Solution Crystallization Detection for double-effect LiBr-H_2O steam absorption chiller

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Abstract

Absorption refrigeration systems gained considerable attention recently for their environmental friendly behavior and for activation using thermal energy sources. In LiBr-H_2O absorption chillers, solution crystallization represents a severe problem. The crystallization of the solution blocks the chiller internal piping and stop the chiller operation. In this paper a crystallization detection function is developed and embedded into a dynamic simulation model to detect solution crystallization due to abnormal operation. The crystallization detection function is developed by introducing critical concentration equation that was generated from linearization of the crystallization line in Equilibrium chart for aqueous lithium bromide solutions. The model successfully depicted the solution concentration when the solution concentration is approaching the crystallization line.

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Keywords: absorption chiller; lithium bromide solution; crystallization; double-effect

1. Introduction

When lithium bromide is dissolved in water, a minimum solution temperature exists for each solution concentration. The nature of LiBr solutions is that the salt component precipitates when the mass fraction of salt exceeds the solubility limit. The solubility limit is a strong function of mass fraction and temperature and a weak function of pressure. Furthermore, crystal nucleation is a process sensitive to the presence of nucleation sites. If no suitable nucleation sites are present, super saturation can occur where the salt content of the liquid is greater than the solubility limit. Once crystals begin to form, the crystals

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themselves provide favorable nucleation sites and the crystals grow on themselves [1]. In an absorption machine if the solution concentration is too high or the solution temperature is too low, crystallization may occur, most likely in the solution heat exchanger. In this case, the concentrated solution temperature should be increased above its saturation point so that salt crystals return to the solution [2]. The crystallization curve of LiBr is shown in Figure A.1 in appendix A. Usually the absorption cycle is plotted in a Dühring P-T chart, a pressure-temperature graph where the diagonal lines represent constant LiBr mass fraction, with the pure water line at the left and crystallization line at the right.

In absorption chillers, usually the crystallization line for lithium bromide and water is very close to the working concentrations needed for practical LiBr-H2O absorption chillers. If the solution concentration is too high or the solution temperature is reduced too low, crystallization may occur and interrupt machine operation. Crystallization must be avoided since the formation of slush in the piping network over time could form a solid and block the flow. To recover absorber operation after crystallization occurs is very labor intensive and time consuming [3].

In the past, two principal technical approaches to LiBr absorption design have been used. They involve: (1) Mechanical design changes, such as very highly efficient heat exchangers, to bring the air-cooled operation within the existing LiBr-H2O crystallization limits. This approach is significantly more expensive per ton of capacity than the conventional water-cooled LiBr-H2O absorption chillers, and therefore it is not considered suitable in most applications [4]. (2) The use of chemical additives, such as 2-Ethyl Hexanol, to shift the crystallization line to higher temperatures to allow air-cooled operation with commercially practical margins of safety from crystallization using conventional heat exchangers. However, all of the suitable chemicals exhibit negative characteristics that effectively limit their practical application.

The most frequent causes of crystallization are given by Florides et al. [5]. One of these causes is the high-generation temperature required when condensation temperature is also high (air-cooled systems). When solution returns to the absorber through the heat exchanger, its temperature decreases and it is possible to achieve crystallization inside the solution heat exchanger.

Kisari, et al. [6] conducted a systematic study to explore the crystallization temperatures of LiBr-H2O solutions that fall below an evaporating temperature of 10°C. Their studies revealed that the rate of cooling of the sample solution influences the crystallization temperature.

Air-cooling for the absorber and condenser can be an important issue to avoid using a cooling tower. For solar air-conditioning applications, the refrigerant-absorbent pair LiBr-H2O is competitive with respect the most universal pair NH3-H2O due to its higher performance, but the use of LiBr as absorbent implies the risk of crystallization, more important in air-cooled systems. Different prototypes of air-cooled H2O-LiBr machines have been developed in the past decade for air-conditioning in buildings [7-9]. However, those machines were gas-fired. Therefore, the type of cycle used in those cases was double effect in order to get the maximum advantage of the input energy. LiBr is sometimes used as absorbent together with LiI to overcome the problem of crystallization [8]. The main problem for all those machines relies on the high electrical consumption of the fans to create adequate cooling effect on the absorber and the condenser, because reduced and compact designs were the main premises. The main

**Nomenclature**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h$</td>
<td>enthalpy</td>
<td>kJ/kg</td>
</tr>
<tr>
<td>$X$</td>
<td>solution concentration</td>
<td>%</td>
</tr>
<tr>
<td>$T$</td>
<td>Temperature</td>
<td>°C</td>
</tr>
<tr>
<td>LiBr</td>
<td>Lithium bromide</td>
<td>-</td>
</tr>
<tr>
<td>$\min$</td>
<td>minimum</td>
<td>-</td>
</tr>
<tr>
<td>$c$</td>
<td>critical</td>
<td>-</td>
</tr>
<tr>
<td>$X_{11}$</td>
<td>concentration of the solution entering absorber</td>
<td>%</td>
</tr>
</tbody>
</table>
objective of this research work is to develop a solution crystallization detection function for dynamic simulation of double effect steam absorption chillers, so that the deterioration of expensive equipment could be avoided.

2. Methodology

Since crystallization is the most severe problem in the LiBr-H2O absorption refrigeration systems, it is essential to avoid the occurrences of it due to the high cost of the maintenance, as the solidification of the solution blocks the pipes of the system and affects the reliability of the operation. To ensure a safe and continuous operation, the chiller should operate above the crystallization line.

