Incorporation of Phase-Change Materials Into a Ground Thermal Energy Storage System: Theoretical Study

Y. Rabin

E. Korin[1]

Department of Chemical Engineering,
Ben-Gurion University of the Negev,
P.O. Box 653,
Beer-Sheva 84105, Israel

An investigation of a ground thermal energy storage system, which includes storage units containing phase-change materials (PCM), is presented. This study is related to a large-diameter helical heat exchanger, which is placed vertically in the ground. The PCM storage units under consideration have a cylindrical shell shape and are located inside and/or outside the helix. A modified numerical scheme for the solution of heat transfer in the ground, in the PCM units, and within the heat exchanger pipe, is presented. The theoretical results show that the thermal diffusivity of the PCM dominates the thermal performance of the system. Incorporation of PCM storage units containing paraffin wax results in a reduction of the thermal efficiency in comparison with a system not containing these units. However, incorporation of PCM having the same thermal diffusivity as of the soil results in a significant improvement of the thermal performance.

Introduction

Thermal energy storage in soil is considered as one of the most promising techniques for long-term application. It is particularly suitable for seasonal storage of solar energy, but it may also be applied for long-term storage of other sources of energy, such as waste heat. Extensive research and development efforts have been devoted to this concept, and a number of full-scale systems have been built and operated successfully in a variety of countries all over the world (International Conferences on Thermal Energy Storage, 1981–1994).[2] Most of these systems are being operated in countries with cold climates, and therefore the technology has been developed to meet the specific conditions in these areas; i.e., the energy storage system is usually designed to operate in concert with a heat pump (Svec and Palmer, 1989; Beck et al., 1991; Svec, 1991).

Our system differs from those described in the foregoing in that it is designed to operate in hot climates. The general concept and theoretical model for seasonal thermal energy storage for use in arid and semi-arid zones have been described by Nir et al. (1986). The method is based on a vertical helical heat exchanger and unsaturated soil as the storage medium, this being the commonly available ground in these areas. A field experimental system based on this concept was designed, built, and operated at the Institutes for Applied Research, which are sited in Beer-Sheva, in Israel's Negev Desert. The experimental data used for validation testing of the theoretical model and the experience obtained from the experimental work regarding engineering and economic aspects have been applied for implementation of the concept in arid and semi-arid zones throughout the world (Bensabat et al., 1988; Nir et al., 1990; Doughty et al., 1990, 1991; Bar-On et al., 1991; Rabin et al., 1991; Korin and Nir, 1992; Nir et al., 1992; Rabin and Korin, 1996). From a combination of modeling and experimental work, we delineated the parameters for the basic module for seasonal energy storage, which comprises one unit of a multiple unit field, as follows. The heat exchanger should consist of a polybutylene pipe in a diameter of 0.03 m, in a helical configuration. Typical helix dimensions are: a diameter of 1.3 m, a length of 18–24 m, and a pitch of 0.1–0.3 m. The helix should be placed vertically, 4 to 6 m below the ground surface. The operation cycle comprises an 8-mo charging period at a 65°C inlet temperature and a 4-mo discharging period at a 25°C inlet temperature. These conditions provide 6 MWh discharge capacity per annual cycle, at a minimum outlet temperature of 36°C, with an energy recovery of 70 percent (Doughty et al., 1991; Bar-On et al., 1991).

A helical shape was chosen for the heat exchanger, since this configuration offers unique flexibility in the design of the system. The required surface for heat exchange per unit length of well can be easily obtained by adjusting the helix pitch. The large well diameter facilitates exploitation of part of the space for the incorporation of special devices that improve the system's thermal performance. Examples of the special devices are irrigation equipment with moisture sensors to control the water content in the soil at a level that ensures optimal thermal properties, and phase-change energy storage elements that may be included to increase the thermal capacity of the system. To exploit these possibilities for system optimization, particularly for shorter cycles than the seasonal cycle, further theoretical and experimental studies of the concept are required, as are described in this paper.

The main disadvantages of using ground as a heat-storage medium are the relatively low volumetric heat capacity of the soil and the high heat losses to the surroundings. The use of a helical heat exchanger with a large diameter opens the possibility of improving the system's thermal performance by incorporating storage units containing phase-change materials (PCMs). The most important feature of PCM systems is their high-energy storage density under almost isothermal conditions, which facilitates a reduction in the size of the storage system and an im-

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[1] Presently, Department of Mechanical Engineering, Carnegie Mellon University, Pittsburgh, PA 15213-3890.

