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Inactivation of airborne microbial contaminants by a heat-pump-driven liquid-desiccant air-conditioning system

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\textbf{ABSTRACT}

The COVID-19 pandemic has led to increasing interest in controlling airborne virus transmission during the operation of air-conditioning systems. Therefore, beyond an examination of the ability of liquid-desiccant material itself to inactivate microbes, a heat-pump-driven liquid-desiccant air-conditioning system was proposed and constructed to experimentally investigate the effect of liquid-desiccant solution on the inactivation of airborne bacteria and fungi in various air-conditioning processes. The proposed system comprises a liquid-desiccant unit to dehumidify or humidify process air using a desiccant-solution and heat-pump unit to cool or heat it and accommodate solution thermal loads. The decrease in the concentration of airborne bacteria and fungi before and after passing through the system (i.e., inactivation efficiency) were compared for the base, summer, and winter operating modes. The results indicated that airborne fungi were less inactivated than bacteria because they possess more stress-resistant cellular structures that resist inactivation. During the air-conditioning processes in both the summer and winter operating modes, the bacterial and fungal inactivation efficiencies improved compared to the base mode owing to the contact with desiccant solution. The higher solution flow rate and solution temperature improved the bacterial inactivation efficiency by 27\% for the winter compared to the summer mode. Conversely, because of possible growth of fungi in the heated and humidified supply air in the winter, the fungal inactivation efficiency improved by only 1.5\% for the winter compared to the summer mode. In conclusion, the proposed system can contribute to control the airborne transmission of microbial contaminants while operating air-conditioning systems.

\textbf{Nomenclature}

\textit{Roman symbols}
\begin{itemize}
\item \textit{C} \hspace{1em} airborne microbial concentration \text{[CFU/ m}^3 \text{]}
\item \textit{N} \hspace{1em} number \text{[–]}
\item \textit{T} \hspace{1em} temperature \text{[°C]}
\item \textit{V} \hspace{1em} sampling volume \text{[m}^3 \text{]}
\end{itemize}

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1. Introduction

In recent years, microbial contaminants, such as bacteria, viruses, and fungi, have deteriorated indoor air quality, leading to discomfort and even diseases. Several conventional air-conditioning systems, in which condensate water generated by the overcooling of process air for dehumidification accumulates on the coil surface, favor the growth of microorganisms \cite{1, 2, 3}. In addition, water can easily stagnate inside a humidifier, allowing microorganisms to grow \cite{4, 5}. Liquid-desiccant (LD)-assisted air-conditioning systems for achieving decoupled humidity control have attracted much attention as an alternative to conventional air-conditioning systems because they can improve the indoor air quality \cite{6, 7}. In an LD-assisted air-conditioning system, the LD solution can either absorb moisture from the process air (i.e., dehumidification process) or, by reversing the LD solution cycle, discharge moisture into the process air (i.e., humidification process) based on the vapor pressure difference between the solution and process air \cite{8}. The LD system is expected to be able to solve the microbial growth problem of conventional air-conditioning systems because no stagnation or accumulation of water occurs \cite{9}. In addition, LD materials (e.g., lithium chloride, lithium bromide, or triethylene glycol) were found to inhibit microbial growth and thermo-chemically destroy microbial cellular structures and genetic material (i.e., inactivation effect) \cite{10, 11}, thereby removing airborne microbial contaminants as the desiccant solution makes contact with the polluted air. Because of the current COVID-19 pandemic, the importance of controlling the airborne transmission of viruses has been seriously discussed in the field of engineering \cite{12, 13}. Thus, the application of the LD system has gained urgency, and research on the inactivation of airborne microbial contaminants by the LD system should be more conducted.

Skinner et al. \cite{14} showed that lithium chloride (LiCl) can inhibit the replication of type 1 and type 2 Herpes simplex viruses and two other DNA viruses (pseudorabies and vaccinia viruses). Slayzak et al. \cite{15} reported that LiCl medium can reduce viable B. subtilis and B. cereus spores by 99.99% in 4–6 h owing to the biocidal effects of salts and dehydration effects on the cellular structures. In addition, LiCl media at higher temperatures (30–60 °C) and higher concentrations (20–40%) were found to be significantly more effective in reducing the viability of surrogates for anthrax spores \cite{16}. Park et al. \cite{17} demonstrated that an LD-assisted air-conditioning system can remove both airborne bacteria and fungi when the process air is dehumidified while passing through the LD unit compared to the case when the process air bypasses the LD unit. Moreover, previous studies \cite{18} have reported that more than 90% of the airborne bacteria were killed via contact with the desiccant solution during dehumidification. Wang et al. \cite{19} revealed that both triethylene glycol (TEG) and LiCl solutions can inactivate airborne fungi, and the LD system using the TEG solution achieved a maximum fungal inactivation efficiency of 93.2%.

Many previous studies have been conducted mostly on the ability of the LD material itself to inactivate microbes from a biochemical perspective. However, research on the inactivation of airborne microbial contaminants via contact with the LD solution during the air-conditioning process is extremely rare. Furthermore, some of the aforementioned studies mainly focused on the microbial inactivation effect only during dehumidification; however, a previous study \cite{16} verified that the LD solution at high temperature, which accompanies the humidification process during the operation of the LD system, can also effectively reduce the viability of the microbes. Nevertheless, no additional research on the microbial inactivation effect during both the dehumidification and humidification processes in the operation of the LD system has been performed. Consequently, in this study, a heat-pump-driven liquid-desiccant (HPLD) air-conditioning system, including annual operating strategies, was proposed, and the effect of the LD solution on the inactivation of
the airborne microbial contaminants was experimentally demonstrated under the practical operation of the proposed system for both the summer (cooling and dehumidification) and winter (heating and humidification) operating modes. The airborne bacteria and fungi were sampled using a bio-contaminant air sampler, and their colony forming units were detected before and after passing through the system to monitor the decrease in the microbial concentration during the operation of the system. Microbial inactivation tests were conducted for various operating modes, and their results were compared and analyzed in detail.

