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RESEARCH ARTICLE

Experimental investigation of a calcium chloride-based liquid desiccant dehumidification system under controlled operating conditions

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Abstract

Dehumidification systems based on liquid desiccant have the potential to lower the latent cooling load of traditional vapour-compression air-conditioning, especially in humid climates. This paper presents an experimental research on a liquid desiccant dehumidification system using calcium chloride that was run under controlled winter conditions. The effects of inlet air velocity and regeneration temperature on the outlet air relative humidity are evaluated. The results indicate that lower air velocities improve moisture removal because of increased air–desiccant contact time. The regeneration at about 58 C gave a relatively stable regeneration behaviour with a small range of outlet air relative humidity under the conditions of the experiment. The work gives experimentally determined operating trends applicable to real-world humidity-control applications and low-grade heat regeneration, and observes that the results are not to establish universal performance standards but to assist in optimising systems.

Keywords: Liquid desiccant dehumidification; calcium chloride; humidity control; regeneration temperature; air velocity

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1. Introduction

In contemporary times, human comfort has become a basic need that has been made possible mainly by air conditioning systems (Behnam et al., 2022). These systems generally experience two kinds of load: sensible and latent. The sensible load is the heat load that can be felt and measured with a thermometer, whereas the latent load is associated with moisture removal (dehumidification). Both of these loads are handled by cooling the atmospheric air below its dew point temperature. (Dai et al., 2001) Desiccant materials effectively reduce the latent load on air-conditioning systems. Desiccants are substances that remove moisture from humid air by the vapour pressure difference between the desiccant and the air. In liquid desiccant systems, moisture is removed by absorption into the liquid phase, whereas in solid desiccant systems, it is removed by surface adsorption. (Niu et al., 2002). In tropical countries with high humidity, the latent cooling load is often elevated. Desiccant materials are crucial in the removal of the moisture in the humid air, thereby mitigating this load (Zhang & Niu, 2003). The use of desiccant materials in air conditioning systems for humidity removal is energy-efficient. A substantial proportion of energy consumed by air conditioning systems is typically devoted to sensible cooling. By using desiccants, the dehumidification load and sensible load can be controlled individually, which results in an increased efficiency(Rafique et al., 2016).There are two main classes of desiccants: solid and liquid. Solid desiccants include polymers, silicas, zeolites, hydratable salts, activated alumina, and mixtures thereof. On the other hand, liquid desiccants are available in the form of lithium chloride, calcium chloride brine, sodium chloride, lithium bromide and glycol (Chen et al., 2016). Figure 1 illustrates the benefits of liquid desiccants and their effectiveness in removing moisture from air-conditioning systems. Liquid desiccants have some advantages, such as efficient dehumidification, economy and the ability to handle high humidity levels prevailing in the tropical climate (Liu et al., 2018). They were so versatile and practical that they became favorites in many air-conditioning applications. In summary, desiccant materials, mainly liquid desiccants, play a very important role in improving the efficiency and effectiveness of air conditioning systems, and especially in areas with high humidity levels (Qi et al., 2020). By properly controlling the removal of moisture as a separate system from the removal of sensible heat, these materials are part of a significant contribution to energy savings and enhanced human comfort (SOLANKI & Pal, 2022).

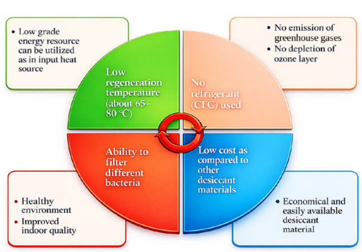

Figure 1. Schematic representation of the key benefits and operational advantages of liquid desiccant–based dehumidification systems in air-conditioning applications

