African Journal of Advanced Pure and Applied Sciences (AJAPAS)
Online ISSN: 2957-644X
Volume 4, Issue 4, 2025
Page No: 807-816
Website: https://aaasjournals.com/index.php/ajapas/index

ISI 2025: 1.126 **SJIFactor 2024: 6.752** **معامل التأثير العربي: 1.62**

Modelling Crystallization Detection in Single-effect Aqua-LiBr Vapor Absorption Cooling Systems

Salem M. Osta-Omar [1 *], Moutaz Elgammi [2]
[1,2] Department of Mechanical Engineering, Faculty of Engineering,
University of Derna, Derna, Libya

نمذجة كشف التبلور في أنظمة تبريد امتصاص البخار ذات التأثير الأحادي باستخدام بروميد الليثيوم المائي

سالم مصطفى أسطى عمر [1*]، معتز أحمد الجامعي [2]
[2،1] قسم الهندسة الميكانيكية، كلية الهندسة، جامعة درنة، درنة، ليبيا

[*]Corresponding author: s.ostaomar@uod.edu.ly

Received: October 10, 2025	Accepted: December 16, 2025	Published: December 25, 2025

Abstract

Single-effect aqua-LiBr vapor absorption cooling systems are widely used in cooling applications due to their ability to utilize low-grade energy sources and their environmentally friendly characteristics. However, a significant operational challenge is the risk of crystallization, which occurs when the aqua-LiBr solution reaches its highest concentration and lowest temperature, exceeding the crystallization boundary. This phenomenon is particularly critical at the inlet of the absorber after aqua-LiBr solution leaving the solution heat exchanger, especially under decreasing ambient temperatures. Crystallization can obstruct system components, reduce efficiency, and ultimately lead to system failure. This paper presents a model for detecting crystallization in single-effect aqua-LiBr vapor absorption cooling systems through thermodynamic analysis, enabling the identification of safe operational conditions. Additionally, a correlation equation is provided for determining the minimum critical temperature (T_{cr}) of the absorber and condenser, beyond which crystallization occurs. This equation is only validated for desorber temperatures ranging from 60°C to 120°C and solution heat exchanger effectiveness values between 0.5 and 0.9, demonstrating a high coefficient of determination (R^2).

Keywords: Crystallization Boundary, Aqua-LiBr Solution, Concentration, Vapor Absorption Cooling System, Regression Analysis.

الملخص

تستخدم أنظمة تبريد امتصاص البخار ذات التأثير الأحادي باستخدام بروميد الليثيوم المائي على نطاق واسع في تطبيقات التبريد نظرًا لقدرتها على استخدام مصادر الطاقة منخفضة وخصائصها الصديقة للبيئة. ومع ذلك، فإن التحدي التشغيلي الكبير هو خطر التبلور، الذي يحدث عندما يصل محلول بروميد الليثيوم المائي إلى أعلى تركيز وأدنى درجة حرارة، متجاوزًا حدود التبلور. تعتبر هذه الظاهرة حرجة بشكل خاص عند مدخل وعاء الامتصاص بعد مغادرة محلول الليثيوم بروميد المائي للمبادل الحراري، لا سيما في ظل انخفاض درجات الحرارة المحيطة. يمكن أن يؤدي التبلور إلى انسداد مكونات النظام، وتقليل الكفاءة، وتوقف عمل النظام. تقدم هذه الورقة نموذجًا للكشف عن التبلور في أنظمة تبريد امتصاص البخار ذات التأثير الأحادي باستخدام بروميد الليثيوم المائي من خلال التحليل الديناميكي الحراري، مما يمكّن من تحديد الظروف التشغيلية الآمنة. بالإضافة إلى ذلك، تم استنتاج معادلة ارتباطية لتحديد الحد الأدنى من درجة الحرارة الحرجة لوعاء الامتصاص والمكثف، والتي يحدث بعدها التبلور. تم التحقق من صحة نتائج هذه المعادلة والتي حدود صلاحيتها العمل عند درجات حرارة مولد البخار تتراوح بين 60°C و120°C وفعالية مبادل الحرارة للمحلول بين 0.5 و0.9.

الكلمات المفتاحية: حد التبلور، محلول بروميد الليثيوم المائي، التركيز، نظام تبريد امتصاص البخار، تحليل الانحدار.

Introduction

The fundamentals of absorption cooling technology are based on the phenomenon of absorption, which occurs due to the chemical affinity of a sorbent to retain sorbate. In aqua-LiBr vapor absorption cooling systems, water refrigerant serves as the sorbate, while the aqua-LiBr solution acts as the sorbent, facilitating both absorption and desorption processes. The desorption process, which involves the separation of the sorbate from the sorbent, occurs in a desorber and requires input of heat. Conversely, the absorption process, in which the sorbate is absorbed by the sorbent, takes place in an absorber through an exothermic reaction. The absorption process effectively reduces the pressure of the refrigerant, resulting in a decrease in its boiling temperature to levels lower than that of the surrounding environment. Consequently, during the evaporation phase, the refrigerant absorbs heat from the surroundings, thereby generating a cooling effect. The absorption process is characterized as heat-releasing process, which subsequently elevates the temperature of the aqua-LiBr solution. To sustain the absorption process, the thermal energy produced by the chemical reaction during the absorption process must be effectively dissipated from the aqua-LiBr solution using the absorber [1,2]. Lithium-Bromide is a solid substance under normal conditions. When Lithium-Bromide dissolves in water, it forms an aqua-LiBr solution with a lower equilibrium vapor pressure than the pure water at the same operating temperature [3]. The solubility of aqua-LiBr solution is significantly influenced by temperature. Consequently, maintaining the temperature of the Aqua-LiBr solution above its solubility limit is crucial to prevent crystallization [4].There are many causes for the crystallization, crystallization due to an air leak into the absorption cooling system, crystallization due to the failed dilution after shutdown of the absorption cooling system, or the crystallization of the aqua-LiBr solution during the operation of an absorption cooling system as a result of significant temperature drops or increases in the lithium bromide mass concentration within the solution [5]. The last case of crystallization is danger because it can obstruct the flow of the aqua-LiBr solution throughout the system, ultimately leading to the shutdown of the vapor absorption cooling system. This crystallization phenomenon frequently tends to occur in the strong aqua-LiBr solution situated between the solution heat exchanger and the absorber, where the temperature of the aqua-LiBr solution is relatively low, and the lithium bromide mass concentration is maximized within the system [3]. Therefore, the absorption and desorption processes in aqua-LiBr vapor absorption cooling systems must be carefully designed to avoid the crystallization of the aqua-LiBr solution, particularly in the crucial component known as the solution heat exchanger.

