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Thermophysical Assessment of Advanced Absorbents for Solar-Driven Open Absorption Refrigeration Systems

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ABSTRACT

This study compares the thermosphysical and operational behavior of LiBr–H_2O, LiBr–$LiNO_3$–H_2O, and LiBr–$ZnCl_2$–$CaBr_2$–H_2O absorbents for solar-driven open-cycle absorption refrigeration. Published experimental data and thermodynamic correlations are assessed in relation to vapor pressure, crystallization, viscosity, volumetric heat capacity, thermal conductivity, heat transfer, hydraulic resistance, and regeneration requirements. The comparative assessment indicates that conventional calcium chloride solutions are less suitable for practical open absorption cooling because of their relatively high vapor pressure and limited absorption capability. Modified lithium bromide solutions offer improved operational stability. In particular, the LiBr–$ZnCl_2$–$CaBr_2$–H_2O formulation shows favorable solubility, lower crystallization sensitivity, improved heat-transfer behavior, and reduced corrosion effects compared with conventional LiBr–H_2O. A concentration of approximately 70–75 % is identified as a practical compromise between absorption potential and increasing viscosity. Relatively high regeneration temperatures remain a limitation, suggesting the use of advanced solar thermal collectors and auxiliary low-grade heat sources. Experimental validation is recommended.

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Keywords: *Solar cooling; Absorption refrigeration; Lithium bromide; Thermophysical properties; Open-cycle cooling*

1. Introduction

The rapid expansion of cooling and air-conditioning demands worldwide has become a major contributor to global energy consumption and environmental degradation. The continuous growth of residential, commercial, and industrial cooling applications places increasing pressure on electrical power systems while simultaneously contributing to greenhouse gas emissions associated with conventional vapor-compression technologies. Consequently, the development of sustainable and energy-efficient cooling solutions has become a critical research priority [6].

Thermally driven refrigeration technologies offer an attractive alternative to conventional electrically powered cooling systems because they can utilize renewable and low-grade thermal energy sources. Among these technologies, open-cycle absorption refrigeration and liquid desiccant air-conditioning systems have received considerable attention due to their capability to provide simultaneous cooling and humidity control, particularly in regions characterized by hot and humid climatic conditions [13, 2].

The overall performance of open absorption systems is governed primarily by the thermophysical properties of the absorbent solution. An effective absorbent should exhibit strong affinity toward water vapor, low equilibrium vapor pressure, high thermal stability, favorable heat and mass transfer characteristics, low viscosity, minimal crystallization tendency, and acceptable compatibility with construction materials [9, 1].

Lithium bromide-water solutions have been extensively employed in absorption cooling applications owing to their excellent hygroscopic behavior and proven operational reliability. Nevertheless, conventional LiBr–H_2O systems remain subject to several limitations, including crystallization risks at elevated concentrations, relatively high regeneration temperatures, and corrosion-related concerns during long-term operation [14, 3].

To address these challenges, recent research has focused on the development of multicomponent absorbent formulations incorporating additives such as lithium nitrate, zinc chloride, and calcium bromide. These additives modify the physicochemical characteristics of the base solution and may improve solubility limits, suppress crystallization, enhance heat transfer behavior, and extend the operational envelope of absorption systems [7, 9].

The present work provides a comprehensive thermophysical assessment of advanced lithium bromide-based absorbents intended for solar-driven open absorption refrigeration and air-conditioning systems. Particular emphasis is placed on evaluating the combined influence of vapor pressure behavior, thermal transport properties, viscosity characteristics, and operational stability on overall system performance and practical applicability [8]; Chen & Yin [3].

2. Literature Review

Numerous studies have investigated the thermodynamic and operational characteristics of absorbent solutions used in open and closed absorption refrigeration systems.

Iyoki et al. [7] investigated the physical and thermal properties of lithium bromide-lithium nitrate-water solutions and reported significant improvements in operational stability and corrosion reduction compared with conventional lithium bromide solutions. Their investigation demonstrated that the addition of lithium nitrate improves thermodynamic behavior and reduces crystallization sensitivity.

