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# Exergy analysis of an enhanced solar pond

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**Abstract**. In this paper we present an investigation of the exergy performance of a mini trapezoidal solar pond (surface of 5.76 $m^2$ and depth of 1.5 m) in Dalian. 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). Exergy efficiency, the ratio of available exergy to the total exergy was defined, basing on the first law of thermodynamics at each zone of the solar pond. The exergy 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 exergy efficiency of LCZ is the highest and most stable and proved to be the best heat extraction position.

## 1. Introduction

As one of clean and sustainable renewable energy source, solar energy has great significance on saving fossil energy,slow down energy-induced global climate change. Solar radiation is affected by many factors such as season, climate and geographical location[1-2].It is easy to cause some questions such as unstable supply, energy interruption and so on. Solar pond is one of the best ways to solve these problems.Solar energy has the advantages of universality，long-term， harmless and huge[3-5].Hull[6] and Hawlader[7] analyzed the thermal efficiency of solar pond,the effect of soil heat dissipation on the thermal efficiency of solar pond is also considered.

To analysis the ability of energy, the concept of exergy has been put forward.The energy can be transformed into the highest parts is exergy. A hard part of the energy that is impossible to translate into is anergy (unavailable energy). Exergy compared with energy can reveal the essence of energy utilization.Exergy efficiency can be derived from the Second law of thermodynamics.The available energy of the system output can be compared with the input energy of the system.

The theory foundation of exergy is First and Second laws of thermodynamics.Combined with the definition of exergy efficiency, useful energy which enter into and depart from Solar pond is analyzed[8-10]. Establish and analyze exergy efficiency formula of Solar pond.

Based on the rational utilization and improve efficiency of exergy, the principle is to match the quality of energy with the quality of energy which users need.For high-quality high-efficiency, so that different quality of energy to the best use.

$$\xi = (\Xi_{\text{out}} / \Xi_{in}) \times 100\%$$

$\xi$ is exergy efficiency (%)， $\Xi_{in}$ is input exergy， $\Xi_{out}$ is output exergy.

## 2. Exergy analysis summary

In order to introduce the exergy efficiency of each layer of the solar pond, the exergy flow between all layers of the solar pond and the external environment is presented.

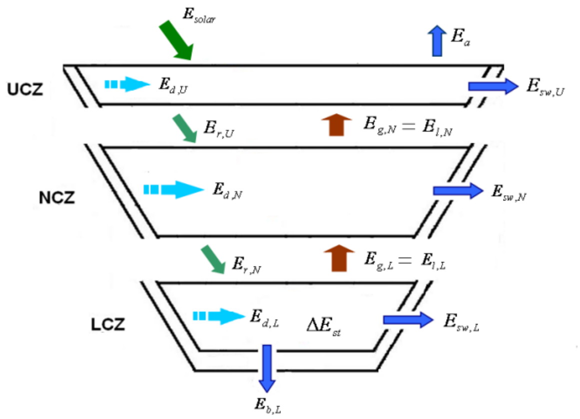


Figure 1. The exergy flux of each layer in the solar pond

### *2.1. Exergy analysis summary*

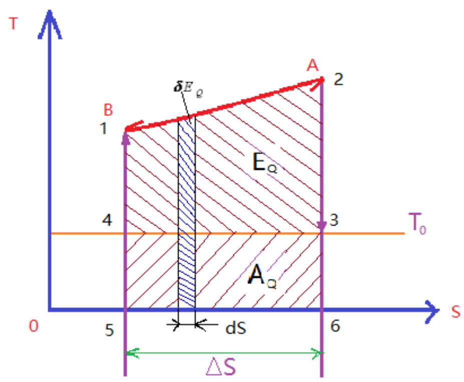


Figure 2. Exergy and Anergy

### *2.2. Exergy analysis for Upper convection layer*

UCZ is abbreviated of Upper convection layer.As shown in above Figure1. the exergy flows in UCZ can be illustrated.We first write the exergy balance equation for UCZ as:

$$\Xi_s + \Xi_N = \Xi_{RU} + \Xi_{DU} + \Xi_a + \Xi_{SWU}$$

$\Xi_S$ is the exergy of solar radiation reaching UCZ surface. $\Xi_N$ is the exergy which NCZ provide. $\Xi_{RU}$ is recovery exergy which UCZ layer obtained from NCZ, $\Xi_{DU}$ is the exergy loss of irreversible heat transfer in UCZ layer. $\Xi_a$ is the exergy loss which UCZ to ambient air. $\Xi_{SWU}$ is the exergy loss which UCZ to the sidewall. $\Xi_{RU}$ can express as:

$$\Xi_{RU} = \Xi_{\mathrm{total},L} - \Xi_{total,I} = \Xi_S + \Xi_N - \Xi_{DU} - \Xi_a - \Xi_{SWU}$$

