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A SOLAR POND FOR AIR CONDITIONING A SMALL FAMILY HOUSE IN QATAR

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ABSTRACT

The concept of using a solar pond to provide air conditioning for a typical small family Qatari house is developed. Though the idea seems appealing for a number of reasons, the design study shows it to be technically feasible but not cost effective. To meet 100% of the cooling load from March till December, the solar pond area needed is 4-5 times the floor area of the air-conditioned space. For space cooling, solar energy cannot compete with conventional sources at today's oil prices.

NOMENCLATURE

A_p : pond surface area, m^2
A_s : total area of four side walls, m^2
A, B : a/D, b/D
a, b : length and width of pond (in x, y directions), m
C : specific heat of brine (function of t & z), J/kg°C
D : depth of the non-convecting layer, m
D_{cL} : depth of the storage layer (LCZ), m
G : hour of the day
h : convective heat transfer coefficient for pond wall, W/m^2 °C
h_w : convection coefficient from cover to wind, W/m^2 °C
l_O : extra-terrestial radiation intensity, W/m^2
k : thermal conductivity of brine, f (t, z), W/m°C
k^* : conductivity of pond insulating material, W/m°C
L_c : D_{cL}/D, ratio of storage to insulating layer thickness
D_{cL} : depth of the storage layer (LCZ), m
q : heat flux, W/m^2
q_L : pond thermal load (rate of heat removal), W/m^2
N : day number (on 1st January, N = 1)
N_s, N_h : starting date & length of warming-up period
T, t : temperature & time °C & second
T_a : ambient temperature, °C
V_w : wind velocity, m/s
x, y, z : Cartesian coordinates, m
α : thermal diffusivity

β_n : attenuation coefficient for the n^{th} portion of the radiation spectrum m^{-1}
η_n : fraction of energy in the n^{th} portion of the radiation spectrum
δ : thickness of the pond wall insulation, m
ψ, ϕ : altitude and azimuthal angles of penetrating radiation
ρ : density of the brine solution, f (t, z), kg/m^3
θ, τ : dimensionless temperature & time, eqn (5)

Subscripts

b, s, : refer to bottom and side walls of pond
o : refers to initial value of the physical property in the storage layer

INTRODUCTION

a. What is a Solar Pond?

A salt-gradient solar pond is a large body of saline water 2-4 m deep whose surface area varies from few hundred square meters to thousands of square meters, and in which the salinity is not uniform but increases linearly downwards until it reaches saturation near the bottom. The density gradient is then large enough to suppress convection and prevent the formation of any large scale convection cells.

The pond depth can be divided into three zones. The main zone in the middle is the Non-Convecting Zone (NCZ) and forms the pond's insulating layer. The bottom layer is a layer of uniform salinity (usually saturated), it is the pond's storage layer referred to as the Lower Convecting Zone (LCZ). Solar radiation reaching the pond's blackened bottom is absorbed and through convection it heats the LCZ, and the heat is not convected to the pond's surface due to the presence of the NCZ above.

Due to wind and other surface phenomena, a second convective layer is formed at the top of the pond. This detrimental Upper Convective Zone (UCZ) is not needed, and if its growth is not checked it could seriously reduce the thickness of the vital NCZ. Wind protection and surface wave suppression mechanisms were found to be essential to ensure a stable and sustainable solar pond operation[1].

Heat can be extracted by one of two possible techniques. A heat exchanger can be placed within the pond's storage layer (LCZ) with the heat transfer medium circulated through. Alternatively, brine from the storage layer can be extracted and circulated through the application device before being returned to the LCZ.

b. Applications

Although the concept of collecting and storing solar energy in solar ponds has been known since the beginning of the century, only in the last two decades have the ponds made the transition from scientific curiosities to practical devices. A review of literature, e.g. reference (2), reveals that solar ponds have been proposed - and in many cases tried - as a power source for a large number of applications among which : electric power generation, salt production, district heating, industrial process heating, water desalination, greenhouse heating and space cooling. Solar pond literature indicates that, in many of these applications, ponds can compete reasonably well with fossil fuels for heat generation at present price levels. The environmental advantages of using solar energy - a clean and renewable energy source - weigh heavily on the side of solar ponds.

c. Solar Ponds for Air Conditioning?

