Transient Performance of Indoor Swimming Pool Heating by Solar Energy

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ABSTRACT

A simple straightforward transient analysis of an indoor swimming pool integrated with panel of collectors through tube-in-tube heat exchanger is presented. The effects of system (pool capacity, movable insulation, heat exchanger, collector area etc.) as well as climatic parameters (wind velocity, relative humidity, solar radiation and ambient air temperature) on the performance of the indoor swimming pool have been taken into account in the analysis. Numerical calculations have been made for an indoor swimming pool which can be extended for general application. Some interesting and useful conclusions have been made which can be used as design criteria for indoor swimming pool.

INTRODUCTION

There are various applications of solar energy for low temperature heating of fluids by either direct or indirect method. The direct method is generally referred to as a passive system while the indirect method is known as an active system. One application of solar energy is to use it for heating swimming pools. Outdoor swimming pools can be heated by both passive and active systems, while indoor swimming pools can be heated only by an active system.

The working principle of passive and active solar heating of swimming pools can be explained as follows:

Passive heating of swimming pools : In this case, a transparent floatable plastic cover is floated over the surface of the water of the swimming pool during sunshine hours. The inner surface of the swimming pool is preferably blackened to absorb solar radiation. After the solar radiation is transmitted through the plastic cover, it reaches the bottom of the pool and is finally absorbed by the blackened surface. Some of the radiation is also absorbed by the water of the pool. Most of the absorbed solar radiation is transferred to the water of the pool by convection and the rest is lost to the ground. This loss can be minimized by using a layer of insulating material beneath the blackened surface. After transferring the heat from the blackened surface by convection, water gets heated and moves in an upward direction due to its low density. Since the water temperature exceeds the ambient air temperature, particularly at night, there is convective and radiative losses from the water surface. To minimize these losses, the pool surface is covered with a waterproof material (tirpal) which acts as an insulating material during off-sunshine hours. As the transparent sheet must be taken out while the pool is in use, there are unavoidable evaporative heat losses during this period. By this method the pool temperature can be raised to a maximum 3-5°C depending on the type of pool.

Active heating of swimming pool: As explained above, swimming pool temperature can be increased marginally by use of a passive system. But under harsh cold climatic conditions, where the ambient air temperature is around 5-10°C or below, the passive heating system is insufficient. For further increase in pool temperature, extra thermal energy is needed. This can be fed in at the bottom of the pool and can maintain the temperature of the pool in a comfortable range (~20°C). This can be achieved by connecting a panel of collectors to the pool either directly or through a heat exchanger. The area of collectors will depend on the capacity of the pool and the climatic conditions.

The use of transparent plastic as the pool cover for passive heating was first suggested by Brook.[1] Later on, different floatable plastic covers namely, polyethylene, polyvinyl chloride (PVC), mylor cover etc. were designed and tested by Lof[2] and Czarnecki[3]. Further, Czarnecki[3] and Sheridan[4] developed a mathematical model to calculate various heat losses for outdoor swimming pools and suggested the use of chemical films and inflated plastic domes for better performance. Francey et al.[5] conducted a detailed experimental study of the performance of a community swimming pool for 3-consecutive days and their results were recently theoretically validated by Yadav and Tiwari.[6] There was good agreement between the theoretical results of Yadav and Tiwari[6] and experimental observation of Francey *et al.*[5] for both transient (1st day) as well as quasi-steady state (3rd day).

Design criteria for indoor swimming pools have been developed by ASHRAE[7], Daly and Bishop[8] and Root[9] and Czarnecki[10] by considering the relevant heat transfer involved and the load characteristics. The aim is to control the deleterious effects of condensation and corrosion of the building elements. An indoor swimming pool has various advantages over an outdoor swimming pool, such as:

(i) It becomes an integral part of the building,
(ii) It is protected from dust, bird and climate etc.,
(iii) Easy to clean,
(iv) Requires less maintenance,
(v) Can be used in harsh cold climatic conditions etc.

