การศึกษาความเป็นไปได้ของการใช้สระแสงอาทิตย์ เป็นแหล่งความร้อนที่อุณหภูมิต่ำ ในภาคตะวันออกเฉียงเหนือในประเทศไทย

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บทคัดย่อ

แบบจำลองทางคณิตศาสตร์ของสระแสงอาทิตย์ได้ถูกใช้เป็นเครื่องมือในการศึกษาความเป็นไปได้ของการใช้พลังงานความร้อนจากสระแสงอาทิตย์ สำหรับการใช้งานที่อุณหภูมิต่ำในภาคตะวันออกเฉียงเหนือในประเทศไทย ผลการคำนวณที่ได้จากแบบจำลองแสดงให้เห็นว่า กรณีการดึงความร้อน 15% จากสระมาใช้งานตลอดปี อุณหภูมิเฉลี่ยของสระที่ไม่หุ้มและหุ้มฉนวนจะมีค่า 67.5^{0}C และ 77^{0}C ตามลำดับซึ่งแสดงให้เห็นว่าเป็นไปได้ในทางปฏิบัติที่จะใช้สระแสงอาทิตย์เป็นแหล่งความร้อนสำหรับการใช้งานที่อุณหภูมิต่ำ ส่วนการใช้งานเพื่อผลิตกระแสไฟฟ้า พบว่า ไม่เหมาะสม ทั้งนี้เพราะประสิทธิภาพรวมของระบบจะต่ำกว่า 1%

A Feasibility Study of Using Salt Gradient Solar Pond as a Low Temperature Heat Source in North-eastern Thailand

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Abstract

A mathematical model of salt gradient solar ponds has been used as a tool to investigate the feasibility of using solar pond thermal energy for low temperature applications in North-eastern Thailand. The simulation results obtained indicate that, at 15% heat extracted yearly, mean temperatures of an unlined uninsulated pond and a lined insulated pond are $67.5^{0}C$ and $77^{0}C$ respectively. This means that it is practically possible to use solar ponds as a heat source for all normal low temperature applications. Power generation applications are at present likely to prove uneconomic due to the low overall system efficiency estimated at less than 1%.

Introduction

At present, mathematical modeling is an economical method used worldwide for determining the technical feasibility of several technology. A feasibility study on the use of salt gradient solar ponds for providing low temperature heat in North-eastern Thailand is, as a consequence, investigated by this approach. In this study, a one-dimensional, explicit, finite difference model of a salt gradient solar pond has been developed for this task, mainly based on the mathematical formulations of Wang and Akbarzadeh (1982). In addition, the effective daily mean position of the sun for solar ponds, proposed by Reddy et al. (1986), is taken into account. The model is then used as a tool to study the possibility of the use of solar ponds for providing low-temperature heat in North-eastern Thailand, where Khon Kaen is the site selected for this study.

A Physical Description of the Solar Pond Model

The physical model of the salt gradient solar pond used in this study is considered to consist of three zones; a top connective zone or a surface mixed layer, a non-connective zone or insulating zone, and a homogeneous storage or bottom zone. The model is illustrated schematically in Figure 1.

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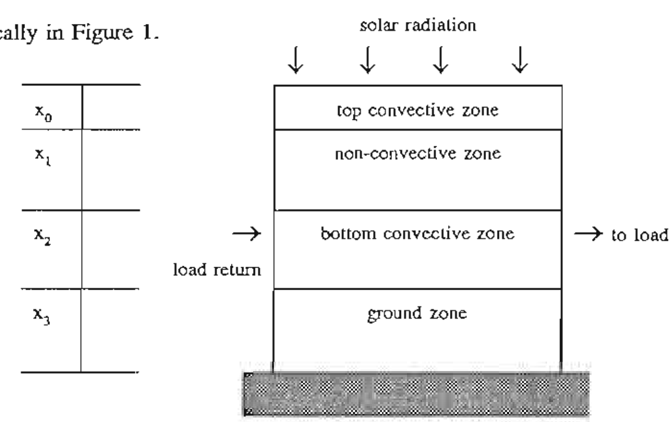