In 1981 Hawlader (3) first proposed the use of solar ponds for space cooling applications in the tropics. His simple analysis was directed at finding the rate of heat extraction under the climatic conditions of Singapore, to maintain the temperature level required for operating an absorption chiller, i.e. above 80°C. The study was further improved in reference (4) by including a detailed formulation of the pond, but no attempt was made to simulate a typical cooling load. This was covered in reference (5) in which a solar pond was proposed to provide air conditioning for an office block in Singapore *during office hours only.* The simulation study indicated that, under these conditions, a solar pond of area 2.5 times the floor area of the air-conditioned space could supply 75% of the power required.

The objective of this paper is to examine the feasibility - both technical and economical - of using solar ponds to operate air conditioning machines in the Arabian Gulf area. More specifically, the air conditioning needs of a typical Qatari residential house are assessed, and - based on previous experience - a solar pond is designed to meet the power requirements of the absorption chiller. The relative advantages and shortcomings of this scheme are examined.

THE BASIC CONCEPT

This study is born out of the fact that air conditioning loads constitute a very heavy burden on the electricity grids in the Arabian Gulf countries, inflating - artificially - their per capita energy consumption to some of the highest levels worldwide and exceeding those in many highly industrialized nations. This is the case - despite the fact that the area is one of the most promising parts of the globe for solar energy harnessing, being blessed with clear skies and uninterrupted sunshine for an average of around 3000 hours/annum. It then becomes sensible to consider the use of a solar energy collection and storage device (the pond) to power a heat-driven refrigeration machine in order to provide the cooling required.

This can be achieved by coupling a salt-gradient solar pond to an absorption chiller, see Fig. 1, thus utilizing the pond's inherent long-term storage capability to secure a continuous power supply to the air conditioning system. This coupling helps overcome two intrinsic difficulties arising from two of the characteristics of solar radiation namely, its low energy density and its intermittence and irregularity. Moreover, maintaining the pond storage layer temperature within the range 75-95°C over a large part of the year, by carefully selecting the heat withdrawal rate, makes the pond a favourite choice for powering an absorption refrigeration system.

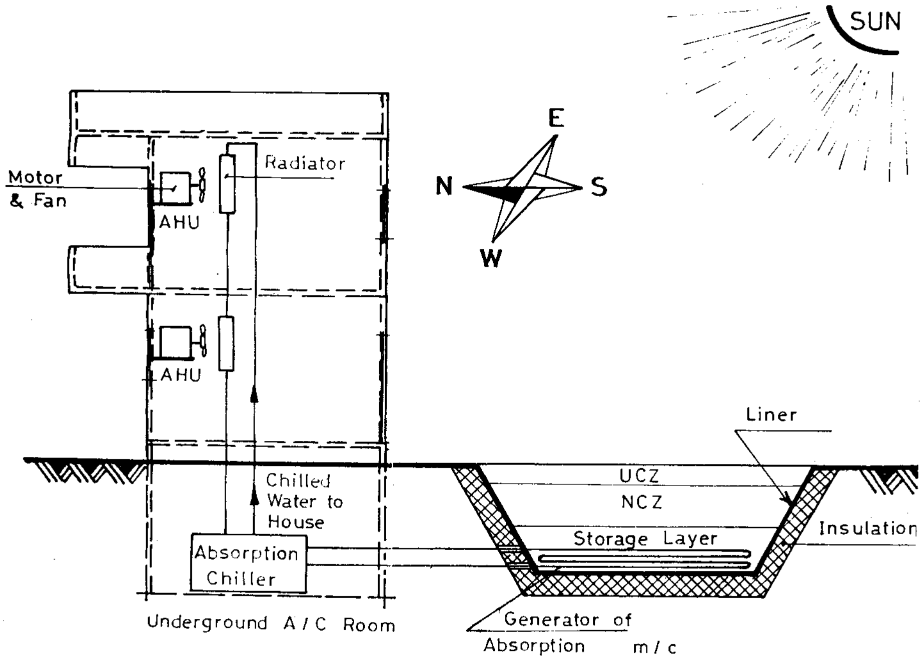

Fig. 1: Schematic of the System (Pond + Chiller)

Motivation

The study is motivated by the following facts:-

1. For most of the year between 60% and 70% of all the electrical power generated in the GCC states is consumed in air conditioning. This burdens their economy with the continuous need for expanding their generating capacity to meet this ever increasing demand.

