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Performance Analysis of a Solar thermal bath complex by f-Chart Method in a remote location in Iran

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Abstract: First solar thermal public bath with capacity of 400 persons per day was designed and installed in an isolated location in south-eastern part of Iran. This paper focuses on solar water heating (SWH) system. The SWH system investigated consists of mainly three parts, namely a flat plate solar collector, a heat exchanger (storage tank) and a circulating pump. The f-chart method was applied for sizing solar water heating system to determine solar collector area.

Keywords: Solar energy, Bath complex, F-chart, Solar water heating.

تعیین عملکرد یک حمام خورشیدی به‌روش f-Chart در بشاگرد ایران

عزت‌الله آزاد پژوهشکده مواد پیشرفته و انرژهای تجدیدپذیر – سازمان پژوهش‌های علمی و صنعتی ایران

چکیده: حمام خورشیدی بشاگرد به ظرفیت ۴۰۰ نفر در روز در منطقه محروم و در جنوب شرقی ایران طراحی و ساخته شد. در این مقاله تأمین آبگرم مصرفی مورد نظر بوده است. این سیستم شامل سه قسمت می‌باشد، آبگرمکن‌های خورشیدی، منبع ذخیره انرژی و پمپ سیکولاسیون. در این روش برای تعین سطح آبگرمکن‌های خورشیدی از روش f-chart استفاده گردیده است..

1. Introduction

The community of Bashagard is located in an isolated area in the south-eastern region of Iran. Bashagard is so located that to its north is Jiroft, to the east is within the limits of the vicinity of Jazmoorian in the Province of Sistan and Baluchestan, and to its western and southern sections is the Province of Hormozgan. It is situated at latitude 26º 38′ 17′′ N and longitude 57.8º E. It enjoys 3500 hours of sunshine annually and an average daily irradiation of 22 MJ/m^2.The distance with nearest city, Minab, is 200 Km. which take six hours to reach because of precarious road conditions. The people live in “Kappar” made from the date-palm leaves, 3-5 m long and finally covered with clothes and is shown in Fig(1).

Bashagard experiences hot weather with scanty rainfall (about 5 days of rain a year), which is mostly in the form of thunder squalls.but the rain that does fall is so heavy that it tends to wash everything away, including the road. Originally local authorities built a public bath complex that used gasoline to heat water, but this turned out to be far to expensive because of the costs of transporting fuel to the site-in Bashagard, gasoline is 15 times more expensive than it is in Minab. It was decided, therefore, that solar energy would be a good replacement for fossil fuel, and the Iranian Research Organization for Science and Technology (IROST) sponsored a project to design and manufacture a suitable solar collector that can supply energy to heat water for the baths, installation and operation. The situation of Bashagard is shown on the map in Fig. (2).

It is the first solar and largest public bath in Iran that was built in this area and it was strange for them to see the public bath and after completion they hesitate to take bath. This project was installed in 1993 in four months time (including manufacturing of solar collectors). The plan of public bath is shown in Fig.3. It consists of 12 showers six for ladies and six for gents. The dressing room is provided for changing their dresses and in washing room there are six hot and cold water taps where they wash and finally they shower. The bath complex can serve up to 400 people a day.

2. Solar Collector

The most important part of a solar water heating system is the collector that absorbs solar radiation and converts it into thermal energy. This heat is then absorbed by water that passes through the collector and stored in heat storage tank.

Solar collector was designed and constructed at IROST. It is a single glazed with 4mm low-iron glass. The absorber consists of an assembly of copper tubes (12.7mm outside diameter) recessed into extruded aluminium plates. The tubes run parallel to one another and are connected to copper manifolds at either end of the collector. The absorber plate is matt black and anodized to provide high solar absorption. The back of absorber plate is insulated with 25 mm layer of fibreglass. The collector frame is also made from hollow section extruded aluminium and coated with anodized silver. Absorber plate and frame is shown in Fig. (4) and solar collector is shown in Fig. (5).