[2] STES and CAES Seattle, WA, 1981; International Conference Subsurface Heat Storage in Theory and Practice, Stockholm, Sweden, 1983; ENERSTOCK 85—Third International Conference on Energy Storage, Toronto, Ontario, 1985; JIGASTOCK 88—Fourth International Conference on Energy Storage, Versailles, France, 1988; THERMASTOCK 91—Fifth International Conference Thermal Energy Storage, Scheveningen, Holland, 1991; CALORSTOCK '94—Sixth International Conference on Thermal Energy Storage, Otaniemi, Espoo, Finland, 1994.

Table 1 Typical thermophysical properties of PCMs and soil (Doughty et al., 1990)

	Thermal conductivity W/m-°C	Volumetric specific MJ/m^3-°C heat
Saturated soil	1.8	3.2
Soil in the experimental system (Rabin, 1991)	1.34	2.84
Unsaturated soil	0.8	2.5
Paraffins	0.1	1.3
Inorganic salt hydrates	0.5	3.5

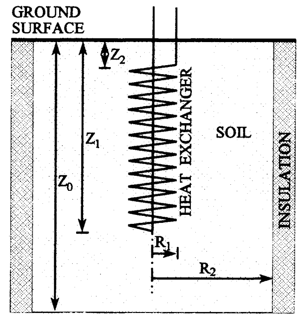

Fig. 1 Schematic description of the basic ground energy storage system (with no PCM). Typical dimensions are: Z_1 = 10 m, Z_2 = 4 m, R_1 = 0.5 m, R_2 = 3 m.

provement in the thermal efficiency. Incorporation of PCM elements into the soil will increase the energy storage capacity within the storage medium. However, the PCMs available for a relatively moderate phase-change temperature range of 40–80°C, such as paraffin waxes, have a relatively low thermal conductivity (0.1 W/m-°C) in comparison with soil (0.8 to 1.8 W/m-°C); see Table 1. Therefore, the possible theoretical benefit of incorporating such PCM elements is an open question.

This study presents the effect of PCM elements' incorporation into the soil on the thermal performance of the ground thermal storage system. A number of module designs combining PCM elements were considered. A mathematical model of the heat transfer in the system was modified for this purpose. The effects of the PCM's thermophysical properties on the system's thermal performance are also presented.

PCM Modules and Mathematical Formulation

A number of modules for theoretical studies on the use of PCM storage units in ground thermal energy storage systems have been suggested by Korin (1990). Assuming that the diameter and the depth of the borehole are larger than those of the helical heat exchanger, the energy storage domain can be separated into four zones: the spaces above, below, inside, and outside of the heat exchanger coil. Placement of a storage unit with a low thermal conductivity outside of the heat exchanger coil will result in a reduction of heat losses from the energy storage domain and improve the energy recovery of the system. With regard to the spaces inside and outside of the coil, two different approaches may be considered: uniform distribution of the PCM elements in the soil or installation of cylindrical shells containing PCM inside and/or outside the helical heat exchanger. A thermal performance analysis of a system containing uniformly distributed PCM elements calls for a study of the following parameters: ''density'' of the PCM elements (i.e., number of elements per unit volume of soil) and thermophysical properties of the PCM (i.e., transition temperature, latent heat, and thermal conductivity). The present study, however, deals with the installation of cylindrical shells of PCM inside and/or outside the heat exchanger coil. The parameters to be studied in this case include: location or distance of the PCM units from the center of the well, thickness of the PCM layer, and thermophysical properties of the PCM.

A schematic description of the basic energy storage system without the PCM elements is given in Fig. 1. The mathematical model and the solution of heat transfer in an energy storage system of this type has been presented elsewhere (Rabin et al., 1991; Rabin and Korin, 1996). Therefore, the corresponding solution is given only in brief for purposes of clarity. The present theoretical model differs from the one employed for previous studies in that it facilitates the incorporation of PCM storage units in the system. The model is considered to be two-dimensional, axisymmetric and semi-infinite in the vertical direction. Heat transfer in the soil is assumed to be solely by means of conduction. The soil is assumed to be isotropic, with average constant thermophysical properties, but the properties may be defined as a function of space. On the basis of the foregoing described assumptions, the governing heat transfer equation in the soil is

