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"Long-Term Storage of Chilled Water in Cisterns in Hot, Arid Regions"

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Long-Term Storage of Chilled Water in Cisterns in Hot, Arid Regions

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Seasonal storage of chilled water in a large underground reservoir was studied by considering a two-dimensional heat flow in water and the soil surrounding the cistern, and by employing a finite-difference technique for the numerical solution of the energy equations. The cistern considered in the analysis was similar to those which have been employed in the hot, arid region of Iran for centuries for the storage of cold potable winter water for summer use. These cisterns were filled with cold water in winter and water removal did not start until mid-spring. During the water storage and usage, there was always a wind-induced airflow over the water surface to maintain an evaporation rate from the water surface. In these cisterns the water removal was from the bottom at such small flow rates that the thermal stratification in the cistern was not disturbed.

It was found that while the temperature of water at the surface was high and followed the ambient air temperature closely, the temperature of the water removed from the bottom was very low, although it increased gradually toward the end of the storage season. During the summer months the temperature of water removed from the bottom of the cistern was below 10°C. This temperature was found to be a function of the size of the cistern, the weather conditions, the initial temperature of water in the cistern, the soil properties, and the year of operation of the cistern.

The system analyzed here finds applications in the hot, arid regions of the developing countries for the storage of cold winter water for drinking, for food preservation, or for other agricultural and industrial applications. It can also be used for air conditioning of buildings.

NOMENCLATURE

- A amplitude of the temperature fluctuations, defined by equation 3
- C the thermal capacity of soil, $kJ\ m^{-3}\ °C^{-1}$
- C_w the thermal capacity of water, $kJ\ m^{-3}\ °C^{-1}$
- C_{pa} the specific heat of air, $kJ\ kg^{-1}\ °C^{-1}$
- h the natural convection heat transfer coefficient, $W\ m^{-2}\ °C^{-1}$. Subscripts a, f, and w refer, respectively, to air, floor, and wall
- h_{fg} the latent heat of vaporization of water, $kJ\ kg^{-1}$
- h_m the mass transfer coefficient, $kg\ m^{-2}\ s^{-1}$
- h_r the radiation heat transfer coefficient, $W\ m^{-2}\ °C^{-1}$
- k the thermal conductivity of the soil, $W\ m^{-1}\ °C^{-1}$
- k_w the thermal conductivity of water, $W\ m^{-1}\ °C^{-1}$
- $\dot{m}_e$ the rate of water evaporation, $kg\ m^{-2}\ s^{-1}$
- T the temperature, °C. Subscripts max and min refer to the mean daily temperatures in July and January, respectively, and subscripts i and j refer to the columns and rows in the network
- T' the temperature at the next time interval, °C
- $\bar{T}$ the mean daily temperature of the ambient air, °C
- ΔT the temperature difference, °C
- t the time, or the day number ($t = 1$ for January 1)
- Δt the time step
- W the humidity ratio of air, $kg\ kg^{-1}$. Subscripts a and s refer, respectively, to the air, and to the air if it were saturated at the water surface temperature
- x the distance from the cistern wall, m, positive toward the soil and negative toward the water
- Δx the horizontal distance between two adjacent nodes, m. Subscripts l and r refer to left and right, respectively
- y the vertical distance from ground level, m
- Δz the vertical distance between two adjacent nodes, m. Subscripts b and t refer to bottom and top, respectively
- α the thermal diffusivity of the soil, $m^2\ s^{-1}$
- α_w the thermal diffusivity of water, $m^2\ s^{-1}$
- ϕ the time lag, days
- ω defined by equation 4.

INTRODUCTION

CLIMATE HAS always influenced people's lifestyles. This has been particularly true in the past, when the lack of abundant sources of energy made the people to take advantage of the climate's diversity, and live with it. For example, in the hot, arid region of Iran, people developed highly advanced passive cooling systems and adapted a lifestyle in order to provide thermal comfort for themselves in a very harsh environment [1, 2]. The performance of some of these systems has been studied and reported before [3–12]. One of these passive cooling systems which involves the seasonal storage of cold potable water for summer use is investigated and is reported here.

Seasonal storage of winter coolness‡ in the forms of ice and chilled water in cisterns is centuries old; it was practiced extensively in Iran and some of the neighboring countries before the advent of piped water and mechanical refrigeration [1, 2]. Research in seasonal storage of cold water in cisterns has been very limited. Borst and Aghamir [13] studied the storage of chilled water in a tank about 35 m^3 in volume. They cooled the water in

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‡ The word coolness is used in this article to mean internal energy at low temperatures.

the cistern by blowing cold winter air over the water surface. Thermal stratification of a small chilled water storage tank, to be used in conjunction with daily storage of coolness as a means of shifting of electrical power to off-peak periods, was studied analytically and experimentally by Truman *et al.* [14]. To the authors' knowledge no experimental or analytical study of seasonal storage of chilled water in large cisterns, similar to those found in Iran to supply cold potable water to a community in summer, have been carried out. Several sporadic measurements of water temperature, withdrawn from the cisterns still in use in the cities of Yazd and Kashan in central Iran, have been made by the authors in the past summer months.

The objective of the study reported here was to numerically investigate the thermal performance of a large potable chilled water cistern or Aub–Anbaur (as it is called in Persian), and compare the results of the analysis with the experimental data which have been collected by the authors earlier.

