Abstract—Based on one of the typical low-grade thermal power cycles, Kalina cycle, the solar auxiliary boosted ocean thermal energy conversion (Kalina Solar-OTEC) system is proposed in the paper. To utilize solar energy in the Solar-OTEC system with high performance and low cost, three kinds of configurations by acting same solar heat transfer rate on different part of the Solar-OTEC system are designed and discussed here. Meanwhile, the corresponding calculation model is built to compare their performance. Results show that Kalina Solar-OTEC in case 1 has better thermodynamics and economic performance than other cases.

Index Terms—Energy-Economic analysis, kalina cycle, solar-otec, thermal power generation.

I. INTRODUCTION

Energy shortage and environmental pollution are two critical issues in this century that must be appropriately solved to produce new energy and at the same time to reduce emissions. Renewable energy is being considered as a more promising way for it, and offering an excellent opportunity to supply clean electricity with a non-CO2 emitting technology. Especially after the Fukushima nuclear accident in Japan, renewable energy is got a growing respect in the world. It is the energy which comes from natural resources such as sunlight, ocean thermal gradients, wind, rain, tides, and geothermal heat, etc. Recently, under the government policy guidance, ocean thermal energy has attracted more and more attentions. Numerous efforts have been paid to try to use it to generate electricity, or ocean thermal energy conversion (OTEC).

OTEC is a power system which generates electricity using the temperature difference between sea surface and deep-sea [1]. In the past few decades, research attentions have focused on the development of OTEC. And ammonia is reported as one of the suitable working fluids for a closed Rankine cycle OTEC plant from the view point of the net power output [2]-[4]. However, its performance is limited since the available temperature difference is small for OTEC, which leads to a high cost of the electricity. Therefore, many researchers devote themselves to improving the cycle performance to reduce the electricity cost. Kalina use an ammonia-water mixture as the working fluid in their cycle, which have been developed and reported to have better performance than the Rankine cycle at same temperature difference [5]. Thus, Kalina cycle is considered as one promising way to be used in OTEC. In addition, since the solar energy is also abundant in the districts with rich ocean thermal energy [6]. Therefore, the solar energy should be taken into consideration as the additional heating source to improve the efficiency of the OTEC. Thus, recently, many researchers devote themselves to study the Solar-OTEC [7]-[11]. All their results suggested that Solar-OTEC may be an effective way to improve feasibility of the power generation system.

In summary, although many studies described that the combination of OTEC with solar energy could be a possible way to improve the availability of the cycle, however the high-efficiency utilization of solar energy in OTEC system is scarcely considered even though it is significant for designing high performance Solar-OTEC system in engineering practice. It prompts us to carry out the present study. In this study, the Kalina Solar-OTEC is firstly proposed. And then, by exerting solar energy to different part of Solar-OTEC system, three kinds of configuration cases are analyzed and compared from the point of view of thermodynamic and economic analysis. Finally, the way of designing high performance hybrid configuration of the Kalina Solar-OTEC system will be clarified.

II. BASIC PARAMETERS AND GENERAL ASSUMPTION

![Fig. 1. Sketch of the Kalina Solar-OTEC system](image-url)
A. *Kalina Solar-OTEC System Description*

As shown in Fig. 1, based on the KCS-11, which is commonly used in recovering energy from the low-temperature heat resources, the Kalina Solar-OTEC system is proposed here. It is mainly including power generation subcycle, solar collector subcycle and cold seawater subcycle. And its working fluid is ammonia-water mixture, whose thermodynamic properties are simulated by using Ibrahim’s data [12]. Therefore, main devices of the system are listed and described as follows.

- A working fluid pump
- A warm seawater pump
- A cold seawater pump
- A regenerator
- An evaporator
- Three solar-evaporators
- A solar collector
- A separator
- A turbine
- A generator
- A diffuser
- An absorber
- A condenser

The turbine exhaust wet vapor (12) is mixed with saturated liquid (10) in the absorber. And the wet vapor (1) leaving the absorber is cooled in the condenser to become the saturated liquid (2). Then it is compressed to the compressed liquid (3) by the working fluid pump. Meanwhile, the working fluid wet vapor is separated into rich ammonia-water mixture saturated vapor (7) and the poor ammonia-water mixture saturated liquid (8). And then the vapor is expanded in the turbine to generate electricity by using a generator. Moreover, the compressed liquid (9) leaving the regenerator releases pressure in the diffuser to become saturated liquid. And the compressed liquid (4) reheated by the regenerator is sent to the evaporator, where it is heated to saturated liquid (5') and then boiled to wet vapor (5) by the ocean thermal energy.

