A techno-economic case study using heat driven absorption refrigeration technology in UK industry

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Large amount of low grade heat are wasted from industries, solar energy, geothermal energy.

Global warming and climate change has been happening since last century.

Recovery of the low grade heat for electrical generation and refrigeration may be one of the solutions.

- Increase the overall energy utilization of the existing system
- Produce extra usable energy
Aim and objectives

- Techno-economic study of a heat driven absorption chiller using in UK industry
  - Design of the absorption chiller for industry heat recovery
  - Construction of a thermodynamic simulation model of a single effect LiBr-H$_2$O to predict the system performance
  - Evaluation of the thermal loads of the absorption chiller to recover thermal energy from the STACK
  - Economic analysis of the system in the case study
Design of the system

Fig. 1 Schematic diagram of the single effect absorption chiller recovering exhaust gases heat from the STACK from a UK Industry.
Table 1 Parameters of exhaust air from the STACK[11] and the operational conditions of the industry case study

<table>
<thead>
<tr>
<th>Name</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exhaust gas temperature</td>
<td>$T_{\text{STACK_bottom}}$</td>
<td>200 °C</td>
</tr>
<tr>
<td>Exhaust gas volume flow rate</td>
<td>$\dot{V}_{\text{exhaust_air}}$</td>
<td>Averagely 9,800 m$^3$/h in operational condition</td>
</tr>
<tr>
<td>Density of exhaust air at 200 °C</td>
<td>$\rho_{\text{exhaust_air}}$</td>
<td>0.748 kg/m$^3$</td>
</tr>
<tr>
<td>Heat capacity of exhaust air</td>
<td>$C_{p\text{_exhaust_air}}$</td>
<td>1.097 kJ/(kg·K)</td>
</tr>
<tr>
<td>Condenser temperature</td>
<td>$T_{\text{con}}$</td>
<td>25 °C</td>
</tr>
<tr>
<td>Electricity price per unit</td>
<td>$C_{\text{electricity_per_kWh}}$</td>
<td>0.083 £/Kwh</td>
</tr>
<tr>
<td>Total operational hours per year</td>
<td>$t_{\text{hours_per_year}}$</td>
<td>(256 days, 21 hours per day)=5376 hours per year</td>
</tr>
<tr>
<td>Coefficient of performance of conventional vapour compression refrigerator</td>
<td>$COP_{\text{con}}$</td>
<td>3.67 [12]</td>
</tr>
</tbody>
</table>

The recoverable heat from the STACK can be calculated by the following equation, where $\dot{m}_{\text{exhaust\_air}}$ is the mass flowrate and $C_{p\text{\_exhaust\_air}}$ is the heat capacity of the exhaust air. The parameters used in the calculation are listed in Table 1.

$$\dot{Q}_{\text{heat}} = \dot{m}_{\text{exhaust\_air}} \times C_{p\text{\_exhaust\_air}} \times (T_{\text{STACK\_bottom}} - T_{\text{STACK\_top}})$$ (1)
Methodologies

A thermodynamic simulation model has been built to evaluate the performance of the single effect LiBr-H₂O in this study. The simulation model has been coded in Engineering Equation Solver [7] using the following listed equations. The pressure condition of the condenser and evaporator are defined by the follow equation[8]

\[ P = \exp \left[ 9.48654 + \frac{3892.7}{42.6776 - (T+273)} \right], \text{ when } P < 12.33 \text{MPa} \]  

(2)

The concentration of LiBr in the strong and weak solutions can be calculated by the following equations[9]

\[ X_{\text{strong}} = X_1 = X_2 = X_3 = \left( \frac{49.04 + 1.125 \times T_{\text{abs}} - T_{\text{eva}}}{134.65 + 0.47 \times T_{\text{abs}}} \right) \]

\[ X_{\text{weak}} = X_4 = X_5 = X_6 = \left( \frac{49.04 + 1.125 \times T_{\text{gen}} - T_{\text{con}}}{134.65 + 0.47 \times T_{\text{gen}}} \right) \]

(3)

The specific enthalpy of the solutions is calculated by the following equation[10], where \( i \) represents different state of the solutions.

\[ h_i(T_i, X_i) = (A_0 + A_i X_i)T_i + 0.5(B_0 + B_i X_i)T^2 + (D_0 + D_1 X_i + D_2 X^2 + D_3 X^3) \]  

\( 40 \leq X \leq 65 \text{wt.\%}, \quad 20 \leq T \leq 210 \degree \text{C} \)

(4)

\[ A_0 = 3.462023; B_0 = -2.679895 \times 10^{-2}; B_1 = 1.3499 \times 10^{-3}; B_2 = -6.55 \times 10^{-6}; \]

\[ D_0 = 162.81; D_1 = -6.0418; D_2 = 4.5348 \times 10^{-3}; D_3 = 1.2053 \times 10^{-3} \]