OPERATION OF THE POTABLE WATER CISTERNS

Before piped water became popular, many houses in Iran had small cisterns to meet the monthly fresh water requirements of their occupants. However, these cisterns could not meet the families' needs for cold water in summer. With the lack of mechanical refrigerators to cool water, people had to either purchase the naturally-made ice in order to have a cold drink of water, or use the river water which was stored in a community Aub–Anbaur in winter. These cisterns were filled during the winter nights with the coldest possible water. Furthermore, because of their very large sizes and thermal stratification, the rate of heat gain by a unit volume of water in these tanks was very small. The cisterns could then supply water at low enough temperatures for drinking.

Because of health problems, cisterns are almost all abandoned now in Iran. Measurements made by the authors during the past summer months on two cisterns which still exist in the cities of Yazd and Kashan in the desert region of Iran have shown that the temperature of water supplied by these cisterns was below 10 C. During this time the maximum outside air temperature was around 40 C. The water temperature was a function of the size of the cistern, the type of soil and its moisture content, and the initial water temperature in the cistern. Except for the size, other relevant data such as soil properties and its moisture content as well as the initial water temperature were not available to the authors at the time of water temperature measurements.

The size of the cisterns was dependent upon the size of the community they were serving; it varied between about 500 to about 5000, with 2000 m^3 designating a more common size. The height of the cisterns varied from about 5 to about 10 m. The brick walls and the floor of the cisterns were lined with an indigenous cement to prevent water leakage.

Figure 1 shows a cross section of a typical cistern which was used in Iran for centuries for the storage of cold potable water for summer use. The cistern was equipped with two to three pairs of wind towers or Baud Geers

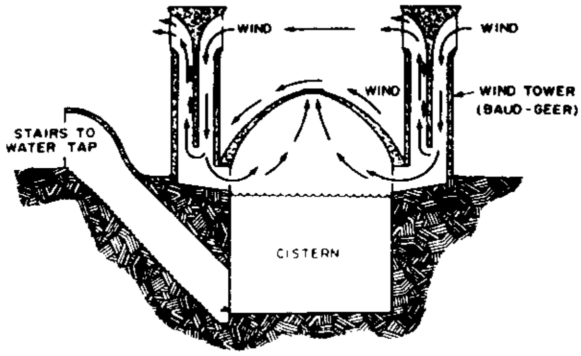

Fig. 1. A schematic drawing of the potable water cistern with wind-induced airflow over the water surface.

which maintained a wind-induced airflow over the water surface [1, 2]. The cistern was filled during winter nights with cold water. Before entering the cistern, water flowed in open channels where it was cooled, evaporatively, and by radiation heat transfer to the clear sky, to temperatures only a few degrees above the freezing point. Water remained in the cistern until summer or when the residential cisterns could no longer supply cold water for drinking. Then, people desiring cold, potable water walked to the community cistern and took the needed amount of water for their use. Water was removed from the bottom at a very low rate (less than 30 l per min) so that there was no disturbance in the thermal stratification of water in the cistern.

The heat gain from the ambient air on top and from the ground surrounding the cistern was partly offset by the evaporative losses from the water surface. The high flow rates of the dry ambient air over the water surface, which was created by wind action on the Baud–Geers and the domed roof opening, maintained a relatively large evaporation rate from the water surface. Furthermore, the high airflow rate kept the ceiling temperature of the dome at about the air temperature all the time [8].

The heat gain by water was primarily near the top and was transferred to the water layers below by conduction. This created a perfectly stratified storage tank—with the warmer water always staying on top. The heat gain from the bottom was generally very small, particularly after several years of operation, so that there was no appreciable mixing and disturbance of the stratification in the cistern. The heat gain from the floor of the cistern uniformly warmed the layers of colder water immediately above it.

Without the wind towers and the circulation of the ambient air over the water surface, the evaporation rate from the water surface was reduced appreciably. Furthermore, due to the solar radiation absorbed by the roof of the storage, the ceiling temperature was higher than that of the ambient air. This increased the thermal radiation heat exchange between the water surface and the ceiling which, together with the reduction in the evaporation rate, increased the water temperature in the cistern.

The use of cisterns in Iran has been diminishing rapidly due to the widespread use of piped water and household refrigerators. Except for a few units still in operation, most of the Aub–Anbaurs have either given way to new developments or have been remodeled as tourist attractions. However, these systems can be made more hygienic, and the operation less labour-intensive, so that they can be employed in developing countries to supply cold potable water for a community. For example, the system can employ a heat exchanger or a cooling tower to cool water in winter and use a pump (electric or hand-operated) for withdrawing cold water from the bottom in summer. These cisterns can also store cold winter water for applications other than drinking water. They can be used for food preservation and other industries in the developing countries.

THERMAL ANALYSIS OF A CISTERN

The exact thermal analysis of cisterns is a formidable task and beyond the scope of this investigation. In order to simplify the analysis and still be able to obtain reasonably accurate results, we need to make several assumptions as listed below.

Assumptions

We consider a cistern, about 2000 m^3 in volume. For simplification purposes we choose a unit with a square floor, 16 m to the side, and a height of 8 m. We further make the following assumptions in order to simplify our analysis:

1. The mean daily temperature of the ambient air can be represented by:

$$T = T_m + \tfrac{1}{2}A \sin \omega(t + \phi), \tag{1}$$

where

$$T_m = (T_{max} + T_{min})/2 \tag{2}$$

$$A = (T_{max} - T_{min}) \tag{3}$$

$$\omega = 2\pi/365 \text{ day}^{-1} \tag{4}$$

and T_{max} and T_{min} are the mean daily temperatures in July (the warmest month) and January (the coldest month), respectively, and t is the day number, and ϕ is a time lag. For $\phi = -106$ days, the minimum and maximum temperatures occur on January 15 (day number 15) and July 16 (day number 197), respectively.