Later, Iyoki and Uemura [8] analyzed the thermophysical properties of $LiBr–ZnCl_2–CaBr_2–H_2O$ systems and observed improvements in solution solubility and operational reliability. Their study also showed that composite absorbent systems exhibit lower crystallization risks and improved heat transfer performance.

Koo et al. [10] studied the vapor pressure and solubility characteristics of multicomponent absorbent systems containing LiBr, LiI, LiNO3, and LiCl. Their results confirmed that composite absorbent systems significantly influence the operational stability and efficiency of absorption cooling systems.

Doroshenko et al. [4] investigated solar-driven absorption refrigeration systems operating with open absorption cycles and concluded that system performance strongly depends on regeneration temperature and absorbent thermophysical properties.

Recent studies have focused on sustainable HVAC technologies and renewable-energy-driven cooling systems.

Although Wang et al. [13] demonstrated the feasibility of solar-driven absorption cooling, their study provided limited assessment of multicomponent absorbent formulations under high-concentration operating conditions.

Kim and Infante Ferreira [9] reviewed recent developments in liquid desiccant and absorption cooling technologies and emphasized the importance of absorbent solution optimization for improving energy efficiency and operational reliability.
Chen and Yin (2023) investigated the thermophysical performance of advanced lithium bromide composite absorbents in solar cooling systems and demonstrated that modified lithium bromide solutions can significantly improve system stability and reduce crystallization risks.

Although previous studies provided valuable information regarding absorbent thermophysical properties, further investigation remains necessary concerning the combined effects of vapor pressure, viscosity, hydraulic resistance, and heat transfer characteristics in open-cycle solar-driven refrigeration systems.

3. Methodology

The present investigation employs a comparative thermophysical assessment approach based on published experimental data and validated thermodynamic correlations reported in the literature. Three absorbent systems were selected for evaluation: LiBr–H_2O, LiBr-$LiNO_3$-H_2O, and LiBr–$ZnCl_2$–$CaBr_2$–H_2O.
The analysis focuses on parameters that directly influence absorber performance and overall system efficiency, including equilibrium vapor pressure, crystallization behavior, viscosity, volumetric heat capacity, thermal conductivity, hydraulic resistance, and heat-transfer performance.
Operational performance was assessed within concentration ranges commonly encountered in solar-driven open absorption cooling systems. Comparative evaluations were conducted using published thermophysical data together with established heat-transfer and fluid-flow correlations. Particular attention was given to identifying concentration ranges that provide an optimal balance between absorption capability, thermal performance, and operational reliability.
The methodology further considers practical engineering constraints including absorber sizing, pumping requirements, regeneration temperature limitations, and long-term operational stability. The resulting comparisons provide a comprehensive framework for evaluating the suitability of advanced absorbent formulations in renewable-energy-driven cooling applications.

4. Working Substances Used in Open Absorption Systems

The present study investigates the following absorbent systems commonly used in open-cycle absorption refrigeration and air-conditioning systems:

- LiBr–H_2O solution (LiBr)
- LiBr–$LiNO_3$–H_2O solution (LiBr+)
- LiBr–$ZnCl_2$–$CaBr_2$–H_2O solution (LiBr++)

4.1 Calcium Chloride Solutions

Calcium chloride solutions are considered environmentally safe and economically attractive. However, previous investigations demonstrated that $CaCl_2$ solutions exhibit relatively high vapor pressure values under practical operating conditions. Consequently, the absorption driving force becomes weak or even negative under moderate climatic conditions, making these solutions unsuitable for practical open absorption refrigeration applications [4].

4.2 Lithium Chloride Solutions

Lithium chloride solutions exhibit excellent hygroscopic properties and high absorption capability. Nevertheless, these solutions suffer from severe corrosion problems when used in metallic heat exchangers and system components. Therefore, special corrosion-resistant materials or anti-corrosion additives are required during practical operation [14].