(Abdel-Salam & Ge, 2014) carried out experimental research to meet the limitations of conventional systems using the vapour pressure technique and aimed to check the energy requirement and environmental impact of the system. This study proposed using porous-cone technology to overcome these challenges. This way, low-viscosity liquid desiccant equipment was used, as well as various composite materials, to address the corrosive nature(Amin, 2024; Sakhri et al., 2021) . (Kabeel et al., 2017) studied the performance of indoor humidity control and liquid desiccant dehumidification with an emphasis on moisture removal in a constant way. Their research showed that such technology is widely applicable, particularly in environments that are susceptible to corrosion and temperature variations and those that need heating. (Gandhidasan, 2004)heat that can be felt and measured by a thermometer, and the latent load is the carried out experimental studies on the low-temperature and concentration of two air dehumidification processes using LiCl as a desiccant material (20°C). They achieved energy savings by installing an improved hybrid air-conditioning system. (Zhang, 2012) investigated the performance of a $CaCl2$-LiCl mixed liquid desiccant system to improve the energy efficiency. They have discovered that a mixing ratio of 3:1 $CaCl2$ to LiCl and a LiCl concentration range of 0% to 30% gave them better efficiency. Three factors that cause the difference between the actual and ideal conditions in liquid desiccant systems were identified and analyzed (Lee et al., 2023). These were heat-cold offset fullness, which is the difference in temperature between the dehumidifier and the regenerator. (Chen & Guo, 2019) discussed air conditioning systems energy consumption reduction strategies, including fresh air requirements management and latent loads reduction. They claimed that there was a lot of potential energy savings by proper control of fresh-air ratios. The performance of lithium chloride, air conditioning system, and artificial neural network models were of concern to (Yang and Li, 2015) and were used to enhance accuracy in predicting the level of humidity in buildings in humid climates. (Luo et al., 2017) have studied mixed liquid desiccant dehumidification processes, which focus on low energy consumption and high coefficients of performance. The importance of fresh air requirements in indoor air quality and human comfort was discussed in (Zhang et al., 2014) where the combination of two desiccant materials was observed to effectively control the moisture content in a non-corrosive and non-volatile Heating, Ventilation, and Air Conditioning (HVAC) system. (Liu et al., 2016) investigated the effect of temperature and humidity control on electricity consumption and revealed the benefit of a reheating process in chilled water systems for energy saving. The experimental design used in the current research is founded on the existing methods that have been reported in the literature on liquid desiccant dehumidification (Liu et al., 2016; Luo et al., 2017; Niu and Xiao, 2009; Zhang et al., 2014).

Calcium chloride was employed as a liquid desiccant in the current study to experimentally determine the behavior of absorption and regeneration under controlled winter operating conditions, by systematically changing the air inlet velocity and regeneration temperature. The study uses a liquid desiccant cooling system to explore key parameters-temperature and humidity in the A/C system-and to offer possible solutions to enhance energy efficiency and environmental performance.

Although much has been done on liquid desiccant dehumidification, there is a paucity of experimental data on laboratory-scale absorption-regeneration loops run under controlled winter conditions with controlled variation in inlet air velocity and regeneration temperature. In this regard, the research gap that will be filled in this study is the absence of experimentally based operating trends that can be used to relate these controllable parameters to outlet-air humidity control in a simple calcium chloride-based system. The novelty of this work is that it offers, in the framework of low-grade heat regeneration, (a) a parametric evaluation of the influence of air velocity and regeneration temperature on the humidity of outlet-air, which is controlled, and (b) a discussion of the operational considerations (stability, carryover risk, and corrosion-related issues) in a practice-oriented manner.

A comparative view also helps to explain the place of calcium chloride-based liquid desiccant dehumidification in the wider dehumidification literature. Calcium chloride has lower material cost and can be regenerated with low-grade heat, compared to lithium chloride and lithium bromide systems, but more effort is typically needed to control corrosion and desiccant carryover. Compared to traditional vapour-compression dehumidification, liquid-desiccant systems decouple the latent-load processing and sensible cooling, and can use waste-heat or solar-assisted regeneration, but they add extra liquid-handling and material-compatibility constraints. Table 2 summarises the comparative implications that are most applicable to the current study (Rafique et al., 2016; Sahlot and Riffat, 2016; Wen et al., 2018; Ren et al., 2017).

