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Comparisons and optimization of two absorption chiller types by considering heat transfer area, exergy and economy as single-objective functions

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Abstract

Absorption cooling technology is an environmentally friendly method to generate continuous chilled water making use of multiple thermal sources, such as waste heat and renewable thermal energy. In this study, two absorption chillers (nominal capacity of 400 kW) with series and parallel connections are evaluated. To research the ideal configuration of chillers after thermodynamic analysis, the structures of the chillers are optimized using the particle swarm optimization algorithm by considering the heat transfer area (HTA), exergy efficiency and total annual cost as single-objective functions. The impact of temperature differences between external and internal flows, heat exchanger efficiencies and the solution allocation ratio is estimated. The optimized HTA, coefficient of performance, exergy efficiency and total annual cost are 149.0 m², 1.56, 29.44% and $229,119 for the series-connected chiller, and 146.7 m², 1.59, 31.45% and $234,562 for the parallel-connected type, respectively. Under the lowest HTA condition, compared with the reference simulation results, the energy and exergy performances are improved, while the annual total cost is higher. The annual total cost is highest when maximizing the exergy efficiency, which is attributed to the increase in the HTA. The operating cost accounts for 27.42% (series type) and 26.54% (parallel type) when the annual cost is the lowest.
Graphical Abstract

Keywords: absorption chiller; series/parallel-connected; temperature difference parameters; solution allocation ratio

Introduction

To meet the energy demands of buildings, almost 30% of the total primary energy is used and >50% is consumed for the cooling and heating of the building [1]. Compared with building heating, which can be generated directly by heat exchange, cooling energy can only be supplied by some complex cycles. Furthermore, environmentally and economically friendly cooling has been a popular topic in recent years to address increasing cooling demands [2]. In the literature, the useful refrigeration technologies are mainly vapour-compression cooling technologies [3] powered by energy with a higher energy level and thermally driven cooling technologies [4], especially the ejector [5], desiccant [6], adsorption [7] and absorption [8] refrigeration methods.

Vapour-compression cooling always has a higher coefficient of performance (COP), but input resources are often electrical and mechanical energies generated by using fossil fuels [9], which causes lower exergy efficiency. To avoid fossil fuel consumption and reduce greenhouse gas emissions, thermally assisted cooling technologies are developed by utilizing waste heat and renewable resources. However, refrigeration methods, including ejector, desiccant and adsorption cooling technologies, often suffer from deficiencies [10], such as (i) intermittent cooling energy supply, (ii) higher economic performance, (iii) lower energy performance and (iv) material limitations. Compared with these options, the absorption cooling method is an ideal technology with friendly economic and energy performance [11].

Based on the simplest configuration of the absorption chiller (single-effect type), researchers have focused their attention on operating structures [12], application scenarios [13] of chillers, etc. For the structure of the chiller, the single-effect chiller with double-lift [14], double-effect [15] and triple-effect chillers [16] are gradually being proposed. Additionally, to make full use of primary energy sources, the variable-effect [17], vapour-compression–absorption coupling chiller [18] and other types have also been examined. In addition, scholars have also explored the performance of various refrigeration fluids, such as ammonia–water (NH₃–H₂O) [19], which is utilized in quick freezing and cold storage, due to the lower evaporation temperature; and
Comparisons and optimization of two absorption chiller types

1. Descriptions of two types of absorption chillers

Double-effect absorption chillers in series and parallel connections, with 400 kW of fixed capacity, are utilized to provide cooling energy to a commercial building [38]. Steam at a temperature of 150°C from parabolic-trough collectors [33] is assumed as the driving resource for the chillers. The details of the chillers are described in this section including energy flow charts and thermodynamic models.

1.1 Flow charts of two types of chillers

The flow charts of two types of chillers with series and parallel connections are shown in Fig. 1: the series-connected chiller in Fig. 1a and the parallel-connected chiller in Fig. 1b.