Recently, the Victorian Solar Energy Council started a programme of heating swimming pools by solar energy throughout Australia in 1983-84 (Charter[11]). Up to the present, there are about thirty six indoor and outdoor swimming pools in Australia being heated either by passive systems or by active systems, depending on the availability of solar flux and the climatic conditions (Higgs[12,13] and Guthrif[14,15]). The economics of solar swimming pool heating also depends significantly on the amount of solar flux available for a particular site and the location of the site. Table 1 presents some of the indoor and outdoor solar swimming pools installed throughout Australia. From this table and the survey conducted by Guthrif[14,15], one can conclude that heating swimming pools by solar energy is more economical than using conventional fuels. Due to this fact, it has already been widely used by both public and commercial bodies.

In the northern part of India near Delhi, the ambient temperature drops to 4-10°C particularly in December and January, and it is difficult to use swimming pools during these months. In order to maintain a comfortable pool water temperature, the nodal agency of Haryana Government (HARTRON) has undertaken a project in collaboration with the Department of Non-Conventional Energy Sources, Ministry of Energy, Government of India, to heat the swimming pool located near the Haryana and Delhi border by using a panel of collectors. This swimming pool will be used mostly by members of the national swimming team for their practices throughout the year. The whole integrated system will be carried out by Bharat Heavy Electrical Limited (BHEL) and is expected to be completed by the end of this year. In this swimming pool both passive and active systems have been used for heating the pool water. The design of the collector used incorporates a tube-in-plate type flat-

Table 1 Indoor and outdoor swimming pools heated by solar energy in Australia (Guthrif[15]).

	Indoor/ Outdoor	Pool Surface	Collector Area	% Of Pool Area	Total Cost $	Brand of Collector	Date of Installation
MELBOURNE METROPOLITAN							
ALTONA	I	350	350	100	22,580	Solaroll	November 86
CAULFIELD	O	1660	625	38	35,000	Solmat	December 86
COBURG TECH SCHOOL	O	250	200	60	12,355	Solaroll	May 85
CLAYTON TECH SCHOOL	I	43	32	75	2,000	Solmat	May 85
CROYDON	O	1134	584	51	28,485	Solmat	May 86
FITZROY	O	1425	SOLAR BOOSTED HEAT PUMP YET TO BE INSTALLED				
FOOTSCRAY	I	1100	500	45	19,946	Solmat	May 87
HIGHETT	I	435	385	88	20,140	Solmat	April 85
KEILOR	I/O	450	380	84	30,398	Solmat	October 86
MITCHAM SPECIAL SCHOOL	I	41	32	78	5,500	Solaroll	April 86
OAK PARK	O	1382	600	43	32,430	Gulfstream	May 85
PASCOE VALE	O	873	443	51	24,808	Solaroll	October 86
RVIB	I	96	86	90	9,200	Gulfstream	May 85
ST. ALBANS	I/O	450	380	84	30,398	Solmat	October 86
COUNTRY							
CASTERTON	O	664	362	55	17,677	Gulfstream	April 86
CHURCHILL	I	340	340	100	22,100	Solaroll	November 84
CLIFTON SPRINGS	O	250	150	60	10,598	Solaroll	November 85
COWES	O	312	234	75	11,920	Solaroll	February 86
CRIB POINT	O	350	300	85	18,200	Solaroll	May 86
INGLEWOOD	O	429	260	61	17,000	Solmat	December 86
JEPARIT	O	180	110	60	6,990	Solmat	February 86
KILMORE	O	315	189	60	12,952	Solaroll	May 85
LEONGATHA	O	520	390	75	27,200	Solaroll	November 84
MERRIGUM	O	300	200	67	10,000	Solaroll	February 85
MT. BEAUTY	I	447	350	80	21,500	Solaroll	Yet to be installed
MULLERATERONG	I	40	20	50	1,610	Solaroll	Sept 85
NEERIM SOUTH	O	242	205	85	12,095	Solaroll	Sept 86
SOUTH BARWON	I	397	440	90	20,900	Solmat	June 85
SHEPPARTON	O	1050	525	50	30,648	Solaroll	February
ST. ARNAUD	O	1250	500	40	25,000	Solmat	December 86
TERANG	O	430	270	63	15,600	Solmat	April 87
TIMBOON	O	370	250	68	14,000	Solaroll	January 87
TRENTHAM	O	268	165	62	9,970	Solmat	January 87
VCAH DOOKIE	O	108	81	75	5,468	Solmat	November 84
WENDOUREE	I	1216	YET TO BE FINALISED				
WOODBINE	I	40		100	3,000	Solaroll	August 86