2. System overview

In this study, an HPLD air-conditioning system consisting of an LD unit and a reversible heat-pump unit via the equipment of a four-way valve was proposed. In the LD unit, the process air is dehumidified or humidified according to the vapor pressure difference between the process air and desiccant solution. The heat-pump unit initially cools and heats the desiccant solution, and the installation of an additional evaporator and condenser enables it to cool and heat the process air and adjust the heat balance during the operation of the proposed system. Fig. 1 shows a schematic of the proposed system in the summer operating mode, and Fig. 2 shows a photograph of the experimental prototype.

In the summer operating mode, the process air (i.e., mixture of room return air and outdoor air (OA)) to be dehumidified enters the absorber of the LD unit and then makes contact with the desiccant solution sprayed at the distributor in the counter-flow type through the packing. The packing used in this prototype is made of a porous wood-fiber material to improve wettability and has a honeycomb structure to widen the contact area between the solution and air. Its dimensions are 0.32 m (width), 0.38 m (depth), and 0.3 m (height). Because an exothermic reaction is accompanied in the absorber during dehumidification, the desiccant solution should be cooled to 20°C by the solution-side evaporator of the heat-pump unit before entering the absorber [20]. Subsequently, the dried process air after leaving the absorber is sensible cooled by passing through the air-side evaporator to meet the target supply air (SA) temperature. On the other hand, the desiccant solution is regenerated in the regenerator of the LD unit by releasing its moisture into the scavenging air (i.e., outdoor air). Because an endothermic reaction is accompanied in the regenerator during regeneration, the desiccant solution should be heated to 40°C by the solution-side condenser of the heat-pump unit before entering the regenerator [21]. The extra condenser is activated to balance the solution heating loads and total heating capacity of the heat pump [22]. In addition, a fraction of the weak and strong solutions of the absorber and regenerator sumps are mixed by activating the solution mixing valves installed between the two sumps to regulate the concentrations of both absorber and regenerator inlet solutions.

In the winter operating mode, the refrigerant cycle of the heat pump, and hence, the solution cycle of the LD towers, are both reversed using the switch of the four-way valve. To humidify the process air in the regenerator, which is the absorber in the summer operating mode, the solution-side condenser heats the desiccant solution to above 40°C to increase its vapor pressure for humidification. Subsequently, the humidified process air leaving the regenerator is sensible heated to the target SA temperature while passing through the air-side condenser, which functions as the air-side evaporator in the summer operating mode. To supplement the heat source in winter, unused heat is recovered from the zone exhaust air and provided to the absorber and air-side evaporator, which is the extra condenser in summer. Accordingly, considering the indoor pressure balance and heat balance during operation, only the OA that flows at the ventilation rate is drawn as the process air of the regenerator. In addition, to meet the target solution concentration for the humidification process, make-up water was added to the regenerator sump instead of the solution-mixing process.

Hence, based on the aforementioned workable operating strategies, the proposed HPLD air-conditioning system can operate in both...
summer and winter. Therefore, one may can investigate the inactivation effect for the airborne microbial contaminants via the contact with the LD solution during not only cooling and dehumidification process, but also heating and humidification process.

3. Experimental overview

3.1. Test conditions

A test that verifies the inactivation of outdoor airborne microbial contaminants via contact with the LD solution when the system operates in the summer and winter operating modes, as compared to the case when the system operates in the ventilation mode without solution spray and air-conditioning processes, is necessary. Therefore, the test considered three experimental cases corresponding to three different operating modes: base (ventilation), summer (cooling and dehumidification), and winter (heating and humidification) modes.

Most previous studies regarded the operating conditions of the LD solution as the critical parameters for the microbial inactivation and neglected the temperature and humidity of the inlet air [17,18]. Therefore, throughout this study, only the solution conditions were thoroughly set in accordance with each experimental case, and the temperature and humidity of the inlet air were not controlled. The test was conducted under OA conditions, which was drawn at a ventilation rate of 300 m$^3$/h (0.1 kg/s). In the base mode, the change in the microbial concentration before and after the system wherein the air-conditioning process did not occur (ventilation mode), was measured and used as a reference value; therefore, the desiccant solution was not sprayed, and the refrigerant did not circulate in the heat-pump cycle. In other words, all the components within the system, except for the process air fan, were deactivated to allow the drawn OA to simply pass through the entire system. To prevent the base mode from being affected by the desiccant solution and ensure that the packing of the LD unit was not wetted by it, water was circulated in the packing for 30 min, and the fan was then operated for 30 min to dry the packing wetted by the water before starting the base mode. In contrast, in the summer and winter operating modes, the solution conditions were set based on the recommended design operating conditions for the respective dehumidification and humidification performance while operating the LD unit. In the summer operating mode, the solution flow rate was set to 5.5 L/min (0.108 kg/s) corresponding to a liquid-to-gas ratio (LG ratio) of 1.0, and the solution temperature and concentration were set to approximately 20°C and 30%, respectively [20]. In the winter operating mode, the solution flow rate was set to 11 L/min (0.216 kg/s) corresponding to an LG ratio of 2.0, and the solution temperature and concentration were set to approximately 40°C and 30%, respectively [23]. LiCl was used as the desiccant solution. The evaporating and condensing temperatures of the heat pump were assigned to meet the target temperature of the desiccant solution for each operating mode. The operating conditions for the tests are summarized in Table 1.

To adjust the LG ratio, the solution flow rate of the variable-speed pump and air flow rate of the variable-speed fan were measured. The temperature and concentration of the absorber or regenerator inlet solution were also measured. In addition, the air temperature and humidity behaviors were monitored to ensure that the air-conditioning process certainly occurred. The detailed specifications of

| Operating mode | Air flow rate | Air DBT | Air humidity | LG ratio | Solution flow rate | Solution temp. | Solution conc. |
|----------------|---------------|---------|--------------|----------|-------------------|----------------|---------------|
| Base           | 300 m$^3$/h (0.1 kg/s) | 19.8–25.5 °C | 38.2–47.8% | –        | –                 | –              | –             |
| Summer         | 1.0           | 5.5 L/min (0.108 kg/s) | 17.6 °C | 30.8%     | 11 L/min (0.216 kg/s) | 41.4 °C | 31%           |
| Winter         | 2.0           | –       | –            | –        | –                 | –              | –             |

Fig. 2. Experimental prototype of the proposed system.
the measuring devices are listed in Table 2.