As shown in Fig. 1a, the lean solution in the absorber (State 1) is first pumped into the low-temperature heat exchanger (LTX) (State 2) to absorb the heat from the rich solution (State 5) and then the solution goes into the high-temperature heat exchanger (HTX) (State 3) to absorb the heat into the rich solution (State 14), which comes from the high-pressure generator (HG). In the HG, the preheated lean solution (State 13) generates the first part of the refrigeration vapour (State 17) and the rich solution (State 14) by absorbing the heat from steam at a temperature of 150°C. It is assumed that the heat in the refrigerant vapour (State 17) is used first in the low-pressure generator (LG) and the rich solution (State 15) can absorb the heat to generate the second part of the refrigerant vapour (State 7) and the rich solution (State 4). The rich solution is fed into the absorber (State 5) after releasing heat to the lean solution in the LTX. On the other hand, two sets of refrigerant vapour (States 7 and 19) are condensed in Condenser 1 by releasing heat to the cooling water (CW) with a temperature of 25°C (State 25). After a throttling process, liquid water (State 8) is converted to low-temperature and low-pressure refrigerant vapour (State 9). Finally, the chilled water (State 28) is generated by heating the refrigerant vapour (States 27 to 29) in the evaporator. The refrigerator (State 10) is then absorbed by the rich solution in the absorber through an exothermic reaction and the heat can also be released to the CW (State 23).

As can be observed from the parallel chiller flow diagram in Fig. 1b, the lean solution (State 2) is split into two sets (States 11 and 20) and one set (State 11) is fed to the HTX, while another set (State 20) flows to the LTX. The flow charts of other components are similar to the flows of the series-connected chiller as mentioned above.

The design parameters of the simulation for two types of chillers are summarized in Table 1.

1.2 Thermodynamic models of two types of chillers

There are many components in the two types of chillers, including the HG, LG, HTX, LTX, condenser, evaporator, absorber and others. For each component, the mass, solution and energy balance equations can be concluded by using the following correlations.

\[ \sum m_{in} = \sum m_{out} \]  
\[ \sum m_{in} u_{in} = \sum m_{out} u_{out} \]  
\[ \sum m_{in} h_{in} = \sum m_{out} h_{out} \]

where \( m \), \( h \) and \( u \) are the mass flow, enthalpy and concentration of each state, respectively. The subscripts in and out represent the inlet and outlet of each state.

For each component, the energy \( Q \) can be determined by the heat transfer area \( (A) \), the heat transfer coefficient \( (U) \) and the logarithmic mean temperature difference \( (\Delta T) \).
Moreover, as shown in Section 1.1, the LiBr solution is split into two parts by controlling the valve and the allocation ratio is determined as the ratio of the mass flow:

\[ D = \frac{m_{12}}{m_3} \]  

The thermodynamic accuracy is ensured by comparing the simulation results to [39] with the design parameters in Table 1. The root mean square error values of mass, pressure, concentration and enthalpy are <6% (Table 2).

2 Optimization method

In recent studies, an optimization method [40] with single or multiple objectives is often used to search for the ideal structure of the equipment, energy system, etc. Compared with single-objective optimization, multiple-objective optimization could consider several indicators simultaneously. For example, the energy, environmental and economic performance has been optimized in the integrated system combining absorption and a water-cooled chiller [41]. However, the multi-objective method has more constraints and it cannot generate a unique solution, which can only be determined by using the decision-making method and the selection of indicators, and the decision-making method has a large impact on the final solution. To avoid this uncertain performance, single-objective optimization consisting of the decision variable,
the objective function, the constraints and the solution algorithm is described in this part considering the HTA, the exergy and the economic performance as the single-objective functions. The optimization method can be displayed in mathematical form and the details are as follows.

2.1 Decision variables
For each component, the temperature differences between the inlet and outlet states have a great impact on the performance of the chiller. Thus, in this study, nine temperature difference parameters are selected as the decision variables. The temperature difference types are described as follows.

(i) Temperature difference between States 23 and 1.