plate collector.*

In this paper, a simple transient analysis of an indoor swimming pool is presented from which suitable design criteria can be derived for similar pools. In order to maintain a comfortable pool temperature, a panel of flat-plate collectors has been integrated to the basin of the pool. The effect of the panel of flat-plate collectors, insulation, heat capacity of the pool, waterproof cover material (tirpal), various heat transfer processes, and climatic parameters have all been incorporated into the analysis. Explicit expression for pool water temperature has been derived for numerical computation. Numerical calculations have been carried out for a typical cold day in the Indian city of Srinagar, (17 January, 1981), which is a very harsh cold place throughout most of the year.

DESCRIPTION OF INDOOR SWIMMING POOL

A schematic diagram of an indoor solar swimming pool heated by an active system is shown in Fig. 1. There are basically three components of the system namely (i) the panel of collectors, (ii) the circulation system consisting of pumps, valves and connecting pipes, and (iii) the control system integrated with a panel of collectors and the pool water. In this case, the cost of an active system mainly depends on the type of collectors used for heating the pool water. The type of collector, used for the purpose, depends mainly on the availability of solar radiation and on atmospheric conditions. The types of collector used for swimming pools are categorised as follows:

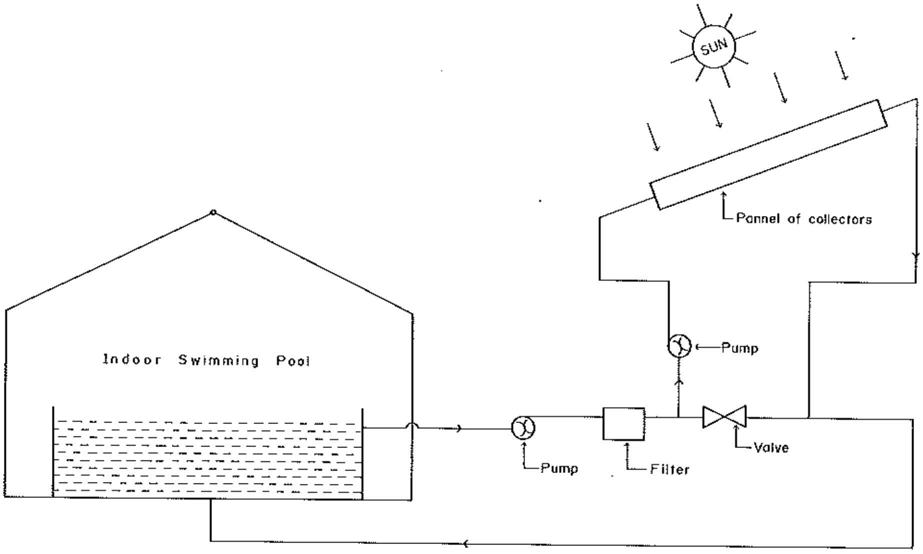

Fig. 1 Schematic diagram of indoor swimming pool heated by an active system.