2. The soil surrounding the cistern is homogeneous, isotropic, and with constant properties. This assumption, although far from reality, is necessary to obtain a general result for the performance of cisterns. Otherwise, one has to determine the soil properties of a site and then analyze the performance of the cistern to be built at that location.

3. The temperature of the soil at vertical surfaces 10 m away from each wall and a horizontal surface 10 m below the floor of the cistern (18 m from the ground level) are unaffected by the presence of the cistern. That is, water in the cistern with a volume of 2048 m^3 is interacting with its surrounding soil with a volume of 21280 m^3.

4. The heat flow in the regions of the undisturbed soil surrounding the cistern (at distances of $x \geq 10$ m or more from the cistern walls) is one-dimensional, with the soil temperature distribution given by [15]

$$T(y,t) = T_m + \tfrac{1}{2}A[\exp(-y\sqrt{\omega/2\alpha}) \times \sin\omega(t - y/\sqrt{2\alpha\omega} + \phi)] \tag{5}$$

where y is the distance from the ground level and α is the thermal diffusivity of the soil.

5. The heat flow in the water in the cistern and the soil surrounding it is two-dimensional. The heat transfer between the water layers is taking place by conduction, and between the surfaces (walls and floor) and water by natural convection. The heat gain from the floor and the walls is used to heat up the colder water layers immediately above or adjacent to it so that thermal stratification is always maintained. This is similar to the model considered by Truman *et al.* [14] in their study of chilled water storage tanks.

6. The heat flow in water at distances of 2 m or more from the wall is one-dimensional (that is, in y-, or vertical direction only). The water temperature at each level is equal to the water temperature at the same level 2 m from the wall.

7. The water surface in the cistern when full is below the ground level (see Fig. 1) at a distance so that the hourly temperature fluctuations in the ground are damped out at that level. This surface is taken as the reference ground level ($y = 0$). At this level the soil temperature remains equal to the mean daily ambient air temperature of that day. Depending on the soil thermal diffusivities considered in this study, this depth is between 30 and 60 cm.

Development of the governing equations

The temperature distributions in water in cistern and in the soil surrounding it was determined through a two-dimensional finite difference approximation of the heat flow in water and the soil. Figure 2 shows the nodes of the network considered in this analysis for a section of the cistern. That is, in our analysis we replace the original cistern with a hypothetical one, infinitely long (normal to the plane of the paper), 8 m wide, and 8 m high (as the original cistern), and consider only a portion or "slice" of

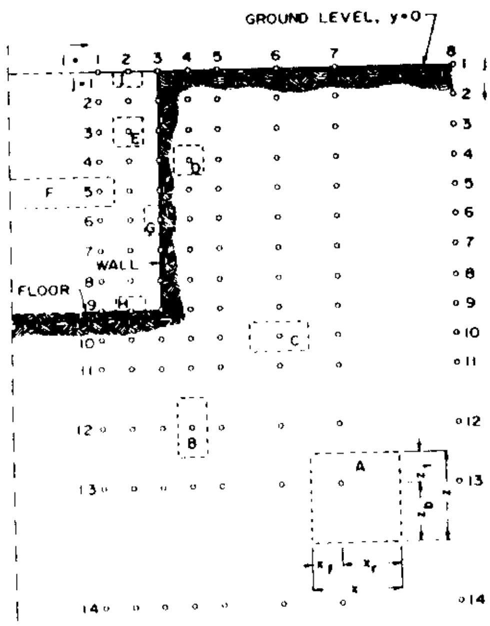

Fig. 2. A section of the cistern and its surrounding soil considered for thermal analysis. The nodes are spaced, depending on their locations, 1, 2 or 4 m from each other.

it, 1 m thick. In this way, the effects of the heat conduction around the vertical edges are ignored and the analysis is simplified appreciably. The grid sizes of 1 m near the wall and the floor of the cistern, then of 2 and finally of 4 m at distances far from the cistern wall and floor are chosen in order to simplify the analysis further.

There are four regions in this network: the soil, the water, the region where the soil and water are in contact with each other, and finally, the water surface. We write the energy balance for different nodes shown in Fig. 2 in explicit form as follows:

1. For node A in the soil, where the node is not at the centre of the grid

$$T'_{i,j} = T_{i,j}[1-\alpha\Delta t(1/2xx_r + 1/2xx_l + 1/2zz_b + 1/2zz_t)] + \alpha\Delta t[T_{i+1,j}/2xx_r + T_{i-1,j}/2xx_l + T_{i,j+1}/2zz_b + T_{i,j-1}/2zz_t] \quad (6)$$

where α is the thermal diffusivity of the soil, Δt is the time interval, T and T' the temperatures of the soil at the present and the next time step, respectively, and x_r, x_l, z_t, z_b, x, and z are the dimensions shown in Fig. 2. In this and the subsequent equations i refers to the columns and j to the rows. For nodes such as B, C and D, where $x_r = x_l = 1/2x$ and $z_t = z_b = 1/2z$, the above relation simplifies to the following equation:

$$T'_{i,j} = T_{i,j}[1-2\alpha\Delta t(1/x^2+1/z^2)] + \alpha\Delta t[(T_{i+1,j}+T_{i-1,j})/x^2 + (T_{i,j+1}+T_{i,j-1})/z^2]. \quad (7)$$

The above explicit finite-difference equation is stable if the following relation is satisfied [16]:

$$1-2\alpha\Delta t(1/x^2+1/z^2) > 1. \quad (8)$$

For the values of x, z, the time steps of one-half hour to one day, and the soil properties considered in this study the condition of equation 8 is always satisfied.