Fig. 1 **Schematic diagram of the solar pond model**

Furthermore, it is assumed that the pond is sufficiently large so that heat losses through the pond walls can be neglected, and the ground under the pond is considered as an infinite slab. The following symbols are used to denote pertinent quantities of the physical model:

x_0 = thickness of top connective zone

x_1 = thickness of non-connective zone

x_2 = thickness of storage zone

x_3 = thickness of ground zone

In nature, when solar radiation impinges on the solar pond surface, the infrared-radiation component will be first absorbed rapidly in the surface mixed layer. The remaining radiation will subsequently be absorbed partly in the connective zone before the last of the radiation reaches the bottom of the pond. The pond bottom will absorb part of the radiation passing through the connective zone, and the rest of the radiation will be reflected. The exact amount of solar energy absorbed at the pond bottom basically depends on both the transmittance of the pond and the absorbtance properties of soil in case of unlined ponds or of liners for lined ponds.

Numerical Simulation Model

Since the salt gradient solar pond investigated in this study is assumed to be adequately large so that heat losses via the pond walls can be neglected. It is therefore appropriate, from both theoretical and practical points of view, to consider a thermal process in the pond by a one-dimensional unsteady state heat conduction plus a heat generation term. The differential equation governing the thermal process is therefore:

$$k\frac{\partial^2 T}{\partial x^2}+\dot{q}=\rho c_p \frac{\partial T}{\partial t} \tag{1}$$

where

c_p = specific heat of salt solution

ρ = density of salt solution

k = thermal conductivity of salt solution

T = temperature

t = time

x = vertical distance measured downward from the pond surface

q = heat generated per unit volume

Generally speaking, equation (1) can be practically solved by either using a numerical approach or an analytical method. However, at the present time, the numerical approach is considered more convenient than the analytical method for design purposes due to the rapid development of computers in recent years. As a consequence, a finite difference method, normally presented in most heat transfer textbooks (e.g. Kreith, 1973: Welty, 1978; Lienhard, 1981), is employed in this study to investigate the thermal behavior of the salt gradient solar pond.

To transform .equation (1) into a finite difference equation, the solar pond, as already depicted in Fig. 1, was divided into n horizontal layers as shown schematically in Fig. 2. The nodes are located at the middle of each layer, but the layers are not necessarily equal in practice.

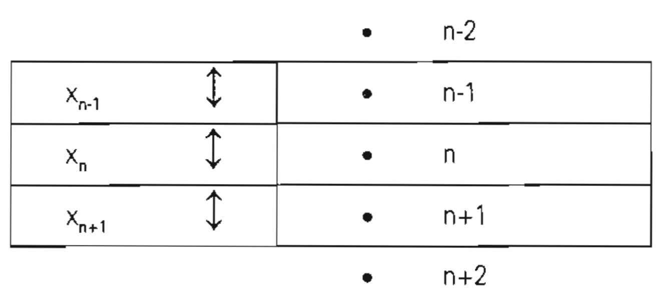

Fig. 2 **The layers employed in the finite difference approximation of a one dimensional solar pond**

By writing an energy balance for the three adjacent nodes as illustrated in figure 2, a relationship between the temperature of node n at time t+Δt and the temperatures of node n and the two adjacent nodes at time t can be expressed by an explicit finite differential equation of the form given below :

$$T_n(t+\Delta t) = \left(\left[\frac{T_{n-1}(t)}{R_{n-1}}\right] + \left[\frac{T_{n+1}(t)}{R_{n+1}}\right]\right)\left(\frac{\Delta t}{\Delta x \rho_n c_n}\right) + \left[1 - \left(\frac{1}{R_{n-1}} + R_{n+1}\right)\frac{\Delta t}{\Delta x \rho_n c_n}\right] T_n(t) + \dot{q}\frac{\Delta t}{\rho_n c_n} \qquad (2)$$

Where

R_{n-1} = $(\Delta x_{n-1}/2k_{n-1}) + (\Delta x_n/2k_n)$

R_{n+1} = $(\Delta x_{n+1}/2k_{n+1}) + (\Delta x_n/2k_n)$

Δx = thickness of each layer

ρ = density

c = specific heat

k = thermal conductivity

The final temperatures of all layers at the end of each time increment can be calculated node by node by repeatedly employing the above equation and the known initial temperature of each node. In this way, the temperature evolution of all whole layers in the solar pond can be numerically evaluated step by step.