3.2. Method

3.2.1. Sampling method

The main method used in this study for investigating the inactivation effect is a culture-based method with direct plating [24]. The inactivation of microbial contaminants (i.e., bacteria and fungi) was investigated by using tryptic soy agar (TSA) in a 90 mm plate and potato dextrose agar (PDA) in a 90 mm plate to sample and quantitatively detect the bacteria and fungi, respectively. A bio-contaminant air sampler (BUCK BioCulture Model B30120), whose specifications are listed in Table 3, was used to sample the airborne bacteria and fungi using each agar plate. The detection flow of the sampler was set to 100 L/min in this study; therefore, the sampling volume can be controlled by modulating the retention time of the sampler. For instance, when the retention time is modulated to 2 min, the sampling volume is constructed to 200 L with detection flow of 100 L/min. Each microbial contaminant was sampled at least four times with two different sampling volumes for each experimental case to ensure the validity of the experiments. Therefore, the microbial contaminants were sampled twice for each sampling volume of 200 and 500 L for each experimental case in this study. Each test set, including all three experimental cases, was conducted daily for each type of microbial contaminant and repeated twice for bacteria and fungi to ensure the reproducibility of the experiments.

3.2.2. Experimental setup

In this study, the changes in the concentration of microbial contaminants before and after passing through the system need to be measured to investigate the microbial inactivation efficiency by operating the proposed HPLD air-conditioning system. Therefore, the microbial contaminants in the inlet air (i.e., OA) and outlet air (i.e., SA) of the entire system were sampled simultaneously. To sample the airborne microbial contaminants efficiently, a small chamber was installed at each sampling position, and then the bio-contaminant air-sampler and agar plate were placed inside it. Fig. 3 shows the experimental setup for sampling airborne microbial contaminants. Before starting each experiment, the sampling area and prototype were sterilized using 70% alcohol to prevent uncontrolled contamination and maintain the same initial conditions in all experimental cases. In addition, a filter and an eliminator were not installed to validate the inactivation effect only by operating the LD system using LiCl solution. However, the desiccant carryover to the air did not occur because the air face-velocity was calculated to be 0.69 m/s at current packing floor area (i.e., 0.12 m$^2$) and air flow rate (i.e., 300 m$^3$/h), which satisfies the target face-velocity (i.e., less than 2.5 m/s) to prevent the carryover [25]. Therefore, all inactivation tests were not affected by the desiccant carryover.

3.2.3. Estimation of inactivation efficiency

After sampling, all the agar plates were sealed with parafilm to prevent contamination by the surrounding environment. The sampled bacteria (TSA plates) were incubated at 35 °C for 2–3 days, while the sampled fungi (PDA plates) were incubated at 25 °C for 4–5 days. After incubation, the number of colony forming units (N$_{\text{CFU}}$) on the cultured agar plates was counted. When the “too numerous to count” (TNTC) state is observed on the cultured agar plates, the corresponding sampling data can be either excluded or converted to N$_{\text{CFU}}$ using a conversion table in the air-sampler manual [26]. Subsequently, the airborne microbial concentration (C), which is defined as the ratio of the total number of colony forming units to the total sampling volume, was estimated using Eq. (1) [24].

Thus, the inactivation efficiency ($\varepsilon_{\text{inact}}$), which is defined as the ratio of the changes in the microbial concentration before and after passing through the system to the inlet microbial concentration, can be estimated using Eq. (2) [19]. The inactivation efficiency is regarded as a performance index to compare the inactivation performance of the three operating modes.

$$C = \frac{\sum N_{\text{CFU}}}{\sum V} \quad (1)$$

$$\varepsilon_{\text{inact}} = \frac{C_{\text{in}} - C_{\text{out}}}{C_{\text{in}}} \quad (2)$$

4. Results and discussion

4.1. Air-conditioning process

Table 4 exhibits the temperature and humidity behaviors of the process air for the various operating modes during the bacterial and fungal inactivation tests. For each operating mode, the average temperature and humidity during the total time required to measure all

| Table 2 Specifications of the measuring devices. |
|-----------------------------------------------|
| Parameter | Type          | Range          | Accuracy     |
| Solution flow rate   | LZT panel flowmeter | 5–35 L/min     | ± 4.0%       |
| Solution temperature | NTC           | −30–100 °C     | ± 0.5 °C     |
| Solution density     | Glass hydrometer | 1.0–1.3 kg/L   | 0.001 kg/L   |
| Air flow rate        | Vane probe 0100 mm | 0.1–15 m/s     | ± (0.1 m/s + 1.5% of mv) |
| Air temperature and humidity | NTC | Temperature −40–120 °C | ± 0.3 °C |
|                        |               | Humidity 0–100% | ± 2.0% RH    |
the sampling volumes (i.e., twice for each sampling volume of 200 and 500 L) were recorded at each state. For each bacterial and fungal inactivation test, test set 1 corresponds to the experimental results obtained on the first sampling date. Test set 2 corresponds to the experimental results obtained on the second sampling date, which was conducted to confirm the reproducibility of the experiments. Owing to the fluctuations in the temperature and humidity of the OA during the one-day period, the conditions of the system inlet air differ slightly for each operating mode despite corresponding to the same test set. However, these differences were not considered to significantly affect the microbial growth and fairness in the inactivation tests. Therefore, the OA was drawn as the system inlet air without additional control in all the inactivation tests, as described in Section 3.1.

