EFFECT OF IRREVERSIBILITY ON COP OF DOUBLE EFFECT STEAM ABSORPTION CHILLERS

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ABSTRACT
Major irreversibilities in the absorption chillers are due to heat transfer between the absorption cycles and the environment. This effect also occurs for LiBr/H2O steam absorption chillers. This study investigated the effect of external heat transfer processes on LiBr/H2O steam absorption chillers installed at two district cooling plants in Malaysia. The study was done by evaluation of operating data. The heat transfer processes occurring at the desorbers, evaporators, condensers and absorbers for the absorption chillers at these two plants were investigated using reversible and zero order models. It is noted that the trends shown by the reversible and zero order models indicate the irreversibilities occurred for the absorption chillers at both plants. The COPs figures for reversible and zero order models for the absorption chillers at one of the plant indicate lower values. One possible cause of this occurrence was due to lower temperatures of returned chilled water. Hence in order to improve COP, the temperatures of returned chilled water should be increased.

Keywords: double effect steam absorption chiller, coefficient of performance, reversible model, zero order model.

INTRODUCTION
The simplest absorption chiller is single effect chiller. Single effect LiBr/H2O absorption chiller uses Lithium Bromide as the absorber and water as refrigerant. The chillers use low pressure steam or hot water as heat source. The thermal efficiency of the chillers are low normally varies from 0.4 to 0.8 [1]. Due to this reason the single effect absorption chillers are not competitive compared to electric chillers. A more competitive chillers are double-effect absorption chillers which are of higher thermal absorption chiller efficiencies reaching COP of 1.2 [2]. The double effect chillers use higher temperatures steam as heat source to generate chilled water. The chillers are normally installed at cogeneration plants.

Studies on absorption chillers performances have been published by many authors. Gamri [3] investigated the potential of single effect, double effect and multiple effect absorption cycles for chilled water production. He reported that the COP of double effect absorption system is two times the COP of single effect system. He also noted that for each condenser and evaporator temperature, there is an optimum generator temperature. Lobus et al. [4] published a study on comparison of four empirically based models: GNA, Δt’, MPR and ANN, using experimental data of small capacity absorption chillers. The authors concluded that all the four modelling methods are suitable for complex simulation environment. The statistical indicators and tests indicate ANN method had slight advantage compared to other two methods. Park et al. [5] analysed the performance of LiBr/H2O absorption chiller during partial load operation. The study was on the effect of cooling water flow rate and cooling water inlet temperature on the absorption chiller performance and energy saving during partial load operation. The authors noted that the performance of the absorption chiller is more sensitive to the changes of inlet water temperature rather than the cooling water flow rate.

Published literatures highlighted various methods used to evaluate COPs of absorption chillers. Among the methods adopted are using experimental data and simulation approach. To complement the studies, the proposed study is based on operating data of actual chillers. The main objective of this study is to use actual data to evaluate COP of LiBr/H2O operating at gas district cooling (GDC) plants. Reversible and zero order models are used. This is to validate theoretical aspects of the models. In addition, the findings of the study could assist the plant owners and operators for monitoring of plant performance.

DOUBLE EFFECT LiBr/H2O SAC
A schematic of double effect LiBr/H2O steam absorption chiller (SAC) is shown in Figure-1 [6].

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Figure-1. Schematic of double effect LiBr/H2O SAC [6].
The understudied absorption chillers are driven by steam generated by heat recovery steam generator (HRSG). As shown in Figure 1, heat is transferred into the cycle in both the high desorber and evaporator. Heat is transferred out from the cycle in the absorber and low condenser. There are two solution heat exchangers in the cycle. Internal heat exchange is achieved by incorporating the high condenser and the low desorber as represented by the continuous line border joining the two components. One side of the exchanger is the high condenser and the other side is the low desorber.

IRREVERSIBILITIES IN Li/Br H2O SAC

Major irreversibilities in LiBr/H2O SAC are due to heat transfer between the absorption cycle and the environment. The heat is transferred into the absorption cycle in both the high desorber and the evaporator. Internal heat exchange also occurs between the high condenser and the low. The internal heat exchange is achieved by incorporating these two components into a single transfer device. One side of the exchanger is the high condenser and the other side is the desorber as can be seen in Figure 1 [6]. The low desorber and low condenser operate at approximately the same conditions as single effect chiller. Due to this configuration the double effect absorption chiller is viewed as a three temperature levels as shown in Figure 2. These processes heat transfer include the solution heat exchanger, which is an internal heat transfer, and the external heat transfer. In the case of external heat transfer processes, the process on the solution side of the machine is coupled heat and mass transfer process. The irreversibilities associated with the coupled processes are lumped together in this study and assigned to the heat transfer. These points toward the type of models needed to predict the performance of absorption cycles. Zero order absorption cycle model is appropriate for this purpose.

REVERSIBLE AND ZERO-ORDER ABSORPTION CYCLE MODEL

(i) Reversible model

The reversible cycle is an ideal performance that can be achieved by an absorption cycle. COP of reversible cycle can be evaluated using equation (1) [7].

(ii) Zero order model

In real absorption cycle the performance is less than the value of that reversible cycle because of irreversibility process due to factors such as thermal mixing, mass mixing and, heat transfer. Since heat transfer is the main reason for irreversibilities, this study focus on this aspect. Zero order model was used to analyse the COP due to irreversibilities. The zero order model is based on the concept of three temperature levels. Figure 3 shows the three temperature levels indicating the relation of internal and external temperatures.