2. Around the Gulf, the air conditioning season extends from March till November, i.e. it lasts for 8-9 months of the year. With the high standard of living in the GCC countries, air conditioning is considered a basic necessity.

3. Solar energy is ideally suited for air conditioning. The air conditioning peak load coincides with the peak of the power source (solar radiation) on both an annual and daily basis. Maximum demand is in summer, so is the maximum insolation. Similarly, during the day both maximum air conditioning demand and maximum solar input occur just after mid-day. This is logical since a large part of the air conditioning load is due to solar radiation.

4. Around the Gulf, during the long summer months, the need for air conditioning extends over the 24 hours of the day, i.e. night and day. This makes a solar pond - with its long-term storage capacity - a clear favourite over solar collector systems, which are not suited for providing power to the chiller during the night. Even if a collector system is designed to provide 24 hours heat, it will then require an impractically large storage tank system.

5. The very idea of having the pond (a large pool) in front or at the back of the house has a great aesthetic appeal, bearing in mind the normal arid background of the Arab Gulf countries. Surely, the sight of water is relaxing in a desert environment, see Fig. 2.

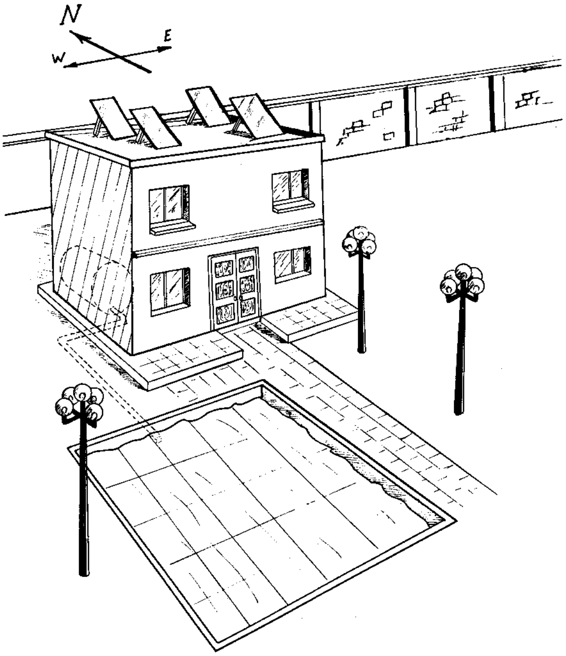

Fig. 2: Artist's Impression of the Pond used for Air-Conditioning

6. Furthermore, the pool will also provide evaporative cooling in the evening and night in areas of the Arabian peninsula which have a dry climate.

Concept Development

The Concept was developed in four main steps:

1. Cooling load estimation
2. Selection of the chiller system
3. Design of the solar pond to meet the thermal load
4. Prediction of the pond performance.

DESIGN STUDIES

1. The Cooling Load

The first step in designing the system was to estimate the air conditioning load of a typical small Qatari family residential dwelling. A typical residence can be assumed to be a 2-storey villa of a total floor area of between 250 and 350m^2. Assuming an energy conscious design is adopted, with proper insulation, shading and overhangs implemented, a design air conditioning load of 10 tons of refrigeration (approximately 35 KW) is estimated. For the purpose of the study, it is assumed that this peak load will be met continuously 24 hours per day for a full nine month of the year (1st March - 1st December) and that the chiller thermal input power will be met *solely* by the solar pond. Naturally, some electrical input will be needed to meet the pumping and other auxiliary needs.