In the base mode, the process air conditions were shown to be almost constant before and after passing through the system in both the bacterial and fungal inactivation tests. Therefore, the process air was certainly not affected by the desiccant solution while passing through the packing of the LD unit, and the air-conditioning process did not occur in the base mode. In contrast, in both the summer and winter operating modes, the solution circulation of the LD unit and activation of the heat pump confirmed that the air-conditioning process occurred in both the bacterial and fungal inactivation tests. In the summer operating mode, the process air was initially dehumidified by approximately 2–3 g/kg (Δω) via contact with the absorber solution and then sensible cooled by approximately 5–7 °C (ΔT) while passing through the air-side evaporator. In addition, because the temperature of the absorber solution (i.e., 17.6 °C)

| Device                        | Type               | Parameter                  | Specifications                                      |
|-------------------------------|--------------------|----------------------------|-----------------------------------------------------|
| Bio-contaminant air sampler   | Impactor type      | Detection flow             | 30–120 L/min                                        |
|                               |                    | Number of holes            | 380 (1 mm diameter)                                 |
|                               |                    | Too numerous to count (TN) | Maximum number of colony forming units: 2,477       |
|                               |                    | Accuracy                   | ± 5% of the set point                               |
|                               |                    | Compatibility              | 90 mm agar plate                                    |

Table 3
Specifications of the bio-contaminant air sampler.

![Fig. 3. Experimental setup for sampling the airborne microbial contaminants.](image-url)

(a) Inlet sampling  
(b) Outlet sampling  
(c) Sampling setup
exceeded all dew-point temperatures ($D_p$) of the system inlet air, and the evaporating temperature was also higher than all dew-point temperatures of the absorber outlet air, the ideal decoupled dehumidification process without humidity condensation was achieved in the summer operating mode in all inactivation tests. In the winter operating mode, the process air was initially humidified by approximately 9 g/kg ($\Delta \omega$) via contact with the regenerator solution and then sensible heated by approximately 12–13 °C ($\Delta T$) while

### Table 4
Temperature and humidity behaviors of the process air during the bacterial and fungal inactivation tests.

#### Bacterial inactivation test

| Operating mode | Property | Test set 1 (First sampling set) | Test set 2 (Second sampling set) |
|----------------|----------|---------------------------------|---------------------------------|
|                |          | System inlet air (OA) | ABS or REG outlet air | System inlet air (OA) | ABS or REG outlet air |
| Base           | $T$ [°C] | 23.6 | 23.6 | 23.6 | 22.9 | 22.6 | 22.6 |
|                | $\omega$ [g/kg] | 7.96 | 8.01 | 8.45 | 6.31 | 6.81 | 6.48 |
| Summer         | $T$ [°C] | 24.6 | 22.4 | 17.8 | 25.5 | 19.4 | 13.2 |
|                | $\omega$ [g/kg] | 8.99 | 6.47 | 6.76 | 7.85 | 5.17 | 5.50 |
|                | $D_p$ [°C] | 12.5 | 7.62 | 8.26 | 10.5 | 4.4 | 5.27 |
| Winter         | $T$ [°C] | 25.1 | 35.0 | 47.3 | 23.5 | 34.9 | 47.1 |
|                | $\omega$ [g/kg] | 9.56 | 18.6 | 18.1 | 7.92 | 16.9 | 16.1 |

#### Fungal inactivation test

| Operating mode | Property | Test set 1 (First sampling set) | Test set 2 (Second sampling set) |
|----------------|----------|---------------------------------|---------------------------------|
|                |          | System inlet air (OA) | ABS or REG outlet air | System inlet air (OA) | ABS or REG outlet air |
| Base           | $T$ [°C] | 19.8 | 19.2 | 18.1 | 24.3 | 24.5 | 24.9 |
|                | $\omega$ [g/kg] | 5.82 | 6.60 | 6.57 | 7.40 | 7.43 | 7.46 |
| Summer         | $T$ [°C] | 24.2 | 19.5 | 13.3 | 25.3 | 21.5 | 14.3 |
|                | $\omega$ [g/kg] | 7.17 | 5.35 | 5.57 | 9.60 | 6.31 | 6.84 |
|                | $D_p$ [°C] | 9.12 | 4.88 | 5.46 | 13.5 | 7.25 | 8.43 |
| Winter         | $T$ [°C] | 22.4 | 34.0 | 47.6 | 22.7 | 36.2 | 49.1 |
|                | $\omega$ [g/kg] | 7.15 | 16.0 | 15.7 | 7.79 | 18.2 | 18.0 |

### Table 5
Sampling data of the airborne bacteria in the base mode.

| Operating mode | Sampling volume | Measurement | Test set 1 (First sampling set) | Test set 2 (Second sampling set) |
|----------------|-----------------|--------------|---------------------------------|---------------------------------|
|                |                 |              | System inlet air (OA) | System outlet air (SA) | System inlet air (OA) | System outlet air (SA) |
| Base           | 200 L           | 1 Cultured agar plate | 1 | 3 | TNTC | 38 |
|                |                 | 2 Cultured agar plate | 3 | 1 | TNTC | 4 |
| Base           | 500 L           | 1 Cultured agar plate | 15 | 1 | TNTC | 74 |
|                |                 | 2 Cultured agar plate | 3 | 0 | TNTC | 29 |

|                |                 | $N_{CFU}$ [CFU] | 7.78 | 4.44 | 500 | 117.5 |

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passing through the air-side condenser.

4.2. Bacterial inactivation test

4.2.1. Sampling of airborne bacteria

Tables 5–7 show the sampling data of the airborne bacterial colonies at the system inlet and outlet for each sampling volume of 200 and 500 L in the base, summer, and winter operating modes, respectively. Based on the size, color, spore shape of the bacterial colonies on the cultured agar plates, the bacterial species is inferred to be Staphylococcus which has less than 2 μm in diameter [27]. The number of bacterial colonies (N_{CFU}) on the cultured agar plates was counted for each measurement. On the other hand, in test set 2, all sampling data of airborne bacterial colonies at the system inlet air for all operating modes corresponded to the TNTC state. Therefore, the sampling data of the airborne bacterial colonies at the system inlet air in test set 2 were included in the available data and then converted to 200 CFU [26]. The use of this conversion value is shown to be appropriate for comparing the inactivation efficiencies, whereas the use of the maximum conversion value of the TNTC state (i.e., 2,477 CFU) is inappropriate because it can obscure the differences in the inactivation efficiencies for the various operating modes. Hence, based on the total N_{CFU} of the available data, the airborne bacterial concentrations at both the system inlet and outlet were estimated for each operating mode.