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* The detail drawing and cost break-up of the system can be obtained from the Secretary, Department of Non-Conventional Energy Sources, Ministry of Energy, Government of India, C.G.O. Complex Block No 14, Lodi Road Complex, New Delhi, INDIA.

i) Unglazed Collectors
  a) Plastic panels,
  b) Strip collectors,
  c) Plastic pipe collectors,
  d) Pavement collectors,
and ii) Glazed Collectors
  a) Boxed collectors,
  b) Integrated collector i.e., an integral part of the roof of a building.

Unglazed collectors are preferred for heating indoor/outdoor swimming pool when only a small increase in pool temperature is required, whereas glazed collectors are preferred where a greater increase in pool temperature is required. Unglazed collectors are more cost-effective than any conventional system. Glazed collectors are more cost-effective for remote areas where conventional systems are very costly.

ANALYSIS

In order to record the energy balance of an indoor swimming pool integrated with a panel of collectors (Fig. 1), the following assumptions have been made:

i) useful energy available from the panel of collectors is uniformly fed at the bottom of the pool basin,
ii) no stratification along the depth of the pool,
iii) heat losses through connecting pipes are negligible,
iv) panel of collectors is disconnected during off-sunshine hours,
v) pool surface is covered with floating waterproof insulating cover (tripal) to minimize upward convective and radiative heat losses,
vi) evaporative heat loss is considered only when the pool is in use and it is taken out by means of an exhaust fan,
vii) bottom heat loss is considered under a steady-state mode,
viii) proper insulating material is used in the basin of the pool to avoid downward heat losses, and
ix) enclosure temperature is almost equal to ambient air temperature.

The energy balance for an indoor swimming pool can be written as

a) without evaporation

$$M_w(dT_w/dt) + A_pU_t(T_w - T_a) + A_ph_b(T_w - T_R) = Q_u \qquad (1)$$

b) with evaporation

$$M_w(dT_w/dt) + A_ph_c(T_w - T_a) + 0.013h_c(p_w - \gamma p_a)A_p + A_ph_b(T_w - T_R) = Q_u \qquad (2)$$

where,

$$Q_u = A_cF_R[\alpha\tau I_t - U_L(T_w - T_a)], \text{ without heat exchanger} \qquad (3)$$

$= U_H(T_f - T_w)$, with heat exchanger and collectors in parallel

$= \lambda$, with heat exchanger, Yadav and Tiwari[6] (4)

$= 0$, when collectors are disconnected from pool.

$T_f = T_w + (T_{fo} - T_w)\exp(-hx/m_f c_f)$,

$T_{fo} = [(\alpha\tau I_t/U_L) + T_a] + [T_{fi} - \{(\alpha\tau I_t/U_L) + T_a\}]\exp[-(A_c U_L F'/m_f m_f)]$, Duffie and Beckman[16]

$\bar{T}_f = (1/L)\int_0^L T_f dx$

$T_{fi} = T_f(x = L)$

$U_H = hL$

$\left.\begin{aligned} P_w &= R_1 T_w + R_2 \\ P_a &= R_1 t_a = R_2 \end{aligned}\right\}$ for small temperature range of pool temperature 15°C - 50°C

$F_R = (m_f C_f/U_L A_C)[1 - \exp(A_c U_L F'/m_f c_f)]$, Duffie and Beckman[16]

$h_b = [(L_i/K_i) + (L_i/K_r) + (1/h_i)]^{-1}$

After substituting the value of Q_u from Eq. (3) in Eq. (1), one gets

$$M_w(dT_w/dt) + A_p U_t(T_w - T_a) + A_p h_p(T_w - T_R) = A_c F_R\ [\alpha\tau I_t - U_L(T_w - T_a)] \tag{5}$$

or

$$dT_w/dt + [U_t/(M_w/A_p) + h_b/(M_w/A_p) + (A_c/A_p)F_R U_L]T_w = (A_c/A_p)F_R[\alpha\tau I_t + U_L T_a] + U_t T_a + h_b T_R$$