The inlet CW (State 23) is set at a constant 25°C, the temperature difference is described as:

\[ \Delta T_{23} = T_{23} - T_{1} \]  

where \( T \) is the temperature.

(ii) Temperature difference between States 23 and 24.

The outlet temperature of the CW in the absorber can affect the operation of the absorber and the temperature difference is set at:

\[ \Delta T_{23} = T_{24} - T_{23} \]  

(iii) Temperature difference between States 22 and 21.

The temperature difference influences the heat transfer conditions in the HG and the temperature difference is set at:

\[ \Delta T_{21} = T_{22} - T_{21} \]  

(iv) Temperature difference between States 14 and 21.

The temperature difference between States 14 and 21 is set at:

\[ \Delta T_{14} = T_{21} - T_{14} \]  

Similarity to the temperature differences in the absorber, two temperature differences in the condenser are set:

(v) Temperature difference between States 26 and 25:

\[ \Delta T_{25} = T_{26} - T_{25} \]  

(vi) Temperature difference between States 8 and 25:

\[ \Delta T_{8} = T_{8} - T_{25} \]  

(vii) Temperature difference between States 27 and 10.

In the evaporator, the temperature difference between the refrigerant vapour in the outlet and the chilled water in the inlet is selected as a decision variable:

\[ \Delta T_{10} = T_{27} - T_{10} \]  

The HTX and LTX can preheat the lean LiBr solution by absorbing the heat from the rich solution. In this study, the heat exchange efficiencies of HTX (\( \eta_{HTX} \)) and LTX (\( \eta_{LTX} \)) are selected as two variable decisions.

For the parallel-connected chiller, the allocation ratio of the solution (\( D \)) can affect the performance of the chiller and it is also one of the variable decisions in this study. The decision variables can then be expressed in matrix form as follows:

\[ X = [\Delta T_{1}, \Delta T_{23}, \Delta T_{21}, \Delta T_{14}, \Delta T_{25}, \Delta T_{8}, \Delta T_{10}, \Delta T_{4}, \eta_{HTX}, \eta_{LTX}, D]^T \]  

2.2 Objective function
To demonstrate performance, in this research, a set of evaluations against HTA, exergy efficiency and annual total cost are considered. Their corresponding objective functions are set as follows.

Heat transfer area (HTA):

\[ \min HTA_{\text{inal}} = \sum_{i} HTA_{i} \]  

Exergy efficiency (\( \eta_{ev} \)):

\[ \max \eta_{ev} = \frac{Ex_{eva}}{Ex_{HG}} \times 100 \]  

where \( Ex_{eva} \) and \( Ex_{HG} \) are the exergy of the chilled water and thermal input, respectively.

Annual total cost (ATC):

\[ \min ATC = CC + OC \]  

where CC and OC are the annual capital cost and the annual operating cost, respectively.

\[ CC = RF \cdot \sum_{i} Z_{i} \]  

where RF and \( Z \) are the capital recovery factor and the initial investment cost for the \( i \)-th component, respectively. The initial investment cost for each component is summarized in Table 3.

The RF is determined by the correlation:

\[ RF = \frac{j \cdot (1+j)^{n}}{(1+j)^{n-1}} \]  

The OC is calculated by the consumption of CW in the condenser and absorber and heating water (HW) in the HG:

\[ OC = C_{cw} \cdot CW + C_{sw} \cdot SW \]  

where \( C_{cw} \) and \( C_{sw} \) are the unit costs of the heating and CW, which are $3.0/ton and $0.0195/ton in this study, respectively [44].

2.3 Constraints
The constraints during optimization for the two chiller types contain equality and inequality forms, such as solution allocation and energy balance. The equality constraints mainly include the energy, mass and solution relationships. The inequality constraints are often limitations related to equipment characteristics.