In the base mode (Table 5), the number of bacterial colonies clearly decreases as the process air passes through the entire system, even though it is certain that the process air has not been in contact with the desiccant solution, as described in Section 4.1. In the summer operating mode (Table 6), during dehumidification via contact with the absorber solution, the decrease in the number of bacterial colonies appears to be more pronounced compared to that in the base mode. Among the three operating modes, the most dramatic decrease in the number of bacterial colonies occurs during humidification via contact with the regenerator solution in the winter operating mode (Table 7). Thus, in test set 1, the airborne bacterial concentrations in the base, summer, and winter operating modes decreased from 7.78 to 4.44 CFU/m$^3$, 19.3 to 7.14 CFU/m$^3$, and 16.4 to 1.43 CFU/m$^3$, respectively. In test set 2, the airborne bacterial concentrations in the base, summer, and winter operating modes decreased from 500 to 117.5 CFU/m$^3$, 571 to 87.9 CFU/m$^3$, and 571 to 25 CFU/m$^3$, respectively.

4.2.2. Inactivation efficiency

Fig. 4 shows a comparison of the inactivation efficiency of the three operating modes for airborne bacteria, along with the standard error. In the base mode, although the process air was not in contact with the desiccant solution and only passed through the entire system as described earlier, the inactivation efficiency of the airborne bacteria was estimated to be 0.60. This is because airborne bacteria, which can be classified as particulate contaminants [28], may have been filtered out by the packing of the LD unit. As shown in Fig. 2, the packing has a porous and honeycomb structure, which is generally applied to air filter devices that specialize in filtering out airborne particulate contaminants [29]. An earlier report [17] also addressed the potential of the LD packing material to filter out airborne microbial contaminants. Therefore, the bacterial inactivation efficiency of the base mode in this study originated from the

| Table 6 |

Sampling data of the airborne bacteria in the summer operating mode.

| Operating mode | Sampling volume | Measurement | Test set 1 (First sampling set) | Test set 2 (Second sampling set) |
|----------------|----------------|-------------|-------------------------------|-------------------------------|
|                |                |             | System inlet air (OA)         | System outlet air (SA)         |
|                |                |             | System inlet air (OA)         | System outlet air (SA)         |
| Summer         | 200 L          | 1           | Cultured agar plate           | Cultured agar plate           |
|                |                | 2           | N_{CFU} [CFU]                 | N_{CFU} [CFU]                 |
|                | 500 L          | 1           | Cultured agar plate           | Cultured agar plate           |
|                |                | 2           | N_{CFU} [CFU]                 | N_{CFU} [CFU]                 |
| Bacterial concentration [CFU/m$^3$] | 19.3 | 6 | 19.3 | 6 | 7.14 | 7.14 | 571 | 22 | 87.9 |
The bacterial inactivation efficiencies, estimated to be 0.74 in the summer and 0.94 in the winter operating modes, improved by 23% and 57%, respectively, compared to the base mode. Based on these results, the LiCl solution was inferred to be capable of destroying the cellular structures of the airborne bacteria and destabilizing their genetic material while dehumidifying or humidifying the process air. Therefore, the proposed HPLD air-conditioning system can inactivate airborne bacteria during various air-conditioning processes in both summer and winter operating modes. In addition, the bacterial inactivation efficiency in the winter operating mode improved by 27% compared to that in the summer operating mode. This is because the LiCl solution was sprayed at a higher flow rate (i.e., 11 L/min) and at a higher temperature (i.e., 41.4 °C) for the humidification process in the winter operating mode compared to the solution conditions for the dehumidification process in the summer operating mode (i.e., 5.5 L/min and 17.6 °C). The higher solution flow rate increased the degree of contact between the process air and desiccant solution, thereby increasing the degree of inactivation of airborne bacteria. According to the literature [16], because higher solution temperatures can further threaten bacterial viability, the LiCl solution at 41.4 °C in winter may inactivate airborne bacteria more effectively than the LiCl solution at 17.6 °C in summer. This indicates that the solution condition with a higher flow rate and higher temperature is the main factor that improves the airborne bacterial inactivation efficiency in the winter operating mode.

Table 7
Sampling data of the airborne bacteria in the winter operating mode.

| Operating mode | Sampling volume | Measurement | Test set 1 (First sampling set) | Test set 2 (Second sampling set) |
|----------------|-----------------|-------------|--------------------------------|--------------------------------|
|                |                 |             | System inlet air (OA) | System outlet air (SA) |
| Winter         | 200 L           | 1 Cultured agar plate | N_{2FU} [CFU] 2 2 | 1 TNTC 8  |
|                |                 | 2 Cultured agar plate | | |
|                | 500 L           | 1 Cultured agar plate | N_{2FU} [CFU] 8 8 | 0 TNTC 2  |
|                |                 | 2 Cultured agar plate | | |
|                |                 | Bacterial concentration [CFU/m³] 16.4 16.4 | 1.43 1.43 | 571 571 | 25 25 |

Fig. 4. Inactivation efficiency of airborne bacteria for various operating modes.
4.3. Fungal inactivation test

4.3.1. Sampling of airborne fungi

Tables 8–10 show the sampling data of the airborne fungal colonies at both the system inlet and outlet for each sampling volume of 200 and 500 L in the base, summer, and winter operating modes, respectively. Based on the size, color, spore shape of the fungal colonies on the cultured agar plates, the fungal species is inferred to be Penicillium, Cladosporium, and Aspergillus which have 3–10 μm in diameter. Only the first measurement of 500 L of the base mode in test set 2, the number of fungal colonies (N_{CFU}) on the cultured agar plate was counted for each measurement. The airborne fungal concentrations at both the system inlet and outlet were then estimated for each operating mode based on the total N_{CFU} of the available data.