The AHP block represents the internal workings of the absorption cycle which are modelled as thermodynamically reversible. The model emphasizes the heat exchanger losses between the absorption cycle and the environment represented by thermal resistances R. The three R corresponding to the three temperature levels. The highest temperature T_h represents the temperature of the steam at desorber. The lowest temperature T_e represents the temperature of chilled water at evaporator. While T_c represents the intermediate temperature level which is the temperature of cooling water at condenser and absorber. The zero order model formulation is discussed in [6]. Equation (2) is the COP of zero model as derived in [6].
Figure-3. Zero order schematic diagram [6].

\[
COP_{so} = \frac{Q_c}{Q_h} = \frac{T_c(i)}{T_h(i)} \left( T_h(i) - T_c(i) \right) \tag{2}
\]

\[
COP_{so} = \frac{Q_c}{Q_h} = \frac{T_c(i)}{T_h(i)} \left( T_h(i) - T_c(i) \right) \tag{3}
\]

For double effect chillers the following equation applies.

\[
T_{h(i)} - T_{c(i)} = 2(T_{c(i)} - T_{e(i)}) \tag{4}
\]

The values of internal temperatures \( T_{h0} \), \( T_{c0} \) and \( T_{e0} \) were calculated by iterative process using the available \( T_h \), \( T_c \) and \( T_e \) as the basis.

Figure-4. Temperatures associated with zero order model.

The zero order model was also used to determine the minimum steam temperature for the absorption cycle based on the three temperature levels associated to zero order model as illustrated on Figure 4. The figure shows the temperatures internal to the SAC as a connected set which are linked by the relationship in Equation (3). The external temperatures \( T_h \), \( T_c \) and \( T_e \) are also shown. \( AT_h \), \( AT_c \) and \( AT_e \) indicate the temperature differences between the SAC absorption cycle and the environments. In this study the temperature differences at the three temperature levels are assumed equal. With this assumption the relationship of the steam temperature to the three temperature differences is expressed by Equation (5). \( AT_{LIFT} \) is the difference between the heat rejection temperature at condenser \( T_c \), and the chilled water temperature \( T_e \). The formulation also applies for absorber. Further, temperature at absorber is assumed same as temperature at condenser. Based on assumptions \( AT_{LIFT} \) between the three levels of temperature are the same, equation (5) was derived.

\[
\Delta T_{LIFT(x)} = (T_c - T_e) \tag{5}
\]

\[
T_h = 2(\Delta T_{LIFT} + 6\Delta T_h) + 2T_e \tag{6}
\]

Equation (5) was used to determine the minimum steam input temperature.

(iii) Actual COP

Actual COP was evaluated using Equation (6).

\[
COP_{sac(actual)} = \frac{1}{\text{Tons refrigerant hour}(RTh)} \left( \frac{(h_{steam} - h_{sacdrom})RT}{kg} \right) \tag{7}
\]

RESULTS AND DISCUSSIONS

COPs of LiBr/H\textsubscript{2}O absorption chillers at GDC Plant 1 and GDC Plant 2 were evaluated using the reversible and zero order models. Operations data 2015 were used for evaluation of the reversible and zero order models for both cases. COP plots of the reversible and zero order for the case of GDC Plant 1 are shown in the Figure 5. While Figure 6 shows the reversible and zero order plots for the case of GDC Plant 2.
For the case of GDC Plant 1 the COPs of the SAC indicate the trend as expected. The reversible COP shows increasing trend with increasing temperature. The zero order COPs indicate constant trend. As expected the reversible COPs are very much higher than zero order COPs, this proves that heat transfer losses occurred at the respective SAC. The plot also indicates actual COPs are lower than zero order COP. The recorded COP by the GDC Plant 1 based on Equation (6) varies from 1.1 to 1.4. This indicates other heat transfer losses such as losses due to other factors including pressure changes, mass fraction changes, super heating and cooling also occurred [6].

Similar trends are noted for the case of GDC Plant 2 reversible and zero order COP values, as shown in Figure-6. However, the reversible and zero order COP values are lower. The lower COP values are due to lower chilled water return temperatures. The return chilled water temperatures for GDC Plant 2 were in the range of 10 °C to 12 °C, while the range of return chilled water for GDC Plant 1 were between 11 °C to 13 °C. For GDC Plant 2 to improve COP is to have higher return temperature of chilled water.

Minimum temperatures of steam for both plants were evaluated using Equation (5). The results for GDC Plant 2 are as shown in Figure-7. The minimum value for GDC Plant 2 is 135 °C as per Table-1. The minimum heat input temperature value for GDC Plant 1 is 122 °C.

The plot indicates minimum steam temperature of 135 °C for the case of GDC Plant 2. It is noted that the minimum temperature of steam for GDC Plant 1 SAC is lower, which is 122 °C, as shown in Table-1.

<table>
<thead>
<tr>
<th>GDC Plant 1</th>
<th>GDC Plant 2</th>
</tr>
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<tbody>
<tr>
<td>Minimum temperature of steam (°C)</td>
<td>122</td>
</tr>
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</table>

CONCLUSIONS

The study proves that the COPs of LiBr/H₂O SAC are influenced by the heat transfer processes between the absorption cycle and the environment. The heat transferred into the absorption cycle through the high desorber and evaporator and heat transferred out from the absorption cycle through the condenser and absorber affect the zero order COPs for both the chillers at GDC Plant 1 and GDC Plant 2. For both cases the COPs showing trends of increasing with increase of heat input temperatures, however it is not the case for COPs of zero order model. This indicates irreversibilities occurred for chillers at both GDC Plant 1 and Plant 2. Since zero order model takes into account only the heat transfer processes that contribute to the largest irreversibilities but not the internal losses, hence the actual COPs are lower than zero order model. It is also noted that lower returned temperatures led
to lower COPs. For future studies the internal losses which contribute to irreversibilities should be considered in evaluating COPs.

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