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T_g}{\partial r}\right)+\frac{\partial^2 T_g}{\partial z^2}=\frac{1}{\alpha_g}\frac{\partial T_g}{\partial t} \tag{1}$$

The initial and boundary conditions are, respectively,

$$T_g(z, r, 0) = T_{g0}(z) \tag{2}$$

Nomenclature

a = radius of heat exchanger pipe, m
b = helical heat exchanger pitch, m
C = volumetric specific heat, J/m^3-°C
$F_{i,j}$ = energy capacity per °C at numerical node ij, J/°C
k = thermal conductivity, W/m-°C
L = volumetric latent heat, J/m^3
$\dot{m}$ = flow rate, m^3/s
q'' = heat flux, W/m^2
r, θ, z = global cylindrical coordinates
r^*, θ^*, z^* = local cylindrical coordinates of heat exchanger pipe
$R_{i,j,n}$ = thermal resistance to heat flow between element ij and its neighbor n, °C/W
R_j = radius in global coordinate system, m; j = 1, of helical heat exchanger; j = 2, of storage system (Fig. 1)
t = time, s
T = temperature, °C
Z_j = depth, m; j = 0, of system; j = 1, bottom of heat exchanger; j = 2, top of heat exchanger (Fig. 1)
α = thermal diffusivity, m^2/s

Indexes

0 = initial
b = bulk
e = pipe elements counter
f = working fluid
g = ground (soil)
in = entrance to pipe element
inlet = entrance to system
i, j, n = space indices
l = liquid phase
out = exit from a pipe element
p = time counter
s = solid phase
sur = surface
t = phase transition
u = depth related to undistributed seasonal temperature profile, Eq. (7)

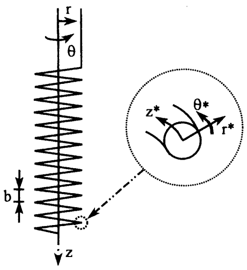

Fig. 2 The heat exchanger pipe and its local coordinate system

$$\frac{\partial T_g}{\partial r}(z, 0, t) = 0 \tag{3}$$

$$\frac{\partial T_g}{\partial r}(z, R_2, t) = 0 \tag{4}$$

$$\frac{\partial T_g}{\partial z}(\infty, r, t) = 0 \tag{5}$$

$$k_g \frac{\partial T_g}{\partial z}(0, r, t) = q''_{\text{sur}} \tag{6}$$

The storage system is assumed to be one unit of a multiple unit field, therefore boundary condition (4) represents no heat flow on the boundary between adjunct units. The last boundary condition is a mixed one, which includes the effects of solar radiation, sky radiation, and heat convection to the surroundings. A detailed description and parametric study of boundary condition (6) is given by Rabin and Korin (1995). For purposes of thermal analysis, boundary condition (6) can be simplified by assuming that the ground temperatures at the upper layer are not affected by the presence of the heat exchanger. This simplified boundary condition is given by

$$T_g(z_u, r, t) = T_u(z_u, t) \tag{7}$$

where T_u is the temperature that would prevail at depth z_u in an undisturbed field (without any energy storage system).

The PCM elements are considered to have a ring configuration, which may be placed anywhere axisymmetrically to the heat exchanger. The mathematical formulation of the heat transfer in the PCM elements is based on the following assumptions: 1) heat transfer in the PCM takes place solely by conduction; 2) the thermal resistance to heat flow of the PCM container's wall may be neglected; 3) thermophysical properties of the PCM are temperature-dependent; 4) the effect of density changes between the solid and liquid states is taken into account only in the determination of the volumetric specific heat; and 5) phase transition occurs over a temperature range.

The volumetric specific heat of the PCM is considered to be a constant property, possessing different values above and below the phase transition temperature range. The effective volumetric specific heat in the phase transition temperature range is considered to be

$$C_t = \frac{1}{2}(C_l + C_s) + \frac{L}{\Delta T_m} \tag{8}$$

where ΔT_m is the transition temperature range (Rabin and Korin, 1993). The effective thermal conductivity in the transition temperature range is assumed to be

$$k_t = \tfrac{1}{2}(k_l + k_s) \tag{9}$$

Under the foregoing described assumptions, the governing equation in the soil, Eq. (1), applies to the PCM elements as well.