2. Methodology

2.1. Absorption and regeneration process

The current research uses a calcium chloride-based liquid desiccant to remove moisture in humid air by an absorption process that is powered by a difference in vapour pressure. The absorption section absorbs moisture in the desiccant solution, which leads to dehumidified air at the outlet. In the regeneration process, the desiccant is diluted and then in contact with hot air to dry the absorbed moisture and reabsorb its capacity. This absorption-regeneration cycle allows the continuous dehumidification under controlled operating conditions.

2.2. Mathematical modeling of an experiment

The mathematical terms used give a simplified psychometric and energy-mass balance description of the absorption and regeneration processes in quasi-adiabatic conditions. The model transforms measured inlet-outlet air conditions into humidity ratio and moist-air enthalpy and facilitates quantitative interpretation of trends. The model-based estimates are presented and compared with the experimental observations and with the representative ranges reported in previous liquid desiccant studies to give some basic validation and an error-based justification of the measurements.

To this end, a mathematical formulation is provided to justify the qualitative interpretation of the experimental observations. In the current work, The adiabatic dehumidification process is plotted on the psychometric chart in Figure 2.

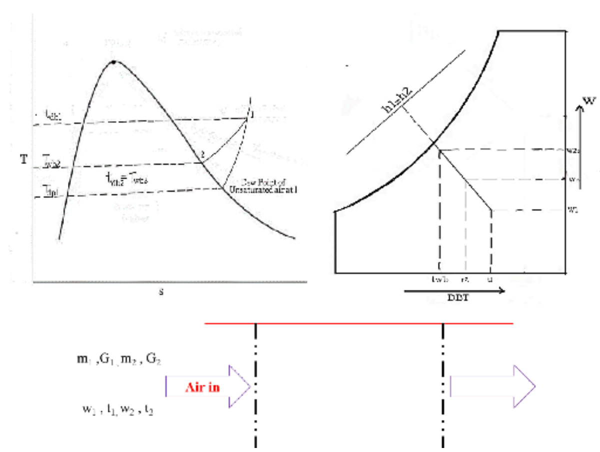

Figure 2. Adiabatic dehumidification process of moist air represented on a psychrometric chart, illustrating the constant-enthalpy absorption path

2.3. Experimental setup

The experimental study was carried out on a laboratory-scale liquid desiccant dehumidification system (LDDS) where calcium chloride ($CaCl_2$) was used as the working desiccant. The desiccant solution was made by dissolving calcium chloride in water and pumped in a closed loop, but in the current system, there was no continuous in situ monitoring of the solution concentration and thus is regarded as a limitation in the interpretation. The system comprises two main sections: (a) an absorption section, where moisture is removed from the humid air, and (b) a regeneration section, where the moisture absorption capacity of the desiccant solution is restored.

The system was fed with atmospheric air in the absorption section through a variable-speed blower that enabled the inlet air velocity to be adjusted. The moist air was introduced into direct contact with the liquid desiccant solution through a packed contact system, which led to the absorption of moisture because of the difference in vapour pressure between the air and the desiccant solution. The dehumidified air then exited the absorption chamber after passing through a demister to minimise desiccant droplet carryover. The calcium chloride liquid desiccant solution for the absorption and regeneration processes is illustrated in Figure 4.

The regeneration section is meant to dry the diluted desiccant solution. Here, the desiccant was put in a stream of hot air using an electric air heater. The air temperature of regeneration was manipulated within the experimental range to examine its effect on the regeneration efficiency of desiccants. The regenerated desiccant solution was recirculated to the absorption section to allow continuous operation.

Calibrated digital sensors were used to measure the temperature and RH of the air at the inlet and outlet of the absorption and regeneration sections. The air velocity was measured using a vane-type anemometer and desiccant-solution temperatures were measured using thermocouples at suitable positions. The rate of flow of the desiccant solution was kept constant during the experiments to separate the influence of air velocity and regeneration temperature.