4.3 Lithium Bromide-Based Solutions

Lithium bromide-water solutions remain the most commonly used absorbent materials due to their excellent absorption characteristics and compatibility with thermal-driven cooling systems. However, crystallization problems and relatively high regeneration temperatures remain major operational limitations.

To improve performance, composite additives such as LiNO3, ZnCl2, and CaBr2 are introduced into conventional LiBr–H_2O systems. These additives improve solubility characteristics, reduce crystallization risks, and enhance operational reliability [8, 3].

5. Thermophysical Analysis

5.1 Vapour Pressure Characteristics

Vapor pressure represents one of the most important parameters influencing absorption performance and dehumidification efficiency. Lower vapor pressure values correspond to stronger absorption capability [10].

The analysis demonstrates that LiBr and LiBr+ solutions exhibit lower vapor pressure values compared with LiCl solutions, especially at high concentration regions near the crystallization line.

The LiBr++ solution demonstrates superior operational stability because the crystallization line is located farther from the practical operational region. Consequently, the probability of crystallization during operation becomes significantly lower.

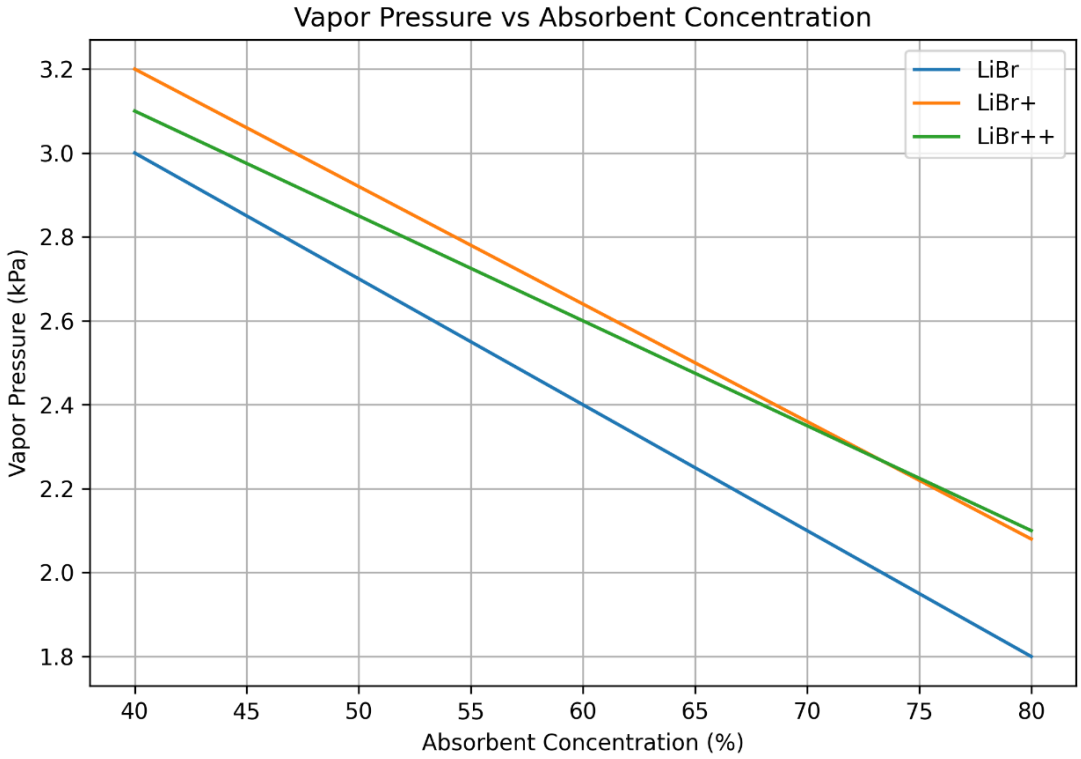


Figure 1. Vapor pressure versus absorbent concentration for LiBr, LiBr+, and LiBr++ solutions.

Table 1. Comparative vapor-pressure characteristics.

