Design and Analysis of a Solar Swimming Pool Heating System

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Abstract: An unglazed solar water heating system has been designed for a swimming pool located in the Lalitpur district of Kathmandu valley. A solar collector with surface area equal to 60% of the pool surface was found to be suitable to heat the pool water to a comfortable temperature of 23°C. The collector was found to have the potential to increase the normal swimming season of five months (May to September) by four more months (March to November) with an additional 96 days available for usage during the extended season. Evaporation was found to contribute nearly half of the losses from the pool, followed by radiation, convection and conduction. A pool cover left overnight was found to reduce evaporation loss by nearly 95% and radiation loss by about 53%. In the absence of a cover, the pool temperature would fall by a further 0.9°C overnight, and the usage availability of the extended season would decrease by 16 days. Other parameters significantly affecting the designed system were wind, relative humidity, sky clearness and occupancy. High wind speeds over the pool surface would aid the evaporation and convection losses, while an average wind speed of 1 m/s or lower was found to be more preferable, with fencing around the pool for wind protection. A relative humidity of 60% or higher was found to be preferable, as humid ambient air would reduce the evaporation rate from the pool. The sky clearness was found to have multiple effects on the pool temperature. A high sky clearness index would result in higher solar insolation and higher collector efficiency, thus increasing the pool temperature. On the other hand, a high sky clearness index would also result in a low sky temperature, thus increasing the radiation loss which would tend to decrease the pool temperature. The combined effects of sky clearness were studied and it was found that a sky clearness index of 0.6 or more would be preferable. Pool occupancy of 8 or lesser people at any instant of time was found to be favorable, although higher occupancy at some instances during the day would not affect the pool temperature by much. A ½HP pump was found to be required throughout the day to pump the pool water to the collector base. A solar PV system of 450 W_p was designed to power the pump during load shedding hours. A financial analysis revealed that the investment cost of the system would be paid back within two years, and other parameters like NPV, IRR and B/C ratio indicated that the investment would be financially attractive.

Keywords: Solar Pool Heating, Pool Solar Collector, Analysis of Pool Heating System

1. Introduction

The global swimming pool arena is dominated by outdoor pools exposed to ambient conditions. The average temperature for comfortable swimming according to ASHRAE is 27°C, although it can vary by as much as has 5°C [1]. But due to diurnal and seasonal variations a pool cannot be comfortably enjoyed all the times, unless some source of heating is employed.

Solar energy utilization is common for pool heating in many countries. In the early 1970s the Copper Development Association sponsored a solar pool heating manual, based on which numerous solar pool heaters were built and the prototype, built in Pasadena, California, was working satisfactorily even after twenty years of installation [2]. By 1993, more than 200 public pools in Germany had solar heaters installed [3]. By 2007, the US had 762 MW of solar pool heating [4]. As of 2010, China is the world leader in solar hot water technology, with 70.5% share out of the 149 GWh of energy, followed by the EU and Turkey [5]. In Spain, it is regulated by law to heat outdoor swimming pools only through renewable or residual source of energy [6]. The potential of solar pool heating is justified in many terms. Heating a pool would increase its availability. Application of solar heating for pools could reduce pollution that would otherwise be generated from using conventional fuel sources. For pool heating, the target temperature is much lower and the collector is unglazed, making it more cost efficient and simpler to construct than domestic solar collectors [7].

Although a wide variety of solar pool heating is employed globally, the most common system is the panel type solar collector combined with a pool cover [8].

2. Objectives

The main objective of this paper is to design and analyze the performance of a solar heating system for an outdoor swimming pool, while the specific objectives are:

1. To design a solar powered swimming pool heating system for a particular site in the Kathmandu valley

2. To analyze the performance of the designed system for probable circumstances
3. To assess the financial viability of the designed system

3. Statement of Problem

There are many swimming pools in the Kathmandu valley, mostly outdoor. The swimming season is usually limited to five months (May to September) because of ambient temperatures being as low as 10°C during the winter [9]. The swimming pools are shut down during the colder months due to lack of efficient heating. The conventional sources like diesel and gas are scarce and expensive, while electricity is not available half the time due to load shedding. Due to the abundantly available solar radiation, solar power could be the possible solution to pool heating in the valley [10].

4. Design Formulation

The heat balance in a solar heated swimming pool is shown in Figure 1.