In the base mode (Table 8), a decrease in the number of fungal colonies in the process air can be clearly observed despite the absence of contact with the desiccant solution, similar to the results of the bacterial inactivation test. In the summer operating mode (Table 9), the decrease in the number of fungal colonies in the process air was slightly increased compared to that in the base mode owing to the contact with the absorber solution. Contrary to the results of the bacterial inactivation test, the number of fungal colonies in the process air did not decrease significantly in the winter operating mode (Table 10) and showed almost the same decrease as in the summer operating mode. Thus, in test set 1, the base, summer, and winter operating modes exhibited a decrease in the airborne fungal concentrations from 118.6 to 42.1 CFU/ m³, 172.9 to 56.4 CFU/ m³, and 98.6 to 32.9 CFU/ m³, respectively. In test set 2, the base, summer, and winter operating modes exhibited a decrease in the airborne bacterial concentrations from 77.8 to 41.1 CFU/ m³, 94.3 to 44.3 CFU/ m³, and 129.3 to 58.6 CFU/ m³, respectively.

4.3.2. Inactivation efficiency

Fig. 5 shows a comparison of the inactivation efficiency of the three operating modes for airborne fungi, along with the standard error. In all three operating modes, the inactivation efficiency of the airborne fungi (Fig. 5) was lower than that of the airborne bacteria (Fig. 4), which is also consistent with the results of a previous study [17]. This is because, from a biological perspective, fungi are more viable than bacteria and are difficult to kill. Bacteria are classified as prokaryotes and unicellular organisms, whereas fungi are classified as eukaryotes and multicellular organisms that have more complex cellular structures [30]. Therefore, fungi may produce more diverse and evolved biological reactions than bacteria, which favor their reproduction and growth. In addition, since fungi are reported to possess various protective cellular components against environmental stresses, fungal spores are inferred to be more stress-resistant than bacterial spores [31]. The abovementioned fungal viability has also been revealed in previous inactivation tests using ultraviolet (UV) irradiation, which demonstrated that fungi can only be inactivated by exposure to higher doses of UV irradiation for a longer period of time compared to bacteria [32]. Based on these surveys, even in the experiments using the LiCl solution in this study, the lower inactivation efficiency for the airborne fungi than the bacteria in all three operating modes can be attributed to the strong viability of the fungi. In addition, the air-side evaporator of the prototype could be another factor that lowers the fungal inactivation efficiency. Although humidity condensation was not shown to be generated in the air-side evaporator, as described in Section 4.1, ideal dry-coil operation cannot be ensured. Therefore, the fungi, which are reported to be significantly affected by the ambient humidity, may be less inactivated due to the uncontrollable dew condensed by the air-side evaporator. Furthermore, the fungi that were inactivated by the LD solution could be re-suspended and grow in the air-side evaporator [33], which can also lower the fungal inactivation efficiency.

The fungal inactivation efficiency was shown to be 0.56 even in the base mode wherein there was no contact between the process air and desiccant solution. This is because, as discussed for the bacterial inactivation efficiency in the base mode, the airborne fungi can also be classified as particulate contaminants, and may be filtered out by the porous and honeycomb-structured packing of the LD unit. The fungal inactivation efficiencies were estimated to be 0.60 in the summer and 0.61 in the winter operating mode, which were improved by only 7% and 9%, respectively, compared to the base mode. Therefore, it can be concluded that the LiCl solution inactivates the airborne fungi while dehumidifying or humidifying the process air. However, the inactivation effect of the LiCl solution on airborne fungi was found to be relatively insignificant compared to that on airborne bacteria, possibly owing to the strong viability of the fungi.

In contrast to the bacterial inactivation efficiencies, the fungal inactivation efficiencies remained almost the same in the summer and winter operating modes. This is because fungal growth is significantly affected by humidity, and hence, is stronger in humid environments [34]. Therefore, in the winter operating mode, the hot and humid system outlet air (i.e., SA) favored the growth of airborne fungi more than the summer operating mode. Similarly, a previous study [19] indicated that when the dehumidification performance is degraded by the high solution temperature, the outlet air humidity ratio is increased, leading to a decrease in the fungal inactivation efficiency. Therefore, in this study, although the LiCl solution conditions of higher flow rate and higher temperature in winter might be highly effective in inactivating airborne fungi, the inactivation efficiency could not be significantly improved owing to the growth characteristics of the fungi in the humid outlet environments.

5. Conclusions

In this study, an HPLD air-conditioning system (including its practical operating strategy) was proposed, and the effect of the LD solution on the inactivation of airborne bacteria and fungi was experimentally analyzed under the summer (cooling and dehumidification) and winter (heating and humidification) operating modes. The airborne bacteria and fungi at the system inlet and outlet were sampled using a bio-contaminant air sampler and agar plates, and the decrease in the concentration of the microbial contaminants before and after passing through the system (i.e., inactivation efficiency) was compared for various operating modes (i.e., base,
### Table 8
Sampling data of the airborne fungi in the base mode.

| Operating mode | Sampling volume | Measurement | Test set 1 (First sampling set) | Test set 2 (Second sampling set) |
|----------------|----------------|-------------|---------------------------------|---------------------------------|
|                |                |             | System inlet air (OA)           | System outlet air (SA)           |
|                |                |             | System inlet air (OA)           | System outlet air (SA)           |
| Base           | 200 L          | 1 Cultured agar plate | N_{CFU} [CFU] 33 14 | N_{CFU} [CFU] 23 7 |
|                |                |             |                                |                                  |
|                |                | 2 Cultured agar plate | N_{CFU} [CFU] 25 4 | N_{CFU} [CFU] 16 10 |
| 500 L          |                | 1 Cultured agar plate | N_{CFU} [CFU] 45 20 | TNTC 18 |
|                |                | 2 Cultured agar plate | N_{CFU} [CFU] 63 21 | N_{CFU} [CFU] 31 20 |