Equations such as 6 or 7 were written for all the nodes with $i = 4$–7, and $j = 2$–13, as well as $i = 1$–3 and $j = 10$–13 (a total of 60 nodes). For the nodes on the ground level or the ones with $i = 4$–8 and $j = 1$, which constitute one of the boundary conditions, the temperatures are determined from equation 1. For all the nodes with $i = 8$ and $j = 1$–14, as well as the nodes with $i = 1$–8 and $j = 14$, which constitute other boundary conditions, the temperatures are determined from equation 5. As can be seen from these equations, the boundary conditions are not constant, but variable with time.

2. For the nodes such as E located in the water near the wall of the cistern, the following relation can be written:

$$T'_{2,j} = T_{2,j}(1 - h_w\Delta t/xC_w - \alpha_w\Delta t/x^2 - 2\alpha_w\Delta t/z^2) + h_w\Delta t T_{3,j}/xC_w + \alpha_w\Delta t T_{1,j}/x^2 + \alpha_w\Delta t(T_{2,j+1} + T_{2,j-1})/z^2 \quad (9)$$

where $x = z = 1$ m, h_w is the convection heat transfer coefficient in the wall of the cistern, C_w the thermal capacity of water, and α_w is the thermal diffusivity of water.

In this equation we have considered a convection heat transfer between the node and the wall adjacent to it, and conduction heat transfer between this node and the nodes surrounding it in water.

Similar relations were written for all nodes with $i = 2$ and $j = 2$–8, or a total of 7 equations. For nodes with $j = 8$ and 9, convection from the floor was considered.

For node F we have

$$T'_{1,j} = T_{1,j}[1-\alpha_w\Delta t(1/2x_r(x_r+x_l)+2/z^2)] + \alpha_w\Delta t[T_{2,j}/2x_r(x_r+x_l) + (T_{1,j+1}+T_{1,j-1})/z^2], \quad (10)$$

where $x_r = 1/2$ m, $x_l = 6$ m, and $z = 1$ m.

Similar relations were written for all similar nodes with $i = 1$ and $j = 2$–8, or a total of 7 equations.

3. For node G, which represents a point on the wall of the cistern, we have the following relation:

$$T'_{3,j} = T_{3,j}[1-2k\Delta t/(C+C_w)x^2 - 2h_w\Delta t/(C+C_w)x - 2(k+k_w)\Delta t/(C+C_w)z^2] + 2k\Delta t T_{4,j}/(C+C_w)x^2 + 2h_w\Delta t T_{2,j}/(C+C_w)x + (k+k_w)\Delta t(T_{3,j+1}+T_{3,j-1})/(C+C_w)z^2 \quad (11)$$

where k is the thermal conductivity and C the thermal capacity of the soil, and the same terms with subscript w refer to water. In this equation $x = z = 1$ m.

Similar relations were written for all the nodes on the wall of the cistern ($i = 3$) and $j = 2$–8, or a total of 7 equations.

For node H or a point on the floor of the cistern, we have a relation similar to that given by equation 11, except that we have to use h_f, or the convection heat transfer coefficient with respect to the floor. The energy equations for other nodes on the floor, including the one at the corner of the cistern were written. For the node at the corner, there is heat transfer by conduction from the soil on three sides and convection from the water side. To shorten the discussions, they are not reproduced here.

4. For node I on the water surface we have:

$$T'_{2,1} = T_{2,1}[1-2(h_a+h_r)\Delta t/C_w z - \alpha_w\Delta t(2/z^2+1/x^2) - h_w\Delta t/C_w x] + 2(h_a+h_r)\Delta t T_a/C_w z + \alpha_w\Delta t(2T_{2,2}/z^2 + T_{1,1}/x^2) + h_w\Delta t T_{3,1}/C_w x - 2m_r h_{fg}\Delta t/C_w z, \quad (12)$$

where h_a is the convection heat transfer coefficient between water surface and the air on top, h_r the thermal radiation heat transfer coefficient between the water surface and the ceiling, m_r the rate of evaporation from the water's surface, and h_{fg} is the latent heat of vaporization of water. Other terms in this equation have been defined before.

Similar equations were written for the other node on the water surface and for the node at the top corner of the cistern. For the node at the top corner ($i = 3$, $j = 1$), we considered heat and mass transfer from the water surface, heat transfer from the node on its right (through the soil) by conduction, and its left (through water) by convection and through the soil and water from the node underneath, by conduction.

When water level drops due to the removal of water from the bottom of the storage, the walls of the cistern become exposed to the air in the cistern. They then exchange heat with the air by convection and with the ceiling by thermal radiation. The same is true when water is completely withdrawn from the cistern (for cleaning purposes) and it is left empty. The heat transfer equations of the nodes on the wall and the floor were modified as these surfaces became in contact with the air.

Selection of the relevant parameters

To solve the above governing equations and obtain the temperature of water in the cistern and the soil surrounding it, we need to select or assume several parameters. In selecting or assuming these parameters, we had to keep in mind the approximate nature of our analysis, the computational costs, and the fact that the exact description of these parameters does not necessarily improve the accuracy of the results greatly.

Of particular importance was the consideration of the soil properties which we assumed remained constant. The soil surrounding the cistern is never homogeneous nor with constant properties. With a rainfall and water migration in the soil, the properties change both spatially and with time. Yet, we had to assume constant properties for the soil (as well as a two-dimensional heat flow) in order to simplify the analysis, save on the high computational costs, and be able to estimate the temperatures of water and the soil.