Finally, the helical heat exchanger is simplified for a numerical solution. A schematic description of the helical heat exchanger with its local coordinate system is presented in Fig. 2. The helical heat exchanger is modeled by a series of horizontal rings with a constant spacing between them (the helix pitch) (Rabin and Korin, 1995). The thermal resistance of the pipe is neglected. The working fluid is assumed to be well mixed, and thus the temperature in each cross section of the pipe is considered uniform. Furthermore, the transient response of the working fluid is neglected. Based on these assumptions, the governing heat transfer equation in the working fluid becomes

$$a \int_0^{2\pi} k_g \left.\frac{\partial T_g}{\partial r^*}\right|_{r^*=a} d\theta^* = \dot{m}_f C_f \frac{\partial T_f}{\partial z^*} \tag{10}$$

where θ^*, r^*, z^* are the local coordinates of the pipe. The initial and boundary conditions along the heat exchanger pipe are, respectively,

$$T_f(z^*, 0) = T_{g0}(z) \tag{11}$$

$$T_f(z^*, t) = T_g(z^*, a, t) \tag{12}$$

$$T_f(0, t) = T_{f,\text{inlet}}(t) \tag{13}$$

where the transformation between the global coordinate system and the local pipe coordinates, starting at the pipe inlet, is given by

$$z = Z_1 - \frac{z^* b}{2\pi R_1} \tag{14}$$

Governing Eq. (1) can be solved numerically, by a finite difference method

$$T_{i,j}^{p+1} = T_{i,j}^p + \frac{\Delta t}{F_{i,j}^p} \sum_n \frac{T_n^p - T_{i,j}^p}{R_{i,j,n}^p} \tag{15}$$

where the indexes i, j referred to the discretization in space and the index p in time, Δt is a time interval, $F_{i,j}$ is the heat capacity per temperature degree at node i, j, and $R_{i,j,n}$ represents the thermal resistance to heat flow between element i, j and its neighbor n. Equation (15) is valid for both cases in the soil (Rabin and Korin, 1996) and in the PCM elements (Rabin and Korin, 1993).

The heat balance equation of the working fluid, Eq. (10), can be solved numerically by a similar technique to the one presented by Eq. (15). Considering a downstream pipe element e, the temperature distribution in the working fluid can be calculated by rearranging Eq. (10) into a finite difference form

$$T_{\text{in},e+1}^{p+1} = T_{\text{in},e}^p + \frac{1}{\dot{m}_f C_f} \sum_n \frac{T_n^p - T_{b,e}^p}{R_{i,j,n}^p} \tag{16}$$

where $T_{\text{in},e}$ and $T_{\text{out},e}$ are the inlet and outlet temperatures of the fluid at element e, respectively, and T_b is the bulk temperature of the fluid in the same element

$$T_{b,e}^p = \tfrac{1}{2}(T_{\text{out},e}^p + T_{\text{in},e}^p) \tag{17}$$

Results and Discussion

All the theoretical results were obtained under system parameters and operation conditions similar to those of the experimental system (Rabin and Korin, 1991), as follows. Dimensions of the helical heat exchanger: 6 m height, 1 m diameter of the coil, 0.1 m pitch, and 0.03 m pipe diameter; soil thermal diffusivity of $4.7 \cdot 10^{-7}$ m²/s; soil thermal conductivity of 1.35 W/m-°C; average initial soil temperature of 20°C; an annual average soil temperature of 20°C at a depth of 0.5 m; working fluid (water) flow rate of 40 kg/h; fluid inlet temperature of 70°C during 3 mo of energy charging and of 20°C during 1 mo of energy discharging; and phase transition range of 44 to 46°C, which is an average of the charging and discharging fluid inlet temperatures.

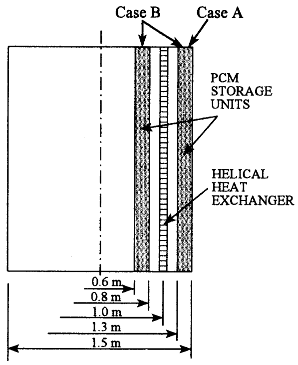

Fig. 3 PCM storage units of a cylindrical shell shapes used for the thermal analysis of case A—the outer shell; and case B—both outer and inner shells