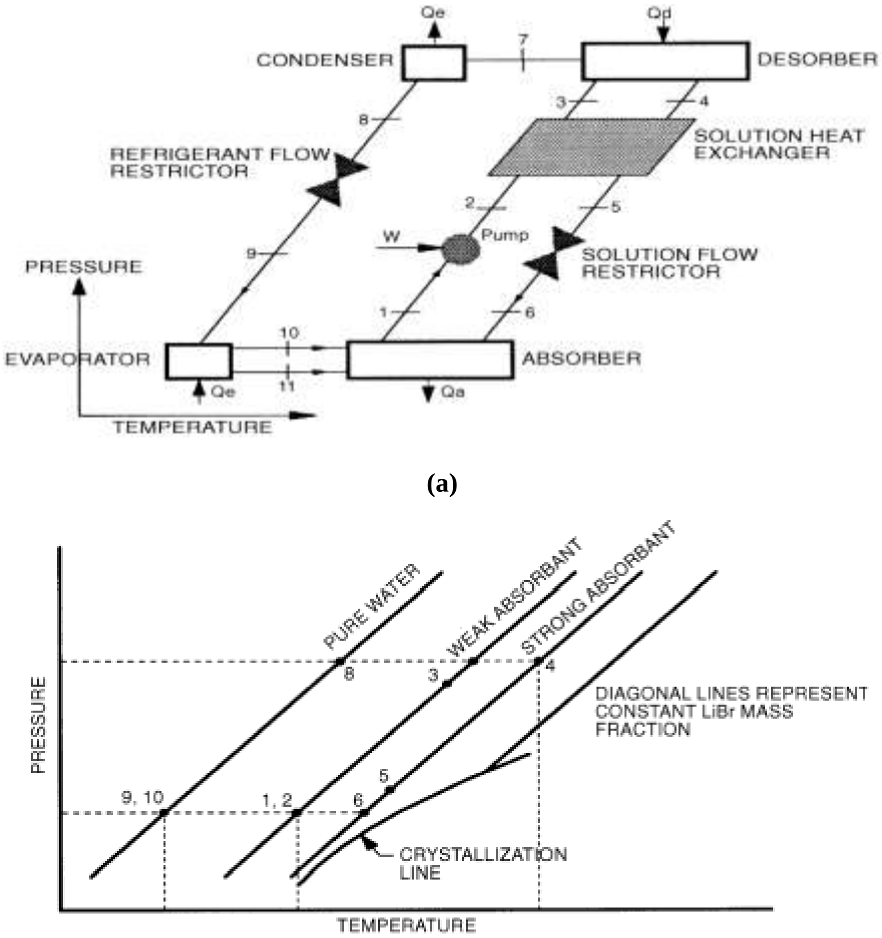
Recent years have witnessed an increase in research focused on the design of aqua-LiBr vapor absorption cooling systems through both theoretical and experimental methodologies. For instance, Liao and Radermacher [5] investigated air-cooled absorption chiller systems, highlighting their advantages in eliminating the necessity for cooling towers and associated maintenance issues. The research identifies the crystallization of the LiBr-H2O solution as a significant operational challenge, largely attributable to elevated temperatures and concentrations inherent in these systems. The study emphasizes the importance of understanding the factors that trigger crystallization, including variations in ambient temperature, air leaks, excessive heat input, and low chilled water supply temperatures. Moreover, it proposes innovative temperature control strategies to mitigate these challenges. The authors also introduce a novel approach for the integration of absorption chillers into combined cooling, heating, and power (CHP) systems, thereby illustrating the economic benefits of the proposed methodology. Farshi et al. [6] investigate the impact of crystallization, a significant operational challenge, on the performance of double effect lithium bromide-water systems, particularly in air-cooled configurations that eliminate the need for cooling towers. This study develops a computational model to analyze the effects of various operating parameters on crystallization phenomena in three configurations: series, parallel, and reverse parallel, all maintaining identical refrigeration capacities. The findings reveal that the parallel and reverse parallel systems exhibit a broader range of operating conditions with minimal crystallization risk compared to the series flow configuration. Furthermore, the research indicates that crystallization risk in series systems increases with higher temperatures at the high-pressure generator and evaporator, as well as with increased effectiveness of the low-temperature heat exchanger. Conversely, higher condenser and absorber temperatures, which are equal in this study, help mitigate this risk. Latorre-Arca et al. [7] examine the influence of five ionic liquids (ILs) as anti-crystallization additives in water/lithium bromide (LiBr) solutions. The solubility of lithium bromide in water was quantitatively assessed over a temperature range of 280 to 360 K, utilizing varying IL/LiBr mole ratios. The findings indicate that the incorporation of ILs enhances the operational range of absorption refrigeration and heat pump systems by promoting greater solubility of lithium bromide. This study underscores the importance of IL selection in optimizing LiBr solubility, thereby improving performance in refrigeration applications. Izquierdo et al. [8] investigate the utilization of low-temperature solar heat for cooling applications at 5°C through a double-stage LiBr–H_2O air-cooled absorption cycle. A solar plant, characterized by flat plate collectors, has been modeled to provide the requisite thermal energy to the generators of the absorption machine. The results indicate that the double-stage absorption cycle can function without crystallization challenges at condensation temperatures reaching 53°C, necessitating a generation temperature of approximately 80°C to sustain a theoretical coefficient of performance (COP) of 0.38 when the condensation temperature is 50°C. In contrast, single-stage absorption cycles are constrained to condensation temperatures not exceeding 40–45°C when supplied by flat plate collectors, as elevated condensation temperatures require generation temperatures that may reach up to 105°C, thereby increasing the risk of crystallization. Florides et al. [9] present a method for evaluating the performance characteristics of a single-stage lithium bromide–water absorption machine. The study defines essential heat and mass transfer equations, along with the properties of the working fluids, which are incorporated into a computer program for conducting sensitivity analysis. Results show that greater differences in LiBr concentrations between the absorber's inlet and outlet lead to reduced mass flow rates. Additionally, maintaining a consistent 6% difference in LiBr concentration between the inlet and outlet of the absorber enhances the cooling performance. Marashli et al. [10] developed a mathematical model using MATLAB/Simulink to investigate lithium bromide-water crystallization in Single-Effect Solar Absorption Cooling systems. This model analyzes how temperature variations within the cooling cycle impact the coefficient of performance and the risk of crystallization. Key findings include the optimal temperatures for system components to operate without crystallization: 105°C for the generator, 38°C for the absorber, 50°C for the condenser, and 5°C for the evaporator, along with aqua-LiBr solution heat exchanger effectiveness of 0.8. The study emphasized the generator temperature as a critical factor in overall system performance, achieving a maximum coefficient of performance of 0.74 at 110°C without crystallization, highlighting the importance of maintaining specific operational conditions to mitigate crystallization risks. Ardehali et al. [11] develop a simulation model for a water–LiBr solar-assisted absorption system with an auxiliary heating source. The numerical model examines the impact of a reduced clearness index based on actual data for both constant and variable cooling loads. The study highlights the need for further experimental validation of the results and calls for more precise prediction methods for available solar energy. Additionally, it emphasizes the importance of preventing crystallization in these solar systems by ensuring that the enthalpy of the strong aqua-LiBr solution at the inlet of the absorber, after leaving the heat exchanger, exceeds a specified minimum value determined by a correlation equation presented in the paper. GiLani and Ahmed [12] study absorption refrigeration systems, particularly for double-effect LiBr-water steam absorption chiller, which are environmentally friendly and utilize thermal energy. A significant issue in these systems is the crystallization of the solution, which can block internal piping and lead to operational failures. To address this, the authors developed a crystallization detection function integrated into a dynamic simulation model. This function uses a critical concentration equation derived from the crystallization line in the equilibrium chart for aqueous lithium bromide solutions. The model effectively monitors solution concentration to identify when it nears the crystallization line, helping prevent costly maintenance and ensuring reliable operation by keeping the chiller above the crystallization threshold. Overall, this tool aids in monitoring and safeguarding the machine's functionality.