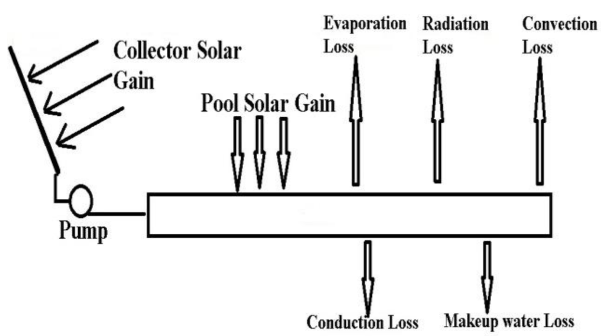

Figure 1: Heat balance in a solar heated swimming pool

The basic heat transfer equation for the solar pool heating system is given by the following equation [6].

$$Q_{reqd.} = Q_c + Q_p - Q_{loss}$$

where,

$Q_{reqd.}$ = heat required to raise the pool water to the desired temperature (J)

Q_c = collector solar heat gain (J)

Q_p = pool solar heat gain (J)

$Q_{loss} = Q_{eva} + Q_{conv} + Q_{rad} + Q_{cond} + Q_{makeup}$

Q_{eva} = evaporation loss (J)

Q_{rad} = radiation loss (J)

Q_{conv} = convection loss (J)

Q_{cond} = conduction loss (J)

Q_{makeup} = makeup water loss (J)

The heat required in raising the pool water from initial temperature T_i (°C) to the final temperature T_f (°C) is given by:

$$Q_{reqd.} = V_p . \rho_w . c_w .(T_f - T_i)$$

where,

V_p = volume of pool water (m^3)

ρ_w = density of pool water (kg/m^3)

c_w = specific heat capacity of water (J kg^{-1} °C^{-1})

The collector solar heat gain is given by:

$$Q_c = G_\beta . A_c . \eta_c$$

where,

G_β = solar insolation over a surface tilted at an angle β (J m^{-2} day^{-1})

A_c = collector area (m^2)

η_c = collector efficiency

The collector efficiency can be obtained from the chart shown in Figure 2 [11].

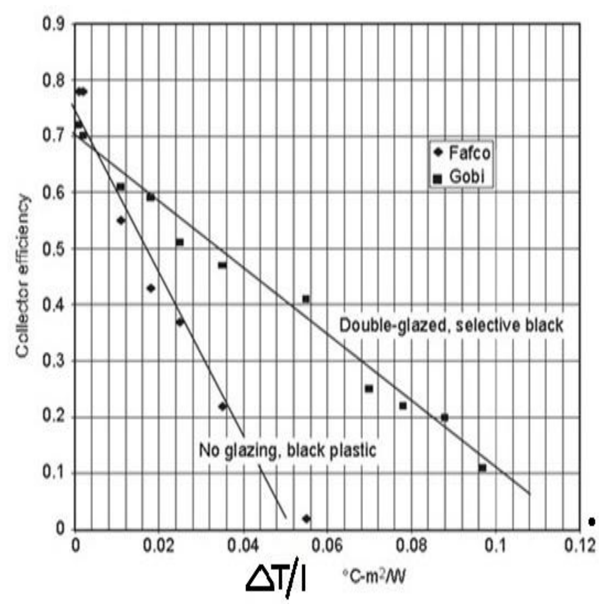

Figure 2 Collector Efficiency Chart

ΔT is the rise in water temperature (°C) and I is the solar irradiance (W/m^2) given by:

$$I = G_\beta / \text{daylight hours}$$

The pool solar heat gain is given by:

$$Q_p = G_H . A_p . \alpha_w$$

where,

G_H = solar insolation over a horizontal surface (J m^{-2} day^{-1})

A_p = pool surface area (m^2)

α_w = absorptivity of pool water

The evaporation loss is given by:

$$Q_{eva} = 1000A_p.h_{eva}.(P_w - P_a).\ t_{eva}.m_{occupancy}$$

where, h_{eva} = evaporative heat loss coefficient

$$= a + b.w$$

a = 0.0506$Wm^{-2}Pa^{-1}$

b = 0.0669 $Wsm^{-3}Pa^{-1}$

w = wind speed (m/s)

t_{eva} = time of pool exposure to the air (s)

$m_{occupancy}$ = occupancy factor

P_w = vapor pressure at pool surface (kPa)

P_a = vapor pressure at ambient air (kPa)

The occupancy factor can be obtained using the following relation [12].

$$m_{occupancy} = 4.27*N/A_p + 1.04$$

where, N = Instantaneous occupancy of the pool (no. of people)

The values of P_w and P_a can be calculated using the following relations [13].

$$P_w = 0.1535\ T_f - 0.6092$$

$$P_a = RH*P_w \text{ (at ambient temperature)}$$

where, RH = Relative humidity

The convection loss is given by:

$$Q_{conv} = A_p.h_{conv}.(T_f - T_a).\ t_{conv.}$$

where,

h_{conv} = convective heat loss coefficient

$$=3.1 + 4.1w$$

t_{conv} = total time over which the pool loses heat through convection (s)