All experiments were carried out in controlled winter conditions. All operating conditions were held until steady readings were achieved and observations were recorded when system parameters had stabilised. The experimental design allowed the systematic study of the impact of air inlet velocity and regeneration temperature on the dehumidification and regeneration efficiency of the liquid desiccant system.

In the current work, controlled winter operating conditions are used to describe experimental operation during the winter season in a laboratory setting, where inlet air temperature and humidity were measured prior to and during each run until quasi-steady values were reached. Even though the full archived test-wise dry-bulb and wet-bulb/dew-point data are not yet available to be tabulated retrospectively, the revised manuscript now clearly indicates that the reported performance trends were obtained after inlet and outlet measurements in the absorber and regenerator sections had stabilised.

The absorber and regenerator were designed as packed contact sections in a closed-loop calcium chloride solution loop with an interposed demister to reduce droplet carryover into the processed air stream. The current manuscript has been updated to explain the functional layout of these sections and the purpose of the demister, but all the archived fabrication information, including packing specifications, actual packing height, wetted area, and complete materials-of-construction records, were not stored in a format that could be easily reported retrospectively. This limitation is now mentioned explicitly in such a way that the reader can see the scope of the experimental documentation.

The air side was regulated by adjusting the blower setting and measured with vane-anemometer velocity measurements at the inlet section, but the circulation rate of the liquid desiccant was held at a nominally constant rate during a single run. Since full run-wise archived air- and solution-mass-flow data are not yet available, precise L/G ratios cannot be reconstituted with adequate confidence in all test cases. The updated text, thus, explains the operating philosophy and points out the lack of a complete run-wise flow log as a reporting limitation, instead of making this point implicit.

2.4. Instrumentation and uncertainty analysis

A tabulated list of measurement instruments, operating ranges, resolutions, and manufacturer-stated accuracies have been given to enable quantitative interpretation and uncertainty propagation(Table 1). The given specifications are grounded on the instruments used in the current setup and should be compared with the corresponding datasheets when resubmitted.

The standard propagation of uncertainty can be used to estimate uncertainties of derived performance indicators. In the case of a generic quantity $y = f(x1, x2, ., xn)$, the total standard uncertainty can be calculated as: $uy = 0.5(\Sigma(\partial f/\partial xi \cdot uxi)2)$. To illustrate, the uncertainty in the difference in humidity-ratio $\Delta\omega = 0.5(u\ 0\ 2 + u\ 2\ 2\ ) = u\ 0\ 2\ u\ 2\ 2$. When the rate of moisture removal is calculated as $\dot{m}w = \dot{m}air(\omega in - \omega out)$, then $u\dot{m}w$ can be calculated by adding the uncertainties in the air mass flow rate and the difference in humidity-ratio.

In the current study, the airflow was estimated based on the measurements of inlet air velocity with the help of a vane anemometer, the area of the inlet section, and the measured thermohygrometric state of the air. The updated manuscript now explains this process in a transparent way, and limits the interpretation to a trend-based performance evaluation, rather than claiming to recreate air mass flow with high accuracy on each historical run. The uncertainty of air-side quantities is therefore treated qualitatively with the instrument accuracy provided by the manufacturer and the standard uncertainty propagation framework.

In the initial experimental campaign, it was not possible to continuously measure the concentration of calcium chloride in situ by density, refractive index, or conductivity. In this regard, concentration drift in a run can no longer be measured retrospectively with adequate rigour by reference to archived records alone. This has been cited as a methodological limitation particularly due to the fact that the concentration of desiccant can vary, which can influence the difference in vapour-pressure, the ability to absorb moisture, and the regeneration behaviour.