Solution	Vapor Pressure	Crystallization Risk	Operational Stability
LiCl	High	High	Poor
LiBr	Low	Moderate	Good
LiBr+	Low	Low	Very Good
LiBr++	Very Low	Very Low	Excellent

Note: Schematic illustration of vapor-pressure behavior in selected aqueous absorbent solutions. The illustration is conceptual and does not represent experimental measurements or quantitatively validated predictions. Quantitative comparisons require verified data at specified temperatures and clearly defined concentration bases.

5.2 Volumetric Heat Capacity

The heat transfer capability of absorbent solutions can be evaluated using the volumetric heat capacity relationship:

$$Q = (\rho C_p)\, \dot{V}\, \Delta T \quad (1)$$

where:

Q = heat-transfer rate

ϱC_p = volumetric heat capacity

$\dot{V}$ = volumetric flow rate

ΔT = temperature difference

The investigation reveals that LiBr+ solution exhibits higher volumetric heat capacity values compared with conventional LiBr systems within the operational concentration range.

LiBr++ solution demonstrates favorable thermal carrying capability at low and moderate concentration regions. However, at concentrations approaching 75%, the thermal carrying capacity slightly decreases due to increasing viscosity [5].

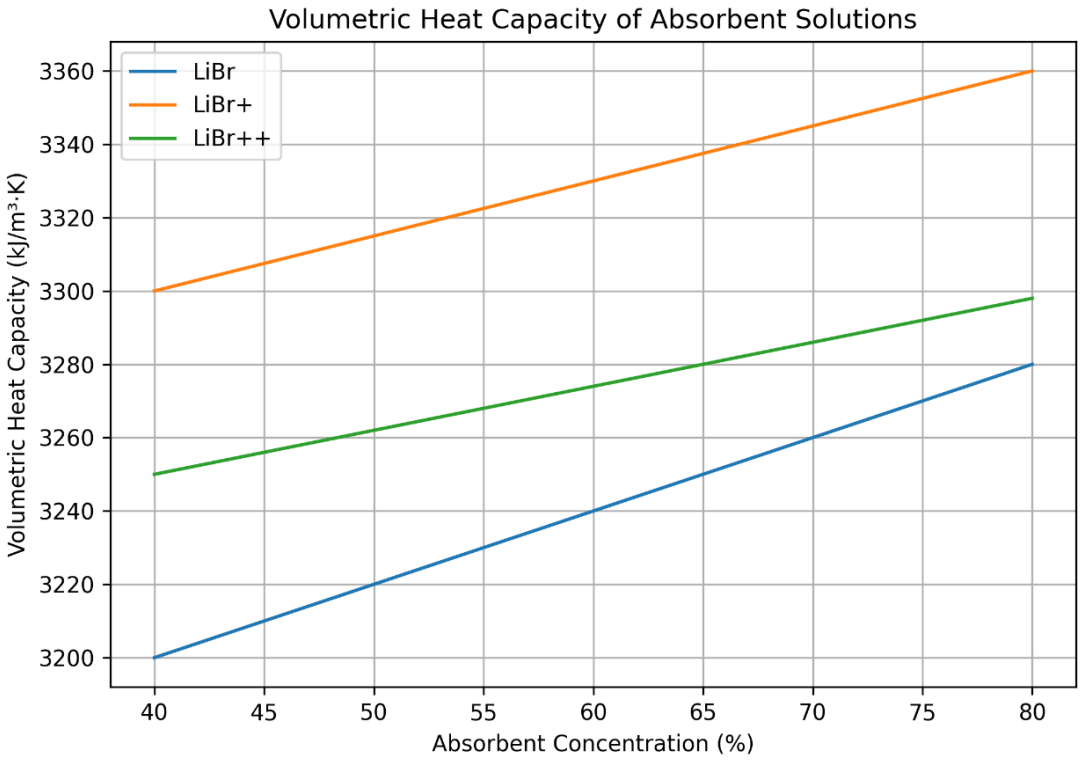


Figure 2. Volumetric heat capacity of the advanced absorbent solutions.