From a computational viewpoint, the smaller the values of Δx and Δt, the more accurate the solution will be, since the error involved with a finite difference approach is normally proportional to $(\Delta x)^4$ (Wang and Akbarzadeh, 1982). However, the selection of Δx and Δt must also satisfy the stability criteria (Kreith, 1973) :

$$\left(\frac{1}{R_{n-1}} + \frac{1}{R_{n+1}}\right)\frac{\Delta t}{\Delta x_n \rho_n c_n} < 1 \qquad (3)$$

If the stability requirement in equation 3 is not satisfied due to an inappropriate selection of Δx and Δt, the coefficient of $T_n(t)$ will become negative, and lead to a violation of the second law of thermodynamics.

In this simulation, the bottom convection zone is considered as a single sublayer with an equivalent thermal conductivity evaluated from the natural connective heat transfer coefficient in that zone (see Eckert and Drake, 1972). The top connective-zone temperature is also assumed to be uniform and equal to the ambient temperature. In addition, the sublayer thickness of the non-connective zone and the time increment used in this simulation are the same as employed by Wang and Akbarzadeh (1982).

Simulation Assumption

Model simulations generally require a number of assumptions, since in reality simple mathematical formulations can not be used to depict natural physical phenomena. As a consequence, for simulating the solar pond model used here the necessary assumptions are presented in detail in this section.

Solar Insolation

In this simulation, the total radiation is assumed to be entirely composed of beam radiation. In other words, the beam and diffuse radiations come directly from the sun at the same angle of incidence according to an effective daily mean position of the sun for solar ponds.

The Transmittance of Salt Gradient Solar Ponds

Various empirical correlations have been employed by several workers (Rabl and Nielsen, 1975; Bryant and Colbeck, 1977; Hull, 1980) to evaluate the transmittance of salt gradient solar ponds. However, the values of transmittance obtained from these empirical formulae close to each other. As a result, the simple empirical formulation first proposed by Bryant and Colbeck (1977) and subsequently modified by Wang and Akbarzadeh (1983) was selected to determine the estimated value of the attenuation of solar radiation is the pond:

$$h = 0.36 - 0.08 \ln y \tag{4}$$

where

h = the fraction of solar radiation which remains after penetrating the water surface to the depth considered.

y = path length or the actual path of the radiation through the water body.

The real distance or path length, y, is related to the distance, x, measured downward from the solar pond surface and the angle of refraction :

$$y = \frac{x}{\cos r} \tag{5}$$

where

x = distance measured downward from the solar pond surface

r = angle of refraction

For water and dilute salt-water solutions, the angle of refraction is related to the incident angle and the indices of refraction of water as illustrated below :

$$\frac{\sin\theta}{\sin r} = 1.33 \tag{6}$$

The angle of incidence, θ , can be evaluated by the equation below :

$$\cos\theta = \sin\delta\sin\phi + \cos\delta\cos\phi\cos\omega \tag{7}$$

where

δ = declination

ϕ = latitude

ω = hour angle

For the coefficient of transmittance due to reflection at the surface of the solar pond, a conservative value of 0.85 is used in this simulation.

Effective Daily Mean Position of the sun for Solar Ponds

In order to determine the incident angle of solar radiation impinging on the pond surface which is subsequently employed to estimate the attenuation of solar radiation in the pond as mentioned in the previous section, the position of the sun at 2 pm on the day considered has been selected as being representative of the mean position of the sun by several researchers such as Rabl and Nielsen (1975) and Wang and Akbarzadeh (1981). However, in reality, the mean position of the sun with respect to the pond changes every day. As a consequence, in this simulation, an effective solar time (EST) proposed by Reddy et al. (1986) is taken into account in the process of determining the effective daily mean position of the sun. The mathematical formulation of EST is given by:

$$EST = 15.328 - 3.13\exp[-2.46\cos(\phi - \delta)] \quad \text{for } 0 < \phi < 50 \qquad (8)$$