For the decision variables, the ranges are first determined to obtain the appropriate results. The ranges of the decision variables are summarized in Table 4.
Table 3: Initial investment cost for each component of absorption chillers [42, 43]

<table>
<thead>
<tr>
<th>Component</th>
<th>Initial investment cost ($)</th>
<th>Component</th>
<th>Initial investment cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HG, LG</td>
<td>1800 · (f · HTA)0.8 + 24915</td>
<td>Condenser</td>
<td>2119 · (f · HTA)0.497</td>
</tr>
<tr>
<td>Evaporator</td>
<td>5900 · (f · HTA)0.552</td>
<td>LTX, HTX</td>
<td>2674 · (f · HTA)0.465</td>
</tr>
<tr>
<td>Absorber</td>
<td>9.976 · (f · HTA)1.820</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$f$ is the area conversion factor, which is 10.764 in this study.

Table 4: Ranges of decision variables

<table>
<thead>
<tr>
<th>Item</th>
<th>Range</th>
<th>Item</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta T_{in}, ^\circ C$</td>
<td>[0.5, 15]</td>
<td>$\Delta T_{vt}, ^\circ C$</td>
<td>[0.5, 25]</td>
</tr>
<tr>
<td>$\Delta T_{ex}, ^\circ C$</td>
<td>[0.5, 15]</td>
<td>$\Delta T_{vt}, ^\circ C$</td>
<td>[0.5, 25]</td>
</tr>
<tr>
<td>$\Delta T_{ex}, ^\circ C$</td>
<td>[0.5, 25]</td>
<td>$\eta_{LTX}$</td>
<td>[0.05, 0.95]</td>
</tr>
<tr>
<td>$\Delta T_{ex}, ^\circ C$</td>
<td>[0.5, 10]</td>
<td>$\eta_{LTX}$</td>
<td>[0.05, 0.95]</td>
</tr>
<tr>
<td>$\Delta T_{ex}, ^\circ C$</td>
<td>[0.5, 15]</td>
<td>$D$ (parallel chiller)</td>
<td>[0.05, 0.95]</td>
</tr>
<tr>
<td>$\Delta T_{ex}, ^\circ C$</td>
<td>[0.5, 25]</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2.4 Solution method

To solve the single-objective optimization problem, multiple optimization algorithms have been proposed, such as the genetic algorithm, the seagull algorithm, the particle swarm optimization algorithm (PSOA), etc. Among these algorithms, PSOA [45] has a strong global optimization ability and could find the global optimal solution with a higher execution efficiency, especially for high-dimensional problems. Moreover, it could also reduce the computational period with a higher accuracy and reliability. Thus, PSOA is selected as the optimization method to find optimal solutions. The optimization procedures of the present work are shown in Fig. 2 including the following steps [45].

Step 1: Input initial parameters. Basic parameters such as technical parameters and PSOA parameters are used to operate the modelling.

Step 2: Initialize the swarm values of the decision variables in Equation (15) randomly.

Step 3: Determine fitness functions for each swarm.

Step 4: Update the best position for each population.

Step 5: Update the algorithm parameter and the dynamic inertia weight.

Step 6: Update the velocity and position of the particles.

The optimization procedure is stopped when the current iteration number reaches the predetermined maximum iteration number (100 times). Otherwise, the search returns to the fitness calculation again until it reaches the maximum iteration number.

3 Results under various conditions

In this part, the simulation results are displayed based on the initial parameters in [39]. In addition, the optimization results are displayed and compared by considering the HTA, exergy and economy as single-objective functions.

3.1 Reference condition

The initial parameters in [39] are summarized in Table 5. The decision variables are mostly located in the mid-ranges. For example, the heat efficiencies of the HTX and LTX are set at 0.50 and the solution allocation ratio for the parallel chiller is 0.54. The performance of each state, including the temperature, pressure and concentration, and the performance of the two chiller types including HTA, COP, exergy efficiency and annual total cost are displayed in Table S1 in the online Supplementary Data and Table 6.