Fungal concentration [CFU/ m$^3$] 118.6 42.1 77.8 41.1

### Table 9
Sampling data of the airborne fungi in the summer operating mode.

| Operating mode | Sampling volume | Measurement | Test set 1 (First sampling set) | Test set 2 (Second sampling set) |
|----------------|----------------|-------------|---------------------------------|---------------------------------|
|                |                |             | System inlet air (OA)           | System outlet air (SA)           |
|                |                |             | System inlet air (OA)           | System outlet air (SA)           |
| Summer         | 200 L          | 1 Cultured agar plate | N_{CFU} [CFU] 45 11 | N_{CFU} [CFU] 20 9 |
|                |                |             |                                |                                  |
|                |                | 2 Cultured agar plate | N_{CFU} [CFU] 30 4 | N_{CFU} [CFU] 19 12 |
| 500 L          |                | 1 Cultured agar plate | N_{CFU} [CFU] 83 35 | N_{CFU} [CFU] 33 19 |
|                |                | 2 Cultured agar plate | N_{CFU} [CFU] 84 29 | N_{CFU} [CFU] 60 22 |

Fungal concentration [CFU/ m$^3$] 172.9 56.4 94.3 44.3
In all three operating modes, the airborne fungi were found to be less inactivated than the airborne bacteria owing to their more stress-resistant cellular structures and non-ideal dry-coil operation and re-suspension effect of the air-side evaporator.

In the base mode, although the process air did not come in contact with the desiccant solution, both the airborne bacteria and fungi were inactivated by 60% and 56%, respectively, owing to the filtration of microbial contaminants by the porous and honeycomb-structured packing.

For the bacterial inactivation tests, the inactivation efficiency in the winter operating mode improved by 27% compared to that in the summer operating mode owing to the stronger inactivation effect at higher solution flow rates and temperatures for humidification in the winter mode.

For the fungal inactivation tests, the inactivation efficiencies were almost the same in the summer and winter operating modes because the inactivation effect by the desiccant solution may have been offset by the fungal growth characteristics in the winter SA conditions (i.e., hot and humid air).

The primary contribution of this study is that the inactivation effect of the desiccant-solution on the airborne microbial contaminants was demonstrated in various air-conditioning processes. This can control airborne virus transmission while operating air-conditioners in summer, and winter operating modes. The major findings of this study are as follows:

- In all three operating modes, the airborne fungi were found to be less inactivated than the airborne bacteria owing to their more stress-resistant cellular structures and non-ideal dry-coil operation and re-suspension effect of the air-side evaporator.
- In the base mode, although the process air did not come in contact with the desiccant solution, both the airborne bacteria and fungi were inactivated by 60% and 56%, respectively, owing to the filtration of microbial contaminants by the porous and honeycomb-structured packing.
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conditioning systems, which will aid in preventing the spread of infectious diseases, such as the current COVID-19 pandemic. Therefore, based on the COVID-19 scenario, a viral inactivation test under the rating conditions for the inlet air conditions, type of microbes, and microbial concentration should be conducted in future.