Table 1. Instruments and sensors used in the experimental setup, along with measurement ranges and uncertainties

Instrument/Sensor	Measured variable	Range	Resolution	Accuracy/uncertainty
Digital thermo-hygrometer	Air temperature & relative humidity	0–50 °C; 10–95 %RH	0.1 °C; 1 %RH	±0.5 °C; ±3 %RH
Vane anemometer	Air velocity	0–10 m/s	0.01 m/s	±0.1 m/s
K-type thermocouple	Solution temperature	0–100 °C	0.1 °C	±1.0 °C
Digital weighing balance	Mass of desiccant/solution	0–10 kg	0.1 g	±0.2 g
Stopwatch/data logger clock	Time	0–24 h	1 s	±1 s
Voltage regulator/controller	Heater input (set-point)	0–230 V	1 V	±1 % of reading

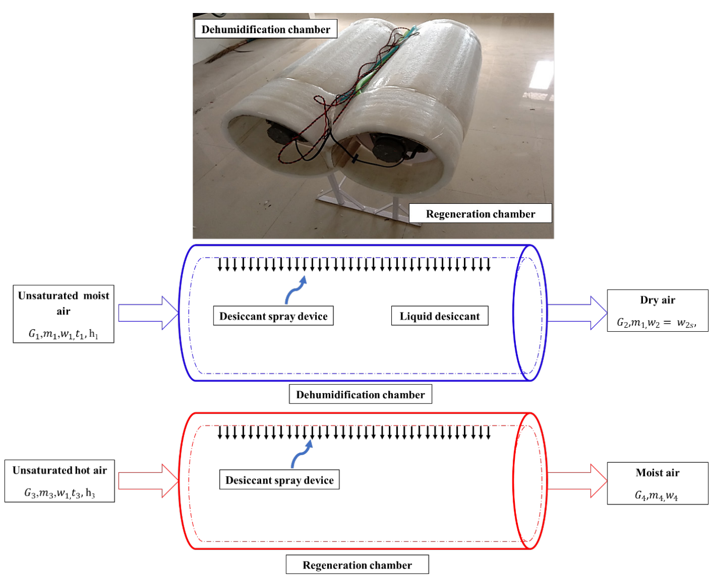

Figure 3. Experimental setup and schematic diagram of the calcium chloride–based LDDS used in the present study

2.5. Modelling framework for performance interpretation

The inlet and outlet air conditions at the absorber and the regenerator are transformed to humidity ratio (kgwater/kgdry air) and moist-air enthalpy by standard psychometric relationships (e.g., ASHRAE formulations) to aid interpretation of the measurements. The rate of moisture removal in the absorber is $\dot{m}$w, abs = $\dot{m}$air(ωin - ωout), and the resultant latent load reduction is Q 0 lat = m 0 w, abs hfg, where hfg is the latent heat of vaporisation at the appropriate temperature. These relations provide a transparent mass–energy accounting framework that can be directly validated against measured air-side states.

Validation and error discussion: The transformed humidity ratio and enthalpy variations across the absorber and regenerator were evaluated on physical consistency and compared with the ranges of the closely related laboratory-scale experiments of calcium chloride liquid desiccant. The agreement is addressed in terms of anticipated trend direction and order-of-magnitude variations, and deviations are explained by solution concentration drift, measurement uncertainty, and non-ideal heat effects.

Besides the psychometric consistency check, the measured trends were compared with representative literature data. Past experimental research has also indicated greater dehumidification at lower process-air velocities due to longer air-desiccant contact time, and better regeneration with higher regeneration temperature or heat input(Chen et al., 2017; Luo et al., 2017; Wen et al., 2018).The current findings thus concur with the anticipated direction of change and the reported operating behaviour of the laboratory-scale calcium chloride and mixed-desiccant systems, thus offering a literature-based validation, although a complete predictive calibration was not within the scope of the current study.

One of the limitations identified by the reviewers is that there was no continuous monitoring of desiccant concentration, which may affect the equilibrium vapour pressure at the solution-air interface. In cases where concentration measurements are known, the equilibrium humidity ratio at the interface can be determined using the solution water activity; otherwise, the current work highlights air-side performance indicators and trend consistency and presents these implications as a constraint and as an objective of future experimental improvement.