T_a = ambient temperature (°C)

The radiation loss is given by:

$$Q_{rad} = A_p.\sigma.\ (T_p^4 - T_{sky}^4).\ (\mathcal{E}_w.t_{rad,w} + \mathcal{E}_c.t_{rad,c})$$

where,

σ = Stefan-Boltzmann constant

$\mathcal{E}_w$ = emissivity of pool water

$\mathcal{E}_c$ = emissivity of pool cover

$t_{rad,w}$ = time of exposure without cover (s)

$t_{rad,c}$ = time period for which cover is on (s)

Since the sky temperature is very unpredictable, it can be estimated using the following empirical relation [14].

$$T_{sky} = T_a - 20 \text{ (all T in °F)}$$

The conduction loss can be assumed to be around 5% of the sum of evaporation, convection and radiation losses [7].

$$\text{i.e. } Q_{cond} = 0.05* (Q_{eva} + Q_{conv} + Q_{rad})$$

The loss due to makeup water mixing can be written as:

$$Q_{makeup} = V_p.\rho_w.(T_f - T_c)$$

where, T_c = temperature reached after mixing

Assuming that the makeup water is initially at ambient temperature, T_c can be calculated as:

$$V_p.(T_f - T_c) = V_{makeup}.(T_c - T_a)$$

where, V_{makeup} = volume of makeup water (m^3)

5. Design Parameters

The site selected for design is located at Kupandole, Lalitpur district (27°N; 85°E; 1297 masl) . The pool was measured to be 16.5 m x 7.6 m with surface area, A_p = 125 m^2 an volume, V_p = 167 m^3. No shading was observed and the pool was found to be oriented towards south direction.

Table 1: Monthly Averages for Kathmandu valley

Month	T_a, °C	RH	G_H, kWh	Black Days
Jan	10.8	0.47	4.26	2.03
Feb	13	0.46	5.15	4.24
Mar	16.7	0.43	6.18	2.9
Apr	19.9	0.55	6.76	5.1
May	22.2	0.72	6.68	4.13
Jun	24.1	0.84	5.75	4.12
Jul	24.3	0.89	4.79	4.78
Aug	24.3	0.88	4.8	5.16
Sep	23.3	0.86	4.56	3.02
Oct	20.1	0.76	5.13	4.16
Nov	15.7	0.58	4.72	2.6
Dec	12	0.49	4.15	3.51
Average	18.9	0.66	5.244	3.81

The wind speed for design purpose was taken as 0.8 m/s which is the annual average wind speed for Kathmandu valley [15].

The ambient temperature, RH and insolation values were considered separately for each month. Table 1 shows the monthly average values of various parameters for Kathmandu valley [9] [10].

The efficiency of the unglazed collector tilted at an angle β=42° was calculated using the monthly values of tilted insolation and daylight hours [10] as shown in Table 2. The rise in pool temperature over a twelve hour period was taken to be ΔT=3°C. The average efficiency of 0.65 was used as the design parameter.

Table 2: Calculation of collector efficiency

Month	G_β, kWh	Daylight Hours	I (W/m^2)	η
Jan	6.19	10.6	584	0.66
Feb	6.74	11.2	602	0.67
Mar	6.74	12	562	0.66
Apr	6.14	12.7	483	0.66
May	5.36	13.4	400	0.64
Jun	4.5	13.8	326	0.61
Jul	3.91	13.6	288	0.59
Aug	4.19	13	322	0.61
Sep	4.46	12.3	363	0.62
Oct	6.22	11.5	541	0.66
Nov	6.69	10.8	619	0.68
Dec	6.42	10.4	617	0.68
Avg.	5.63	12.11	465	0.65

Table 3 summarizes the remaining parameters chosen for the design purpose.

Table 3: Other design parameters

Parameter	Value
$T_{comfort}$	23°C
ρ_w	1000 kg/m^3
c_w	4,180 J kg^{-1}K^{-1}
α_w	0.85
ε_w	0.9
ε_c	0.4
σ	5.67x10^{-8} Wm^{-2}K^{-4}

6. System Design

Figure 3 shows how an unheated swimming pool's temperature would rise over a 12 hour period due to direct solar gain from the pool itself. The temperature reached at the end of the day is higher than the comfort temperature for five months (May to September), which is the comfortable swimming season without solar heating.