Solar collector was tested at IROST in Tehran and the results of tests are presented in Fig.6. The instantaneous collector efficiency is expressed as [1].

$$\eta = Q_u / AI_T = \\ = F_R(\tau\alpha)_n - F_R U_L (T_i - T_a)/I_T \tag{1}$$

$$\begin{cases} F_R(\tau\alpha)_n = 0.72 \\ F_R U_L = 4.33\ \mathrm{W/m^2.K} \end{cases} \tag{2}$$

Therefore the collector efficiency versus $(T_i - T_a)/I_T$ can be written as

$$\eta = 0.72 - 4.33(T_i - T_a)/I_T \tag{3}$$

3. F-Chart Method

The method was developed by Beckman et al. [2].The method provides a means for estimating the fraction of a total heating and DHW that will be supplied by solar energy for a given solar heating system. The major design variable is the collector area whereas minor variables are collector type, storage capacity, fluid flow rates, and load and collector heat exchanger sizes. The conditions of simulations were varied over suitable ranges of parameters of practical system designs. The resulting correlations give f, the fraction of the monthly load supplied by solar energy as a function of two dimensionless parameters. One is related to the ratio of collector losses to heating loads, and the other is related to the ratio of absorbed solar radiation to heating loads. Detailed simulations of these systems have been used to develop correlations between dimensionless variables and f; the monthly fraction of loads carried by solar energy. The two dimensionless parameters X and Y can be written:

$$X = F_R U_L \times \left(\frac{F_{R'}}{F_R}\right) \times \left(T_{ref} - \overline{T}_a\right) \times \Delta t \times \frac{A}{L} \tag{4}$$

$$Y = F_R(\tau\alpha)_n \times \left(\frac{F_{R'}}{F_R}\right) \times \frac{(\overline{\tau\alpha})}{(\tau\alpha)_n} \times \overline{H}_T \times \frac{A}{L} \tag{5}$$

$F_R U_L$ and $F_R(\tau\alpha)_n$ are obtained from collector test results. The dimensionless parameters X and Y have some physical significance. The parameter X represents the ratio of the reference collector total energy loss to total heating load or demand whereas the parameter Y represents the ratio of the total absorbed solar energy to the total heating load or demand during the same period. The fraction f of the monthly total load supplied by the solar water heating system is given as a function of the two parameters, X and Y which can be obtained from the following equations:

$$\begin{aligned} f = {} & 1.029\mathrm{Y} - 0.065\mathrm{X} - 0.245\mathrm{y}^2 \\ & + 0.0018\mathrm{X}^2 + 0.0215\mathrm{Y}^3 \end{aligned} \tag{6}$$

For $0 < Y < 3$ and $0 < X < 18$

The monthly average daily radiation on the tilted surface, $\overline{H}_T$ can be expressed

$$\overline{H}_T = \overline{R}\,\overline{H} \tag{7}$$

Where:

$\overline{H}_T$: is the monthly average daily radiation on the horizontal surface

$\overline{R}$: defined by Eq. (8) and it is the ratio of the monthly average daily radiation on tilted surface to that on a horizontal surface for each month

$$\begin{aligned} \overline{R} = {} & \left(1 - \frac{\overline{H}_d}{\overline{H}}\right)\overline{R}_b + \\ & + \frac{\overline{H}_d}{\overline{H}} \cdot \frac{1 + \cos\theta}{2} + \varphi \cdot \frac{1 - \cos\theta}{2} \end{aligned} \tag{8}$$

Where:

$\overline{H}_d$: is the monthly average daily diffuse radiation and is defined by Eq. (9)

$\overline{R}_b$: is the ratio of the monthly average beam radiation on tilted surface to that on a horizontal surface for each month