Thermal Properties of Salt Water

A sodium chloride salt was selected for creating a salt gradient in this solar pond model. The mathematical formula of thermal properties of a sodium chloride solution, proposed by Wang and Akbarzadeh (1982) as a function of both salt concentration and temperature, were employed in this simulation.

$$k_w = 0.5553 - 0.0000813S + 0.0008(T - 20) \qquad (9)$$

$$\rho_w = 998 + 0.65S - 0.4(T - 20) \qquad (10)$$

$$c_w = 4180 - 4.396S + 0.0048S^2 \qquad (11)$$

where

k_w = thermal conductivity of sodium chloride solution

ρ_w = density of sodium chloride solution

c_w = specific heat of sodium chloride solution

S = concentration

T = temperature

Thermal Properties of Soil Beneath the Pond

In this simulation, it is assumed that the bottom of the pond is lined with 5-m deep clay. Moreover, the average temperature of the soil at the depth just mentioned is also assumed to be constant and equal to the yearly average of the ambient temperature. Conservative values of thermal properties of clay, obtained from a heat transfer textbook (Incorpera and DeWitt, 1981) and employed in this study, are as follows.

k_g = clay thermal conductivity

= 1.28 W/m K

ρ_g = clay density

= 1460 kg/m^3

c_g = clay specific heat

= 880 J/kg K

Simulation Inputs

In practice, it is feasible to simulate solar pond models by using deterministic, reduced data sets, or stochastic inputs, depending on the models employed, the purpose of the calculations and the availability of the actual measured climatological data. For instance, Weinberger (1964), Rabl and Nielsen (1975) and Akbarzadeh and Ahmadi (1982) employed stochastic inputs. Wang and Akbarzadeh (1982) used both stochastic inputs and reduced data sets to simulate solar pond models whereas Hawlader (1984) employed deterministic inputs. Reduced data sets, monthly average daily solar radiation and monthly average daily ambient temperature, are employed in this numerical model simulation. The monthly average daily solar radiation and monthly average daily ambient temperature available at the site considered in this study, namely Khon Kaen as previously mentioned, are shown in Table 1.

Table 1

Recommended average days for each month (Klein, 1976), monthly average daily solar radiation and monthly average ambient temperatures.

Month	Day of the year	Monthly average daily radiation (MJ/m^2 - day)	Monthly average ambient temperature (°C)
Jan.	17	15.7	23.2
Feb.	47	16.0	25.7
Mar.	75	16.5	28.8
Apr.	105	18.0	30.2
May.	135	18.5	29.4
Jun.	162	16.7	28.7
Jul.	198	16.5	28.1
Aug.	228	15.3	27.7
Sep.	258	14.9	27.2
Oct.	288	17.0	26.7
Nov.	318	15.8	25.0
Dec.	344	14.5	23.2

Source : Khon Kaen Meteorological station

Simulation Results and Discussions

The results obtained from numerically simulating the solar pond model, using the monthly average daily solar radiation and monthly average ambient temperature data of Khon Kaen as simulation inputs, are presented and discussed in this section.

Effect of Load on the Solar Pond Thermal Performance

In order to investigate the influence of load on the solar pond thermal performance, the pond in this case is considered to have 0.2 m top convective zone, 1-m non connective zone, 1-m bottom connective zone, and 5-m dry clay beneath the pond bottom. Furthermore, the pond is assumed to be sufficiently large so that the wall heat losses may be neglected. The thermal properties of clay mentioned previously in section 4.5 are employed in this investigation. An operation of the pond commences on 1st January with heat extraction 5%-20% of monthly average solar radiation, starting after 120 days of operating the pond. Both an unlined uninsulated pond and a lined insulated pond (insulated with 0.1 m Styrene foam) are investigated in this study, and the simulation results, ten years of predicted bottom zone temperatures, are illustrated graphically in Figures 3 and 4 respectively.