Similarly, the archived experimental log could not be used to fully reconstruct inlet psychometric ranges, geometric details, and run-wise L/G ratios. The revised manuscript thus approaches these items in a conservative manner, explains the philosophy of measurement and control, and recognizes them as documentation constraints to be resolved more fully in subsequent test campaigns.

Figure 4. Liquid calcium chloride desiccant solution employed in the absorption and regeneration processes

3. Results and discussion

The dehumidification and regeneration performance of a calcium chloride-based liquid desiccant system was tested under controlled winter operating conditions through experiments. The inlet and outlet air temperature, RH, and velocity of the absorption and regeneration sections were measured at various operating conditions. All operating conditions were held until steady readings were achieved; the trends reported are based on repeated measurements under the same conditions.

3.1. Performance of the absorption chamber

The moisture in the humid air is absorbed in the liquid desiccant in the absorption chamber, which is caused by the difference in vapour-pressure between the incoming air and the calcium chloride solution. Figure 5 shows the variation of the liquid desiccant's RH and temperature during the experimental period. The measured data show that changes in the inlet air conditions affect the temperature and moisture content of the desiccant solution, which in turn affect the desiccant dehumidification behavior of the system.

Figure 6 shows the variation of outlet-air RH with air inlet velocity in the absorption section at a regeneration temperature of 55 °C. It is noted that the lower the air velocities, the lower the outlet RH. This behaviour is attributed to the fact that the air stream has more time in contact with the liquid desiccant, resulting in more moisture uptake. The higher the air velocity, the lower the contact time, and the less moisture is transferred, leading to a comparatively higher outlet RH.

The system has a better dehumidification performance at lower air velocities in the range of air velocities tested. In addition, an increase in inlet air RH will enhance the difference in vapour pressure between the air and the desiccant solution, thus facilitating the absorption of moisture. These observations suggest that the air velocity and inlet humidity are critical factors in the operation of the liquid-desiccant absorption system.

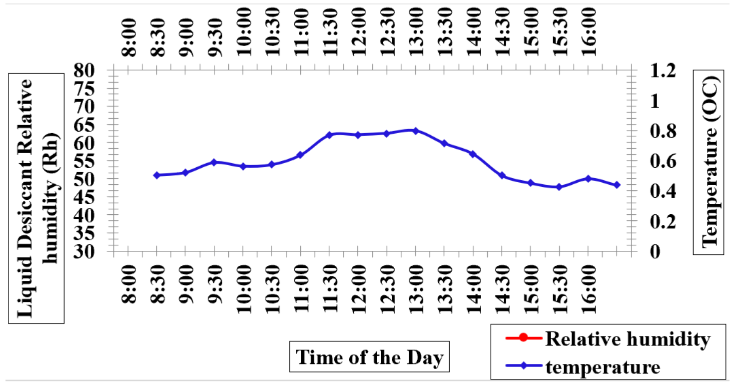

Figure 5. Variation of liquid desiccant RH and temperature during the experimental period under controlled operating conditions

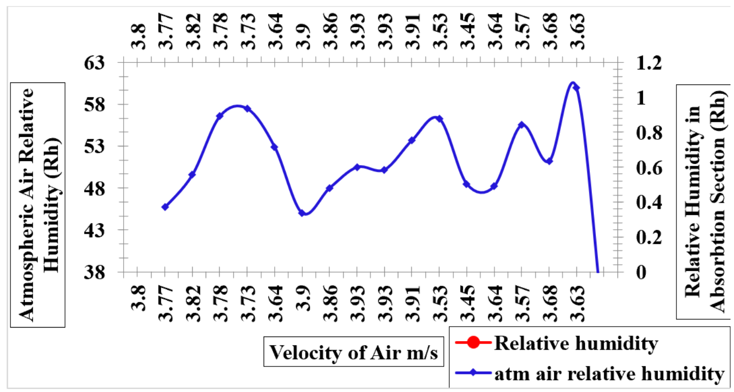

Figure 6. Variation of outlet air RH with air inlet velocity in the absorption section at a regeneration temperature of 55 °C

3.2. Performance of the regeneration chamber

The regeneration process replenishes the moisture absorption capacity of the liquid desiccant by extracting the absorbed water by contact with heated air. Figure 7 shows how the desiccant and the atmospheric air change in RH with the regeneration air velocity. The results show that variation in regeneration air velocity has a negligible impact on outlet RH when the regeneration temperature is kept within the range tested in this paper.