Selection of the use pattern of the potable water. The utilization of the stored cold water generally begins at about mid-April. It reaches its peak during the summer months, then reduces toward winter. To simplify our analysis we assumed a constant water consumption rate from the cistern beginning mid-April and ending mid-December. We further assumed a step-wise water withdrawal rate such as shown in Fig. 3. That is, we assumed that the cistern remained full during the months of January–April, then during each succeeding month the water level in the cistern dropped by 1 m.

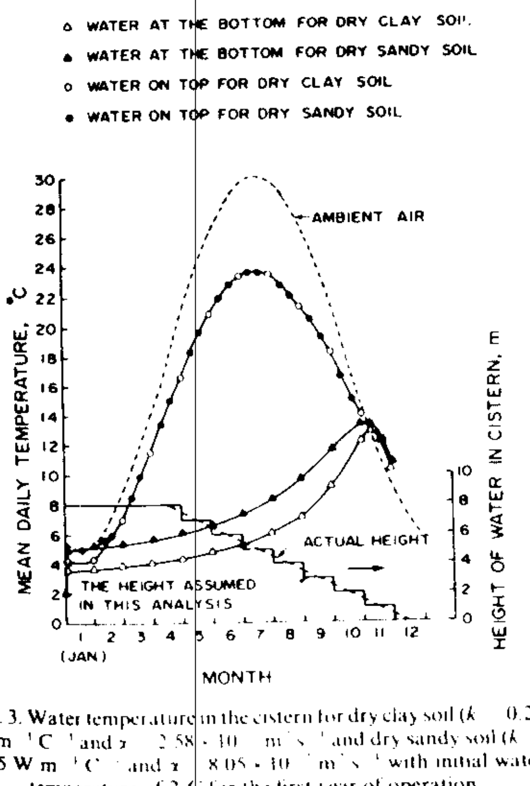

Fig. 3. Water temperature in the cistern for dry clay soil ($k = 0.25$ W m^{-1} °C^{-1} and $\alpha = 2.58 \times 10^{-7}$ m^2 s^{-1}) and dry sandy soil ($k = 1.25$ W m^{-1} °C^{-1} and $\alpha = 8.05 \times 10^{-7}$ m^2 s^{-1}) with initial water temperature of 2°C for the first year of operation

Selection of the soil properties. We considered two types of soil; (1) a dry clay soil with 5% moisture content with a density of 1000 kg m^{-3}, thermal conductivity of $k = 0.25$ W m^{-1} °C^{-1}, and a thermal diffusivity of $\alpha = 2.58 \times 10^{-7}$ m^2 s^{-1}; (2) a dry sandy soil with 5% moisture content with a density of 1600 kg m^{-3}, thermal conductivity of $k = 1.25$ W m^{-1} °C^{-1}, and thermal diffusivity of $\alpha = 8.05 \times 10^{-7}$ m^2 s^{-1}. These two types of soil were selected to provide rather extreme conditions for dry soils which may be found in the hot, arid regions.

Selection of water and air properties. We assumed water with constant properties of: thermal conductivity, $k_w = 0.56$ W m^{-1} °C^{-1}, thermal diffusivity, $\alpha_w = 1.34 \times 10^{-7}$ m^2 s^{-1}, and latent heat of vaporization, $h_{fg} = 2480$ kJ kg^{-1}. The air properties were evaluated at the mean daily temperature of the ambient air.

The ambient air conditions. We assumed the potable water storage system to be located in a hot and rather arid region with daily temperatures fluctuating between 20 and 40°C in July, and between 0 and 10°C in January. These correspond with the mean daily temperatures in July, T_{max}, and in January, T_{min}, of 30 and 5°C, respectively. It is clear that the hourly temperature variations do not affect the operation of the storage greatly and are neglected in our analysis.

The average ambient air dew point temperatures for different months were selected as follows: Jan., −5; Feb., −4; Mar., −3; Apr., −2; May, −1; Jun., 0; Jul., 1; Aug., 0; Sep., −1; Oct., −2; Nov., −3; Dec., −4°C. With the above average dry-bulb temperatures and dew points, the corresponding relative humidities in January and July are 46% and 15%, respectively.

Evaluation of the heat and mass transfer coefficients. We need to determine h_w, h_f, h_a, h_r, and $\dot{m}_v$.

Convection between water and the walls and the floor of the cistern. With the operating conditions of the cistern considered in this analysis, the Rayleigh number is between 10^{11} and 10^{13}, and the natural convection heat transfer between the cistern's walls and the floor with water is turbulent. Therefore, the heat transfer coefficients h_w and h_f can be determined from the following relations [16]:

$$h_w = 0.1a(\Delta T_w)^{1/3}$$

$$h_f = 0.15a(\Delta T_f)^{1/3},$$

where a is a constant which depends on the mean water/surface temperature in the cistern, and ΔT is the temperature difference between the surface and water with subscripts w and f referring to the wall and floor, respectively. Through trial and error process, the average wall (when in contact with water) and floor temperatures were estimated, with water temperatures near each surface being very close to it. To simplify our analysis, we assumed a fixed value for the water surface mean tem-

$C^{-4/3}$. Then, the above heat transfer coefficients become:

$$h_w = 76.5(\Delta T_w)^{1/3} \qquad (13)$$

$$h_f = 114.75(\Delta T_f)^{1/3} \qquad (14)$$

where subscripts w and f in h refer to wall and floor, respectively.