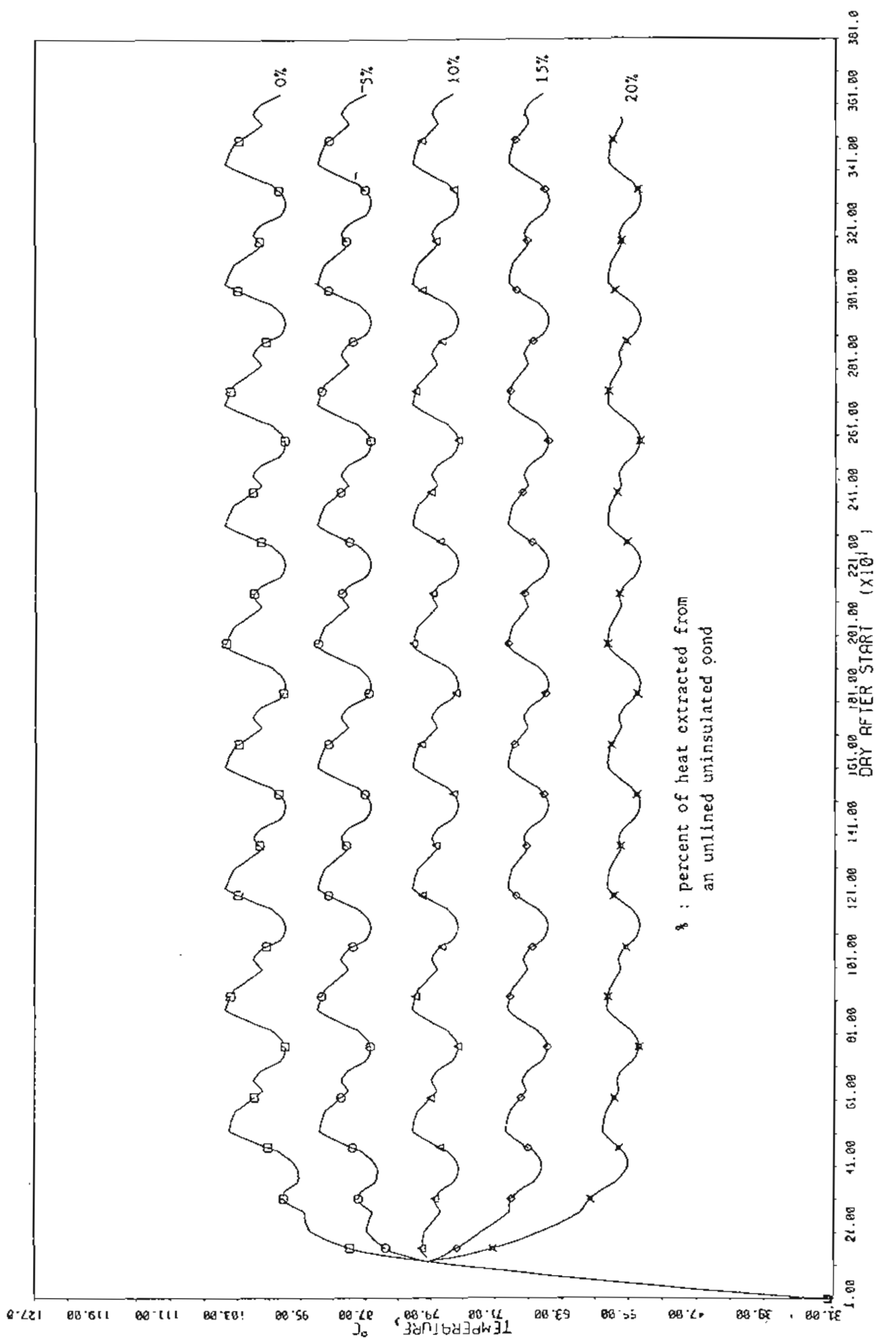

Figure 3 **Variation of bottom zone temperature due to changes of load in unlined uninsulated pond.**