Despite extensive research, there is a notable deficiency in comprehensive studies that examine the combined effects of varying desorber, absorber, and condenser temperatures, along with the effectiveness of the solution heat exchanger, on the crystallization phenomenon. The primary objectives of this study are to quantify these impacts and identify the safe operation conditions that prevent crystallization in the crucial component known as the solution heat exchanger. To achieve these aims, a model for crystallization detection in single-effect aqua-LiBr vapor absorption cooling systems was developed, facilitating the determination of the safe operation conditions for the system.

Methodology:

1- System Description

The basic single-effect aqua-LiBr vapor absorption cooling cycle, as illustrated in Figure 1(a), consists of four primary components: an absorber, a desorber, an evaporator, and a condenser. This absorption cycle is thermally driven by the desorber, where the refrigerant vaporizes from the aqua-LiBr solution, resulting in a concentrated absorbent solution (strong concentration of aqua-LiBr solution) that is conveyed back to the absorber through a throttling valve. As this strong absorbent solution passes through the solution flow restrictor, its pressure is decreased from that of the desorber to that of the absorber. The vapor refrigerant extracted from the desorber is subsequently cooled and condensed in the condenser. The resulting liquid refrigerant is then channeled through the refrigerant flow restrictor into the evaporator, where it evaporates by absorbing heat from its surroundings, thus generating a cooling effect. The vaporized refrigerant is absorbed by the strong absorbent solution, forming a diluted absorbent solution (weak concentration of aqua-LiBr solution), which is then pumped back to the desorber, completing the cycle. To enhance the efficiency of the absorption cooling cycle, a solution heat exchanger is incorporated between the absorber and the desorber, facilitating the recovery of heat from the strong aqua-LiBr solution to the pumped weak aqua-LiBr solution [1,13,14].



(a)

(b)

Figure 1: **(a)** Single-effect aqua-LiBr vapor absorption cooling cycle, **(b)** Single-effect aqua-LiBr vapor absorption cooling cycle superimposed on Dühring plot [1].