Above equation can be rewritten as $(dT_w/dt) + aT_w = f(t)$ (6)

where $a = [U_t/(M_w/A_p) + h_p/(M_w/A_p) + (A_c/A_p)F_R U_L]$

and $f(t) = (A_c/A_p)F_R[\alpha\tau I_t + U_L T_a] + U_t T_a + h_b T_R$

The solution of Eq. (6) can be written as

$$T_w = (\overline{f(t)}/a)(1 - \exp(-at) + T_{wo}\exp(-at) \tag{7}$$

where T_{wo} is the temperature of pool water at $t = 0$ for 0 -- t interval and $\overline{f(t)}$ is the average value of function f(t) for 0 -- t interval.

Equation (7) will determine the temperature of pool water when (i) pool surface is covered with waterproof insulating cover, and (ii) panel of collector is connected with basin of the pool without heat exchanger.

Similarly, Eq. (2) can be solved by taking into account evaporation from the pool surface during operation of the indoor pool. Effect of heat exchanger on the performance of the pool temperture can be seen by using the Eq. (4) in Eqs. (1) and (2) respectively.

NUMERICAL RESULTS AND DISCUSSION

In order to study the numerical results of the indoor swimming pool, numerical caculations have been made for a typical cold day in Srinagar, Jammu and Kashimir, India (17 January, 1981). The hourly variation of solar radiation and ambient air temperatures is shown in Fig. 2. The other parameters used for calculation for the proposed indoor swimming pool are as follows:

Indoor Swimming pool:

M_w = 27.654 x 10^7 J/°C (66,000 litres and depth = 1.5 m)

A_p = 45 m^2

U_t = 5.7 W/m^2 °C

h_b = 0.85 W/m^2 °C

h_c = 5.7 W/m^2 °C

R_1 = 325 N/m^2 °C

R_2 = -5154 N/m^2 °C

y = 0.8

T_r = 8°C

T_{wo} = 8°C

Panel of collectors:

U_L = 8 W/m^2 °C

$\alpha\tau$ = 0.8

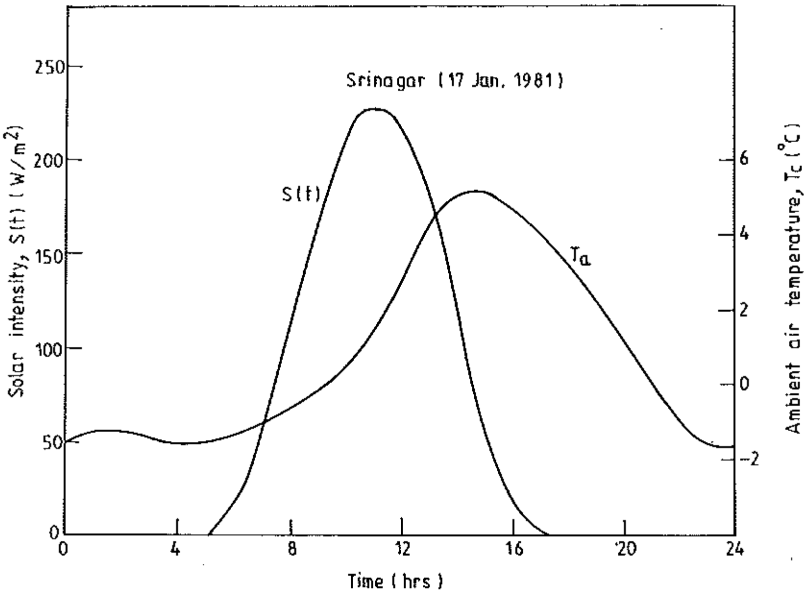

Fig. 2 Hourly variation of solar intensity and ambient temperature on 17 January 1981 at Srinagar.

