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Simulation of Solar Air-Conditioning System with Salinity Gradient Solar Pond

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Abstract

In hot dry climates, due to the high demand for space air conditioning during summer and the abundance of solar radiation, solar air conditioning is a promising approach to reduce the energy consumption and negative environmental impact of buildings. Solar cooling systems have used various types of collectors to drive chillers. In this paper, a salinity gradient solar pond is suggested as a collector to drive an absorption chiller, to provide cool air for a house during hot and dry weather. A coupled simulation between MATLAB and TRNSYS has been used to solve the problem. MATLAB code was written to solve the governing equations for the salinity gradient solar pond and the ground underneath it. TRNSYS software was used to model the solar cooling system including the absorption chiller and building. The weather data used was for Baghdad in Iraq. It was found that the salinity gradient solar pond could be used to drive the absorption chiller and produce cool air for a single family house during the summer period. Different solar pond areas were tested with the same chiller capacity. It was found that a solar pond area of approximately 400 m² was required to provide satisfactory cooling for a typical house with a floor area of approximately 125 m².

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Keywords: Salinity gradient solar pond; solar cooling; solar thermal energy; TRNSYS simulation.

1. Introduction

Air conditioning of residential and commercial buildings is essential in hot and dry weather such as in the Middle East. A common solution to provide thermal comfort is a conventional air conditioning system

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using electricity from power stations burning fossil fuel. The electricity consumption for air conditioning in Saudi Arabia exceeds 70% of the electricity consumption during the summer months [1]. The financial and environmental cost of this makes renewable energy sources attractive for buildings.

<table>
<thead>
<tr>
<th>Nomenclature</th>
<th>Greek letters</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_p$</td>
<td>specific heat capacity for brine (J/kg °C)</td>
</tr>
<tr>
<td>$C_{pg}$</td>
<td>specific heat capacity for soil (J/kg °C)</td>
</tr>
<tr>
<td>$E$</td>
<td>rate of solar irradiance absorption per unit volume of water (W/m$^3$)</td>
</tr>
<tr>
<td>$H_o$</td>
<td>insolation incident on horizontal surface (W/m$^2$)</td>
</tr>
<tr>
<td>$H_x$</td>
<td>incoming radiation flux at depth $x$ (W/m$^2$)</td>
</tr>
<tr>
<td>$H_b$</td>
<td>incoming radiation flux at bottom of the pond (W/m$^2$)</td>
</tr>
<tr>
<td>$h$</td>
<td>convection heat transfer coefficient for LCZ (W/m$^2$ °C)</td>
</tr>
<tr>
<td>$k$</td>
<td>thermal conductivity (W/m °C)</td>
</tr>
<tr>
<td>$k_g$</td>
<td>soil thermal conductivity (W/m °C)</td>
</tr>
<tr>
<td>$L_g$</td>
<td>depth of water table (m)</td>
</tr>
<tr>
<td>LCZ</td>
<td>Lower Convective Zone</td>
</tr>
<tr>
<td>NCZ</td>
<td>Non-Convective Zone</td>
</tr>
<tr>
<td>$T$</td>
<td>temperature (°C)</td>
</tr>
<tr>
<td>$T_b$</td>
<td>temperature at the bottom (°C)</td>
</tr>
<tr>
<td>$T_g$</td>
<td>ground or soil temperature (°C)</td>
</tr>
<tr>
<td>UCZ</td>
<td>Upper Convective Zone</td>
</tr>
<tr>
<td>$x$</td>
<td>distance from the surface of the solar pond (m)</td>
</tr>
<tr>
<td>$X$</td>
<td>layer thickness (m)</td>
</tr>
</tbody>
</table>

One of the possible options is to use solar thermal energy to drive an absorption chiller. Different types of solar thermal collectors have been used in such solar cooling systems, such as: flat plate solar collector and evacuated tube collectors. [2]

A salinity gradient solar pond has also been suggested as a combined collector and heat store to drive an absorption chiller. As well as cooling of buildings, solar pond technology has various other applications such as industrial process heating, heating of buildings, refrigeration, desalination and salt production, and power generation.

A solar pond is an artificial large body of liquid (usually water) that collects and stores solar thermal energy. The solar radiation landing on the surface of the pond penetrates the liquid and falls on the blackened bottom which is thereby heated. If the liquid is homogeneous then convection currents will be set up and the heated liquid will travel towards the surface and dissipate its heat to the atmosphere. In a salinity gradient solar pond these convection currents are prevented by having a concentration gradient of salt, the concentration and solution density being highest at the bottom and lowest at the top. Typically ponds are composed of three zones as shown in Figure 1. The topmost zone is the Upper Convective Zone (UCZ), which has low salt concentration. The middle zone is the Non-Convective Zone (NCZ) or insulation layer, which has salt concentration increasing with depth. Water in the NCZ does not rise if it is
hotter than the water immediately above because the water above has a lower salt concentration and is, therefore, less dense. Similarly, water in the NCZ does not fall if it is cooler than the water immediately below, because the water below has a higher salt content and is, therefore, denser. Thus, convection motions are hindered and upwards heat transfer from the lowest zone, the Lower Convective Zone (LCZ), is only by conduction. Heat may be extracted from the LCZ to drive an absorption chiller. The other main components of the solar cooling system are a cooling tower to reject heat to the ambient, a fan and cooling coil for distributing cool air inside the building, a heat exchanger between the solar pond and the chiller, pumps and controls.