Table 2. Heat-transfer performance comparison.

Property	LiBr	LiBr+	LiBr++
Thermal Conductivity	Good	Very Good	Excellent
Heat Transfer Capability	Good	Very Good	Excellent
Thermal Stability	Moderate	Good	Excellent
Operational Efficiency	Good	Very Good	Excellent

Figure 2 illustrates the variation of volumetric heat capacity with absorbent concentration. The LiBr+ solution exhibits higher thermal storage capability than conventional LiBr over most of the practical operating range.

5.3 Viscosity Characteristics

Viscosity significantly affects fluid flow behavior and heat transfer performance inside heat exchangers. Excessive viscosity increases hydraulic resistance and reduces turbulent flow formation [14].

The investigation indicates that LiBr and LiBr+ solutions exhibit relatively similar viscosity behavior under practical operating conditions. However, LiBr++ solution demonstrates noticeable viscosity increases at concentration values exceeding 75%. Therefore, the recommended operational concentration range for LiBr++ solution is approximately 70–75% [5].

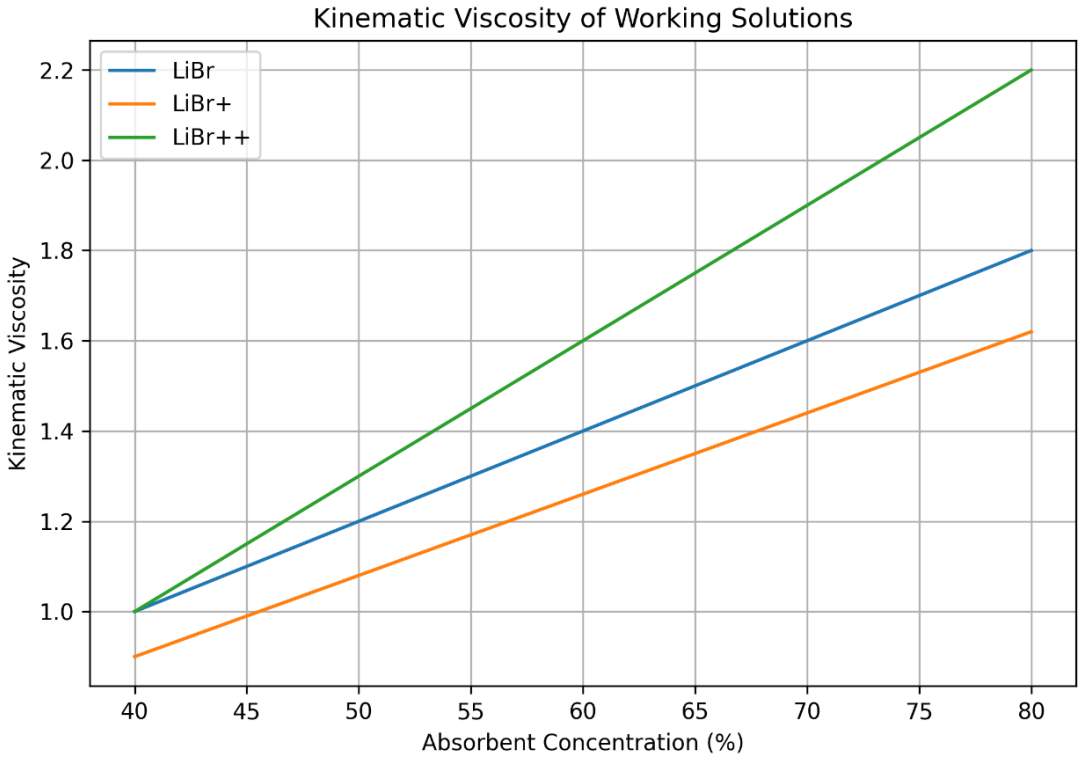


Figure 3. Kinematic-viscosity variation with absorbent concentration.

Table 3. Viscosity and hydraulic characteristics.