As shown in Table S1, the differences between the temperature, pressure and concentration for each internal state are lower. The performance in Table 6 shows that: (i) the HTA for the parallel chiller is larger than the area for the series chiller type (30.3 m²); (ii) the energy and exergy performances evaluated by using the COP and the exergy efficiencies are higher for the chiller connected in parallel. This can be explained by the higher HTA for the parallel chiller, which causes a higher heat exchanger capacity. (iii) Due to the higher HTA, the annual total cost of the parallel chiller is higher and the cost of the series chiller is only 74.17% of the cost of the parallel chiller.

The exergy destruction ratio and HTA of each component are shown in Fig. 3. In Fig. 3a, the order of the destruction ratio of the series chiller is HTX, absorber, HG, condenser, evaporator, LTX and LG. In the parallel type, the destruction ratios for the LTX and LG are higher than the ratios of the evaporator and condenser. This
is mainly because one part of the LiBr solution is fed to the LG to preheat the refrigerant vapour and rich solution. Moreover, in the LTX, the heat from the LG increases and the destruction exergy improves at the same time.

In Fig. 3b, it can be seen that the absorber needs the largest HTA to ensure the fixed cooling output of 400 kW. The absorber areas for the two types are 52.07% and 58.37% of the total HTA, respectively. Then the area of the LG increases by 4.8 m² for the parallel chiller, while the area of the HG decreases by 4.9 m² due to the distribution of the solution.

3.2 The lowest HTA

Based on the optimization procedures, the optimization results considering the minimization of the HTA are shown in Tables 7 and 8. The parameters of the states are summarized in Table S2 in the online Supplementary Data.

As shown in Table 8, $\Delta T_{1,1}$, $\Delta T_{1,2}$, $\Delta T_{2,1}$ and $\eta_{\text{LTX}}$ are set at the lower limit (0.5°C). Under this condition, the heat from the steam is easily absorbed in the HG with inlet and outlet temperatures of 150°C and 149.5°C, respectively, and the waste heat in the absorber and condenser is easily removed by the CW with inlet and outlet temperatures of 25°C and 25.5°C, respectively.

Table 8 displays the multicriteria performance of the two types of chillers. Compared with Table 6, the heat transfer, energy and exergy performance are improved. The lowest HTAs for the two types of chillers are only 149.0 and 146.7 m², respectively. The energy performance described by using the COP increases 18.75% and 18.56%, respectively. Due to the same external parameters, such as steam and cooling temperatures and fixed capacity, the exergy efficiency has a similar trend with the COP and the exergy efficiencies increase by 2.80% and 2.89%, respectively.

However, the chiller with the lowest HTA has a higher annual total cost. Under this condition, the total annual costs are 4.6 and 4.83% and 4.84%, with the lowest HTA, but the annual operating costs are almost 19.65% and 19.67% times the annual capital costs, respectively.

The exergy destruction ratio and HTA of each component are shown in Fig. 4. Unlike the almost uniform distribution in Fig. 3a, the exergy destructions of the HG and absorber are almost 70% of the total destruction, due to the higher temperature differences between the external and the internal flows. Compared with the series chiller, the destruction ratios of the LG, LTX and evaporator increase, while the ratios of other components are reduced.

By analysing the HTAs of each component in Fig. 4b, it can be seen that the HTAs of the absorber and the evaporator are >40 m², while the areas of the HTX and LTX are <5 m². Compared with Fig. 3b, the evaporator area has the lowest change, at 46.4 m² in Fig. 3b and 43.8 m² in Fig. 4b, while the absorber areas obviously change.