Furthermore, the corresponding solar collector subcycle can be designed by adjusting its solar collector area and mass flow rate. And the comparative performance analysis with same solar heat transfer rate acted on different part of the system can be carried out in the following cases.

Case 1 (solar collector subcycle is a-b-c-h-i-j-a), in this case, the saturated vapor (7) will be superheated to the superheated vapor (11) in the Solar-Evaporator 1.

Case 2 (solar collector subcycle is a-d-e-h-i-j-a), in this case, the wet vapor (5) will be further heated to wet vapor (6) in the Solar-Evaporator 2.

Case 3 (solar collector subcycle is a-f-g-h-i-j-a), in this case, the warm seawater will be firstly heated in the Solar-Evaporator 3 before it enters the evaporator.

In addition, in the Solar-OTEC system, heat rate absorbed from the heat exchanger is \( \dot{Q} = \dot{m} \cdot c_p \cdot \Delta T \), in which, \( \dot{m} \) is mass flow rate of the heat or cold sources, \( c_p \) represents the specific heat at constant pressure, \( \Delta T \) means the temperature difference of the heat exchanger. Meanwhile, heat rate supplied to the cycle (evaporator) is shown as \( \dot{Q}_{ev} = \dot{m}_g \Delta h_i \). Heat rate rejected from the cycle (condenser) is given as \( \dot{Q}_{rej} = \dot{m}_g \Delta h_i \), where, \( \dot{m}_g \) is mass flow rate of the working fluid. In addition, heat conduction in the exchanger is assumed as \( \dot{Q} = UA \Delta T_m \), where \( \dot{Q} \) is the rate of heat transfer; \( U \) is the overall heat-transfer coefficient; \( A \) is the cross-section area normal to the direction of heat transfer; \( \Delta T_m \) is called the logarithmic mean temperature difference (LMTD) and gives \( \Delta T_m = (\Delta T_i - \Delta T_c) / \ln(\Delta T_i / \Delta T_c) \).

B. *Comparative Economic Analysis of the Kalina Solar-OTEC Configurations*

In order to have an economic analysis and cost comparison of the proposed Kalina solar-OTEC hybrid configurations, simple comparative analysis of the generating cost is introduced here. Reference [13], it is assumed that \( A_{K,K} \) represents annuity of payments linked to capital, which is calculated as product of the investment \( A_k \) and the annuity factor \( a \) determined by the interest rate \( i \) and the economic life time \( e \), that is \( A_{K,K} = a_1 \cdot A_k = A_k \cdot (1+i)^e \cdot i / ((1+i)^e - 1) \).

In addition, \( f_k \) shows the factor for repairs, maintenance and insurance and \( h_{full load} \) stands for full load hours. As a result, the system electricity production costs \( C_{elec} \) can be expressed as \( C_{elec} = [A_{K,K} + A_k \cdot (f_k / 100))] / (W_{net \cdot h_{full load}} \cdot 1) \). Let \( \varphi = ((1+i)^e \cdot i / ((1+i)^e - 1) + f_k / 100) / h_{full load} \), then \( C_{elec} = \varphi \cdot A_k / W_{net} \). In addition, dimensionless parameters are introduced as follows for comparative economic analysis of the Solar-OTEC cases: \( \eta_{case1} = C_{elec, case1} / C_{elec, case1} = 1 \), \( \eta_{case2} = C_{elec, case2} / C_{elec, case1} \), \( \eta_{case3} = C_{elec, case3} / C_{elec, case1} \). It should be noted that the smaller \( \eta_{case} \), the lower generating cost. And \( \eta_{case2} > 1 \) means that the cost performance in case II is better than that of case 1. Conversely, \( 0 < \eta_{case2} < 1 \) means that the cost performance in case 1 is better than that of case II, where II represents the number of the case.

Moreover, the following assumptions are applied to the Solar-OTEC.

1) The rate of heat transfer from solar collector is constant in all cases.
2) The thermodynamic cycle of the Solar-OTEC is an ideal cycle. Turbine efficiency and pump efficiency are given 100%.
3) The piping and other auxiliary are considered to be ideal and no heat losses.

Based on aforementioned assumptions and the temperature condition in Solar-OTEC, the initial condition for Kalina Solar-OTEC is given in Table I.

