Energy efficiency analysis of a trapezoidal solar pond

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Abstract. In this paper we present an investigation of the energy performance of a mini trapezoidal solar pond (with surface of 2.4m×2.4m and depth of 1.5 m) which was built in Dalian,China. The pond was filled with salty water to form the upper convective zone (UCZ), the non-convective zone (UCZ), and the lower convective zone (LCZ). Energy efficiency, the ratio of available energy to the total energy, was defined basing on the first law of thermodynamics at each zone of the solar pond. The energy efficiency of the three layers were analyzed separately accounting to the simulation results of the temperature distribution in the trapezoidal solar pond. It shows that the energy efficiency of the solar pond is relatively high at the beginning of the operation, and the energy efficiency of the UCZ is the lowest while the LCZ is the highest.

1. Introduction
Solar pond is a typical solar energy collecting and storing device, which has been successfully built and operated in a number of countries due to its good environmental and economical performance[1].

There have been many studies performed with thermal behavior of solar ponds such as the heat and mass transfer, the double-diffusive convection, the multi-reflection and so on. Methods of experimental and numerical investigations are carried out to understand the characters of the heat-salt diffusion, stability, the turbidity, the heat extraction etc[2-7]. Contrast experiment is an important method for the analysis of solar pond performance. Dehghan et al.[2] discussed the influence on thermal efficiency by the cross section shape, through the contrast experiment of square, round sun pond. ElSebaii et al.[3] analyzed the influence of structure on energy efficiency, through the energy efficiency comparison of solar pond in the two heat extraction mode of open and closed. Ridha et al.[4] analyzed the working process of solar pond with a numerical study on heat and mass transfer in a salinity gradient solar pond. Sakhrieh et al.[5] using the experimental data (short-term), predicted the long-term trends of the solar pond’s temperature. Jeffrey et al.[6] presented the concept of evaporation rate, which is used to quantify the negative effects evaporation bring to heat storage of solar pond. Liu et al.[7] studied the characteristics of a trapezoidal salt gradient solar pond with experimental and numerical simulation methods, which involved the stability and turbidity of the pond. Some special methods such as adding passive device incorporating thermosyphons and thermoelectric cells[8], building thermal...
water pump to provide an alternative circulating system\cite{9}, using nanofluid to improve the thermal efficiency and the storage capacity of the pond\cite{10} are also employed in the solar pond.

In this study, basing on the first law of thermodynamics, we define the energy efficiency of each zone in the solar pond as the ratio of available energy to the total energy. Energetic performance of a mini trapezoidal solar pond is investigated and assessed through energy efficiency analysis.

2. Energy efficiency analysis

The definition of energy efficiency can be obtained from the first law of thermodynamics, which is known as energy analysis method, which is defined as the ratio of available energy in the solar pond to the total energy in the pond. Considering the different temperature distribution characteristics of each layer of the solar pond, the energy efficiency of the three layers are analyzed separately.

![](Fig.1_Energy_equilibrium_diagram_in_Solar_pond.png)

**Fig.1** Energy equilibrium diagram in Solar pond

2.1 Energy efficiency for the upper convective zone (UCZ)

Energy flows in UCZ can be illustrated as shown in Fig.1, and the energy balance equation for UCZ is:

\[
\eta_U = 1 - \frac{Q_{\text{loss}} + Q_{w,\text{U}}}{Q_{S,\text{U}} + Q_{N,\text{U}}} \tag{1}
\]

where \( \eta_U \) is the energy efficiency for UCZ, \( Q_{S,\text{U}} \) is the energy of solar radiation reaching to the surface of UCZ, \( Q_{N,\text{U}} \) is the heat transfer from NCZ to UCZ, \( Q_{\text{loss}} \) is the heat loss from UCZ to the ambient air, \( Q_{w,\text{U}} \) is the energy loss through side walls of UCZ.

The energy values of each part can be calculated according to the definition. The formula for calculating the solar radiation energy transmitted to UCZ is:

\[
Q_{S,\text{U}} = (1 - \gamma)(1 - l)\Phi_0[A_0 - A_{U,N}h(L_U)] \tag{2}
\]

where \( \gamma \) is the percentage of reflected long-wave solar radiation onto the pond surface, \( l \) is the percentage of absorbed long-wave solar radiation on the surface, \( \Phi_0 \) is the total solar energy to reach the surface of the solar pond (W), \( A_0 \) is the upper surface area of solar pond (m\(^2\)), \( A_{U,N} \) is the interface area between the UCZ and NCZ (m\(^2\)).