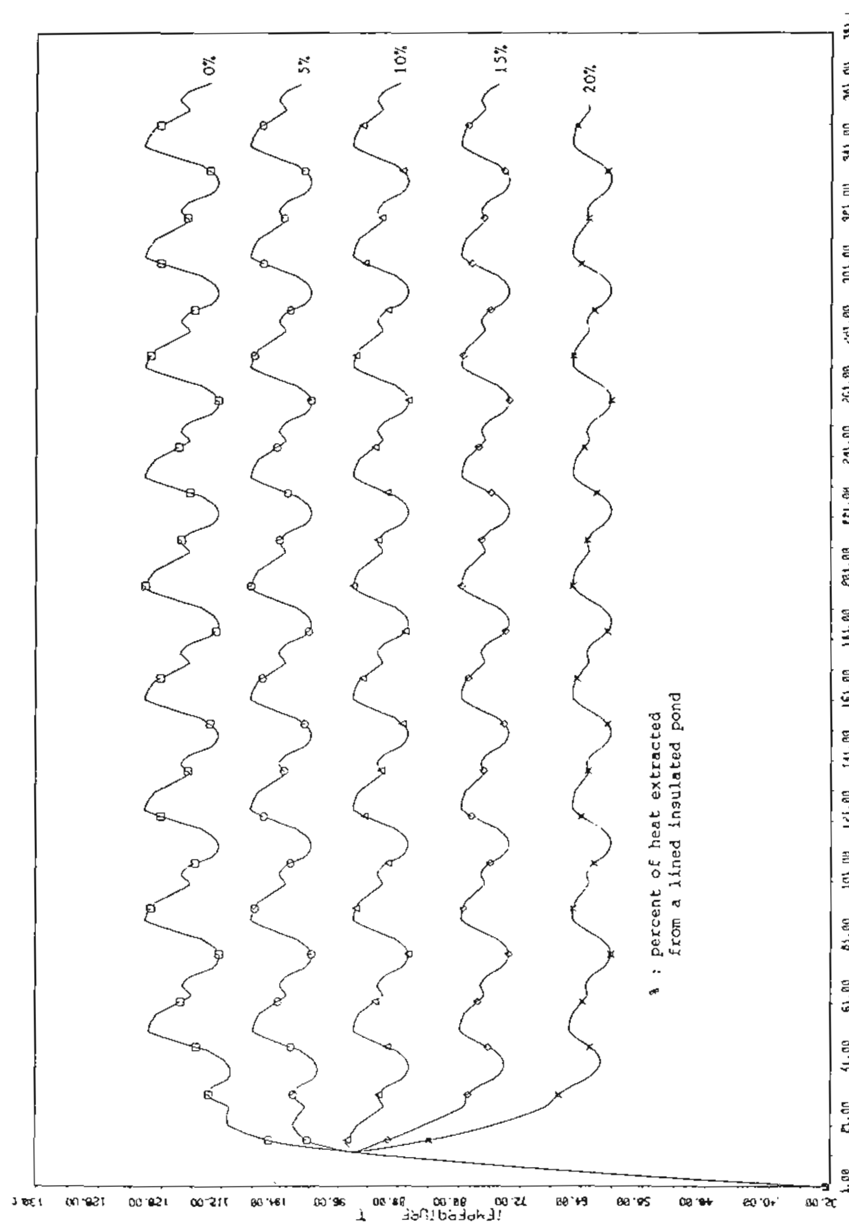

Figure 4 **Variation of bottom zone temperature due to changes of load in lined insulated pond.**

It can be seen from Figures 3 and 4 that the bottom zone temperature of both ponds are in quasi- steady state conditions after 2 years of operating the pond. The maximum, minimum and mean temperatures of the bottom zones under quasi-steady state conditions are presented in Table 2 .

Table 2

The effect of load on the bottom zone temperatures.

Pond type	% heat extraction	bottom zone temperatures, ^{0}C			
		maximum	minimum	mean	fluctuation
unlined uninsulated pond	0	104	97	100.5	7
	5	92.5	86	89.3	6.5
	10	81	75.7	78.2	5.5
	15	70	65	67.5	5
lined insulated pond	0	122	112	117	10
	5	108	100	104	8
	10	94	87	90.5	7
	15	80	74	77	6

Table 2 also indicates that the temperature fluctuations of both ponds shown an insignificant decrease, from $7^{0}C$ to $5^{0}C$ for the unlined uninsulated pond and from $10^{0}C$ to $6^{0}C$ for the lined insulated pond, as the heat extracted from the bottom zone of the ponds increases from 5% to 15%. This is probably due to the steady availability of solar radiations and relatively constant ambient temperatures at Khon Kaen over the year (see Table 1) .