Figure 8 shows the effect of regeneration temperature on outlet RH at different air velocities. The results show that, with increasing regeneration temperature, the RH at the outlet decreases slightly, indicating improved regeneration of the desiccant solution. A regeneration temperature of about 58 C is one of the conditions that have been tested and gives a relatively constant outlet humidity, suggesting good regeneration behaviour.

The trends that have been observed show that the regeneration temperature is more influential on the regeneration effectiveness than the regeneration air velocity. Sufficient regeneration temperatures enable the desiccant to enhance its moisture-removal capacity in subsequent absorption cycles and result in more predictable system operation.

Overall, the experimental results demonstrate that the performance of the liquid desiccant system is sensitive to air inlet velocity in the absorption section and to regeneration temperature in the regeneration section. Since the experiments were carried out in controlled winter conditions, these findings are to be interpreted as reflective of similar inlet air conditions.

3.3. Operational considerations and comparison with literature

Operational stability and material compatibility are critical for the practical deployment of calcium chloride-based systems. Common metals may be corroded by calcium chloride solutions; thus, long-term operation usually involves corrosion-resistant materials, protective coatings, and periodic inspection of wet components. Moreover, the absorber can be a source of droplet and aerosol carryover, especially at higher air velocities; the manuscript has been updated to highlight the importance of demisters and to suggest the measurement of carryover (e.g. by conductivity or ion analysis of downstream condensate or filters) in future studies. The trends observed-enhanced dehumidification at lower air velocities and regeneration at higher temperatures-are in line with previous liquid desiccant research that indicates high sensitivity to contact time and regeneration heat input. In this regard, a more explicit comparison has been included in the discussion to place the current results in the reported operating ranges.

The present experiments measured operational stability by achieving quasi-steady air-side measurements and the lack of sudden drift throughout the acquisition period. Nevertheless, this short-term campaign did not establish long-term stability, direct measurement of aerosol carryover, and cumulative corrosion behaviour, which should be taken into account in future research. Published corrosion research and zero-carryover design research indicate that the viability of the technology in practice is dictated by corrosion-resistant materials, periodic maintenance, and effective mist elimination equipment in the case of calcium chloride systems (Lowenstein et al., 2006; Ren et al., 2017).

Table 2. Comparative perspective between calcium chloride-based LDDS, other common liquid desiccants, and conventional dehumidification approaches

Approach	**Typical strengths**	**Typical limitations**	**Relevance to the present study**
$CaCl_2$-based LDDS	Low material cost; regeneration possible with low-grade heat; suitable for latent-load control.	Requires corrosion management and demister effectiveness; concentration drift and carryover should be monitored.	Represents the configuration tested experimentally in this work.
LiCl/LiBr liquid desiccants	High hygroscopicity and strong moisture affinity; widely reported in liquid-desiccant literature.	Higher salt cost; material compatibility and crystallisation control may become important depending on operating conditions.	Used as the principal benchmark family for qualitative comparison of trends.
Conventional vapour-compression dehumidification	Mature technology; no liquid desiccant handling; widely deployed in HVAC practice.	Latent and sensible loads are coupled; less suitable for direct low-grade-heat utilisation in humidity control.	Provides the conventional reference route that liquid-desiccant systems aim to complement or partly offset.