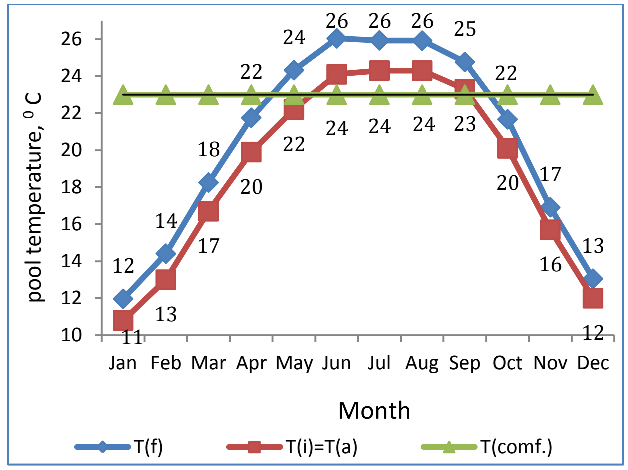

Figure 3: End of day pool temperature without solar heating

Figure 4 shows that a 60 % collector (i.e. A_c=60% of A_p) would be suitable to heat the pool to comfort temperature within a day, for April and October. For the colder months, a collector twice the area of the pool would be required, which is not practical. Thus, a 75m^2 unglazed solar collector was selected.

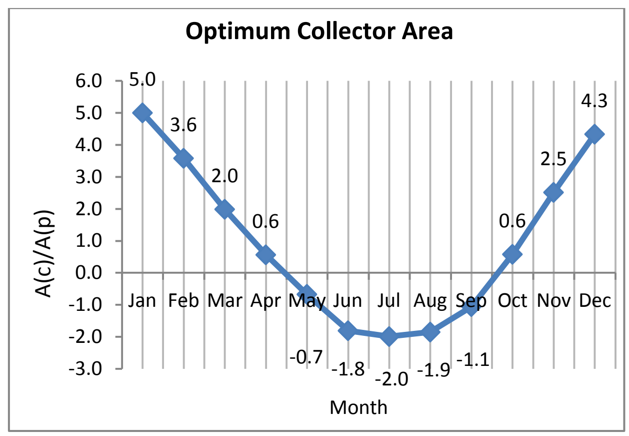

Figure 4: Optimum Collector Area

7. Performance Analysis

7.1 Daily Makeup water requirement

Figure 5 shows how the need to add makeup water at the end of the day due to evaporation changes by month. A tank of 400 liters was selected to fulfill the maximum makeup water requirement in March.

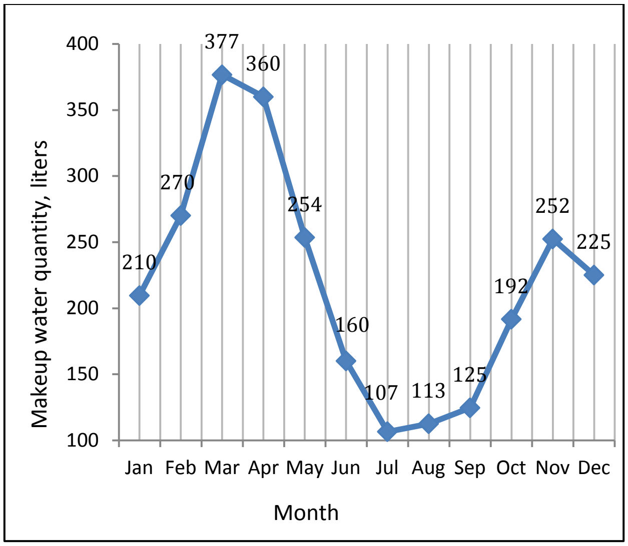

Figure 5: Makeup water required per day

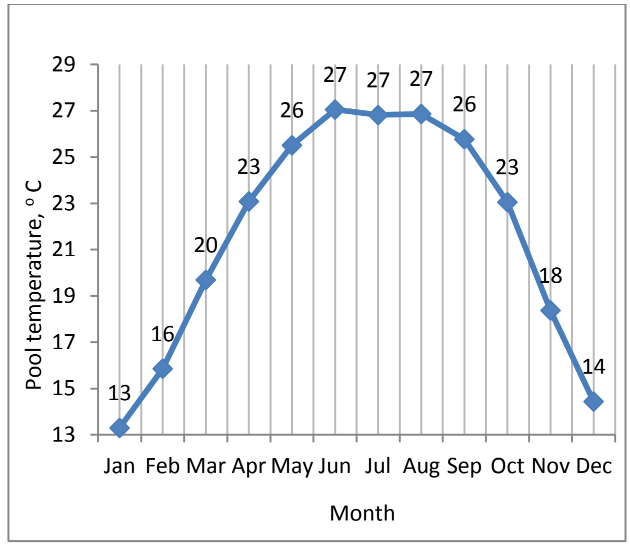

Figure 7: End of day pool temperature with 60% collector

7.2 Contribution of Different losses

Figure 6 shows the contribution of different losses over a 12 hour period. Having a negligible impact, the makeup water loss can be safely neglected and there is no need to heat the makeup water at the end of the day before mixing it with the pool water.