2. The Chiller System

A lithium bromide - water absorption chiller is the most suitable system for the present application. It should be possible to operate it with hot water from the solar pond at 75°C to 100°C. A survey of commercially available systems revealed that a Yazaki chiller unit, model WCF - 3000, meets exactly the required specifications. Further details of the system are as follows:

Capacity	:	34.9 kW (= 10 RT)
Chilled water inlet & outlet	:	14 & 9°C
Chilled water flow rate	:	1.67 l/s
Heat input	:	49.8 kW (C.O.P. = 0.7)
Design Hot water inlet & outlet	:	88 & 83°C
Design Hot water flow rate	:	2.38 l/s
Cooling water inlet & outlet	:	29.5, 34.5°C
Cooling water flow rate	:	4 l/s
Electrical consumption	:	5 W for chilled water bypass valve 30 W for palladium cell heater

The chilled water bypass valve improves part load performance, and a novel refrigerant storage system ensures efficient cooling capacity with variations in hot water temperature. The chilled water is circulated to a central air handling unit or multiple fan-coil units for air conditioning needs. The heat is rejected through a cooling tower.

3. The Solar Pond

Based on the author's own experience with solar ponds and on the results of parametric studies (6 and 7) aimed at designing and sizing small-scale solar ponds, a heat withdrawal rate of 35 W/m^2 i.e. 3 MJ/m^2 per day is suggested. Thus, the pond surface area is given by: $A_p = (49.8 \text{ X } 10^3)/35 = 1430M^2$

A pond of width 24m in the E-W direction and length of 60m in the N-S direction is suitable. This is a disappointingly large pond, but is to be expected in view of the extremely harsh design conditions of 100% solar input and operation at full load from March till December, day and night. A more realistic and less severe loading pattern would result in a smaller pond.

An optimization of the pond parameters yielded the following design:

Dimensions : 24 × 60m
Total depth : 2.5 - 3m
Depth of the UCZ : 0.3 - 0.5m
Depth of the NCZ : 1.5m
Depth of the LCZ : 0.5 - 1m

The pond side walls could be vertical or sloping at a maximum of 45° to the vertical. Both the pond bottom and sides should be insulated with a layer of polystyrene foam of thickness of 300mm and 200mm respectively. A black XR-5, or Hypalon liner is needed to prevent any brine leakage. Wind protection in the form of a floating network of hollow PVC pipes has to be used to suppress any excessive upper convective zone growth. The presence of the house on the North side of the pond will provide a reasonable measure of protection against excessive wind speeds and gusts since the prevailing wind direction in Qatar is North - North West.

4. Prediction of the Pond Performances

The last step of the design study was to examine the response of the solar pond to the application of the load after a certain intitial heating period, and the effects on the storage Zone (LCZ) temperature development of the heat removal up to the first of December of the first year and then from March to December in the subsequent years. This was performed to ascertain that at the values of heat withdrawal rate suggested, the temperature of the storage layer will remain within the operational range of the chiller - i.e. within the range 75-100°C.

THE THEORETICAL MODEL

Consider a pond of surface area A_p and whose non-convective (insulating) zone thickness is D. The heat balance for an infinitesimal layer of the NCZ of thickness dz (Fig. 3), considering both heat losses by convection and absorption of solar radiation reaching the side walls, can be written as:

$$\rho C A_p \, dz \frac{\partial T}{\partial t} = A_p \left(\frac{\partial q_c}{\partial z} + \frac{\partial q_r}{\partial z} \right) dz - \frac{dz}{D} \sum_{i=1}^{4} \left[A_i \, h_s \, (T - T_a) - A_i \, q_s \right] \qquad (1)$$

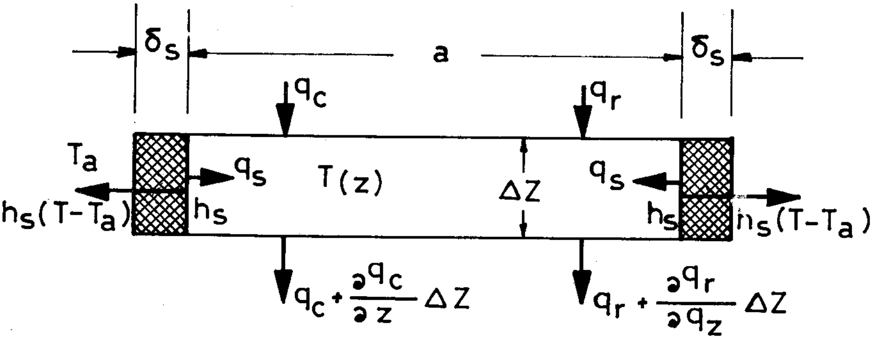

Fig. 3: Energy Balance for a Section of the Insulating Layer (NCZ)