CRediT author statement

**Jae-Hee Lee:** Conceptualization, Methodology, Data curation, Writing original draft preparation. **Jong-II Bang:** Methodology, Data curation, Validation. **Minki Sung:** Methodology, Validation. **Jae-Weon Jeong:** Supervision, Validation, Reviewing and Editing.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] P.R. Morey, J.C. Feeley, J.A. Otten, Biological Contaminants in Indoor Environments, ASTM Baltimore, MD, 1990.
[2] X. Liu, Z. Li, Y. Jiang, B. Lin, Annual performance of liquid desiccant based independent humidity control HVAC system, Appl. Therm. Eng. 26 (2006) 1198–1207, https://doi.org/10.1016/j.applthermaleng.2005.10.043.
[3] A. Bakker, J.A. Siegel, M.J. Mendell, A.J. Prussin, L.C. Marr, J. Peccia, Bacterial and fungal ecology on air conditioning cooling coils is influenced by climate and building factors, Indoor Air 30 (2020) 326–334, https://doi.org/10.1111/ina.12632.
[4] S.A. Hines, D.J. Chappell, R.A. Lordo, B.D. Miller, R.J. Janke, H.A. Lindquist, K.R. Fox, H.S. Ernst, S.C. Taft, Assessment of relative potential for Legionella species or surrogates inhalation exposure from common water uses, Water Res. 56 (2014) 203–213, https://doi.org/10.1016/j.watres.2014.02.013.
[5] R.L. Tyn dall, E.S. Lehman, E.K. Bowman, D.K. Milton, J.M. Barbarea, Home humidifiers as a potential source of exposure to microbial pathogens, endotoxins, and allergens, Indoor Air 5 (1995) 171–178, https://doi.org/10.1111/j.1600-0668.1995.t01-1-00003.x.
[6] M.M. Rafique, P. Gandhisasan, H.M.S. Bahadurah, Liquid desiccant materials and dehumidifiers - a review, Renew. Sustain. Energy Rev. 56 (2016) 179–195, https://doi.org/10.1016/j.rser.2015.11.061.
[7] A. Gurubalan, M.P. Matya, P.J. Geoghegan, A comprehensive review of liquid desiccant air conditioning system, Appl. Energy 254 (2019) 113673, https://doi.org/10.1016/j.apenergy.2019.113673.
[8] C.E.I. Nobrega, N.C.L. Brum, Desiccant-Assisted Cooling: Fundamentals and Applications, Springer, 2013.
[9] X. Liu, Y. Jiang, T. Zhang, Temperature and Humidity Independent Control (THIC) of Air-Conditioning System, Springer, 2014.
[10] K.A. Robertson, T.K. Ghosh, A.L. Hines, D. Novoel, R.C. Warder Jr., Airborne microorganisms: their occurrence and removal, in: Fifth Int. Conf. Indoor Air Qual. , Clim., Toronto, 1990, pp. 565–570.
[11] Z. Weirong, Q. Kaiyang, L. Xiaohua, C. Xiaomin, Pilot study of the impact of liquid desiccant dehumidification on IAQ, Hv Ac 11 (2004) 28.
[12] L. Moraw ska, J.W. Tang, W. Bahnhelt, P.M. Bliaussen, A. Boerstra, G. Buonanno, et al., How can airborne transmission of COVID-19 indoors be minimised? Environ. Int. 142 (2020) 105832, https://doi.org/10.1016/j.envint.2020.105832.
[13] K.J. Goedl Pollitt, J. Peccia, A.I. Ko, N. Kamiński, C.S. Dela Cruz, D.W. Nebert, J.K.V. Reichardt, D.C. Thompson, V. Vasiliiou, COVID-19 vulnerability: the potential impact of genetic susceptibility and airborne transmission, Hum. Genom. 14 (2020) 1–7, https://doi.org/10.1016/s40246-020-00267-3.
[14] G.R.B. Skinner, C.E. Hartley, A. Buchan, L. Harper, P. Gallimore, The effect of lithium chloride on the replication of herpes simplex virus, Med. Microbiol. Immunol. 168 (1980) 139–146, https://doi.org/10.1007/BF02121762.
[15] S. Slayzak, D. Blake, J. Ryan, T. Vinzant, Liquid Desiccant Regenerable Filters for Indoor Environmental Quality and Security, National Renewable Energy Laboratory, 2003.
[16] R.D. Judkoff, D.M. Blake, T.B. Vinzant, J.P. Ryan, P. Examiner, F.M. Lawrence, Using liquid desiccant as a regenerable filter for capturing and deactivating contaminants, U.S. Patent No. 7 (306) (11 Dec. 2007), 650.
[17] J.Y. Park, D.S. Yoon, S. Li, J. Park, J. Il Bang, M. Sung, J.W. Jeong, Empirical analysis of indoor air quality enhancement potential in a liquid-desiccant assisted air conditioning system, Build. Environ. 121 (2017) 11–25, https://doi.org/10.1016/j.buildenv.2017.05.011.
[18] H.X. Fu, X.H. Liu, Review of the impact of liquid desiccant dehumidification on indoor air quality, Build. Environ. 116 (2017) 158–172, https://doi.org/10.1016/j.buildenv.2017.02.014.
[19] Y.F. Wang, T.W. Chung, W.M. Jian, Airborne fungi inactivation using an absorption dehumidification system, Indoor Built Environ. 20 (2011) 333–339, https://doi.org/10.1111/j.1469-8062.2011.00844.x.
[20] X.H. Liu, X.Q. Yi, Y. Jiang, Mass transfer performance comparison of two commonly used liquid desiccants: LiBr and LiCl aqueous solutions, Energy Convers. Manag. 52 (2011) 180–190, https://doi.org/10.1016/j.enconman.2010.06.057.
[21] G.A. Longo, A. Gasparella, Experimental and theoretical investigation in heat and mass transfer in a packed column dehumidifier/regenerator with liquid desiccant, Int. J. Heat Mass Tran. 48 (2005) 5240–5254, https://doi.org/10.1016/j.ijheatmasstransfer.2005.07.011.
[22] X. Niu, F. Xiao, Z. Ma, Investigation on capacity matching in liquid desiccant and heat pump hybrid air-conditioning systems, Int. J. Refrig. 35 (2012) 160–170, https://doi.org/10.1016/j.ijrefrig.2011.08.004.
[23] H. Lim, S.J. Lee, Y. Su, J.-W. Jeong, Experimental study and prediction model of a liquid desiccant unit for humidification during the heating season, J. Build. Eng. (2021) 103549, https://doi.org/10.1016/j.jobe.2021.103549.
[24] ISO 16000-17: Indoor Air — Part 17: Detection and Enumeration of Moulds — Culture-Based Method, International Organization for Standardization (ISO), 2008.
[25] E. Elsarrag, E.E.M. Ali, S. Jain, Design guidelines and performance study on a structured packed liquid desiccant air-conditioning system, HVAC R Res. 11 (2005) 319–337, https://doi.org/10.1007/s10796-005-10391-0.
[26] Bio-culture B, Flow C Model B30120 Instruction Manual. n.d.
[27] W. Kowalski, Ultraviolet Germicidal Irradiation Handbook: UVGI for Air and Surface Disinfection, Springer, 2010.
[28] V.L. Dhadge, C.R. Mebdi, M. Changmai, M.K. Purkait, House hold unit for the treatment of fluoride, iron, arsenic, and microorganism contaminated drinking water, Chemosphere 199 (2018) 728–736, https://doi.org/10.1016/j.chemosphere.2018.02.057.
[29] X. Chen, Y. Xu, M. Liang, Q. Ke, Y. Fang, H. Xu, X. Jin, C. Huang, Honeycomb-like polyphosphate/polyurethane nanofiber filter for the removal of organic/inorganic species from air streams, J. Hazard Mater. 347 (2018) 325–333, https://doi.org/10.1016/j.jhazmat.2018.01.012.
[30] A.M. Poole, M.J. Phillips, D. Penny, Prokaryote and eukaryote evolution, Biosystems 69 (2003) 163–185, https://doi.org/10.1016/S0303-2647(02)00131-4.
[31] W. Nakpan, M. Yermakov, R. Indugula, T. Reponen, S.A. Grinshpun, Inactivation of bacterial and fungal spores by UV irradiation and gaseous iodine treatment applied to air handling filters, Sci. Total Environ. 671 (2019) 59–65, https://doi.org/10.1016/j.scitotenv.2019.03.310.

[32] M.Y. Menetrez, K.K. Foorde, T.R. Dean, D.A. Betancourt, The effectiveness of UV irradiation on vegetative bacteria and fungi surface contamination, Chem. Eng. J. 157 (2010) 443–450, https://doi.org/10.1016/j.cej.2009.12.004.

[33] J.C. Luongo, S.L. Miller, Ultraviolet germicidal coil cleaning: decreased surface microbial loading and resuspension of cell clusters, Build. Environ. 105 (2016) 50–55, https://doi.org/10.1016/j.buildenv.2016.05.024.

[34] A. Rajasekar, R. Balasubramanian, Assessment of airborne bacteria and fungi in food courts, Build. Environ. 46 (2011) 2081–2087, https://doi.org/10.1016/j.buildenv.2011.04.021.