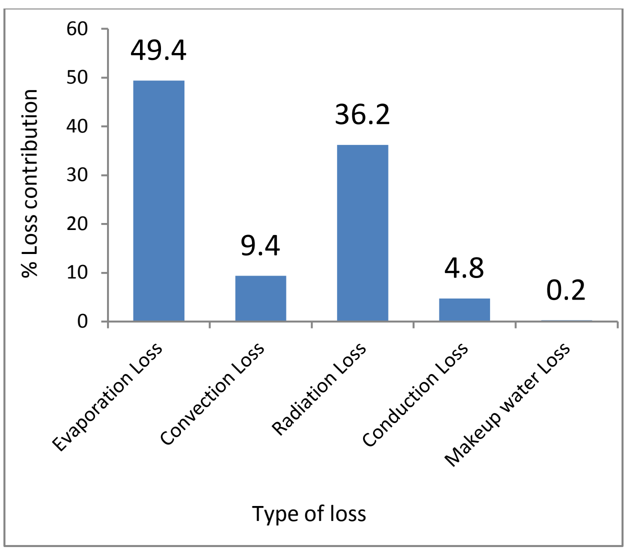

Figure 6: Contribution of Losses

7.3 End of day pool temperature with 60% collector

The Figure 7 shows the pool temperature at the end of 12 hours for each month with a 60% collector. It is obvious that a number of days is required before the pool finally attains comfort temperature during the colder months.

7.4 Threshold temperature

For the pool to be at or above the comfort temperature at the start of the day, the end of previous day's pool temperature is defined as the threshold temperature and is calculated for various months as shown in Figure 8.

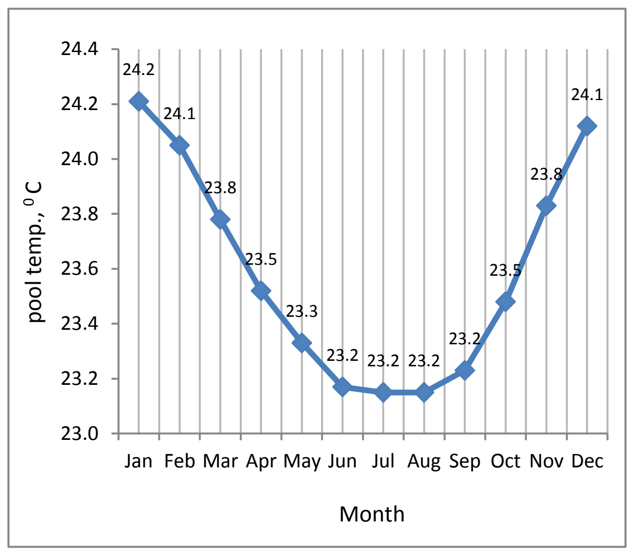

Figure 8: Threshold temperature

7.5 Number of days to reach $T_{threshold}$

The time (in days) required to reach the threshold temperature is shown in Figure 9. It can be seen that the warmer months require much lesser number of days of continuous solar heating before the pool finally reaches beyond the threshold temperature, while the coldest month of January requires as long as 13 days.

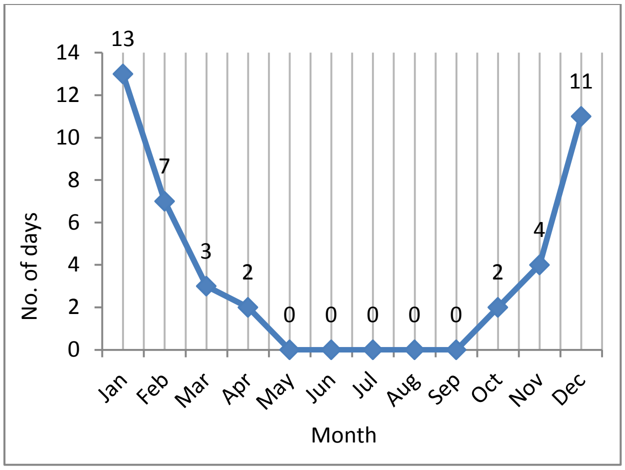

Figure 9: Number of days to reach threshold temperature

7.6 Usage Availability of the pool

The usage availability can be defined as:

Usage Availability =

No. of days in the month – $N_{threshold}$ – No. of Black Days

The % usage availability of the solar heated pool for various months is shown in Figure 10. The months from December to February have extremely low usage availability along with having ambient temperatures much below the comfort temperature. Thus, the extended swimming season with the 60% collector is 9 months from March to November, with a total extension of 96 days.