Weinberger [3] studied the thermal energy balance for a large solar pond in 1964. Rabl and Nielsen [4] developed the model of Weinberger with a two-zone pond. Hull [5], Rubin et al. [6], and Kurt et al. [7] used a finite difference method to solve the partial differential energy equation for the solar pond. The thermal performance of solar pond can be significantly affected by heat loss through the bottom. Saxena et al. [8] investigated the effect of water table depth on solar pond thermal performance. Simulation analysis indicates that deeper the water table, the lower the heat losses and the higher the temperature achieved by the pond. Ranjan and et al. [9] mention some instances of utilization of solar ponds for refrigeration and air-conditioning. Tsilingiris [10, 11] investigated the possibility of using solar ponds as low-cost solar collectors combined with an absorption chiller in a large scale solar cooling system. The analysis is based on the combination of a steady state solar pond mathematical model with operational characteristics of a commercial absorption chiller.

In the current paper, a coupled simulation between a transient model of the solar pond and the ground in MATLAB and of the chiller, air conditioning and building in TRNSYS is used to investigate the performance of the complete system.

2. Mathematical Modelling

2.1. Solar pond and ground model

The simulation model is one-dimensional and is modified from [8, 12]. The vertical coordinate (x) is measured as a positive downward, and x = 0 at the surface of the pond as shown in Figure 1. The heat flow equation for the solar pond is given by Eq. (1). [6]

\[ \rho C_p \left( \frac{\partial T}{\partial t} \right) = k \left( \frac{\partial^2 T}{\partial x^2} \right) + E(x, t) \]  

(1)

The rate of solar energy absorption by the fluid per unit volume can be expressed by Eq. (2).

\[ E = -\frac{\partial H(x, t)}{\partial x} \]  

(2)

The solar radiation penetrating the water decays exponentially with depth and is given by Eq. (3). [15]

\[ \frac{H_x}{H_0} = \left\{ 0.36 - 0.08\ln \left( \frac{x}{\cos \theta_r} \right) \right\} \]  

(3)

The heat flow equation through the soil underneath the solar pond is given by Eq. (4). [13]

\[ \rho_g C_{pg} \left( \frac{\partial T_g}{\partial t} \right) = k_g \left( \frac{\partial^2 T_g}{\partial x_g^2} \right) \]  

(4)

Assuming no insulation between the pond and the soil, the heat transfer equation between the bottom of the solar pond and soil is given by Eq. (5). [13]

\[ k_g \left( \frac{\partial T_b}{\partial x_g} \right) + h(T_b - T_{LCZ}) = H_b \]  

(5)
MATLAB code is used to solve the governing equations of heat transfer for the solar pond and ground underneath, using an explicit finite difference method. The most important output from the code is the LCZ temperature, as this is used to drive the absorption chiller.

2.2. System description

The complete simulated solar cooling system consisted of a single effect vapour absorption water chiller with rated capacity of 7 TR and based on [14], thermally powered by the salinity gradient solar pond. Chilled water is passed through a cooling coil, and the cool air distributed by a fan to a 125 m² single family house in Baghdad, Iraq (33.32° N, 44.42° E), based on typical house. The heat rejected from the chiller is dissipated to the environment by a wet cooling tower. Pumps are used to regulate the flow rate, and a controller provides automatic operation of the system. Real component data is used in the simulation. The MATLAB code for the pond and soil are called by TRNSYS [16] using the Type 155 component as shown in Figure 2.

Different solar pond areas were tested with the same chiller capacity, house and other components. For each pond area, the simulation was run for two years to allow the system to approach its long-term performance.

3. Results and Discussion

Figure 3 shows the chilled water outlet temperature for different solar pond areas for two years simulation time. With 250 m² pond area, the chilled water outlet temperature does not stabilise at the set point (7°C) even in the second year. With 400 m² or more pond area, the chilled water outlet temperature
stabilises at the 7°C set point temperature by the end of the first summer and during the second summer. 400 m² is therefore suggested as a suitable pond area for this 125 m² single family house.

Figure 3. Chilled water outlet temperature with different pond area

Figure 4 shows hot water inlet temperature to the absorption chiller with different solar pond areas. It can be seen that the larger the solar pond area, the higher the temperature achieved for the same amount of heat extracted from pond. Comparing Figures 3 and 4, it is found that when the hot water inlet temperature is 70°C or higher, then the absorption chiller works normally and the chilled water outlet temperature is close to the set point temperature.
4. Conclusions

A coupled simulation between MATLAB and TRNSYS has been used to develop a model for a solar pond and cooling system. It was found that the salinity gradient solar pond could be used to drive an absorption chiller and produce cool air for a single family house during the summer period in Iraq. Different solar pond areas were tested with the same chiller capacity. It was found that a solar pond area of approximately 400 m$^2$ was required to provide satisfactory cooling for a typical new house with a floor area of approximately 125 m$^2$. A hot water inlet temperature of 70°C or higher made the absorption chiller work at its design condition.

Acknowledgements

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References