$F' = 0.77$ $h = 4\ \text{W/m}^2\ {}^\circ\text{C}$

$A_c = 400, 700, 1200\ \text{m}^2$ $L = 50\ \text{m}, 100\ \text{m}$

$F_R = 0.55$

Fig. 3 shows the effect of heat capacity of swimming pool water on hourly variation of its water temperatures; the collector area is 400 m^2. Curves I, II and III of this figure correspond to various values e.g. 27.654×10^7 J/°C, 13.83×10^7 J/°C and 7.0×10^7 J/ °C of the heat capacities of water mass in the pool. It is found from the results of this figure that as the heat capacity of water mass decreases water temperature increases which is the expected result.

The effect of collector area on the hourly variation of water temperature is shown in Fig. 4. Here the heat capacity of the water mass in the pool has been taken as constant. This study has been carried out for three consecutive days. Curves I, II, III refer to collector areas of 400 m^2, 700 m^2 and 1200 m^2 respectively. These results are useful for estimating the collector area required for heating a solar swimming pool, of known capacity, to a desired temperature. The results of this figure are also expected, as they reveal that as the collector area increases water temperature increases. Fig. 5 depicts the effect of heat exchanger length on hourly variation of water temperature. This study has been made keeping both heat capacity of water mass and the collector area constant i.e. 27.654×10^7 J/°C, and 1200 m^2 respectively. Curves I, II and III of this figure indicate the various lengths (i.e. 0.0 m, 100 m, and 50 m) of the heat exchanger. It is evident from the results that as the length of the heat exchanger decreases, water temperature decreases because of less heat transfer. The 0.0 m length of the heat exchanger means no heat exchanger. The above results and discussion may be summarized as follows:

i) The present analytical approach is a simple one and may be used for optimizing the collector area and the heat exchanger length for a swimming pool of any capacity.

ii) As the heat capacity of pool increases water temperature decreases for a constant collector area.

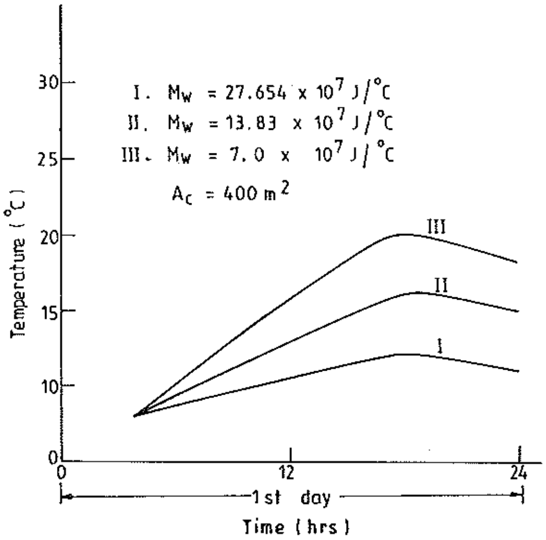

Fig. 3 Effect of heat capacity of pool water on hourly variation of water temperature of the pool.

iii) Increasing collector area results in increasing water temperature of the swimming pool.
iv) Decreasing heat exchanger length also results in decreasing water temperature.