θ : is the tilt of the surface from horizontal

φ : is the ground reflectance

$$\frac{\overline{\mathrm{H}}_\mathrm{d}}{\overline{\mathrm{H}}} = 1.39 - 4.03\overline{\mathrm{K}}_\mathrm{T} + 5.53\overline{\mathrm{K}}_\mathrm{T}^2 - 3.11\overline{\mathrm{K}}_\mathrm{T}^3 \tag{9}$$

$\overline{R}_b$: can be estimated as the ratio of extraterrestrial radiation on the tilted surface to that on horizontal surface for the month, it is given as a function of φ, the latitude, and θ, the collector slope and is estimated by Eq. (10).

$$\overline{R}_b = \frac{\cos(\phi-\theta)\cos\delta\sin\omega_{s'} + \left(\frac{\pi}{180}\right)\omega_{s'}\sin(\phi-\theta)\sin\delta}{\cos\phi\cos\delta\sin\omega_s + \left(\frac{\pi}{180}\right)\omega_s\sin\phi\sin\delta} \qquad (10)$$

Where:

ω_s : is the sunset hour angle on a horizontal surface given by:

$$\omega_s = \arccos(-\tan\varphi \times \tan\delta)$$

$\omega_{s'}$: is the sunset hour angle on a tilted surface given by:

$$\omega_{s'} = \min.[\omega_s, \arccos(-\tan(\varphi-\theta)\times\tan\delta)]$$

δ : is the solar declination given by:

$$\delta = 23.45\sin[360\times(284+n)/365]$$

n : is the day of the year.

The water heating load was calculated by allowing for a hot water consumption of 40 litres per person (for 400 people per day) and water delivery temperature of 45°C and water main supply temperature. The monthly water heating load can thus be estimated as:

$$L_w = N\times(n_p)\times V\times(T_w - T_m)\times\rho\times C_p \qquad (11)$$

Where:

N: is the number of days in the month

n_p : number of persons

T_W: is the minimum acceptable hot water temperature:45°C

T_m: is the main supply water temperature

V : the daily average hot water consumption for each person per day (40 l/day)

ρ : is the density of water

CP: is the specific heat of water.

The design of a solar hot water heating system is a three-part problem. The first is to estimate the hot water load. The second is to determine the fraction of the monthly heating load supplied by solar energy, and third is to perform an economic analysis that weighs the cost of the energy saved against the solar cost. In present case the economic analysis will not be carry out due to high cost of fuel and transportation as mentioned earlier therefore solar collectors is calculated from f-chart method for 100% solar fraction i.e. independent of fossil fuel as a result the total collector area is 150 m^2.

4. System Description

Fig. (7) illustrates the system that could be used to meet the hot water demand for 400 persons per day. The system designed under the IROST project is divided into three subsystems; the collector subsystem, storage subsystem and demand hot water subsystem [3].

4.1 The Collection Subsystem

The collection subsystem consisted of two collector fields (collector field #1 and collector field #2), each designed with a collector closed loop and the heat exchange.

The 75 solar collectors are arranged in two solar collector fields. These collectors are mounted on a rigid metal frame. The array support structure as shown in Fig.8 is tilted 45° (latitude+20 degrees) toward south. The array row spacing is calculated for no shading of the array on the worst solar day of the year (21 December, when the sun is lowest in the sky in the northern hemisphere). A full assembly solar collector is shown in Figs. (9-10).

In collector field #1 (33 collectors) there are three rows and each having two banks and each bank contains six and five collectors. The collectors are connected in series through internal manifold built into the collector unit and finally two banks are connected in parallel. Collector fluid in field#1is pumped through U-tube heat exchanger placed at the bottom of storage tank 1. In field #2 (42 collectors) there is three rows and each having three banks and the banks contain 5-5and 4 collectors each that supply heat to the storage tank 2. Fig.11. shows the solar collector fields.