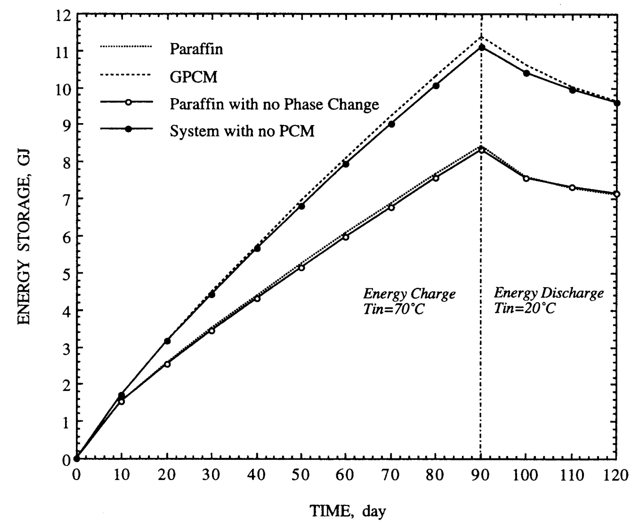

Fig. 5 Energy storage versus time in the system in case A

The parametric studies were carried out for four systems containing storage media as follows: 1) basic system with no PCM elements; 2) system with PCM elements containing paraffin; 3) system with PCM elements containing paraffin that does not undergo phase transition; and 4) system with PCM elements containing a material that has the same thermophysical properties as those of the soil, but latent heat and phase transition temperatures as of paraffin (designated GPCM). An average latent heat value of 200 MJ/m^3 is assumed for paraffin in this study. It should be noted that the effective thermal conductivity of the PCM can be increased by using metal matrix structures (De Jong and Hoogendoorn, 1980).

The first case study (case A) was performed for a system having a 0.2-m-thick cylindrical shell of PCM, which is located at a radius of 1.3 m, Fig. 3. The fluid outlet temperature and the energy storage in the system are presented in Figs. 4 and 5, respectively. The thermal performance, i.e., the working fluid outlet temperature and the energy storage of the system, of the system with a paraffin that does undergo a phase transition was almost the same as that of the basic system with no PCM element. The comparison between the first two cases indicated that the paraffin acted as a thermal insulator. It caused a reduction in the effective energy storage volume of the system and the rate of heat charging between the working fluid and the energy storage medium. An examination of the temperature field in the cylindrical PCM element indicated that only a 0.02-m-thick layer of paraffin melted, while the GPCM melted completely in the other system (0.2 m thick). It was found that the thermal performance of a system with the GPCM was superior to that of the basic system. Although the energy transferred from the working fluid to the storage medium was almost the same for system with no PCM and for the system with GPCM, the fluid outlet temperatures during the month of discharging were much higher in the system with the GPCM than in the system with no PCM.

The second case study (case B) was conducted for a system with two cylindrical shells, each filled with 0.2 m of GPCM, with radii of 0.6 and 1.3 m, Fig. 3. The fluid outlet temperatures and the energy stored within three charging cycles are presented in Figs. 6 and 7. These figures also present a comparison between the first case study (case A) and the present case study. It can be seen that during the 3-mo charging period, the thermal performances of the systems with one or two GPCM shells were almost the same as that of the system with no PCM. The fluid outlet temperatures during the discharging periods indicate that the incorporation of GPCM shells conferred a significant advantage. At the end of the third energy storage cycle (after 1 mo of discharging), the fluid outlet temperatures dropped about 4, 8, and 15°C, for the system containing two cylinders of GPCM, one cylinder of GPCM, and no PCM, respectively.