Convection between the water surface and the air. Through trial and error process it was found that water temperature is always lower than the air temperature except for the month of November, when the water level in the cistern is at its minimum. The natural convection heat transfer coefficient, h_a, between water and the air in October was estimated to be 1.25 W m^{-2} C^{-1}. When the cistern is full of water (assumed to be during the months of January through April), the wind towers circulate air over the water surface with an average speed estimated to be 0.5 m s^{-1}. In this case, the convection heat transfer coefficient was estimated to be 4.3 W m^{-2} C^{-1}. For the months of April through October we assumed a linear variation of h_a between the above two values. When the walls of the cistern are exposed to the air, the natural convection heat transfer coefficient was estimated to be 3.35 W m^{-2} C^{-1}.

The thermal radiation heat transfer coefficient. The thermal radiation heat transfer coefficient between the water surface and the ceiling of the cistern, assumed to be equal to the mean daily temperature of the ambient air, was estimated during each time step. It was found to vary between 4 to 5 W m^{-2} C^{-1}.

Evaporation rate from the water surface. The rate of evaporation from the water surface was determined from the following relation:

$$\dot{m}_e = h_m(W_s - W_a), \qquad (15)$$

where h_m is the mass transfer coefficient and W_a is the humidity ratio of the air above the water surface and W_s is that if the air were saturated at the water surface temperature. Due to high ventilation rates created by the wind towers, condition of the air above the water surface was taken as that of the ambient air.

The Lewis relation gives

$$h_m = h_a / C_{pa}, \qquad (16)$$

where C_{pa} is the specific heat of air at constant pressure.

The relations between the humidity ratio and other atmospheric parameters are found in air-conditioning texts or ASHRAE Handbooks [17]. They will not be repeated here.

SOLUTION OF THE GOVERNING EQUATIONS AND PRESENTATION OF THE RESULTS

Solution of the governing equations

A total of 94 energy equations similar to equations 6–12, written for all the nodes in the soil and water in the cistern, along with equations 1–5 and 13–16, and the equations determining h_a, W_a and W_s (not given here

climatological condition, two types of soil, two initial water temperatures, and one cistern use pattern as described earlier. The following initial conditions were assumed for the solution of these equations.

On January 1 of the first year of operation, it was assumed that the cistern is empty and the temperature of the soil surrounding the cistern is determined through equation 5. That is, we assumed that the presence of an empty cistern has not disturbed the normal heat conduction through the soil (which resulted in the temperature distribution given by equation 5). We assumed that on the following day the cistern was filled with chilled water at a fixed temperature. That is, at time $t = 0$ chilled water at an initial temperature T_0 is suddenly brought in contact with the cistern whose floor and wall temperatures are determined by equation 5. In actual operation of cisterns, it normally takes several nights to fill a cistern. However, for simplification purposes, we assumed that the time it takes to fill the cistern is negligible and the cistern is full of water at midnight on January 1.

As the cold water becomes in contact with relatively warm soil, there is a high rate of heat transfer from the soil to the water during the first few hours of the storage. This corresponds with rapid heating of water and cooling of the soil surrounding the cistern. To determine the soil and water temperatures more accurately, we took a time step of $t = 30$ min for the first 5 days of operation followed by a time step of 1 day for the rest of the year. During each time step the ambient air temperature was determined from equation 1, the heat transfer coefficients from equation 13 and 14, and other governing energy equations were solved simultaneously as it was discussed earlier.

In our analysis, we first considered a perfect mixing of water in the cistern. This resulted in a very high temperature of water at the bottom of the storage during the summer months, in disagreement with the experimental data obtained by the authors for Aub-Anbaurs in Iran. Then, using the equations referred to in this section, a thermal stratification model for water in the cistern was employed, which resulted in a more reliable result. This model was used for the rest of the analysis.

The major source of heat gain by water is from the air which warms the water layers on top. Since the rate of heat gain from the soil is small (except for the first few days of the first year of operation), and since there is no agitation of water in the cistern as cold water is being withdrawn from the bottom, thermal stratification is maintained in the cistern at all times. The heat transferred from the floor of the cistern to the layer of water adjacent to it is in turn transferred to the cooler water layers above it. During each time step, we first estimated the temperature of water at different nodes in the cistern (which showed a warmer water at the bottom), then considered a mixing of this warmer water with only those layers of water above it which were at a lower temperature than this layer. The resulting temperatures were then used as the initial values for the next step of simulation. The heat gain from the wall by convection was assumed to warm the water adjacent to the wall which in turn exchanged heat with its surrounding water (nodes)