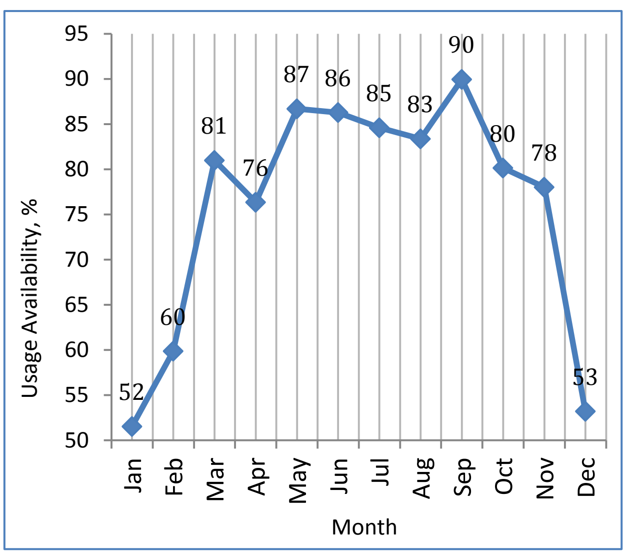

Figure 10: Usage Availability

7.7 Effects of Pool Cover

The design is based on the assumption that an effective pool cover will be placed on the pool when not in use overnight. With the cover on, only 5% of the water is exposed to the ambient air, which means a 95% decrease in evaporation loss and about 53% decrease in radiation loss throughout the night.

Figure 11 shows the average difference of 0.9°C between the morning pool temperature with and without cover would, which would require nearly 180 kWh of energy if the whole pool was to be heated through that temperature.

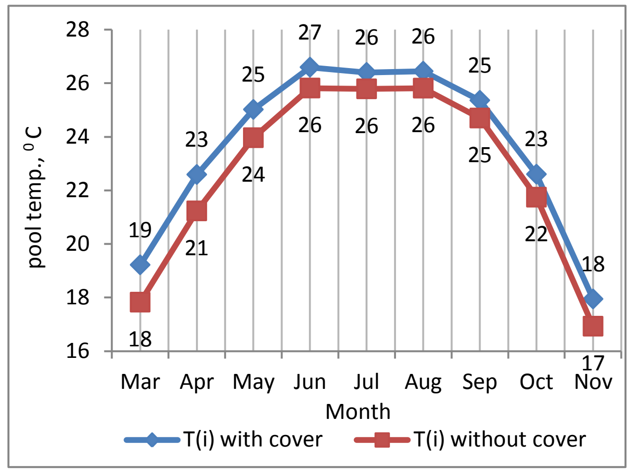

Figure 11: Effect of cover on pool temperature

The importance of cover can also be realized through the increase in number of days to reach a higher threshold temperature and subsequently a decline in usage availability as shown in Figure 12. There could be a total decline of 16 days in the usage availability during the extended swimming season when a cover is not kept overnight.

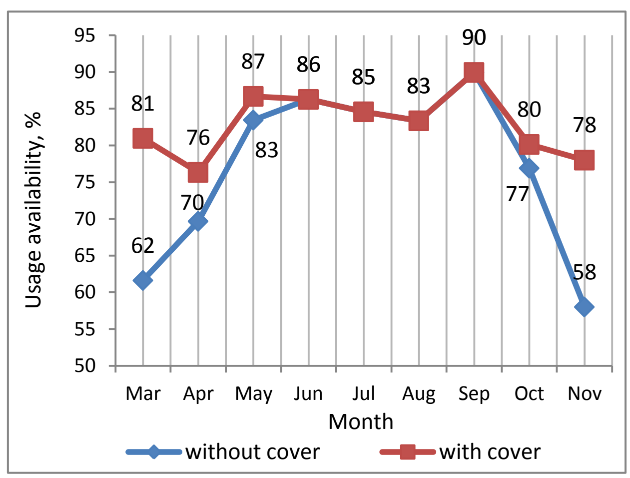

Figure 12: Effect of cover on usage availability

7.8 Effect of wind

Figure 13 shows how the end of day pool temperature would decrease if the wind speed increased to beyond 1 m/s. Although it is unlikely that the pool will experience high wind speeds throughout the day, a protective fencing seems essential to prevent sudden wind gusts.