The heat transfer from NCZ to UCZ:

\[
Q_{N,\text{U}} = \frac{k_U A_{U,N}}{L_U} (T_N - T_U) \tag{3}
\]

where \( T_U \) is the temperature of UCZ (K), \( k_U \) is the average coefficient of thermal conductivity (W/m·K), \( L_U \) is the thickness of UCZ (m).

Surface heat loss of UCZ:

\[
Q_{\text{loss}} = U_w A_0 (T_U - T_a) \tag{4}
\]
where \( T_a \) is the average ambient air temperature, \( U_{wa} \) is heat transfer coefficient between the ambient air and upper surface solar pond.

Wall heat loss of UCZ: \( Q_{w,U} = A_{w,U} (T_U - T_U^c) / R_c \)  

(5)

where \( T_U^c \) is ambient air temperature of UCZ (K), \( A_{w,U} \) is the surface area on the side walls (m\(^2\)), \( R_c \) is the thermal resistance, \((\text{K} \cdot \text{m}^2/\text{W})\) and \(1 / R_c = k_p k_s / (s_p k_s + s_s k_p)\), where \( k_p \) and \( k_s \) are thermal conductivity of the paint polystyrene board and cement layer (W/m·K), \( s_p \) and \( s_s \) are the corresponding thicknesses (m).

2.2 Energy efficiency for the upper convective zone (NCZ)

The energy entering the NCZ layer includes the energy of solar radiation reaching to NCZ \( (Q_{S,N}) \) and the heat transferred from LCZ to NCZ \( (Q_{L,N}) \). Energy leaving the layer includes the heat loss from the side wall of NCZ \( (Q_{w,N}) \) and the heat transfer from NCZ to UCZ \( (Q_{N,U}) \).

The remaining energy is NCZ can be calculated according to the energy of each zone, and the expression of NCZ energy efficiency is obtained as:

\[
\eta_N = 1 - \frac{Q_{N-U} + Q_{w,N}}{Q_{S,N} + Q_{L-N}}
\]

(6)

The energy of each zone can be expressed as the solar radiation reaching to NCZ:

\[
Q_{S,N} = (1 - \gamma)(1 - \Phi_0)[A_{U,N}h(L_U) - A_{N,L}h(L_U + L_L)]
\]

(7)

where \( L_N \) is the thickness of NCZ (m), \( L_U \) is the thickness of UCZ (m), \( A_{N,L} \) is the interface area between the NCZ and LCZ (m\(^2\)).

Heat transferred from NCZ to LCZ: \( Q_{L-N} = k_N A_{N,L} (T_L - T_N) \)

(8)

where \( k_N \) is the heat conductivity of NCZ (W/m·K); \( T_N \) is the temperature of NCZ (K), \( T_L \) is the temperature of LCZ (K).

Wall heat loss of NCZ: \( Q_{w,N} = A_{w,N} (T_N - T_N^c) / R_c \)

(9)

where \( T_N^c \) is external ambient temperature of NCZ (K), \( A_{w,N} \) is the side-wall of solar pond (m\(^2\)), \( R_c \) is thermal resistance of side wall (K·m\(^2\)/W).

Heat transferred from NCZ to UCZ: \( Q_{N-U} = k_U A_{U,N} (T_N - T_U) \)

(10)

2.3 Energy efficiency for the lower convective zone (LCZ)

The energy entering the LCZ layer includes the energy of solar radiation reaching to LCZ \( (Q_{S,L}) \) and the side-wall heat loss of LCZ \( (Q_{w,L}) \). Energy leaving LCZ includes the bottom heat loss of LCZ \( (Q_{Lg}) \) and the heat transfer from LCZ to NCZ \( (Q_{L,N}) \).

The remaining energy in LCZ can be calculated and the energy efficiency can be expressed as:

\[
\eta_N = \frac{Q_{S,L} - Q_{w,L} - Q_{Lg} - Q_{L,N}}{Q_{S,L}}
\]

(11)

Solar radiation energy transmitted to NCZ: \( Q_{S,L} = (1 - \gamma)(1 - \Phi_0)A(z)h(L_L) \)

(12)
where $L_L$ is the thickness of LCZ(m). $A(z)$ is the area for the depth of Z (m$^2$).

Heat loss from the side wall of LCZ: 
$$Q_{w,L} = A_{w,L} \left( T_L - T_L^c \right) / R_c$$  \hspace{1cm} (13)

where $T_L$ is the temperature of LCZ (K). $T_L^c$ is the external ambient temperature (K).