If the temperature of the four side walls of the pond are assumed equal and a function of the vertical co-ordinate z only, (Equation 1) reduces to the 1-D heat diffusion equation, and can be written in a dimensionless form as

$$\frac{\partial \theta}{\partial \tau} = \frac{\partial}{\partial Z} \left(K \frac{\partial \theta}{\partial Z} \right) - \frac{\partial Q_r}{\partial Z} - H_S (\theta - \theta_a) + Q_s \qquad (2)$$

subject to the following initial and boundary conditions:

$$\theta = 0 \qquad \tau = 0 \qquad Z > 0 \, ,$$

$$K \frac{\partial \theta}{\partial Z} - H_u (\theta - \theta_a) = - Q_r (0) \qquad Z = 0 \, ,$$

$$K \frac{\partial \theta}{\partial Z} + H_b (\theta - \theta_a) + L_c \frac{\partial \theta}{\partial \tau} = Q_r (1) - Q_L \qquad Z = 1 \qquad (3)$$

where all lengths are normalized through D, i.e.

$$A,\ B,\ L_c,\ Z = \frac{a,\ b,\ D_{cL},\ z}{D} \quad , \quad k = \frac{k}{k_o} \tag{4}$$

The dimensionless temperature, time and heat flux are given by:

$$\theta = \frac{T - T_o}{I_o\ .D/K_o} \qquad \tau = \frac{t\ \alpha_o}{D_2} \qquad Q = \frac{q}{I_o} \tag{5}$$

The dimensionless heat transfer coefficients from the top, sides and bottom are given by:

$$H_u = \frac{D}{k_o}\ [h_w + \sigma\epsilon_s\ (\ T^2 + T_a^2\ )\ \ (\ T + T_a\ )\ ]$$

$$H_S = \frac{A_S}{A_P}\ \frac{D}{k_o}\ \ \frac{1}{[\delta/k^* + 1/h_w\ ]}$$

$$H_b = L_c\ H_s + (\frac{k^*}{k_o}\ .\ \frac{D}{\delta}) \tag{6}$$

where

$$Q_S = [\frac{Q_x\ (\ 0\ \text{ or }\ A\ )}{A} + \frac{Q_y\ (\ 0\ \text{ or }\ B\ )}{B}]$$

It should be noted that the terms Q_s, Q_r (0) and Q_r (1) vanish from sunset to sunrise.

Now, to evaluate the amount of radiation reaching a certain depth Z in the NCZ, Q_r (Z), and also the amount of radiation absorbed at the pond's inside walls Q_s, the radiation attenuation model first suggested by Rabl and Nielsen (10) is adopted. Thus the radiative heat flux arriving at any depth Z can be written as:

$$Q_r = \sum_{n=1}^{4} \eta_n \int_{\phi=0}^{\phi=\frac{\pi}{2}} \int_{\psi=0}^{\psi_{max}} \exp\ (-\beta_n\ Z \sec\ \psi)\ .F\ (\psi,\ \phi)\ \Omega\ \sin\ \psi\ d\ \psi\ d\ \phi \tag{7}$$

where Ω is the solid angle vector

$$\Omega = \Omega_b + 2\, C_S\, \Omega_d \tag{8}$$

and the solid angle vector for either beam or diffuse radiation is given by

$$\Omega_m = \sin\psi_m \cos\phi\, \hat{i} + \sin\psi_m \sin\phi\, \hat{j} + \cos\psi_m\, \hat{k}, \qquad (m = b \text{ or } d) \tag{9}$$