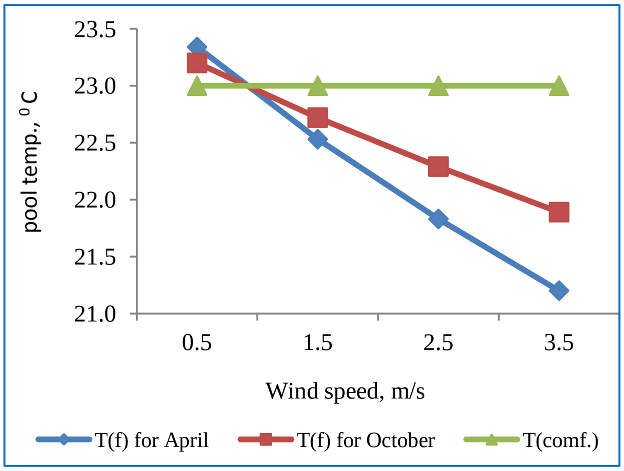

Figure 13: Effect of wind on pool temperature

7.9 Effect of relative humidity

Figure 14 shows how the decline in RH would decrease the pool temperature at the end of day, because there would be more evaporation if the surrounding air gets dryer. A preferred RH value would thus be 60% or higher.

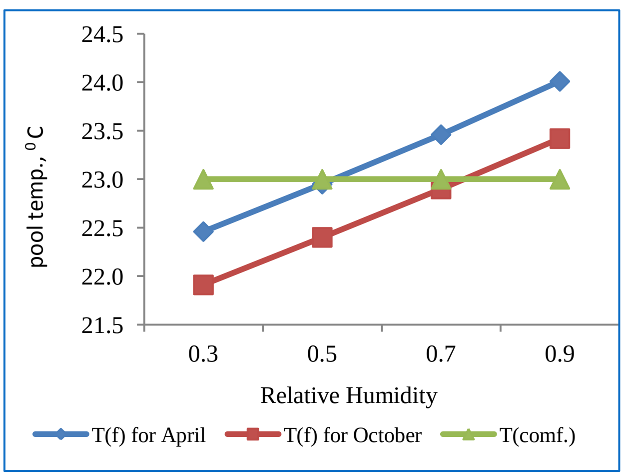

Figure 14: Effect of RH on pool temperature

7.10 Effects of sky clearness

The sky clearness index, K_t is directly proportional to insolation (and consequently, efficiency) while it is inversely proportional to T_{sky} (and consequently Q_{rad}). Hence, a less clear sky would tend to decrease the overall solar gain on one hand, but it would also tend to increase the sky temperature and reduce the radiation loss subsequently. The Figure 15 shows how the combined effects of variation of K_t would affect the end of day pool temperature, and it is desirable to have a sky clearness index of 0.6 or more.

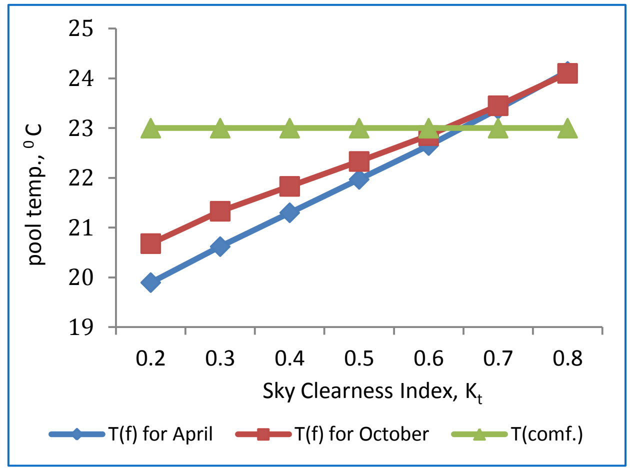

Figure 15: Effect of sky clearness on pool temperature

7.11 Effect of instantaneous occupancy

The instantaneous occupancy directly affects the rate of evaporation from the pool, hence it also has its effects on the pool temperature. Figure 16 shows the effects of pool occupancy on the end of day pool temp. An average occupancy of 8 or less seems to be desirable.

