

5) The experimental validation shows that the model developed in this paper is feasible and can be used to investigate the resumption characteristics of soil temperature in various alternate modes for the SGSHP.

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太阳能-地源热泵系统的交替运行特性

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摘要:为了探讨太阳能-地源热泵系统的交替运行特性,提出并定义了各交替运行模式,建立了交替运行时考虑冻融相变的U形埋管周围土壤传热模型. 基于对该模型的数值求解,探讨了各交替运行模式下地下埋管周围土壤温度的变化趋势. 结果表明:各交替运行模式均可有效改善埋管周围土壤温度的恢复效果,对于无太阳能补热的昼夜交替与短时间间隔交替运行模式,在以24 h为交替运行周期时,其太阳能热源承担的时间比例可控制在50% ~58%;同时,利用日间太阳能补热来强制土壤温度的恢复,可有效克服土壤温度的自然恢复缺陷,与其他交替模式综合使用可达最佳运行效果. 此外,利用钻孔壁实测数据对所建模型的预测精度进行了验证. 研究结论可为太阳能-地源热泵系统的优化运行提供参考.

关键词:太阳能-地源热泵;交替运行特性;数值模拟;实验验证
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