Before entering the absorber, the strong aqua-LiBr solution is cooled in the solution heat exchanger to a temperature lower than that of the desorber, approaching the crystallization boundary depicted in Dühring's chart (Figure 1(b)). The solution heat exchanger is a critical component concerning crystallization; when the ambient temperature decreases, it causes the temperature of the cooling fluid used to reject heat from the condenser and the absorber to drop. This, in turn, leads to reduced temperatures in both the condenser and the absorber. Under these critical conditions, where the strong aqua-LiBr solution is at its highest concentration and lowest temperature (as indicated at point (6) in Figure 1(a)), there is a risk of entering the crystallization region, which could lead to the formation of slush. This slush can obstruct the pipes and halt system operation [3,15].

2- Thermodynamic Analysis of Single-Effect Aqua-LiBr Vapor Absorption Cooling Cycle

Energy analysis is a typical method used to evaluate energy consumption in thermodynamic cycles. This work derives the mass and energy balance equations for each component of the aqua-LiBr vapor absorption cooling system based on the findings from Ref. [16-19].

$$\sum(\dot{m}\,h)_{in} - \sum(\dot{m}\,h)_{out} + \left[\sum Q_{in} - \sum Q_{out}\right] = 0 \tag{1}$$

$$\sum(\dot{m})_{in} - \sum(\dot{m})_{out} = 0 \tag{2}$$

$$\sum(\dot{m}\,x)_{in} - \sum(\dot{m}\,x)_{out} = 0 \tag{3}$$

Where Q is the heat transfer rate (kW), h is the specific enthalpy (kJ/kg), $\dot{m}$ is the mass flow rate (kg/s), and x is the mass concentration of aqua-LiBr in the solution (%).

The percentage LiBr mass concentration of aqua- LiBr solution (x) is calculated by the following equation [1]:

$$\sum_{0}^{3} B_n\, x^n - t' \sum_{0}^{3} A_n\, x^n = t \tag{4}$$

Where A & B are Coefficients for the polynomial of degree n, $t'$is the refrigerant water temperature (℃), and t is the aqua-LiBr solution temperature (℃). The validity of this equation is for a refrigerant temperature in the range between −15 ℃ and 110 ℃, and a solution temperature in the range between 5 ℃ and 175 ℃ [1].

The specific enthalpy (h) of the aqua-LiBr solution (kJ/kg) is calculated by the following equation [1]:

$$h = \sum_{0}^{4} A_n\, x^n + t \sum_{0}^{4} B_n\, x^n + t^2 \sum_{0}^{4} C_n\, x^n \tag{5}$$

Where $A, B,$ & C are Coefficients for the polynomial of degree n, t is the aqua-LiBr solution temperature (℃), and x is the LiBr mass concentration in the aqua-LiBr solution (%). The validity of this equation is for a LiBr mass concentration of solution range between 40 % and 70 % and for an aqua-LiBr solution temperature range between 15 ℃ and 165 ℃ [1].

Ardehali et al. [11] established the equation for the minimum specific enthalpy of the aqua-LiBr solution to prevent crystallization, expressed as:

$$h_{min} = -1396670 + 24000\, x \tag{6}$$

Where h_{min} is the minimum specific enthalpy (kJ/kg) below which the aqua-LiBr solution starts to crystallize, and x is the percentage mass concentration of LiBr in the aqua-LiBr solution.

Consequently, it is crucial to monitor the specific enthalpy h in relation to the calculated h_{min} to ensure the safe operation of systems employing aqua-LiBr solutions. This monitoring is particularly important at critical components, the solution heat exchanger, where the solution exits and enters the absorber at its highest concentration and lowest temperature, increasing the risk of crystallization.

3- Modelling set up

The energy and mass balance equations for the various components (Equations 1, 2, and 3) were applied within the algorithm described in the model flowchart shown in Figure 2. This model was implemented in MATLAB 2022b [20]. Additionally, crystallization analysis was conducted using Equations 4,5 and 6. The MATLAB program was also utilized to generate graphs related to the crystallization analysis.

To perform the crystallization analysis of a single-effect aqua-LiBr vapor absorption cooling system, certain basic assumptions and input values must be considered. Referring to Figure 1 (a & b), the following basic assumptions are established:

- Heat loss and pressure loss are negligible.
- At points 1, 4, 8, and 11, only saturated liquid is present.
- At points 7 and 10, only saturated vapor exists.
- Flow restrictors are assumed to be isenthalpic.
- The work performed by the pump is negligible.
- Liquid carryover from evaporator $\dot{m}_{11} = 2.5\ \%\ \dot{m}_{10}$, as recommended by ASHREA [1]

Based on these assumptions, the following input values for specifications are established:

- The cooling capacity (Q_{eva}) at the evaporator is set at 1 kW.
- The evaporator temperature $(T_{eva})$is fixed at 3 ℃, which is appropriate for using water as a refrigerant, as recommended by Stoecker and Jones [3].
- The temperature range for the condenser $(T_{con})$and absorber $(T_{abs})$is set between 10 ℃ and 60 ℃, making it suitable for various ambient conditions as an external sink.
- The desorber temperature (T_{des}) range is set from 60 ℃ to 120 ℃.
- The effectiveness (ε) values of the solution heat exchanger are chosen to be 0.5, 0.7, and 0.9.
- The minimum heat capacity rate (c_{min}) is 1.9, which is considered suitable for the properties of the aqua-LiBr solution, as recommended by Kaita [21].