Solution	Viscosity Behavior	Hydraulic Resistance	Recommended Concentration
LiBr	Moderate	Moderate	60–65%
LiBr+	Moderate	Moderate	65–70%
LiBr++	Higher at high concentration	Higher above 75%	70–75%

As shown in Figure 3, viscosity increases considerably at concentrations exceeding 75%, which may negatively affect pumping power requirements and hydraulic performance.

5.4 Heat and Mass Transfer Performance

The thermophysical performance parameter for heat transfer in plate heat exchangers can be expressed as:

$$F_\alpha = 0.135\,\lambda^{0.57}\,(\rho C_p)^{0\,.\,43}\,\nu^{-0.3} \quad (2)$$

The results indicate that LiBr++ solution exhibits superior heat transfer characteristics compared with conventional LiBr and LiBr+ systems due to improved thermal conductivity and favorable thermophysical behavior.

The improved heat transfer capability contributes to reducing heat exchanger size and improving overall system efficiency [3, 11].

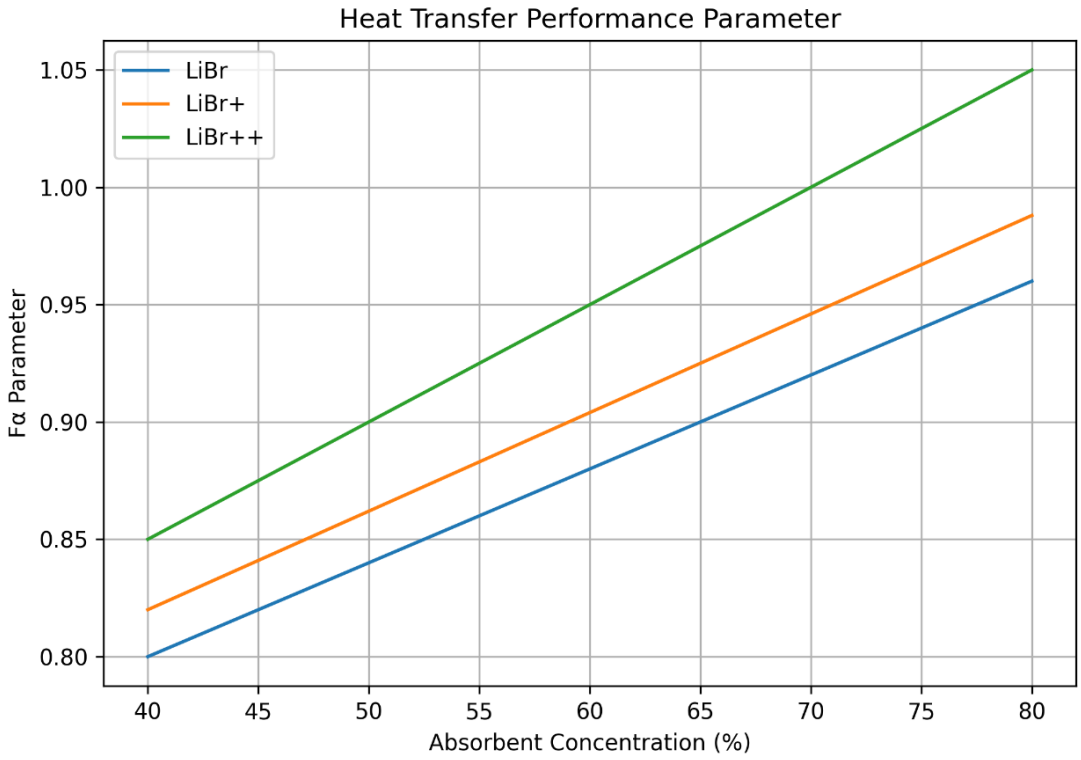


Figure 4. Heat-transfer performance parameter (Fα) for the investigated absorbent systems.

Table 4. Comparative engineering assessment of the investigated absorbents.