F (ψ, ϕ) is the shape factor for direct and diffuse radiation. The exponential decay of solar radiation with depth, as a function of wave-length in (Equation 7) has the following coefficients:

$\eta_1 = 0.231$	$\beta_1 = 0.032\text{m}^{-1}$	0.2 - 0.6m
$\eta_2 = 0.193$	$\beta_2 = 0.45\text{m}^{-1}$	0.6 - 0.75m
$\eta_3 = 0.167$	$\beta_3 = 3.0\text{m}^{-1}$	0.75 - 0.9m
$\eta_4 = 0.179$	$\beta_4 = 35.0\text{m}^{-1}$	0.9 - 1.2m

For the ambient temperature, a model for Doha has been developed. Minimum and maximum temperature data for the last 30 years can be correlated to within ± 1.3°C by the expressions:

$$T_{\max} = 31.8 + 9.6 * \sin\left(\frac{N + 252}{365} \,.\, 2\pi\right)$$

$$T_{\min} = 21.4 + 8.2 * \sin\left(\frac{N + 245}{365} \,.\, 2\pi\right) \tag{10}$$

while for the hourly ambient temperature variation, the following expression is suggested:

$$T_a = T_{\min} + (T_{\max} - T_{\min}) * f_1(G) + f_2(G - 6), \tag{11}$$

$$\textit{with } f_2(G) > 0 \textit{ for } 6 < G < 14.5.$$

Both f_1 and f_2 are simple polynomials of G. An 8th-degree polynomial gave the best fit to the available data.

To account for the presence of the upper mixed layer (UCZ), the value of thermal diffusivity of the top three sections of NCZ (in the numerical model) is increased to some 30 times its value in the rest of the zone.

Reference Data

For the purpose of simulating the pond performance, the basic pond dimensions and insulation thickness are those proposed in the previous section. Furthermore, the environmental conditions of Doha (25.2°N) are considered through models for both the solar radiation and the ambient temperature variation, while an average wind speed of 4 m/s is assumed. The pond is assumed to start operation on the first of March and the load is first applied after a warming up period of 90 days i.e. on the first of June. The load is kept at a constant value until the first of December. During December, January and February no air conditioning is needed, so $Q_L = 0$. In the second and subsequent years, the load is applied continuously from March till December.

RESULTS

(Fig. 4) shows the storage layer temperature evolution under these conditions for three values of the load. From the figure, it is clear that even at the higher heat removal rate of 40W/m², the pond still maintains a temperature suitable for the chiller operation. This implies that a smaller pond can supply the required thermal load. Based on the new value, the pond area reduces to 1250m² (25 × 50m say).