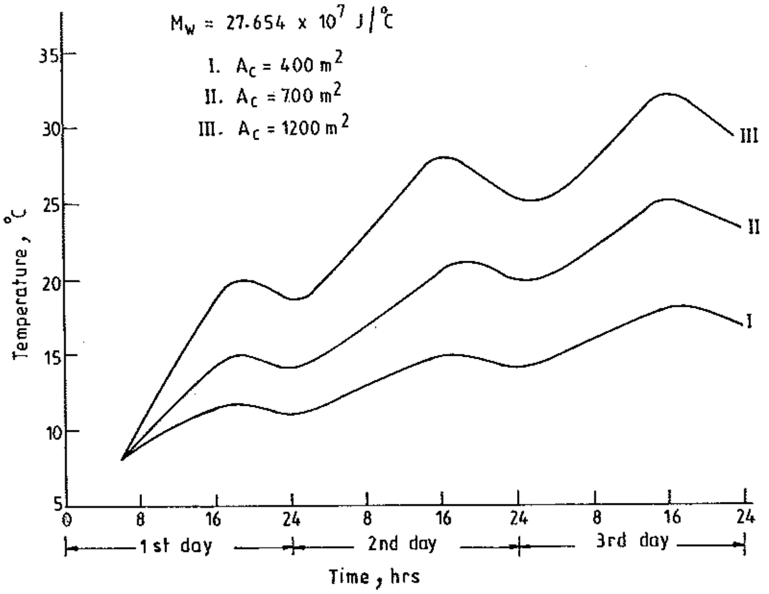

Fig. 4 Effect of collector areas on hourly variation of water temperature of the pool.

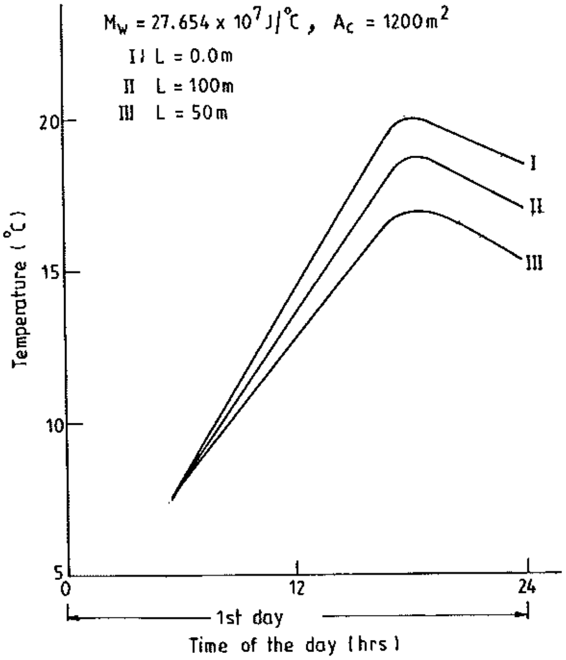

Fig. 5 Effect of heat exchanger length on hourly variation of swimming pool temperature.

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NOMENCLATURE

A_c	Collector area (m^2)
A_p	Surface area of the swimming pool (m^2)
C_f	Specific heat of fluid flowing through the heat exchanger (J/kg °C)
F'	Collector efficiency factor
F_R	Heat removal factor
h	Heat transfer coefficient per unit length of the heat exchanger (W/m^2 °C)
h_b	Overall heat transfer coefficient from bottom of the pool (W/m^2 °C)
h_c	Convection heat transfer coefficient from water surface (W/m^2 °C)
h_i	Heat transfer coefficient from bottom surface of the pool to room (W/m^2 °C)
I_t	Solar intensity (W/m^2)
L	Heat exchanger lenght (m)
L_i	Thickness of insulation (m)
L_r	Thickness of bottom of the pool (m)
K_i	Thermal conductivity of insulation (W/m °C)
K_r	Thermal conductivity of bottom of the pool (W/m °C)
m_f	Mass flow rate of fluid in the heat exchanger (kg/s)
M_w	Heat capacity of water (J/°C)
P_w	Partial pressure at water temperature (N/m^2)
P_a	Partial pressure at ambient temperature (N/m^2)
Q_u	Useful energy from the collector (W/m^2)
t	time (S)
T_a	Ambient temperature (°C)
T_f	Fluid temperature (°C)
T_{fi}	Inlet fluid temperature (°C)
T_R	Room temperature (°C)
T_{fo}	Outlet fluid temperature (°C)
T_w	Water temperature (°C)
U_L	Overall heat transfer coefficient of the collector (W/m^2 °C)
U_t	Upward heat loss coefficient from the water surface of the pool (W/m^2 °C)
x	Space coordinate (m)
$\alpha\tau$	Transmittance-absorptance product
r	Relative humidity

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