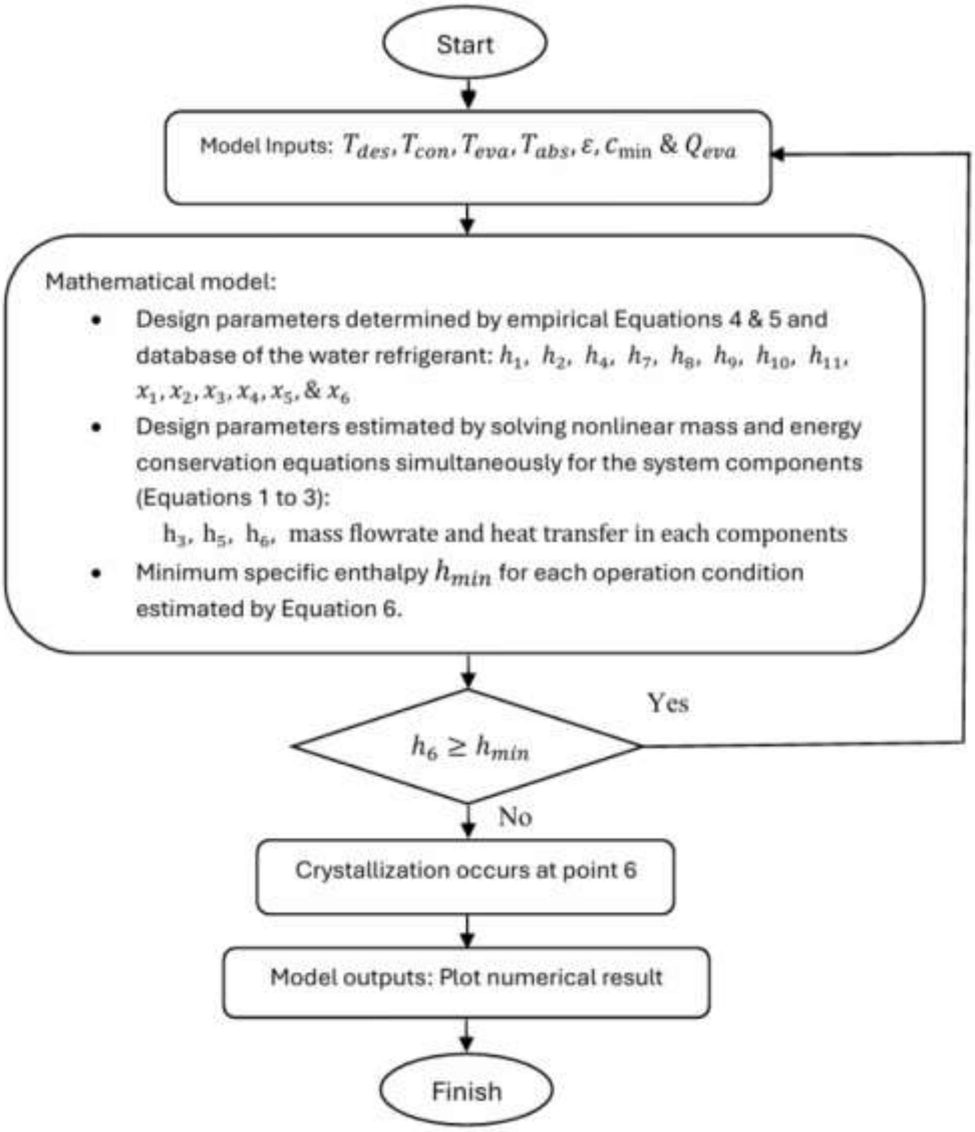


Figure 2: Model flowchart of single-effect aqua-LiBr vapor absorption cooling system to detect crystallization.

Results and discussion

To begin with, Figure 3 illustrates the effects of absorber and condenser temperatures on the temperature and concentration of the strong aqua-LiBr solution entering the absorber. As the temperatures of both the absorber and condenser decrease, the concentration of the strong aqua-LiBr solution increases while its temperature decreases. This trend indicates a potential risk of operational failure due to crystallization, as higher concentrations combined with lower temperatures raise significant concerns. The graph is based on a desorber temperature of 90℃ and a solution heat exchanger effectiveness of 0.7, with varying temperatures for both the absorber and condenser.

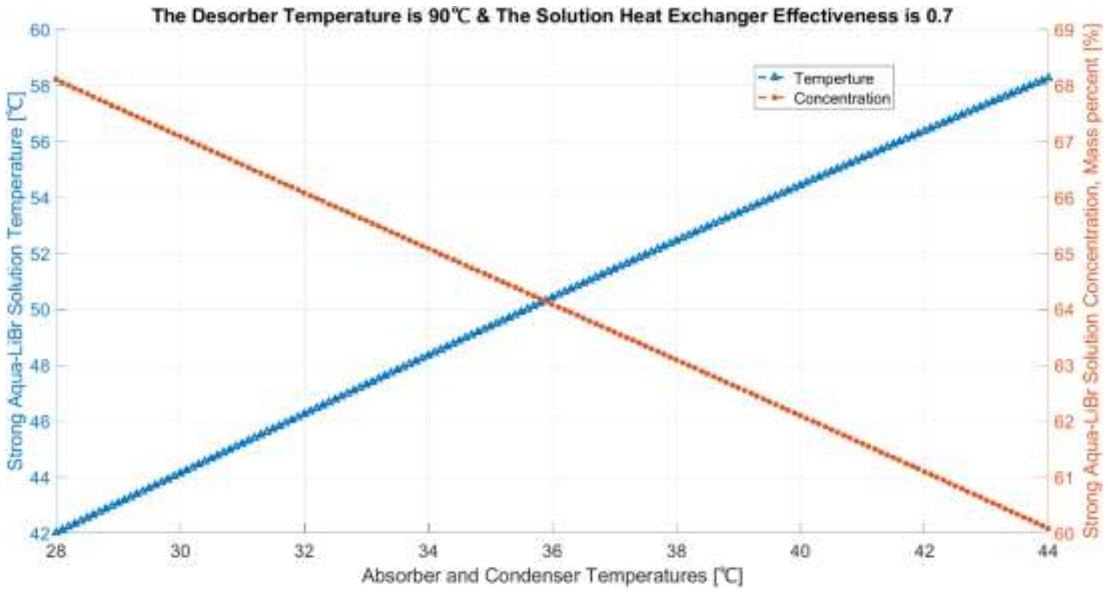


Figure 3: Graph showing the variation of Absorber and Condenser temperatures with the temperature and concentration of strong Aqua-LiBr solution entering the absorber.