To avoid solution crystallization Ardehali et al. [10] reported a constraint equation for enthalpy of the solution stream entering absorber, the place where crystallization usually happens.

They stated that this enthalpy should be higher than a minimum amount which is a function of the concentration of the stream entering the absorber. The constraint equation for enthalpy is as follows:

\[
    h_{\text{min}} = \left( -1396670 + 24000 \times X \right) / 1000
\]

(1)

The constraint to avoid crystallization is that the enthalpy of solution stream entering absorber should be greater than \( h_{\text{min}} \). This constraint is used for a set of temperatures and concentrations data that are directly above and below the crystallization line in the equilibrium chart of lithium bromide solution. Table 1 shows the calculated enthalpy based on temperature and concentration and the minimum enthalpy based on solution concentration. For the first five sets of temperature and concentration, these points are above the crystallization line, in the safe operation area, i.e. the value of \( h \) is greater than \( h_{\text{min}} \). While for the rest of the data set, the points are below the crystallization line, in the crystallization zone, i.e. \( h < h_{\text{min}} \).

<table>
<thead>
<tr>
<th>No.</th>
<th>( T ) (°C)</th>
<th>( X ) (%)</th>
<th>( h ) (kJ/kg)</th>
<th>( h_{\text{min}} ) (kJ/kg)</th>
</tr>
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<tr>
<td>1</td>
<td>50</td>
<td>64</td>
<td>162.0392</td>
<td>139.33</td>
</tr>
<tr>
<td>2</td>
<td>55</td>
<td>65</td>
<td>177.9507</td>
<td>163.33</td>
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<td>3</td>
<td>60</td>
<td>65.5</td>
<td>190.3877</td>
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<tr>
<td>4</td>
<td>65</td>
<td>66</td>
<td>202.8279</td>
<td>187.33</td>
</tr>
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<td>70</td>
<td>66</td>
<td>211.6041</td>
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<td>55</td>
<td>66.5</td>
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<td>8</td>
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<td>65</td>
<td>68</td>
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</tr>
<tr>
<td>10</td>
<td>70</td>
<td>68</td>
<td>226.9872</td>
<td>235.33</td>
</tr>
</tbody>
</table>

Table 1 Comparison between enthalpy of selected point above and below crystallization line

This method can provide a protection tool from operating in the crystallization range, however, this method is valid only from the solution stream entering absorber, where the most crystallization is
occurring. Remembering that the solution crystallization occurs in an absorption chiller when the solution temperature decreases and solution concentration increases, and it effects the solution solubility limit to drop as well. Solution crystallization will start if the solubility limit is decreased.

To avoid the solution crystallization in other components such as generators and solution heat exchangers, a new crystallization detection functions is developed based on stream temperature. Curve fitting for the crystallization line in the equilibrium chart for aqueous lithium bromide solutions in Figure A.1 is made and approximated to linear relationship between the stream temperature and the solution concentration at crystallization limit or critical concentration $X_c$. Figure 1 shows the relation between the stream temperature and the critical concentration at any component in the absorption chiller. The critical concentration is chosen as a measure to detect the crystallization rather than the stream temperature because the common practical treatment for the crystallization is executed to the solution concentration such as dilution cycle [11] in which the refrigerant liquid is allowed to flow to the absorber to decrease the solution concentration.

$$X_c = 0.08097 \times T + 61.341$$

The sensitivity of the dynamic model to catch critical system operations that may cause solution crystallization has been examined. Crystallization represents a big challenge for LiBr-H$_2$O chillers due to the blocking of chiller pipes and stopping the chiller operation and consequently the high cost of the maintenance.
3. Results and discussion

To assess sensitivity of the dynamic simulation model to depict solution crystallization, extreme cooling capacity change was simulated after normal operating conditions, for a certain period of time. The chiller cooling capacity at normal condition was changed to half after one hour of operation as shown in Figure 2 (a).

Figure 2 (a) Reduction of cooling capacity after one hour of operation (b) Solution concentration approaching crystallization limit

The immediate effect of decreasing the cooling capacity to half appears in increasing the solution concentration from both generators, but still within the safe zone or at the left of the crystallization line. By exchanging heat with a cold, weak solution pumped from the absorber, the temperature of concentrated solution entering absorber dropped. Due to low solution temperature and high solution concentration, the solution approaches the crystallization zone, as shown in Figure 2 (b).

4. Conclusions

In LiBr-H2O absorption chillers, solution crystallization represents a severe problem. The crystallization of the solution blocks the chiller internal piping and stop the chiller operation. The developed crystallization detection function is embedded into a dynamic simulation model to detect solution crystallization due to abnormal operation. The model successfully depicted the solution concentration when the solution concentration is approaching the crystallization line. This function can be used for monitoring of machine operation to avoid machine failure and the consequent maintenance cost.

Acknowledgements

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References


Biography

Dr S. I. Gilani has been working as an Associate Professor, in ME Department at University Technology PETRONAS, Malaysia since 2003. He has 22 years of experience in teaching as well as industry. He has authored more than 60 research publications in the areas of Energy, GDC and Cogeneration, etc.
Appendix A. Equilibrium chart for aqueous lithium bromide solutions

Figure A 1 Equilibrium chart for aqueous lithium bromide solutions [13]