Criterion	LiBr	LiBr+	LiBr++
Vapor Pressure	Good	Very Good	Excellent
Crystallization Resistance	Moderate	Good	Excellent
Corrosion Resistance	Moderate	Good	Very Good
Solar Compatibility	Good	Very Good	Excellent

Figure 4 demonstrates that the LiBr++ solution provides the highest heat-transfer performance parameter among the investigated absorbents.

6. Results and Discussion

The comparative analysis clearly demonstrates that the incorporation of secondary and tertiary salts into conventional lithium bromide solutions substantially modifies the thermophysical behavior of the absorbent and influences the overall performance of open absorption cooling systems.

Among the investigated formulations, the $LiBr–ZnCl_2–CaBr_2–H_2O$ solution consistently exhibited the most favorable combination of absorption capability, thermal stability, and operational flexibility. The reduction in equilibrium vapor pressure observed for this solution increases the driving potential for moisture absorption while simultaneously extending the safe operating region away from crystallization boundaries.

The improved solubility characteristics associated with the composite absorbent are particularly important for solar-driven applications, where fluctuations in operating temperature and concentration frequently occur. A wider operational envelope reduces the probability of unexpected crystallization events and enhances system reliability during transient operating conditions.

Heat-transfer analysis revealed that the modified absorbents provide measurable improvements in thermal transport characteristics compared with conventional LiBr solutions. Enhanced thermal conductivity and favorable volumetric heat capacity contribute to improved absorber effectiveness and may allow reductions in heat exchanger size, leading to lower system cost and improved compactness.

From a hydraulic perspective, increasing concentration improves absorption potential but simultaneously increases solution viscosity. This trade-off becomes increasingly significant at concentrations above approximately 75%, where pumping power requirements rise rapidly and fluid-flow resistance becomes more pronounced. Consequently, the concentration range of 70–75% appears to represent

an optimal compromise between absorption effectiveness and acceptable hydraulic performance.

The results further indicate that regeneration temperature remains one of the principal engineering challenges associated with advanced absorbent systems. Although the LiBr++ solution demonstrates superior absorption characteristics, its effective regeneration requires relatively high thermal input. The application of evacuated-tube solar collectors, solar-assisted thermal storage systems, or hybrid renewable heat sources can significantly improve regeneration feasibility and overall system sustainability.

Overall, the findings suggest that advanced composite lithium bromide absorbents provide a promising pathway toward improving the efficiency, reliability, and commercial viability of next-generation solar-driven refrigeration and air-conditioning systems.

7. Practical Engineering Considerations

The practical implementation of open absorption cooling systems requires careful consideration of several engineering aspects including:

- Heat exchanger design
- Corrosion protection
- Crystallization prevention
- Solar collector selection
- Thermal energy storage

Plate heat exchangers are considered highly suitable for such applications due to their compact structure and high heat transfer efficiency.

Corrosion-resistant materials such as copper alloys and aluminum are recommended for long-term system durability.

For solar-driven systems, evacuated tube solar collectors are recommended because they can provide the relatively high regeneration temperatures required for advanced lithium bromide composite solutions [13, 12].

8. Conclusion

This study presented a comprehensive thermophysical investigation of advanced working substances used in solar-driven open absorption refrigeration and air-conditioning systems.

The analysis demonstrated that conventional calcium chloride solutions are unsuitable for practical absorption cooling applications due to their relatively high vapor pressure and poor absorption capability.

Among the investigated absorbents, the $LiBr–ZnCl_2–CaBr_2–H_2O$ composite solution demonstrated the best overall operational performance. The solution exhibited:

- Improved solubility
- Lower crystallization sensitivity
- Reduced corrosion effects
- Enhanced heat transfer characteristics
- Superior operational stability

The investigation also confirmed that the recommended operational concentration range for LiBr++ solution is approximately 70–75%.

Although the advanced composite solution requires relatively high regeneration temperatures, the integration of solar thermal collectors with auxiliary low-grade heat sources can significantly improve operational feasibility.

Future research should focus on:

- Experimental validation
- Numerical simulation
- Dynamic system optimization
- Hybrid renewable-energy-assisted regeneration systems

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