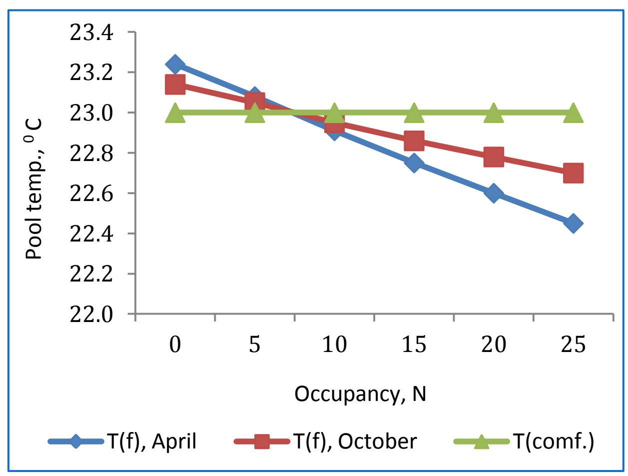

Figure 16: Effect of occupancy on pool temperature

8. Design of Auxillary Equipment

8.1 Pump Selection

For operating the solar collector 12 hours a day, a 232W AC pump was designed with a net head of 5.5m and flowrate of 3.9 lps. However, the pump actually available in the market that would nearly meet the above requirements was a 375 W (1/2 HP) pump with a flowrate of 250 lpm. The actual operation time of the selected pump was calculated to be 11.1 hours per day.

8.2 *Design of PV Backup*

Assuming an average of 5 hours of load shedding each day, a PV backup system was designed to run the pump during power cuts. The PV module was sized at 3m^2 with a peak power of 450 W_p. A 500 VA inverter and five batteries of 100Ah capacity were found to be required additionally.

8.3 *Solar Collector Configurations*

The 75 m^2 unglazed solar collector was designed to have 3 aluminum sheets of 5 mm thickness and dimensions of 10m x 2.5m, tilted at an angle of 42° with the horizontal and facing south. A total of 100 HDPE pipes of 16 mm diameter would be glued to each sheet. The arrangement would then be connected to the pump and pool via 50 mm diameter PVC pipes. The collector would be painted with two coats of dust resistant black paint. The whole arrangement would be fitted with a gate valve and filter and accompanied by a 5mm thick polythene fabric of size equal to the pool surface acting as the pool cover, operated through a roller. Figure 17 shows the designed configurations.

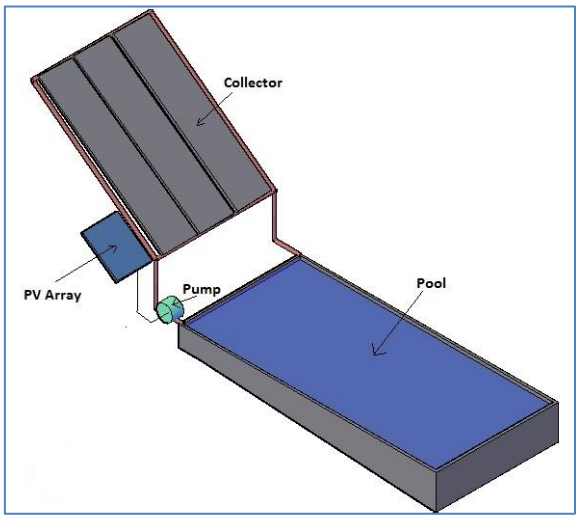

Figure 17: Layout of Designed System

9. Financial Analysis

The total investment cost of the system was estimated to be NRs. 499,221. The annual O&M cost was estimated at NRs. 20,594. The annual revenue during the extended usage period (i.e. 96 days) was estimated at NRs. 288,000.

The following assumptions were made for the financial analysis:

MARR = 10%

Revenue increment per year = 2.5%

O&M Cost Inflation per year = 5%

Insurance Cost per year = 15% of revenue

Depreciation per year = 15% of revenue

Service Life (years) = 20

The results of the financial analysis over the service life with applicable tax rates are shown in Table 4. The results show that the investment on the designed solar pool heating system would be an attractive option.

Table 4: Results of Financial Analysis

S.N.	Parameter	Unit	Value
1.	Simple Payback Period	year	1.73
2.	Net present Value (NPV)	NRs.	1,513,890
3.	Internal rate of return (IRR)	%	47.1
4.	Benefit to Cost Ratio (B/C)	-	1.94

10. Conclusions

From the analysis of the designed system it can be concluded that a solar thermal collector is indeed a feasible option for heating swimming pools, provided that it is well designed and the external factors like temperature, wind, RH and insolation do not go too beyond expectation.

11. Scope for Further Research

The desinged system needs to be put under actual field tests after installation for more detailed and accurate performance analysis. The solar pool heater may be technically as well as financially compared with a heat pump. Scope for further reasearch may also include the analysis of the ease of installation, operation and maintenance of such a system, as compared to conventionally available water heating systems, like the electric heater, gas heater or the heat pump.

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