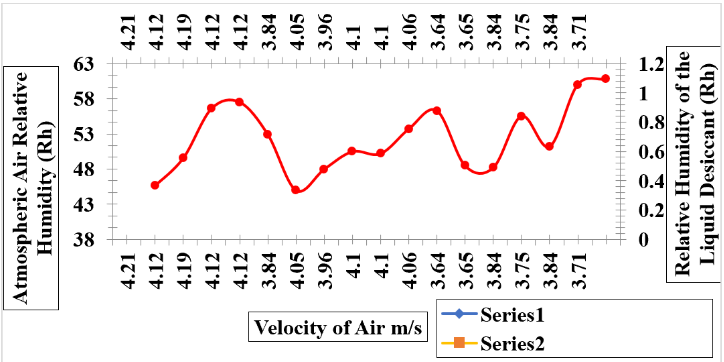

Figure 7. Variation of RH of the liquid desiccant and atmospheric air with regeneration air velocity under controlled regeneration conditions

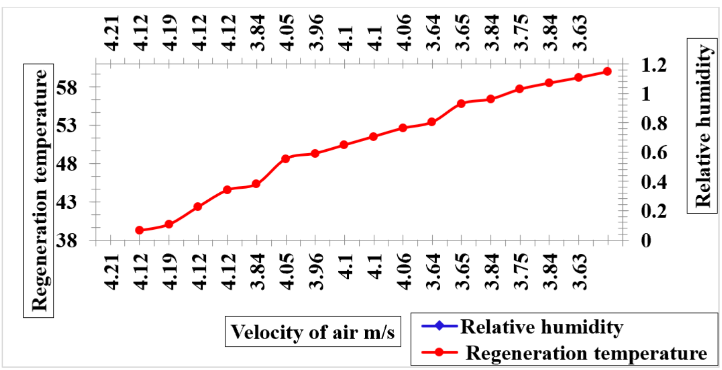

Figure 8. Effect of regeneration temperature on outlet air RH at different air velocities in the regeneration section

4. Conclusion

This paper experimentally investigated the operation of a liquid desiccant dehumidification system based on calcium chloride under controlled winter operating conditions, with the aim of investigating the influence of inlet air velocity and regeneration temperature on the outlet air relative humidity. The findings show that the slower the inlet air velocities, the more moisture is removed due to the longer contact time between the air stream and the desiccant solution. Temperatures of regeneration of about 55-60 C gave relatively constant regeneration behaviour, and there was a small range of outlet air relative humidity under the conditions of the experiment.

In general, the results indicate that liquid desiccant dehumidification using calcium chloride can be used to maintain humidity and potentially lead to lower latent cooling requirements when properly combined with air-conditioning systems. Since the experiments were conducted in laboratory conditions and did not involve a direct energy comparison with conventional vapour-compression systems, the results are to be viewed as indicative. Future research must involve working under a wider variety of climatic conditions, regular measurement of desiccant concentration, and comparative energy and exergy evaluation to define performance envelopes and deployment recommendations. Comparatively, the current findings suggest that calcium chloride is a viable, inexpensive solution to humidity control applications that are motivated by low-grade heat, as long as operational stability, corrosion prevention, and droplet carryover are carefully controlled in design and operation.

However, the study is to be understood with a proper consideration of the limitations in the experimental documentation that were found during the revision, especially the lack of fully archived test-wise psychometric records, complete geometric specifications, run-wise L/G ratios, and direct concentration-tracking data. These parameters should be documented in future studies in a systematic manner to allow more rigorous scale-up, quantification of uncertainty, and cross-study comparison.

Authorship contributions

Authors equally contributed to this work.

Data availability statement

The authors affirm that the data that underpin the findings of this study are accessible in the article. The raw data that substantiate the findings of this study can be obtained by the respective author on reasonable request.

Conflict of interest

The authors stated that they had no possible conflicts of interest regarding the research, authorship, and/or publication of this article.

Ethics

There are no ethical issues with the publication of this manuscript.

Statement on the use of artificial intelligence

Artificial intelligence was not used in the preparation of the article.

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