Next, Figure 4 illustrates the effect of varying absorber and condenser temperatures on the enthalpy of the strong aqua-LiBr solution entering the absorber, as well as the minimum enthalpy. At higher temperatures, the enthalpy of the solution exceeds the critical minimum, indicating safe operating conditions. However, as the temperatures decrease, the critical minimum enthalpy rises and approaches that of the solution, heightening the risk of crystallization. This crystallization occurs when the enthalpy of the solution drops below the minimum enthalpy, ultimately leading to system failure. Specifically, in this operational scenario, crystallization occurs at absorber and condenser temperatures of 34.3℃, with a desorber temperature of 90℃ and a solution heat exchanger effectiveness of 0.7. These findings highlight the importance of maintaining the absorber and condenser temperatures above 34.3℃ to ensure efficient operation and prevent crystallization in the single-effect aqua-LiBr vapor absorption cooling system under these specific conditions.

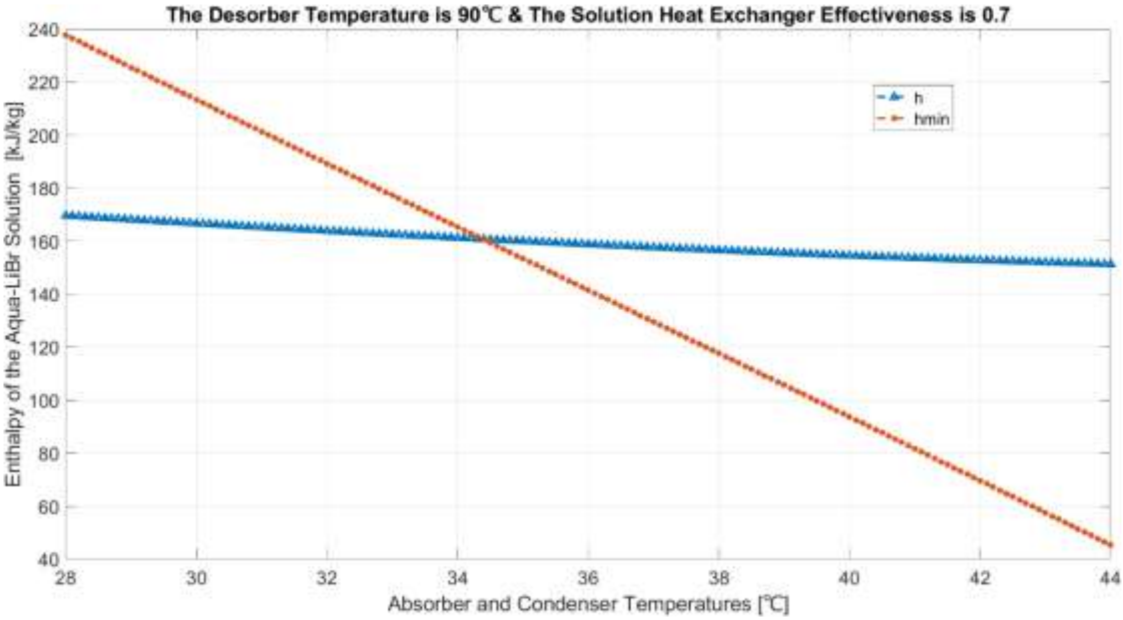


Figure 4: Graph showing the variation of the absorber and condenser temperatures with the enthalpy (h) of the strong aqua-LiBr solution entering the absorber and the minimum enthalpy (h_{min}).

Furthermore, this model has been employed to examine various operational scenarios, with the desorber temperature varying between 60℃ and 120℃ and the solution heat exchanger effectiveness ranging from 0.5 to 0.9. This approach has led to the identification of numerous absorber and condenser temperatures for several operational scenarios at which crystallization occurs during the operation of single-effect aqua-LiBr vapor absorption cooling systems. These specific temperatures, referred to in this study as the minimum critical temperatures of the absorber and condenser, have been plotted against the desorber temperature for different solution heat exchanger effectiveness values in Figure 5. The plot shows that as the desorber temperature increases, the minimum critical temperatures of the absorber and condenser also increase, indicating a linear relationship between them for all effectiveness values. This linear regression is utilized to analyze and establish a correlation between absorber and condenser temperatures, desorber temperature, and solution heat exchanger effectiveness, as shown in Equation 7.