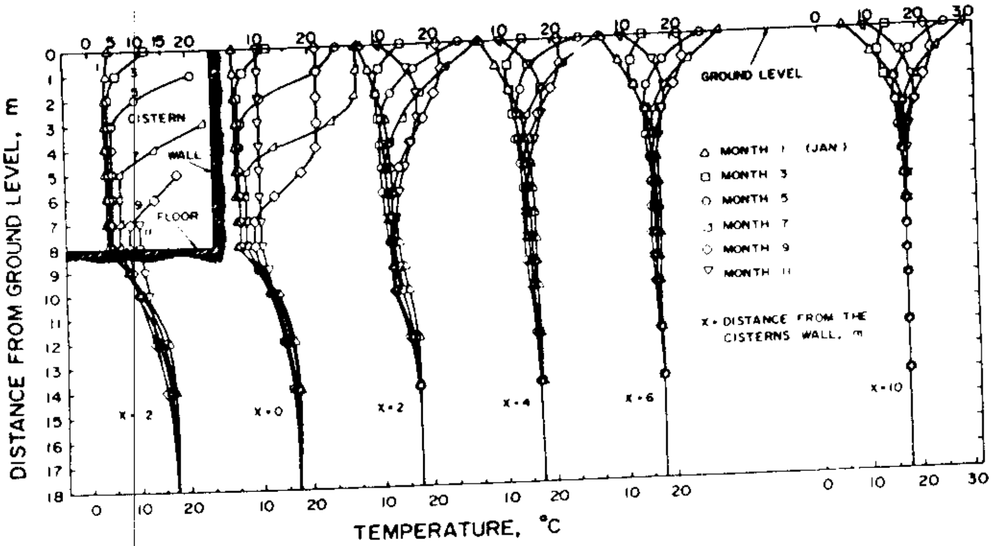

Fig. 4. Mean daily temperatures of water and the soil surrounding the cistern for the last day of the month indicated. The soil is dry clay with $k = 0.25$ W m^{-1} C^{-1} and $\alpha = 2.58 \times 10^{-7}$ m^2 s^{-1}, and the data are for the first year of operation with an initial water temperature of 2°C.

by conduction. With this model, the final estimated water temperatures were in good agreement with the sporadic experimental measurements which had been made by the authors in the past summer months. (Since there was no experimental data on the properties of the soil surrounding the cisterns, and no initial water temperatures were available, no direct comparison of the measured water temperatures with those determined analytically was possible.)

Presentation of the results

Figure 3 shows the temperature of water at the top and the bottom of the cistern for the two types of soil considered in our analysis. The figure is for an initial water temperature at 2°C, and only for the first year of operation of the cistern.

It is interesting to note that while the water temperature on top follows the ambient air temperature very closely, the temperature of water at the bottom layer, or the temperature of water being withdrawn by people for consumption, is very low. The water temperature at the bottom is higher for dry sandy soil with higher α than it is for clay soil which has a much lower α. For both types of soil, water temperature increases very rapidly during the first few days of the storage (as was mentioned before), then the increase becomes gradual.

It is seen from Fig. 3 that the temperature of the water on top is mostly affected by the ambient air temperature rather than the soil properties. It is also seen from this figure that the water temperature at the bottom layer, while being appreciably lower than that of the top layer, increases with time as water is being withdrawn from

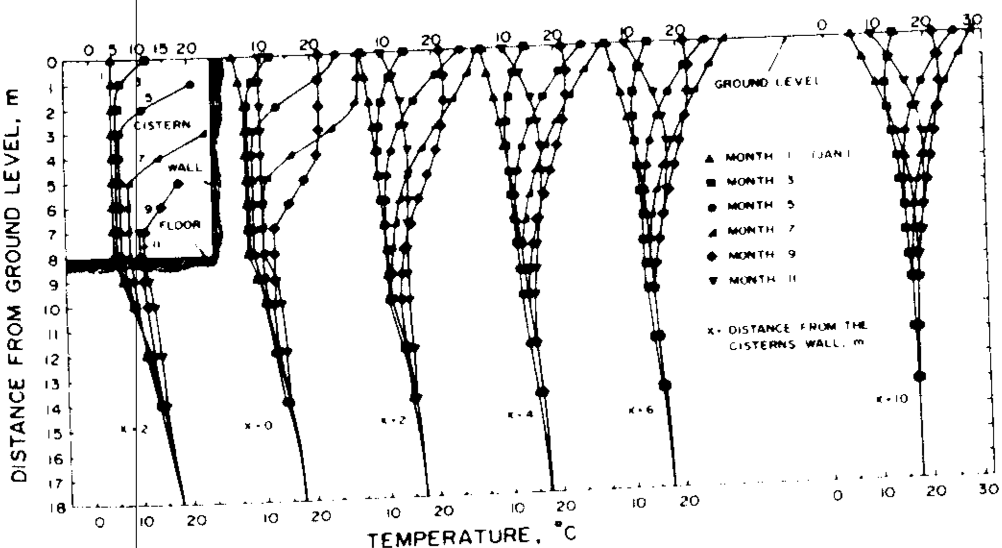

Fig. 5. Mean daily temperatures of water and the soil surrounding the cistern for the last day of the month indicated. The soil is dry sandy with $k = 1.25$ W m^{-1} C^{-1} and $\alpha = 8.05 \times 10^{-7}$ m^2 s^{-1}, and the data are for the first year of operation with an initial water temperature of 2°C.

the cistern. But for the hottest months of June through August the water temperatures are below 10°C. It is indeed the thermal stratification in water which makes it possible to maintain such a large temperature gradient from top to bottom of the cistern and keep the winter water cool for summer use.

Figures 4 and 5 show the temperature distributions in water and the soil surrounding the cistern for different months of the first year of the storage for the same initial water temperature of 2°C and for the two types of soil considered in this analysis. In these figures, x represents the distance from the wall of the cistern. Comparison of these figures show that at any given distance from the wall, the presence of chilled water in the cistern has a more pronounced effect on the soil temperature when the soil has a higher thermal diffusivity.

The above energy analysis was repeated for another case with an initial water temperature of 4°C. The energy simulation was carried out for 5 years of operation of the cistern. At the beginning of each new year of the storage, the same initial water temperature (4°C) and the weather data of the first day of the new year were employed. The initial conditions for the soil temperatures were those of the last day of the previous year.

Figure 6 shows the temperature of water at the bottom of the cistern for 5 years of operation for the two types of soil considered here. It is seen that at any given month of the year, the water temperature reduces greatly from first to the second year of operation, changes very little from the second year on, and does not change beyond the fourth year of operation. However, the monthly warming trend of water remains the same as that of the first year of the storage.

The soil temperature distributions were also determined during this simulation. It was found that while the soil temperature at any given location and a given day of the year changed from the first to the second year, the changes were small after this year and negligible beyond the fourth year of the storage.