$\Xi_{\text{total},L}$ is the total exergy loss including irreversible heat transfer loss, $\Xi_{\text{total},I}$ is the total input exergy of UCZ.The exergy of solar radiation can be expressed as Petela formula:

$$\Xi_S = \Xi_{\text{net}}\left[1 - \frac{4T_0}{3T} + \frac{1}{3}\left(\frac{T_0}{T}\right)^4\right]A_0$$

The exergy received from UCZ: $\Xi_N = m_N C_{P,N}\left|T_{m,N} - T_U - T_0 \ln\left(\frac{T_N}{T_U}\right)\right|$

The UCZ exergy loss of irreversible heat transfer can be expressed as: $\Xi_{dU} = T_0 \cdot \Delta S_{net,U}$

After substituting each of the entropy change term.Brought each part of the entropy into the equation, $E_{d,U}$ can be calculated.

$$E_{d,U} = T_0[m_U C_{p,U} \ln(\frac{T_U}{T_0}) - (\frac{Q_{wa}}{T_U} + \frac{Q_{sw,U}}{T_0}) + (\frac{Q_{g,N}}{T_N} + \frac{Q_{sw,U}}{T_0})]$$

In addition, the exergy loss through the ambient air and side walls .In addition, we write the exergy losses to the ambient air and through side walls can be expressed as:

$$E_{sw,U} = m_U C_{p,sw}[(T_U - T_{sw,U}) - T_0 \ln(\frac{T_U}{T_{sw,U}})]$$

We can now define the exergy efficiency for UCZ as the ratio of the exergy recovered from UCZ to the total exergy input to UCZ:

$$\psi_U = \frac{E_{r,U}}{E_{ti}} = 1 - \frac{E_{d,U} + E_a + E_{sw,U}}{E_{solar} + E_{g,N}}$$

*2.3 E*xergy analysis for the NCZ

On the basis of the exergy flows in NCZ, the exergy balance equation can be written as:

$$E_{r,U} + E_{g,L} = E_{r,N} + E_{d,N} + E_{l,N} + E_{sw,N}$$

Here $E_{r,N}$ can be expressed as:

$$E_{r,N} = E_{ti,N} - E_{tl,N} = E_{r,U} + E_{g,L} - E_{d,N} - E_{l,N} - E_{sw,N}$$

$$E_{g,L} = m_L C_{p,L}[(T_L - T_N) - T_0 \ln(\frac{T_L}{T_N})]$$

The exergy destruction in NCZ is then written as: $\Delta S_{net,N}$

where $\Delta S_{net,N}$ is the net entropy change of NCZ that $\Delta S_{net,N} = \Delta S_{sys} + \Delta S_{surr}$ ,each part can be substituted into the formula of entropy.

Therefore, the exergy loss $E_{sw,N} = m_N C_{p,sw}[(T_{m,N} - T_{sw,N}) - T_0 \ln(\frac{T_{m,N}}{T_{sw,N}})]$ expression of NCZ layer is:

$$E_{d,N} = T_0[m_N C_{p,N} \ln(\frac{T_{m,N}}{T_0}) - (\frac{Q_{g,N}}{T_{m,N}} + \frac{Q_{sw,N}}{T_0}) + (\frac{Q_{g,L}}{T_{m,N}} + \frac{Q_{sw,L}}{T_0})]$$

$$E_{l,N} = m_N C_{p,N}[(T_{m,N} - T_U) - T_0 \ln(\frac{T_{m,N}}{T_U})]$$

We can now define the exergy efficiency for the NCZ as the ratio of the exergy recovered from NCZ to the total exergy input to NCZ:

$$\psi_N = \frac{E_{r,N}}{E_{ti}} = 1 - \frac{E_{d,N} + E_{l,N} + E_{sw,N}}{E_{r,U} + E_{g,L}}$$