Possible Applications for Solar Pond Thermal Output in North-Eastern Thailand

From the simulation results illustrated in Table 2, salt gradient solar ponds established in North-eastern Thailand may possibly be employed for the following low temperature applications such as cooling of buildings, power generation, desalination, salt production, low temperature industrial process heating, greenhouse heating and grain drying.

Space Cooling

Space cooling in North-eastern Thailand is normally required nearly throughout the year. Fortunately, the cooling load pattern in this region coincides with the steady solar radiation associated with insignificant variations at Khon Kaen. Hence, if salt gradient solar ponds are designed for space cooling in this area, it may not be necessary to provide interseasonal storage facilities. In practice, the minimum temperature required for the efficient operation of an absorption chillier for space cooling is approximately $75^{0}C$. From table 2, it can seen that the heat required for the absorption chillier can be supplied either by 10% of heat extracted from the unlined uninsulated pond or by 15% of heat withdrawn from the lined insulated pond, without reducing the temperatures of the storage zones below $75^{0}C$. It is obvious from this point of view that for the same cooling heat loads, the unlined uninsulated ponds required larger surface areas than that of the lined insulated ponds. On the other hand, the total costs of construction of unlined uninsulated ponds are normally lower than those of lined insulated ponds. As a consequence, no firm conclusion can be drawn at this stage regarding either the suitability of using unlined uninsulated ponds or lined insulated ponds for space cooling applications unless an economic feasibility study is undertaken. The unlined uninsulated pond can also supply 15% of the heat extracted for the chillier, but the temperature will be lower than the desired value so that in this case an auxiliary heater may be necessary.

Power Generation

From the power generation point of view, if salt gradient solar ponds situated at and location attain high temperature approaching $100^{0}C$, it is technically possible to convert heat extracted from those solar ponds into electricity through the Organic Rankine Cycle engine. The temperatures of the bottom zones illustrated in Table 2 indicate that it is not technically feasible to use heat withdrawn from the unlined uninsulated solar ponds for power generation, since the bottom zone temperature at 5-15% of heat extraction rate are lower than the desired temperature. In contrast, at 5% heat extraction rate, the lined insulated solar ponds can supply thermal energy for a solar power plant at the desired temperature. Generally, the overall estimated-system efficiencies of solar pond power plants are in the range of 1% to 2% if practical operational collection efficiencies of solar ponds are in the range of 10% to 20% (Charters, 1986). From this point of view, it is obvious that overall estimated-system efficiencies of solar pond power plants, supplied by 5% of heat produced by the insulated solar ponds, must be lower than 1%. An economic feasibility study is, as a consequence, considered necessary to verify the suitability of establishing solar ponds for power generation in North-eastern Thailand. At present two small experimental solar ponds are being investigated in Thailand (Wibulswas, 1986). However, further research and development of solar ponds is absolutely essential, especially in North-eastern region, before any firm conclusion can be drawn concerned with appropriateness of the use of the solar ponds for power generation in this area.

Desalination and Distillation

It is a well-known fact that the fresh water required for drinking and domestic use is scarce in rural areas of North-eastern Thailand especially in the dry season. Quite a few solar stills have been designed and constructed locally for distillating local available brackish or saline water, but the yields of the stills just mentioned are very low as compared with other conventional desalination processes (Kreith et al., 1891; Wibulswas, 1984). The development of multi-effect distillation plant (MEDP) operating at approximately 70^{0}C allows solar ponds to be considered as potential heat sources for this application (Tabor, 1975; Golding., 1984). It can also be seen from Table 2 that the thermal energy required for the MEDP can be supplied at the desired temperature by either 10% of heat extracted from the unlined uninsulated solar ponds or 15% of heat produced by the lined insulated solar ponds. Even though the MEDP can significantly give more yield than that of the solar stills, the initial costs of this equipment are quite expensive and as well it has to be imported from overseas, since it is presently impossible to locally design and construct the MEDP . In addition, the MEDP is rather complicated for unskilled or semi-skilled people in rural areas of North-esatern Thailand to operate and maintain. As a consequence, the use of solar pond heat for desalination through the MEDP may probably be inappropriate from both technical and economical points of view.