![Fig. 3: Exergy destruction ratio and heat transfer area for each component in two types of chillers](https://academic.oup.com/ce/article/8/1/55/7512602)

![Fig. 4: Optimization results to minimize heat transfer area](https://academic.oup.com/ce/article/8/1/55/7512602)
Table 8: Performance of chillers with minimization of heat transfer area

<table>
<thead>
<tr>
<th>Performance</th>
<th>Series chiller</th>
<th>Parallel chiller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat transfer area, m²</td>
<td>149.0</td>
<td>146.7</td>
</tr>
<tr>
<td>COP</td>
<td>1.14</td>
<td>1.15</td>
</tr>
<tr>
<td>Exergy efficiency, %</td>
<td>20.89</td>
<td>21.24</td>
</tr>
<tr>
<td>Annual total cost, $</td>
<td>3 394 873</td>
<td>3 336 778</td>
</tr>
</tbody>
</table>

Fig. 4: Exergy destruction ratio and heat transfer area for each component in two types of chillers

3.3 The highest exergy performance

Based on the same external parameters, including the inlet temperature of the steam (State 21), CW temperature (States 23 and 25), and inlet and outlet temperatures of the chilled water (States 28 and 27), the chillers obtain the highest energy and exergy performance with the same decision variables.

It can be seen in Table 9 that $\Delta T_1$ is set at the lowest limit of 0.5°C, while the heat efficiencies (0.95) and $\Delta T_4$ (15°C) are set at the upper limit for both the series and parallel chillers. Based on the decision variables shown in Table 9, the performance of the two types is displayed in Table 10. The parameters of the states are summarized in Table S3 in the online Supplementary Data.

Compared with the lowest HTA in Table 8, the HTAs with the highest exergy performance are ~5.6 and ~5.8 times higher for the series and parallel chillers, respectively. The energy performance calculated by using the COP is improved by 36.84% and 38.26%, respectively, and the exergy efficiencies are increased by 40.93% and 48.07%, respectively. However, compared with the annual cost, the annual total cost is 3.98 and 4.0 times that of the chillers with the lowest HTAs, respectively. Analysis of the annual total cost shows that the CC accounts for 99.12% and 99.65% of the total costs, which is caused by the higher HTA.

Table 9: Optimization results for maximal exergy efficiency

<table>
<thead>
<tr>
<th>Item</th>
<th>Series chiller</th>
<th>Parallel chiller</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta T_1$</td>
<td>0.5°C</td>
<td>0.5°C</td>
</tr>
<tr>
<td>$\Delta T_2$</td>
<td>15°C</td>
<td>15°C</td>
</tr>
<tr>
<td>$\Delta T_3$</td>
<td>9.4°C</td>
<td>9.9°C</td>
</tr>
<tr>
<td>$\Delta T_4$</td>
<td>5.2°C</td>
<td>5.2°C</td>
</tr>
<tr>
<td>$\Delta T_5$</td>
<td>9.2°C</td>
<td>9.2°C</td>
</tr>
<tr>
<td>$\Delta T_6$</td>
<td>9.9°C</td>
<td>25°C</td>
</tr>
</tbody>
</table>

Table 10: Performance of chillers with maximal exergy efficiency

<table>
<thead>
<tr>
<th>Performance</th>
<th>Series chiller</th>
<th>Parallel chiller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat transfer area, m²</td>
<td>979.8</td>
<td>989.2</td>
</tr>
<tr>
<td>COP</td>
<td>1.56</td>
<td>1.59</td>
</tr>
<tr>
<td>Exergy efficiency, %</td>
<td>29.44</td>
<td>31.45</td>
</tr>
<tr>
<td>Annual total cost, $</td>
<td>13 505 107</td>
<td>13 438 742</td>
</tr>
</tbody>
</table>

3.4 The lowest annual total cost

In the optimization based on minimization of the annual total cost, $\Delta T_4$ is set at the upper limit of 15°C and the solution allocation ratio is 0.95. Based on the decision variables in Table 11, the performance of the two types of chillers is shown in Table 12. The parameters of states are listed in Table S4 in the online Supplementary Data.