*2.4. Exergy analysis for LCZ*

The exergy flows in LCZ are clearly shown in Figure2. and the exergy balance equation in this regard results in:

$$E_{r,N} - (E_{d,L} + E_{l,L} + E_{sw,L} + E_{b,L}) = \Delta E_{st}$$

$$E_{d,L} = T_0(\Delta S_{net,L})$$

Where $\Delta S_{net,L}$ is the net entropy change of LCZ as $\Delta S_{net,L} = \Delta S_{sys} + \Delta S_{surr}$ ,each part of the entropy can be calculated into the formula $E_{d,L}$ .

The exergy losses, including exergy destruction within NCZ,can be derived as follows:

Exergy loss of LCZ:

$$E_{d,L} = T_0[m_L C_{p,L} \ln(\frac{T_L}{T_0}) - (\frac{Q_{g,L}}{T_L} + \frac{Q_{sw,L}}{T_0}) + (\frac{Q_b}{T_0})]$$

$$E_{l,L} = m_L C_{p,L}[(T_L - T_{m,N}) - T_0 \ln(\frac{T_L}{T_{m,N}})]$$

$$E_{sw,L} = m_L C_{p,sw}[(T_L - T_{sw,L}) - T_0 \ln(\frac{T_L}{T_{sw,L}})]$$

Note $E_{b,L} = E_{sw,L}$, due to the fact that both side wall and bottom layer have the same insulating materials and are surrounded by the ambient air.The exergy efficiency of LCZ is defined as:The exergy is stored in the LCZ and the total exergy of the input LCZ is recovered from the basic layer.

$$\psi_N = \frac{\Delta E_{st}}{E_{r,N}} = 1 - \frac{E_{d,L} + E_{l,L} + E_{sw,L} + E_{b,L}}{E_{r,N}}$$

## 3. Results and discussion exergy efficiency

During the daytime when the solar radiation intensity is bigger,the temperature of the solar pond is gradually increasing,the whole process of absorbing energy.And in the night due to the absence of solar radiation,the solar pond presents an outward exothermic state.The energy efficiency is negative.Comprehensive calculation of energy efficiency throughout the day remained basically zero.When the ambient temperature is further reduced directly reach ambient temperature,for small solar pond and even the appearance of freezing pond table.

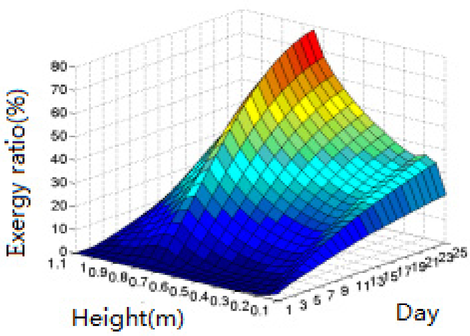


Figure 3. Exergy efficiency analysis of Trapezoidal solar pond

This indicates that the temperature of the solar pond is unlikely to increase indefinitely，Frequent heat extracted will affect the stability of the solar pond,but for a long time without heat extracted will reduce the energy efficiency of the solar pond.So choose the appropriate season to extracted heat.Reasonable heat extraction according to the heat capacity of solar pond is an important method to improve the energy efficiency of solar pond.

The variation of the exergy of the trapezoidal pond at different depths with time is given.From the figure 3. we can see in space and increases with depth from up to down ,there is a maximum value of the exergy efficiency of each layer in the solar pond,the position is in the range of depth 0.7-0.8m,correspond to top of LCZ, It is shown that this region is an ideal location for the solar pond,this is consistent with the experimental findings. Although the hours,from the time point of view, the efficiency of each layer in the solar pond is generally low,the exergy efficiency of each layer increases obviously with time，it shows that the solar pond has entered a stable state,the temperature has entered into the stable state at the same time.At this time, the maximum exergy efficiency of the solar pond is close to 50%, which appears near the top of the LCZ,it is shown that the stable time of the solar pond or the appropriate time to extracting heat the solar pond is 20 days after the operation.