The differential temperature controller of the collector loop pump in field#1 is switched on if temperature difference between the collector outlet and tank1 exceeds 5^{o}C and is switched off if the above difference is lower than 5^{o}C. The similar DTC is used in collector loop. In field#1 and field#2 the water is heated indirectly by a heat transfer fluid. The transfer fluid absorbs heat from the collectors. The fluid then passes through a heat exchanger inside the tank that transfers the heat to the water inside the storage tank. A heat exchanger inside the tank provides indirect heating and prevents any cross contamination between the potable water and the collector fluid.

4.2 The Storage Subsystem

The storage subsystem: consisting of three storage tanks (storage tank 1 and storage tank 2, 3000 litres capacity each).

Two storage tanks, each 3000 litres capacity are fabricated with galvanized iron to store hot water. The tank diameter is 1.25m and height is 2.5m. Both tanks are well insulated to minimize thermal losses to the environment. The storage tanks are located adjacent to the west wall of the bath in order to reduce the piping cost as well as heat loss due to piping Fig. (12) shows the two storage tanks. During a demand hot water consumption phase, cold water from the main enters the bottom of the first tank, thus removing an equal volume of water from the main tank and finally to the user.. This arrangement ensures that the storage tanks are always full. The tanks 1 and 2 are connected in series. The demand hot water is preheated in storage tank1 by solar field#1 before it passes to the storage tank2 take up all energy delivered by solar field#2. In storage tank 2 following the preheat tank insufficient hot water temperature is heated up to required temperature. The water in main storage tank (6000lit.capacity) is heated by circulating hot water between storage tank 2 and main storage tank by a circulating pump. The main storage tank supplies hot water to twelve shower public bath. A 200-litre expansion tank is installed on the roof. This tank provides volume for liquid expansion and permits boiling to occur in the collectors without pressure built up. If the circulating pump fails, boiling result in some loss but expansion tank can refill the.

4.3 The DHW delivery Subsystem

This consists of the main storage tank (6000 litres capacity) and the pipeline that delivers hot water to baths. The main storage tank is 6000 litres capacity is insulated with 0.1m fibreglass insulation and is heated by circulation of hot water from storage tank2 by a circulating pump. The hot water is drawn from this tank.

5. System Performance

The performance of two collector fields was evaluated under same environmental conditions in the month of October. In this test there is no water draw-off. The water temperature of the storage1 and storage2 and main storage tank in the end of the day reaches 64.3^{o}C, 77^{o}C and 18^{o}C respectively, the temperature in storage2 is higher because of larger area of solar collectors and main storage tank temperature is remain constant because the circulating pump between storage2 and main storage is off. In next day the circulating pump between storage tank 2 and main storage tank is on therefore it causes to raise the temperature of the main tank and decrease the temperature in storage tank2. In day 6 they reach to 89.9^{o}C, 88.5^{o}C and 88.5^{o}C. Fig.13 shows the temperature distribution in three storage tanks.

An average water consumption profile used in the present study is given in Fig.14. It is based on data obtained from authorities. The energy required for hot water heating depends on the mains water temperature. The mains temperature varies from a low of 17°C in January to a high of 26°C in June and July for Bashagard.

6. Conclusion

The use of solar thermal energy for solar bath complex is at its inception. There is still much work to do in optimizing implementation and in researching better design methods. First case studies show that the use of solar thermal energy in solar bath complex is possible and a lot more applications will be seen in the near future. The most important conclusions from the work done to date are:

- There is low temperature hot water that is suitable for using solar thermal energy in principle.
- Although the payback period of solar thermal energy systems is long, the cash flow of such a system may be positive at today's energy prices.
- Energy efficiency brings health, productivity, safety, comfort, and savings to the people
- Local and global environmental benefits. The use of renewable energy resources could play an important role in this context, especially with regard to responsible and sustainable development.
- It represents an excellent opportunity to offer a higher standard of living to local people and will save local and regional resources.