<table>
<thead>
<tr>
<th>Table I: Initial Condition for Calculation</th>
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<tbody>
<tr>
<td>( t_{\text{sat}} = 28.0[^\circ \text{C}] )</td>
</tr>
<tr>
<td>( m_{\text{in}} = 40[^\circ \text{Kg}] )</td>
</tr>
<tr>
<td>( X_{\text{sat}} = 0.95[^\circ \text{Kg}] )</td>
</tr>
<tr>
<td>( (UA/\dot{Q})_{\text{in}} = 0.25[^\circ \text{C}] )</td>
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</table>
III. Calculation Model of the Solar-OTEC System

As mentioned above, three configuration cases are chosen to be calculated. And the corresponding flow chart is given here as shown in Fig. 2.

\[ t_0 = t_1 - t_0 = \frac{Q_{swf}}{(m_{swf} \cdot c_p)} + v + Q_{swf} = \frac{Q_{swf}}{m_{swf} \cdot c_p} \]

\[ t_1 = t_1 - t_0 = \frac{Q_{swf}}{(m_{swf} \cdot c_p)} + v + Q_{swf} = \frac{Q_{swf}}{m_{swf} \cdot c_p} \]

Meanwhile, \( t_0 = t_0 = \frac{Q_{swf}}{(m_{swf} \cdot c_p)} + v + Q_{swf} = \frac{Q_{swf}}{m_{swf} \cdot c_p} \)

For case 2, Solar-Evaporator 2 is effective, which means that the solar collector subcycle is a-d-e-h-i-j-a. In this case, the calculation approach for most points is same with that of case 1 except some special points, such as point 11, which has same properties as point 7 since there is no Solar-Evaporator 1 here. In addition, there is also no Solar-Evaporator 3 here, so \( t_{wso} = t_{wso} \). Meanwhile, by using the heat balance in the Solar-Evaporator 2, the enthalpy of point 6 can be given as \( h_6 = h_6 + Q_{swf} / m_{swf} \) and combined with \( y_6 = y_7 \) and \( P_{11} = P_1 \) in this case, the state of point 11 will be solved here. And through the heat balance in Solar-Evaporator 1, the temperature \( t_3 \) is solved as following:

\[ t_3 = t_3 - t_2 = \frac{Q_{swf}}{(m_{swf} \cdot c_p)} + v + Q_{swf} = \frac{Q_{swf}}{m_{swf} \cdot c_p} \]

\[ t_4 = t_4 - t_3 = \frac{Q_{swf}}{(m_{swf} \cdot c_p)} + v + Q_{swf} = \frac{Q_{swf}}{m_{swf} \cdot c_p} \]

Moreover, \( t_5 = t_5 = \frac{Q_{swf}}{(m_{swf} \cdot c_p)} + v + Q_{swf} = \frac{Q_{swf}}{m_{swf} \cdot c_p} \)

Thus, the thermal efficiency of the Kalina Solar-OTEC in this case can be given as \[ \eta_{OTEC} = \frac{W_{net,case2}}{Q_{swf,case2}} \] in...
where, \( W_{\text{net, case}2} = m_{f2} \cdot (\xi_2(h_1 - h_2) - (h_3 - h_4)) \), \( \xi_2 = m_2 / m_0 \), \( Q_{e, \text{case}2} = m_{f2} (h_0 - h_1) \).

C. Kalina Solar-OTEC Case 3

About case 3, Solar-Evaporator 3 is effective, that means the Solar-Evaporator 3 is connect with the solar collector pump and solar collector directly. In this case, the approach of calculation for most points is same with that of case 1 or 2 except some special points (point 11 and 6), which has same properties as point 7 and 5 respectively since there are no Solar-Evaporator 1 and 2 here. Meanwhile, by using the heat balance in the Solar-Evaporator 3, we know that \( t_{swf} = t_{swf} + Q_{swf} / (m_{swf} \cdot c_p) \). And through heat balance in Solar-Evaporator 3, the temperature \( t_g \) is solved as following

\[
    t_g = \left( t_{swf} - t_{swf} \cdot e \left( \frac{Q_{swf}}{m_{swf} \cdot c_p} \right) - \left( \frac{Q_{swf}}{m_{swf} \cdot c_p} \right) \right) / \left( 1 - e \left( \frac{Q_{swf}}{m_{swf} \cdot c_p} \right) \right)
\]

(3)

Meanwhile, \( t_f = t_a = Q_{swf} / (m_{swf} \cdot c_p) + t_g \) and \( Q_{swf} = Q_e \).