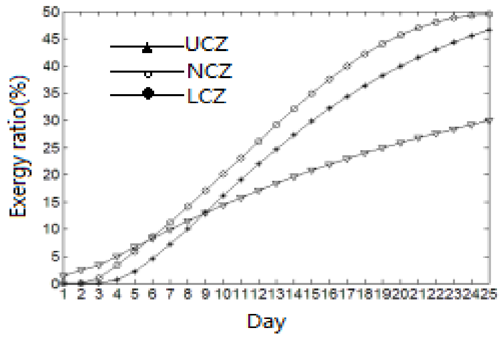


Figure 4. The layers of solar pond exergy efficiency variation over time

In order to analyze the exergy efficiency of each layer in the three layer structure of the solar pond.The Figure4. shows the exergy efficiency of UCZ, NCZ and LCZ of the solar pond with time, the temperature parameters in the calculation is the average value of each layer in the above structure,the lowest exergy efficiency is UCZ,up to about 25%.and the highest exergy efficiency is about 50% of LCZ, exergy efficiency of NCZ is between two layers.This is due to we take the average temperature of the temperature parameters in the calculation.

As the heat absorbed by the solar pond is mainly concentrated in LCZ and the layer is the main store place for store heat exergy.The layer is little impact by circumstance.So when the solar pond is in steady operation. LCZ is the most efficient and stable. However, because of the low temperature of surface heat loss and the large fluctuation of UCZ ,so the exergy efficiency is lower.and even if the solar pond is in a stable state, there is the increasing trend of UCZ and the stability is very bad. It should be noted that, in order to avoid the impact of wind、rain and other extreme weather on the performance of the solar pond.The solar radiation entering the solar pond is calculated according to the model and not taken from actual weather parameters.Therefore the change trend of exergy efficiency is relatively stable and have no abrupt change.Further research is needed in subsequent work.

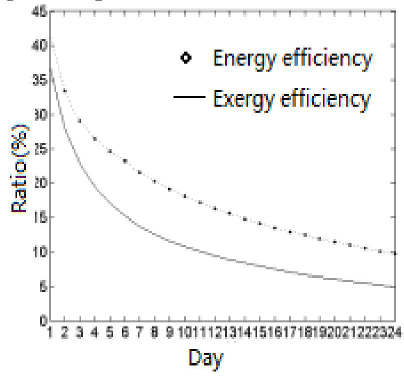


Figure 5. Exergy efficiency analysis of LCZ

In addition,the exergy efficiency of each layer is higher than that of energy.This is due to the exergy formula in this calculation, energy efficiency is defined as the ratio of the output heat to the total heat input of each layer and exergy efficiency is defined as the ratio of the output available energy to total available energy.Although the output available energy for each layer is only part of the output of the output of the layer.However, the input available energy can be lower than the input heat of each layer,therefore, the above results were brought.If the exergy percentage is defined as the ratio of the available energy of each layer to the total heat input, the exergy percentage is lower than the energy efficiency as shown in the figures.

Taking into account the exergy analysis of LCZ is the key point of the analysis of solar pond,The comparison between the exergy percentage of LCZ and the energy efficiency of this layer is given, It can be seen that the percentage of exergy in total heat is lower than the energy efficiency fraction (energy efficiency).The two showed with similar trends.

## 4. SUMMERY

In this paper, based on the first law of thermodynamics and the second law of thermodynamics. Combined the definition of energy efficiency and exergy efficiency ,the energy of each layer of the solar pond is analyzed,and authors establish expression of energy efficiency and exergy efficiency of trapezoidal solar pond,the energy efficiency and exergy efficiency of the trapezoidal solar pond are analyzed and gain the conclusion,prove the energy utilization rate of the solar pond.

(1) After the stable operation of the solar pond, the exergy efficiency of LCZ is the highest and most stable.There is a maximum value of the exergy efficiency from top to bottom.The position is in the depth range 0.7-0.8m,correspond to the upper part of LCZ,It is shown that this region is an ideal location for heat extraction.

(2) The exergy efficiency of each layer is generally low at the beginning of the solar pond,The exergy efficiency increases with time,The final exergy efficiency remained relatively stable,the stable time of the solar pond or the proper time to heat extraction is 20 days after the operation.

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