Compared with Tables 6, 8 and 10, the annual total costs account for 31.19%, 6.75% and 1.70% for the series-connected chiller, and 23.68%, 7.03% and 1.75% for the other type, respectively. The HTAs for the two types of chillers are not the lowest, but the HTAs for the series type, and 20.37% and 40.63% for the parallel type, respectively. The HTA for the evaporator is ~4.4 times that of the lowest HTA. These phenomena can be attributed to the lower temperature differences of $\Delta T_1$ (0.5°C) and $\Delta T_4$ (5.2°C), and the need for more HTA of the chillers to ensure fixed capacity.
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...energy, while the areas for the LTX are 0.99 and 1.02 m², respectively. Because of the solution allocation ratio, which is 0.95 in this part, the HTA of the LG increases by 81.01%, but the area of the HTX decreases by 58.47%.

4 Conclusion

In this study, two 400-kW double-effect absorption chillers with series and parallel connections are established and evaluated. Comparison and optimization are done by considering the HTA, exergy and economy, which can be used to evaluate the operation performance, as single-objective functions. The nine temperature differences, two heat exchange efficiencies for both series and parallel types, and the solution allocation ratio for parallel chillers are selected as decision variables due to the higher impacts on performance.

The results of the performance simulation and optimization show the following:

(i) The simulation results with reference data show that exergy losses in the two types of chillers are almost uniformly distributed and the HTA of the absorber accounts for 52.07% (series) and 58.37% (parallel) of the total HTA.

(ii) The lowest HTAs for two types of chillers are 149.0 and 146.7 m², respectively. Compared with the reference simulation results, the performance in terms of energy and exergy is improved, while the annual total cost is higher.

<table>
<thead>
<tr>
<th>Table 11: Optimization results to minimize annual total cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Item</td>
</tr>
<tr>
<td>ΔT₁</td>
</tr>
<tr>
<td>ΔT₂</td>
</tr>
<tr>
<td>ΔT₃</td>
</tr>
<tr>
<td>ΔT₄</td>
</tr>
<tr>
<td>ΔT₅</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 12: Performance of chillers with minimization of annual total cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Performance</td>
</tr>
<tr>
<td>Heat transfer area, m²</td>
</tr>
<tr>
<td>COP</td>
</tr>
<tr>
<td>Exergy efficiency, %</td>
</tr>
<tr>
<td>Annual total cost, $</td>
</tr>
</tbody>
</table>
The double-effect absorption chiller is an effective method for converting thermal or renewable energy into the needed cooling demand. Future research could include performance comparisons between the simulated and experimental results of different types of chillers, performance analysis for different absorption heat pumps to generate both chilled water and space HW, and absorption applications coupled with other novel renewable devices.

**Supplementary data**

Supplementary data is available at Clean Energy online.

**Nomenclature**

\[
\begin{align*}
A & : \text{area, m}^2; \\
AC & : \text{annual total cost, $}; \\
C & : \text{specific cost, $/ton}; \\
CC & : \text{annual capital cost, $}; \\
CW & : \text{cooling water consumption, ton}; \\
D & : \text{allocation ratio}; \\
Ex & : \text{exergy, kWh}; \\
f & : \text{area conversion factor}; \\
h & : \text{enthalpy, J/kg}; \\
\eta & : \text{interest rate}; \\
HTA & : \text{heat transfer area, m}^2; \\
m & : \text{mass flow rate, kg/s}; \\
n & : \text{operating year}; \\
OC & : \text{annual operating cost, $}; \\
Q & : \text{energy, kWh}; \\
RF & : \text{capital recovery factor}; \\
SW & : \text{heating water consumption, ton}; \\
T & : \text{temperature, °C}; \\
U & : \text{heat transfer coefficient, kW/(m}^2\text{ K}); \\
Z & : \text{initial investment cost, $}; \\
w & : \text{concentration of LiBr solution}; \\
\zeta & : \text{logarithmic mean temperature difference}; \\
\eta & : \text{efficiency, %}; \\
\Delta T & : \text{temperature difference, °C}.
\end{align*}
\]

**Conflict of interest statement**

None declared.

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**Data Availability**

All relevant data are within the paper and Supplementary Data files.

**References**


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