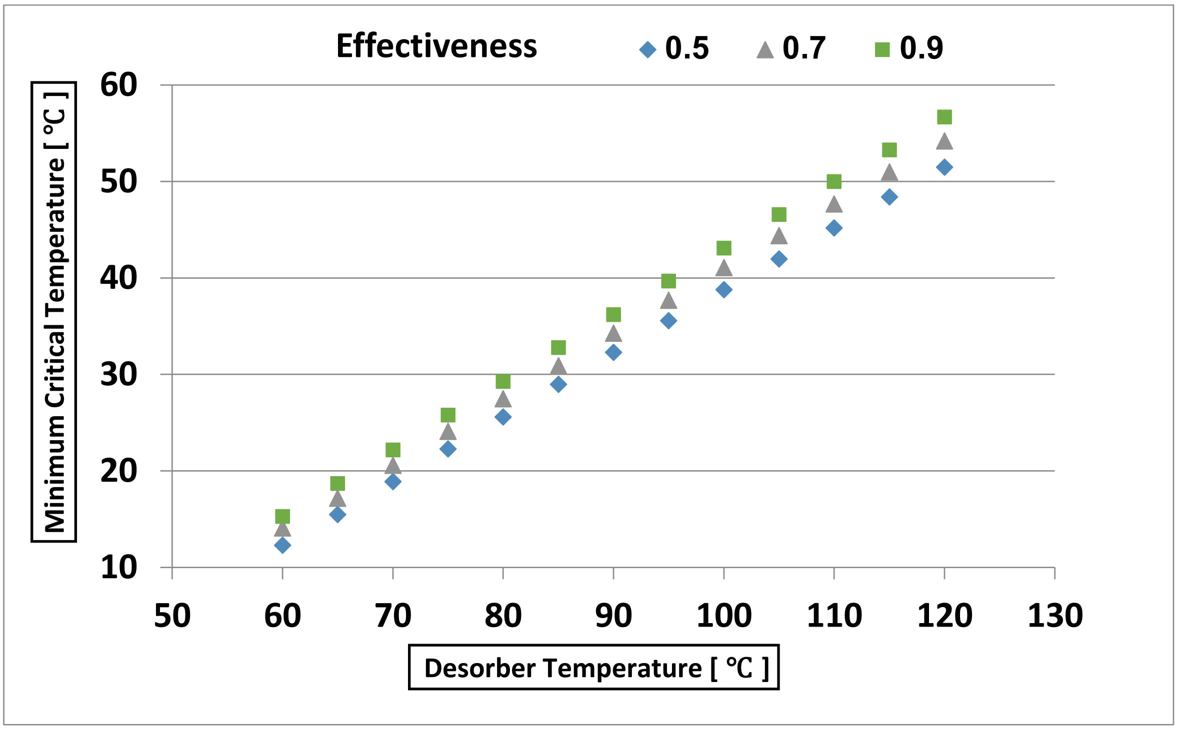


Figure 5: Graph showing the variation of the minimum critical temperature of the absorber and the condenser with the dersorber temperature for different solution heat exchanger effectiveness.

A linear regression analysis using all data was performed in order to arrive at the correlation equation as shown below:

$$T_{cr} = \frac{T_d + 14.92 \times \varepsilon - 49.78}{1.48} \tag{7}$$

Where T_{cr} is the minimum critical temperature of the absorber and condenser at which the crystallization occurs (°C), T_d is the temperature of the desorber (°C), and ε is the solution heat exchanger effectiveness. This correlation equation is only valid for an effectiveness range of $0.5 \leq \varepsilon \leq 0.9$ and for a Desorber temperature range of $60°\text{C} \leq T_d \leq 120°\text{C}$.

The correlation equation can be utilized to determine the minimum critical temperature (T_{cr}) of the absorber and condenser, at which the crystallization occurs in the aqua-LiBr solution as it exits the solution heat exchanger and enters the absorber (for specific values of T_d *and* ε). This correlation has been derived using predictive values (P-values) of 6.88×10−60 and 3.81×10−28 for the crystallization temperature and the solution heat exchanger effectiveness, respectively. Both P-values are substantially lower than the conventional alpha level of 0.05, thereby indicating that both variables, temperature and effectiveness are statistically significant [22]. Furthermore, the obtained linear regression equation yields a correlation coefficient (Multiple R) of 0.999, alongside a coefficient of determination (R^2) that is similarly high, suggesting an exceptionally strong relationship between the variables. The relatively small standard error associated with this model indicates a better fit of the data.

Conclusion

This study developed a model for detecting crystallization in single-effect aqua-LiBr vapor absorption cooling systems, which is essential for maintaining efficient operation. Through thermodynamic analysis, we identified the minimum critical temperatures (T_{cr}) for both the absorber and condenser that prevent crystallization. Our findings indicate that crystallization occurs when the enthalpy of the solution falls below the minimum threshold, potentially leading to system failure. Specifically, crystallization was observed at absorber and condenser temperatures of 34.3°C, with a desorber temperature of 90°C and a solution heat exchanger effectiveness of 0.7. Therefore, it is crucial to maintain absorber and condenser temperatures above 34.3°C to ensure safe operation.

Furthermore, this model was applied to examine various operational scenarios, with desorber temperatures ranging from 60°C to 120°C and solution heat exchanger effectiveness values from 0.5 to 0.9. This analysis revealed numerous absorber and condenser temperatures that can lead to crystallization during the operation of single-effect aqua-LiBr vapor absorption cooling systems. This has led to the establishment of a correlation that enables operators to determine safe operational conditions, thereby enhancing system reliability.

This model serves as a valuable tool for determining safe operational conditions and preventing costly failures in vapor absorption cooling systems. Future research can build on this work by exploring additional variables to further improve crystallization predictions.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that they have no conflict of interest.

References

[1] American, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. 2003.

[2] P. Srikhirin, S. Aphornratana, and S. Chungpaibulpatana, “A review of absorption refrigeration technologies,” Renewable and Sustainable Energy Reviews, vol. 5, no. 4, pp. 343–372, Dec. 2001, doi: https://doi.org/10.1016/s1364-0321(01)00003-x.

[3] W. F. Stoecker and J. W. Jones, Refrigeration and Air Conditioning. McGraw-Hill Science, Engineering & Mathematics, 1982.

[4] K. E. Herold, Reinhard Radermacher, and S. A. Klein, Absorption chillers and heat pumps. Boca Raton: Crc Press, Taylor & Francis Group, 2016.