Heat loss at the bottom of LCZ : 
$$Q_{wg} = A_{wg} \left( T_L - T_{wg} \right) / R_{wg}$$  \hspace{1cm} (14)

where $T_{wg}$ is the soil layer temperature(K); $A_{w,L}$ was LCZ side wall surface area (m$^2$), $A_{wg}$ is the area of contact surface between LCZ and soil layer. $R_{wg}$ is the thermal resistance of the soil (K.m$^2$W$^{-1}$).

Heat transferred from LCZ to NCZ : 
$$Q_{L-N} = k_N A_{N,L} \frac{L_N}{T_L - T_N}$$  \hspace{1cm} (15)

3. Results and discussion energy efficiency

A mini trapezoidal solar pond with surface 2.4m$\times$2.4m and bottom 1.0m$\times$1.0m is constructed outside the laboratory in Dalian University of Technology, China. Dalian located in north latitude 39°55´ Tokyo 121°31´, and it also is a seashore city with rich resources of water and salt. The structure diagram of the solar ponds is shows as in Fig.2\cite{7}.

![Fig 2. Schematic diagram of solar pond](image)

![Fig 3. The temperature distribution cloud solar pond](image)

Thermal performance of the trapezoidal solar pond is numerically simulated by an one-dimension model base on the experimental data\cite{7}. Fig.3 shows the simulation result of the temperature changing with time and depth. The simulations starts from zero o’clock on September 1 and finished at 24 o’clock on September 12. The solar radiation and temperature data used in the simulation are also extracted from experiments\cite{7}.

We can see that with the time running, the overall temperature of solar pond is increasing, the top temperature of each day occurs near the 14th hours, and the highest temperature reaches to 41.7°C on the 12th day near depth of 0.8~0.9m. It can be seen that the temperature of UCZ (0-0.2m) is low and instability due to the heat loss on the surface, and the lowest temperature is about 12.79°C. The temperature of NCZ increasing linearly with depth, which indicates the gradient of salinity in NCZ can restrain the heat convection.

Fig.4 shows the variation of solar energy efficiency of different depth from the beginning of the filling day. It can be seen that energy efficiency in different depth is relatively high in the early days (1-10 days). The position of LCZ has the highest energy efficiency while the UCZ has the lowest one. The highest energy efficiency appears on the first day of the operation at LCZ, which is close to 63%. On the view of heat transfer, that is because that the temperature difference between initial operation of the solar pond and the environment is not large, and heat loss is also relatively small. As the most of solar radiation has been absorbed by the water, higher energy efficiency appeared during...
the initial operation. It can be seen that the energy efficiency score and its change rate decrease with time, especially when the solar pond is in a stable phase (20 days later).

**Fig.4.** The energy efficiency distribution cloud  **Fig.5.** Variations of the energy efficiency of each zones

Fig.5 shows the UCZ, NCZ, LCZ energy efficiency changed with time. At the beginning of the operation, the temperature of the solar pond changed greatly, the overall change trend is that the energy efficiency of LCZ and UCZ fall sharply in the first three days, then the downward trend kept relatively moderate. However, the energy efficiency of NCZ in the first seven days does not decrease significantly. It appears a sharp decline translation on the seventh day and then keeps stabilized gradually. As the energy efficiency keep stability relatively, the energy efficiency of UCZ is the lowest, because the heat loss on the surface layer is much large while the absorbed solar radiation is relative small. It means that the thickness of UCZ should be reduced as much as possible in order to improve the overall energy efficiency of the solar pond. The energy efficiency of NCZ is about 1%-5% at the stability stage, which is higher than UCZ on the initial 20 days, and then keeps coincide with UCZ gradually. As the NCZ plays a role of insulation, enhancing the thickness of NCZ will play an actively effects on the temperature of LCZ, on the other hind, more thicker NCZ means more lower energy efficiency of the pond. The value of the energy efficiency in LCZ is between 10%-25%, which is highest scores in the three layers.

**4. Conclusions**

In this paper, basing on the first law of thermodynamics of thermodynamics, energy efficiency of each layer in the solar pond are defined and a trapezoidal solar pond are analyzed by the simulation results. The energy efficiency of the solar pond change greatly in the initial operation period, the energy efficiency of UCZ is the lowest and the LCZ is the highest. Due to the limited temperature increasing of solar pond, solar pond runs into a stable condition. About 60 days after the first filling day, when the heat amount of loss equals to that of the absorption with the changes of season, the energy efficiency even reduced to zero. Therefore, appropriate season which can provide enough radiation heat, as well as reasonable heat extraction according to the heat capacity of the solar pond, are determining factors to improve the energy utilization rate of the solar pond.

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