7. Acknowledgement

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8. Nomenclature

A : Collector area (m^2)
C_P: Specific heat of water(kJ/kg.K)
F_R: Collector heat removal efficiency factor
f : Fraction of the monthly total heating load
$\overline{H}_d$: Monthly average daily diffuse radiation
I_T : Solar radiation incident (W/m^2)
L_w : Water heating load (W)
N: Number of days in the month
n : Day of the year
n_p :Number of persons
Q_u : Useful energy W
$\overline{R}_b$: Ratio of the monthly average beam radiation on tilted surface to that on a
T_w: Minimum acceptable hot water temperature:45 °C
T_m: Main supply water temperature °C
T_i: Temperature of the fluid entering the collector °C
T_a: Outside ambient temperature °C
U_L : Collector overall energy loss coefficient ($W/^oC.m^2$)
V: Daily average hot water consumption for each person per day (40 l/day)
α: Solar absorptance of the collector plate
θ: Tilt of the surface from horizontal
ρDensity of water Kg/m^3
τ: Transmittance of the transparent cover
φ: The ground reflectance
η : Collector efficiency

9. References

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Fig. (1): Kappars where they live.

Fig. (2): Map of Iran shows the location of Bashagard

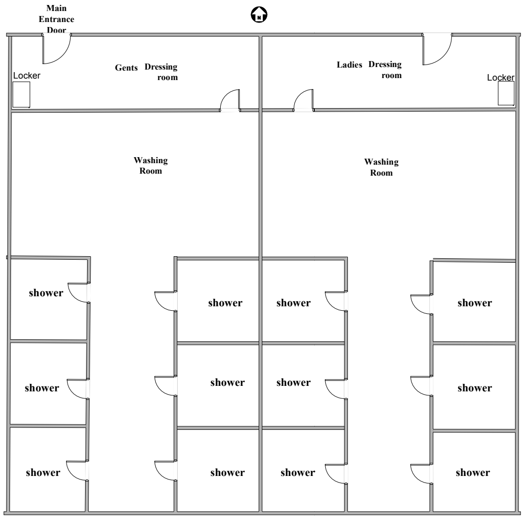

Fig. (3): The plan of public bath

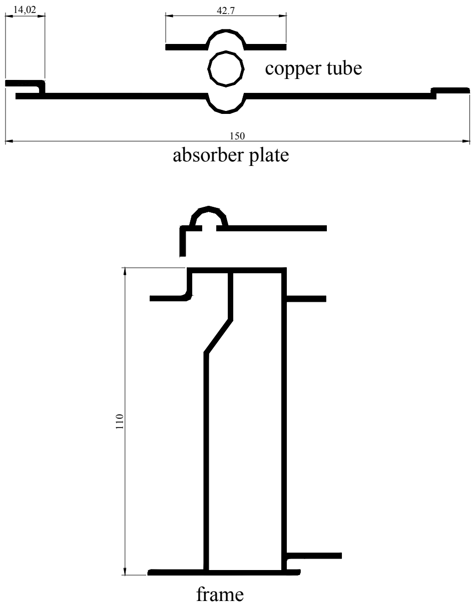