Product Drying

In Thailand, traditional sun-drying has consideralby been used successfully for centuries. However, this traditional drying method is generally affected by rain, dust, infestation of insects and so on. To overcome the problems just mentioned, various types of solar dryers have, as a consequence, been locally designed, tested and developed for a wide variety of drying applications. These include the box type and the cabinet free convection dryers for cash crops, meat and marine products (Wibulswas, 1984); solar assisted tobacco-curing barns (Boon-long, 1984); free convection solar groundnut dryer (Limtragool and Direcksataporn, 1985) and so forth. Field experimental test results indicate that the initial costs of solar dryers seem to be too expensive for normal individual rural farmers. The dryers will only be economically attractive if they can be employed as all year round multi-crop dryers. In addition, it is worth noting that large scale solar dryers have a high potential for rural industrial applications. The simulation results obtained from the solar pond model has also show that thermal energy produced by solar ponds can be technically employed for drying applications. Moreover, due to the intermittent nature of solar radiation, the solar pond dryer is potentially more attractive than the flat plate forced convection dryers, especially for continuous drying applications, since no form of energy storage or of auxiliary heating system is required. It is obvious from this point of view that if solar ponds are to be used for drying applications, they should be concentrated on large scale industrial dryers. The development of solar pond dryers should, in addition, be accelerated and promoted at the national level.

Industrial Process Heat

According to the government policy of decentralizing industries with an aim of creating jobs in rural areas, there are presently many medium scale industries established and being constructed in North-eastern region, such as fruit canning, pulp and paper production, sugar refineries, tapioca pelleting and so on (Sims et al., 1984). Typically, low temperature thermal energy is needed in the industries just mentioned, especially food and paper industries, and at present this is mainly based on imported heavy oil from overseas. It can be seen from the simulation results in Table 2 that this industrial process heat can alternatively be supplied by heat extracted from solar ponds if sufficient land is available for this construction. Moreover, in reality, these factories are normally situated in a non-urban area of this region in order to lessen the social conflict and problems inherent in urban environments. As a consequence, the use of solar ponds for this application is potentially feasible if water is also available at the factory sites or nearby. However, the research and development of solar ponds for supplying industrial process heat should be first undertaken by the government sector. If economic investigation results indicate that the costs of low temperature thermal energy produced by solar ponds are relatively lower than that by conventional fuel, demonstration programs should be carried out subsequently to encourage private companies on the use of solar pond heat for this application.

Salt Production and Mineral Processing

The production of rock salt, used as feed stock for producing caustic soda and chloride gas, is one of the important industries in this region. The total indicated reserves of rock salt is approximately 4,600 million (metric) tonnes, and the total amount of inferred reserves of rock salt is as much as 2,000,000 million tonnes (Sims et al.,1984). At present rock salt, locally produced by the only salt manufacturer in this region namely the Thai-Ashahi company, is obtained through solar distillation of low salinity water in a consecutive series of evaporation pans. About 100-150 tonnes/day of rock salt is produced presently for 4-6 months of the year. It can be seen from this point of view that rock salt production is another high potential application of solar ponds established in this region. The use of solar pond heat will substantially increase both the yield and the quality of the salt produced, and make it possible to produce rock salt throughout the year. However, an economic evaluation as compared with the traditional method is considered necessary before a firm conclusion can be drawn concerned with the suitability of the use of solar ponds for this application.

Horicultural Production

Even though the use of solar pond heat for greenhouse heating is also feasible for the area under consideration, this application is, however, practically limited at rural industrial level since salt gradient solar ponds can be economically attractive only on a relatively large scales and besides, the total costs on the use of solar ponds for the process just metioned are too expensive for normal rural farmers.

Conclusion

The salt-gradient solar pond appears to offer a simple and attractive approach to collect and store solar energy for low temperature application in North-eastern Thailand. However, the salt-gradient solar ponds are, for the time being, not in widespread use. This is because there are still numerous practical problems to be solved.

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