The heat capacity of the strong and weak solutions are defined as [10]

\[ C_p = (A_0 + A_i X_i) + (B_0 + B_i X_i) \times T \]

(5)
Mass flow rates of the refrigerant, strong and weak solutions are calculated by

\[ \dot{m}_r = \frac{\dot{Q}_{eva}}{h_0 - h_9} \]

\[ \dot{m}_{\text{strong}} = \dot{m}_r X_{\text{weak}} / (X_{\text{strong}} - X_{\text{weak}}) \quad (6) \]

\[ \dot{m}_{\text{weak}} = \dot{m}_r X_{\text{strong}} / (X_{\text{strong}} - X_{\text{weak}}) \]

The heat transfer relationship in the heat exchanger can be defined by the following two equations[5]. The temperature condition of strong solution after the solution heat exchanger (State 5) is calculated by equation (7) and the equation (8) is used to calculate the temperature condition of State 3.

\[ T_5 = T_{\text{gen}} - \eta_{\text{SHR}} \times (T_{\text{gen}} - T_{\text{abs}}) \quad (7) \]

\[ (T_3 - T_{\text{abs}}) \times X_{\text{strong}} \times C_{p_{\text{weak}}} = \eta_{\text{SHR}} \times X_{\text{weak}} \times C_{p_{\text{strong}}} \times (T_{\text{gen}} - T_{\text{abs}}) \quad (8) \]

The heat balance of the absorber, generator and condenser are defined as the following equations,

\[ \dot{Q}_{\text{abs}} = \dot{m}_r \times h_0 + \dot{m}_{\text{strong}} \times h_6 - \dot{m}_{\text{weak}} \times h_1 \quad (9) \]

\[ \dot{Q}_{\text{gen}} = \dot{m}_r \times h_7 + \dot{m}_{\text{strong}} \times h_4 - \dot{m}_{\text{weak}} \times h_3 \quad (10) \]

\[ \dot{Q}_{\text{con}} = \dot{m}_r \times (h_7 - h_8) \quad (11) \]
Results and discussion

In order to evaluate the refrigeration performance, the COP of the single effect absorption chiller has been calculated the results of three different evaporating temperatures under the heat sink temperature at 25 °C have been plotted in Fig. 2. When the evaporating temperature is 5 °C, an optimal generator temperature exists, which is about 60 °C and the optimal COP is about 0.825. The increase of evaporating temperature will slightly improve the cooling performance. When the generator temperature is between 60 to 90 °C, every 5 degree increase of evaporating temperature can improve the COP by around 0.02 as shown in Fig 2. Under the evaporating temperature at 10 °C, the peak COP of the absorption system is about 0.86 with 55 °C generator temperature.

The thermal loads of the system components are analysed under the generator temperature from 50 to 90 °C and the evaporating temperature is set at 10 °C. The results are drawn in Fig. 3. In this case study, the dumped heat load of the absorber requires around 190 kWh and the condenser consumes about 175 kWh. The results suggested the single effect absorption chiller can be operated under the optimal condition, when the generator temperature is maintained around 60 °C and the cooling production can be as high as 172 kW.
Results and discussion

The economic analysis has been conducted on this case study to estimate the potential electricity cost saving, when the absorption chiller has been installed in the UK industry. The pay-back period and annual electricity cost saving under different designed generator temperature have been calculated. The results are plotted in Fig. 4. The highest annual electricity cost saving is about £21k, when the generator temperature is at 53 °C. With the increase of designed generator temperature from 53 °C, the annual electricity cost saving drops from £21k to £19.8k. The results suggested the average payback period by adopting this technology in the UK case study is about 2.5 years. The changes of designed generator temperature will slightly effect the payback period of this technology. When the generator temperature is set at 60 °C, the annual electricity cost saving can be as high as £20.85k with 2.54 payback period as illustrated in Fig. 4.
Conclusions

• The techno-economic study of using absorption refrigeration technology in a UK industry has been reported. A thermodynamic simulation model has been developed and built.

- Optimal COP of the system exists (5 °C ref, 25 heat sink) is about 0.825 with 60 °C generator temperature. The maximum COP of the absorption chiller under 10 °C evaporating temperature is 0.86.

- Average thermal loads of absorber and condenser are 190 kWh and 175 kWh. Recover 200 kWh from the STACK can be as high as 172 kW, when the generator temperature is set at 60 °C.

- Maximum annual electricity saving by using the heat driven absorption chiller can be as high as £21k. Drops slightly from £21 to £19.8 with the increase of designed generator temperature from 53 to 90 °C. Average payback period by using this technology in UK industry is about 2.5 years.
Thanks for your attention!