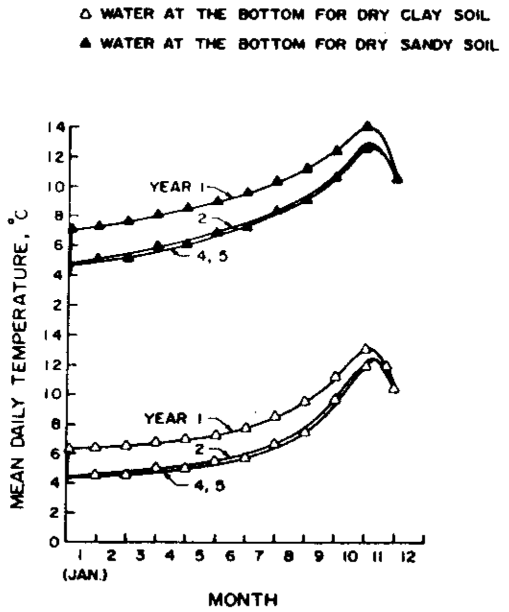

Fig. 6. Water temperature at the bottom of the cistern for different years of operation for dry clay and dry sandy soils. The initial water temperature is 4°C.

CONCLUSIONS

Seasonal storage of chilled water in a large underground storage was investigated by considering a two-dimensional heat flow in water and the soil, and employing a finite-difference technique for the numerical solution of the governing energy equations. The heat gain by water is mostly from top from the ambient air circulating over the water surface, from the ceiling, and from the soil surrounding the cistern. There is also a heat loss from the water surface due to evaporation to the dry ambient air flowing over the water surface. Thermal stratification is maintained in water in the cistern, with cold water being withdrawn at small flow rates from the bottom without disturbing the thermal gradient.

The analysis showed that while the water temperature at the top layer follows the ambient air temperature closely, and it is very high, the water at the bottom remains at very low temperatures. For a cistern located in a hot and very dry location (such as the desert region of Iran), where the maximum summer temperatures reached 40°C in July afternoons, and for two types of dry sandy and clay soils considered in this analysis, the water temperature at the bottom layer in July was below 10°C. This temperature was dependent upon the soil properties, the initial water temperature in the storage, and the year of operation of the cistern.

The system analyzed here can find applications in the hot, arid regions of the developing countries. The winter cold water may be stored for summer use in a large community cistern either for drinking, food preservation, or other applications. The system can also be used for cooling of buildings.

REFERENCES

1. M. N. Bahadori, Passive Cooling Systems in Iranian Architecture. *Scientific American*, Vol. 238, No. 2, pp. 144–154 (1978).
2. M. N. Bahadori, Natural coooling in hot, arid regions, in *Solar Energy Application in Buildings* (Edited by A. A. M. Sayigh). Academic Press, 195–225 (1979).
3. M. N. Bahadori and A. Kosari, Performance of natural ice makers. International Solar Energy Society Congress, New Delhi, Vol. 3, pp. 1976–1978 (1978).
4. M. N. Bahadori, Passive and hybrid convection cooling systems. International Passive and Hybrid Cooling Conference, American Section of the International Solar Energy Society, Miami Beach, Florida, pp. 715–727 (1981).

5. M. N. Bahadori, Pressure coefficients to evaluate air flow patterns in wind towers. International Passive and Hybrid Cooling Conference, American Section of the International Solar Energy Society, Miami Beach, Florida, pp. 206–210 (1981).
6. M. N. Bahadori and T. P. Jantzi, Natural production of ice in shallow ponds. Solar World Congress, International Solar Energy Society, Perth, Australia, pp. 51–56 (1983).
7. M. N. Bahadori, Passive space cooling in hot, humid and hot, arid climates. Expert Group Meeting on Use of Solar Energy in the Design of Buildings in Developing Countries, UN Habitat, Nairobi, Kenya (1983).
8. M. N. Bahadori and F. Hagighat, Passive cooling in hot, arid regions in developing countreis by employing domed roofs and reducing the temperature of internal surfaces. *Bldg Environ* 20, 103–113 (1985).
9. M. N. Bahadori, An improved design of wind towers for natural ventilation and passive cooling. *Solar Energy J.* **35**, 119–129 (1985).
10. M. N. Bahadori and F. Haghighat, Weekly storage of coolness in heavy brick and adobe walls. *J. Energy Bldg* **8**, 259–270 (1985).
11. M. N. Bahadori and F. Haghighat, Thermal performance of adobe structures with domed roofs and moist internal surfaces. *Sol. Energy J.* **36**, 365–375 (1986).
12. C. Karakatsanis, M. N. Bahadori and B. J. Vickery, Evaluation of pressure coefficients and estimation of air flow rates in buildings employing wind towers. *Sol. Energy J.* **37**, 363–374 (1986).
13. W. L. Borst and F. Aghamir, Longterm storage of coolness. Proceedings of the 1980 AS/ISES Annual Meeting, Phoenix, Arizona, 908–912 (1980).
14. C. R. Truman, L. G. Roybal and M. W. Wildin, A finite-difference model for stratified chilled water thermal storage tanks. Enerstock '85, Third International Conference on Energy for Building Heating and Cooling, Toronto, Ontario, Canada, 613–617 (1985).
15. M. N. Ozisik, Heat conduction. John Wiley, New York (1980).
16. F. P. Incropera and D. P. DeWitt, Introduction to heat transfer. John Wiley, New York (1985).
17. ASHRAE Handbook. Fundamentals, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, Georgia (1981).