Fig. (4): Absorber plate and frame

Fig. (5): Solar collector

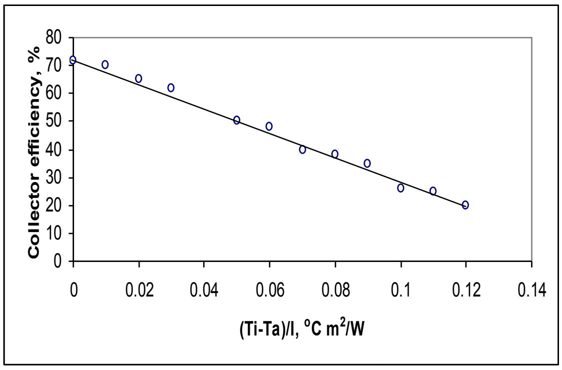

Fig. (6): Performance test of solar collector

Fig. (8):The array support structure

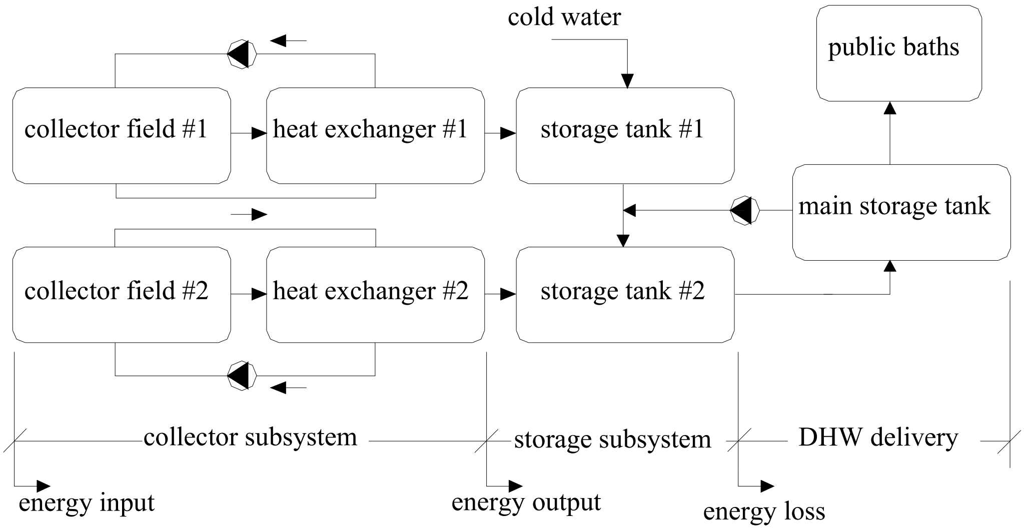

Fig. (7): Schematic diagram of DHW solar system

Fig. (9): Full assembly solar collector

Fig. (10): Front view of solar collector assembly

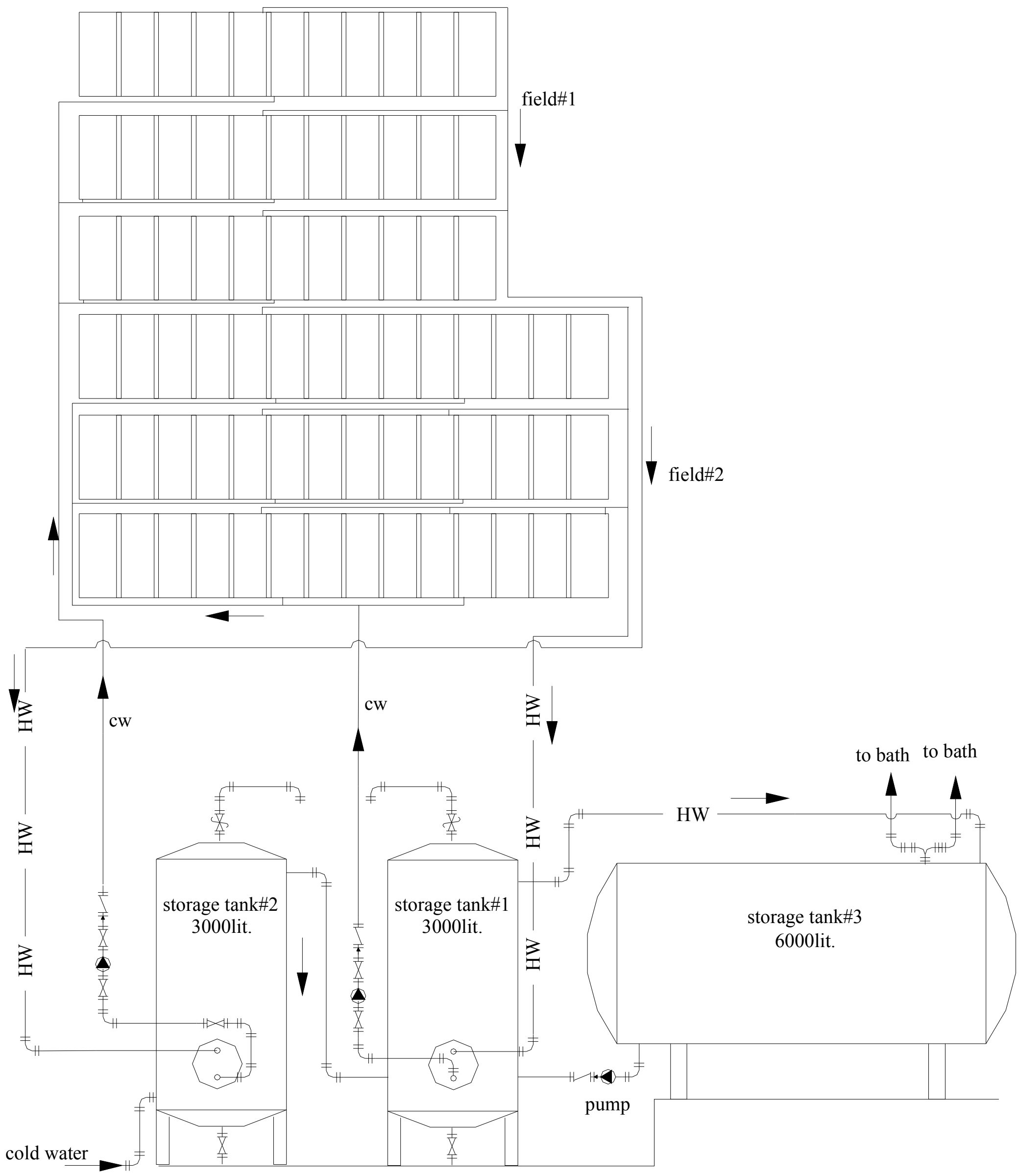

Fig. (11): Solar collector fields

Fig. (12): Two storage tanks connected in series

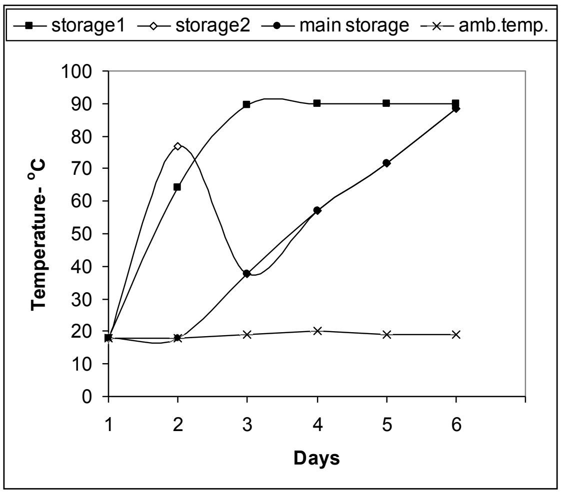

Fig. (13): Temperature distribution in three storage tan

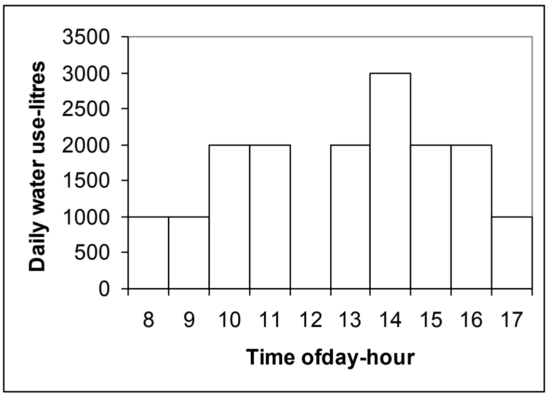

Fig. (14): Average water consumption profile ks