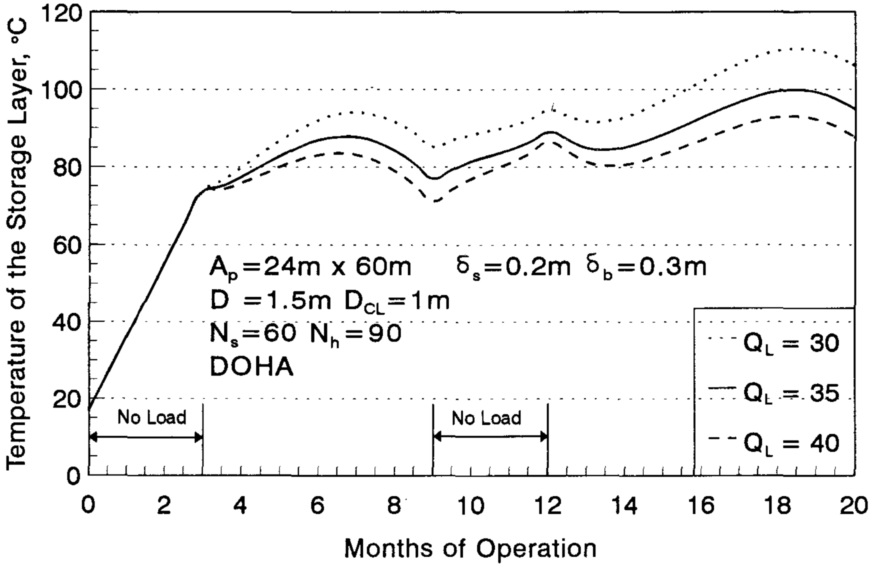

Fig. 4: Storage Layer Temperature Evolution - Effects of Varying the Load

An extensive parametric study revealed that at the proposed pond loading of 35 W/m², a pond bottom insulation of 200mm will be sufficient. However, reduction of the pond's insulating layer (NCZ) thickness from its references value of 1.5m was found to cause the storage layer temperature to decrease significantly below 80°C, making it unsuitable for powering the chiller, and is therefore not recommended.

The thickness of the storage layer (LCZ) was the next parameter investigated. With all other parameters fixed at their optimum values (i.e. values yielding maximum performance at minimum excavation and capital costs) (Fig. 5) indicates clearly that a relatively thin (0.5m) mixed storage layer yields the best results for this type of application. This is to be expected since the maximum loads occur in the summer months, and not much storage is needed. The result confirms an earlier finding reported in reference (6), and based on a study of small-scale salt-gradient solar ponds.

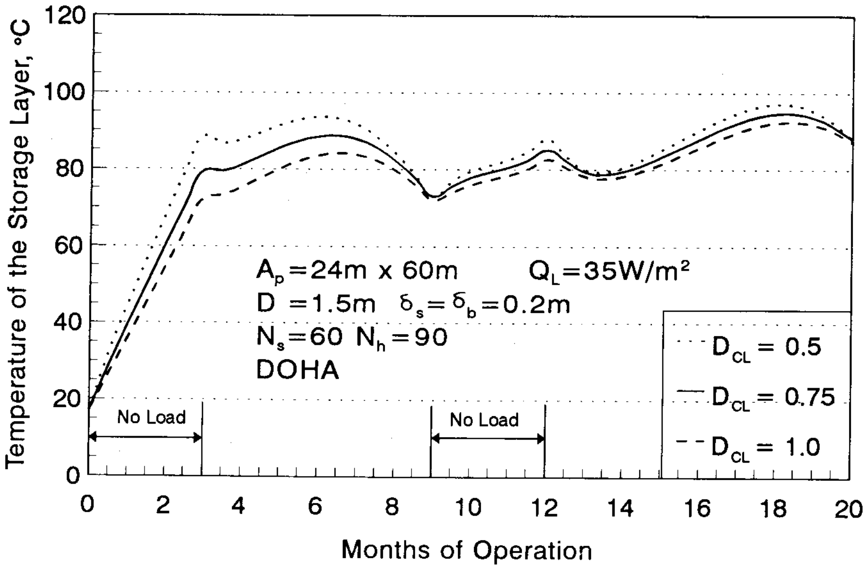

Fig. 5: Storage Layer Temperature Evolution - Effects of Varying the Storage Layer (LCZ) Thickness

CONCLUSIONS AND RECOMMENDATIONS

1. A more realistic analysis of the cooling load, i.e. a study of the hourly air conditioning load pattern, is required. Feeding a typical variable load to the solar pond model could significantly enhance the value of the study.

2. If matching of the load and pond performance is achieved a smaller pond 20 × 50m say - would possibly be sufficient to meet the loading requirements of a typical Qatari small family house. Generally, the current study indicates that for a solar pond to meet 100% of the cooling load under Qatari climatic conditions a pond of area 4-5 times the floor area of the air conditioned space is needed.

3. Compared to a conventional electricity or gas powered chiller the solar pond-powered chiller incurs the added costs of pond excavation, filling and maintenance, piping and controls. Adding the price of land, the cost becomes excessively forbidding. However, even if the cost of land is taken out of the equation, solar air conditioning does not seem to be cost-effective, even when every conceivable cost-saving measure is considered. This - unfortunately - confirms the results of earlier studies considering solar ponds for Singapore (5) and solar collectors for Kuwait (8). Recently, Flochitto (9) has shown that for a solar pond to be competitive with conventional (fossil-based) energy sources, under Italian conditions, an area in excess of 25,000m^2 - possibly 1 km^2 - is needed.

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