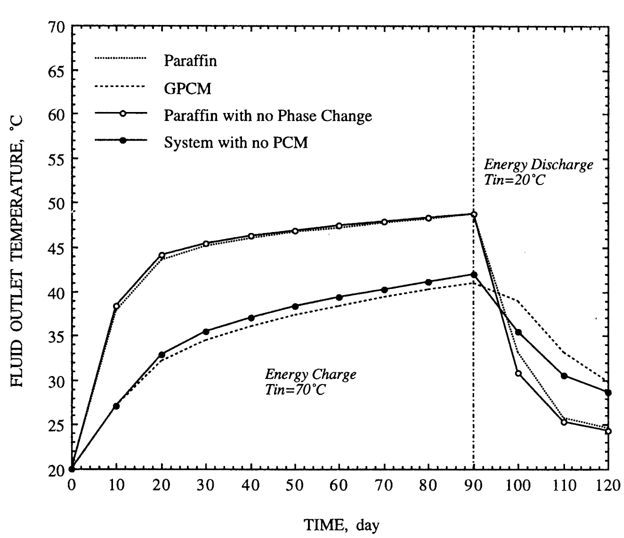

Fig. 4 Fluid outlet temperatures versus time in case A

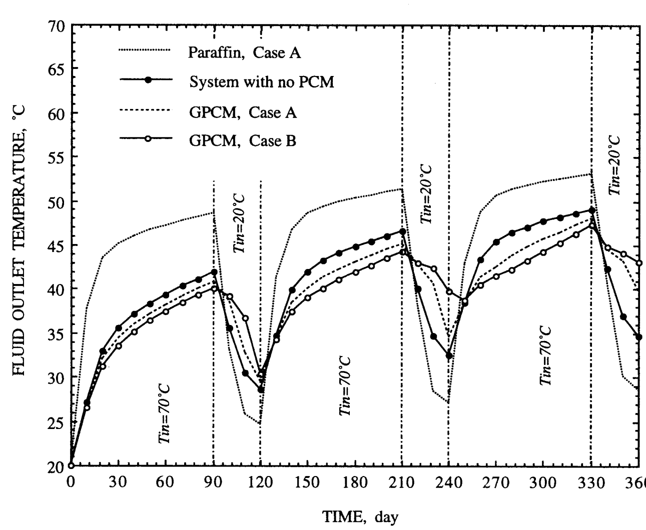

Fig. 6 Fluid outlet temperatures versus time in case B compared with case A

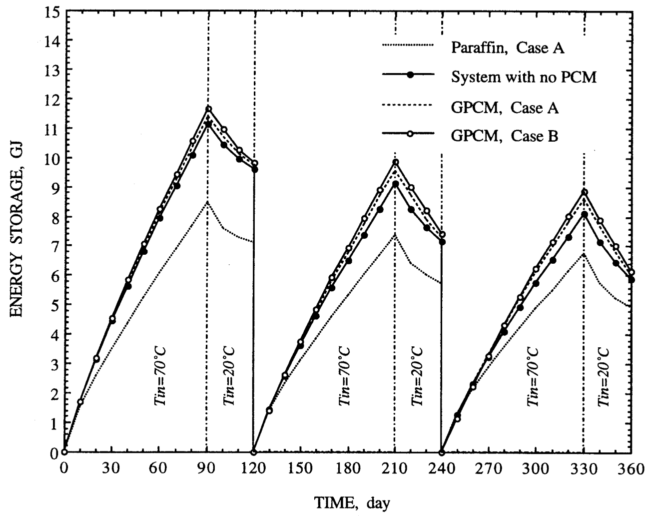

Fig. 7 Energy storage versus time in case B compared with case A

The ability to maintain a narrow fluid outlet temperature range of the storage systems containing the GPCM increased significantly with an increasing number of storage cycles. The fluid outlet temperatures at the end of first, second, and third cycles (3 mo of charging followed by 1 mo of discharging) were: 30, 40, and 43°C for the system with two GPCM shells; 30, 35, and 40°C for the system with one GPCM shell; and 28, 32, and 35°C for the system with no PCM.

Conclusions

The dimensions of a system designed for long-term energy storage in the ground depend on the thermophysical properties of the soil, the heat source of the system, the energy demands from the system during the discharge period, the number of subsequent energy storage cycles, and economic considerations. The performance of the energy storage system can be improved significantly by the incorporation of PCM storage units. This study indicates that it is advisable to place the PCM elements inside or around the helical heat exchanger, especially in the lower area where the working fluid enters the system. The overall efficiency of a system containing PCM elements reaches its steady-state condition after larger number of cycles than a system that does not contain them. In order to improve the thermal performance of the system by incorporating PCM storage units, the effective thermal conductivity of the PCM must be equal to or higher than that of the soil. This demands a special design of the PCM storage units such as addition of internal fines of a material with a higher thermal conductivity.

It should be noted that special attention has to be paid to possible environmental problems such as contamination of ground water resources. The PCM has to be insoluble in water and encapsulated in a hermetically sealed container. Currently available PCM products are usually not cost-effective for most solar applications. Therefore, the combination of PCM elements with a ground thermal storage system may be considered only for special cases, in which a significant improvement in the thermal efficiency can be obtained and in which the system is designed to operate in short-cycle periods.

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