Therefore, the thermal efficiency of the Kalina Solar-OTEC in this case can be given as

\[
    \eta_{\text{case, 3}} = W_{\text{net, case}3} / Q_{in, case3},
\]

in which

\[
    W_{\text{net, case}3} = m_{f3} \cdot (\xi_3(h_1 - h_2) - (h_3 - h_4)), \quad \xi_3 = m_3 / m_0,
\]

\[
    Q_{e, \text{case}3} = m_{f3} (h_0 - h_1).
\]

Finally, the rationality of the designed calculation program is checked successfully based on the characteristics of the Kalina Solar-OTEC system.

IV. RESULT AND DISCUSSION

As the first step of studying on Solar-OTEC in Kalina cycle, the optimized mass flow rate of working fluid to maximize net power output in Kalina cycle is carried out under the given condition of Table I with \( \bar{Q_e} = 0[kW] \). It shows that the optimized mass flow rate of working fluid in Kalina cycle is \( (m_{f3})_{opt} = 1.8[kg/s] \), which corresponding to the maximum net power output of the Kalina cycle \( (W_{\text{net, max}} = 44.6[kW]) \), and its thermal efficiency is 3.56%.

Therefore, the optimized mass flow rate of working fluid is chosen as the further initial condition for performance comparison analysis of the Kalina Solar-OTEC configurations.

To clarify the performance of the Solar-OTEC in Kalina cycle, the relationship between solar heat transfer rate and net power output in three configuration cases are shown in Fig. 3. It is obvious that the net power outputs of Solar-OTEC in all cases are increased with increasing the solar heat transfer rate since it is known that the more solar energy is utilized in Solar-OTEC system, the more net power output is obtained.

However, it should be noted that the net power output of Solar-OTEC system in case 1 is evidently higher than other cases at a certain solar heat transfer rate. It means that the solar energy directly heats the saturated ammonia vapor to superheat vapor and then drive it to do work in the turbine of the Solar-OTEC system for power generation, which can enhance the net power output of the Solar-OTEC systems.

In addition, simple economic comparative analysis is also introduced here to highlight the interest of the proposed Kalina Solar-OTEC hybrid configurations. Firstly, it should be noted that \( \eta_{\text{case}1} \), \( \eta_{\text{case}2} \) and \( \eta_{\text{case}3} \) are assumed to be approximately equal. And \( A_{\text{case}1} \), \( A_{\text{case}2} \) and \( A_{\text{case}3} \) are also considered approximately equal since the solar heat transfer rate is discussed as a constant.

Thus, from the above mentioned analysis, it is known that the \( R_{\text{case}2} \) and \( R_{\text{case}3} \) can be written in the following forms:

\[
    R_{\text{case}2} = W_{\text{net, case}1} / W_{\text{net, case}2}
\]

and

\[
    R_{\text{case}3} = W_{\text{net, case}1} / W_{\text{net, case}3}
\]

And then, from the Fig. 4 it is observed that \( R_{\text{case}1} \) is always less than \( R_{\text{case}2} \) and \( R_{\text{case}3} \) in the condition of \( \bar{Q}_e > 0 \). This means that the system electricity production costs \( C_{\text{op}} \) in case 1 is lower than that of case 2 and 3 for Kalina Solar-OTEC system. Meanwhile, it is also noticed that the \( R \) gap between case 1 and the other cases of Kalina Solar-OTEC system is becoming larger and larger with increasing \( \bar{Q}_e \). This means that the larger system size, the better economic superiority of case 1. Overall, the Kalina Solar-OTEC system in case 1 is the best choice for Solar-OTEC system.

Fig. 3. Relationship between solar heat transfer rate and net power output

Fig. 4. Relationship between solar heat transfer rate and net power output
V. CONCLUSIONS

Three kinds of Kalina Solar-OTEC configurations are studied by exerting same solar heat transfer rate to different part of the system in the paper. And the comparative performance analysis between them is carried out for high-efficiency utilization of solar energy in Solar-OTEC system. Results show that Kalina Solar-OTEC in case 1 has better thermodynamics and economic performance than other cases. This means that the solar superheater is essential in Kalina Solar-OTEC system for power generation if the initial conditions are same. In this case, it can enhance the net power output of the system.

REFERENCES