[5] X. Liao and R. Radermacher, “Absorption chiller crystallization control strategies for integrated cooling heating and power systems,” International Journal of Refrigeration, vol. 30, no. 5, pp. 904–911, Aug. 2007, doi: https://doi.org/10.1016/j.ijrefrig.2006.10.009.

[6] L. Garousi Farshi, S. M. S. Mahmoudi, and M. P. Rosen, “Analysis of crystallization risk in double effect absorption refrigeration systems,” vol. 31, no. 10, pp. 1712–1717, Jul. 2011, doi: https://doi.org/10.1016/j.applthermaleng.2011.02.013.

[7] D. Latorre-Arca, M. S. Larrechi, D. Salavera, and A. Coronas, “Influence of five protic and aprotic ionic liquids as anti-crystallization additives of water/lithium bromide on the solid–liquid equilibrium,” Journal of Molecular Liquids, vol. 427, p. 127302, Jun. 2025, doi: https://doi.org/10.1016/j.molliq.2025.127302.

[8] M. Izquierdo, M. Venegas, P Rodríguez, and A. Lecuona, “Crystallization as a limit to develop solar air-cooled LiBr–H2O absorption systems using low-grade heat,” Solar Energy Materials and Solar Cells, vol. 81, no. 2, pp. 205–216, Dec. 2003, doi: https://doi.org/10.1016/j.solmat.2003.11.002.

[9] G. A. Florides, S. A. Kalogirou, S. A. Tassou, and L. C. Wrobel, “Design and construction of a LiBr–water absorption machine,” Energy Conversion and Management, vol. 44, no. 15, pp. 2483–2508, Sep. 2003, doi: https://doi.org/10.1016/s0196-8904(03)00006-2.

[10] Abdullah Marashli, Enas Alfanatseh, M. Shalby, and M. R. Gomaa, “Modelling single-effect of Lithium Bromide-Water (LiBr–H2O) driven by an evacuated solar tube collector in Ma’an city (Jordan) case study,” Case Studies in Thermal Engineering, vol. 37, pp. 102239–102239, Jul. 2022, doi: https://doi.org/10.1016/j.csite.2022.102239.

[11] M. M. Ardehali, M. Shahrestani, and C. C. Adams, “Energy simulation of solar assisted absorption system and examination of clearness index effects on auxiliary heating,” Energy Conversion and Management, vol. 48, no. 3, pp. 864–870, Mar. 2007, doi: https://doi.org/10.1016/j.enconman.2006.08.012.

[12] S. I.-H. Gilani and M. S. M. S. Ahmed, “Solution Crystallization Detection for Double-effect LiBr-H2O Steam Absorption Chiller,” Energy Procedia, vol. 75, pp. 1522–1528, Aug. 2015, doi: https://doi.org/10.1016/j.egypro.2015.07.304.

[13] A. Xu et al., “Performance analysis of a cascade lithium bromide absorption refrigeration/dehumidification process driven by low-grade waste heat for hot summer and cold winter climate area in China,” Energy Conversion and Management, vol. 228, p. 113664, Jan. 2021, doi: https://doi.org/10.1016/j.enconman.2020.113664.

[14] R. K. De and A. Ganguly, “Performance comparison of solar-driven single and double-effect LiBr-water vapor absorption system based cold storage,” Thermal Science and Engineering Progress, vol. 17, p. 100488, Jun. 2020, doi: https://doi.org/10.1016/j.tsep.2020.100488.

[15] M. F. M. Fahmy and H. I. Nabih, “Impact of ambient air temperature and heat load variation on the performance of air-cooled heat exchangers in propane cycles in LNG plants – Analytical approach,” Energy Conversion and Management, vol. 121, pp. 22–35, Aug. 2016, doi: https://doi.org/10.1016/j.enconman.2016.05.013.

[16] K. Saka and Mehmet Fatih Orhan, “Energy and exergy analysis of a series-flow double-effect H2O–LiBr absorption cooling system,” Case Studies in Thermal Engineering, vol. 76, pp. 107423–107423, Nov. 2025, doi: https://doi.org/10.1016/j.csite.2025.107423.

[17] D. Micallef and C. Micaleff, “Mathematical model of a vapour absorption refrigeration unit,” International Journal of Simulation Modelling, vol. 9, no. 2, pp. 86–97, Jun. 2010, doi: https://doi.org/10.2507/ijsimm09(2)3.153.

[18] S. Osta-Omar and C. Micallef, “Mathematical Model of a Lithium-Bromide/Water Absorption Refrigeration System Equipped with an Adiabatic Absorber,” Computation, vol. 4, no. 4, p. 44, Nov. 2016, doi: https://doi.org/10.3390/computation4040044.

[19] Cabrera César J, Caratt Ortiz J, Ochoa GV, Restrepo RR, Alvarez JRN. A New Computational Tool for the Development of Advanced Exergy Analysis and LCA on Single Effect LiBr–H2O Solar Absorption Refrigeration System. Lubricants. 2021; 9(8):76. https://doi.org/10.3390/lubricants9080076

[20] MATLAB version R2022b. Computer software, The MathWorks Inc., Natick, Massachusetts.

[21] Y. Kaita, “Thermodynamic properties of lithium bromide–water solutions at high temperatures,” International Journal of Refrigeration, vol. 24, no. 5, pp. 374–390, May 2001, doi: https://doi.org/10.1016/S0140-7007(00)00039-6.

[22] R. L. Wasserstein and N. A. Lazar, “The ASA Statement on p-Values: Context, Process, and Purpose,” The American Statistician, vol. 70, no. 2, pp. 129–133, Apr. 2016, doi: https://doi.org/10.1080/00031305.2016.1154108.