Journal of Civil Engineering and Architecture 19 (2025) 74-81
doi: 10.17265/1934-7359/2025.02.003

Development of a Liquid Desiccant Air Conditioning System Using Ionic Liquids

Hiroshi Nakayama[1], Masatoshi Harada[2] and Xinming Wang[3]

1. Chubu Electric Power co., Inc., Advanced Research Laboratory, Aichi 4598522, Japan

2. Dyna Air co., Ltd., Tokyo 1010051, Japan

3. Evonik Japan co., Ltd, Tokyo 1630938, Japan

Abstract: LDACs (liquid desiccant air-conditioners) with heat pump can perform cooling dehumidification or heating humidification, and have high energy-saving and sterilization performance. Therefore, they are installed in hospitals, nursing homes, and food factories, where humidity control is required. However, LiCl (lithium chloride), a conventional humidity control liquid, is highly corrosive to metals, requiring the use of highly corrosion-resistant materials for the pipes and the heat exchangers. These lead to the problem that the manufacturing cost of the air conditioner increases. Therefore, we developed an inexpensive and compact LDAC by adopting a novel IL (ionic liquid) that does not corrode the metals commonly used in air conditioners. In this study, we evaluated the metal solubilities and sterilizing properties of the IL. Based on the physical properties of the IL, the humidity control module was improved for the purpose of downsizing and cost reduction of the unit. Moreover, we conducted a performance evaluation of the LDAC in the environmental test room under the condition in which temperature and humidity change rapidly in short period of time to simulate the condition of sudden showers of rain in summer. Test results showed that processed air was supplied at very stable level.

Key words: Liquid desiccant air conditioning, ILs, heat pump, dehumidification.

1. Introduction

The development of an efficient air-conditioning system has become more and more important from the standpoint view of realizing a sustainable society. In hospitals and factories where temperature and humidity control throughout the year are required, gas as fuel has been used as heat sources of boilers and absorption chillers. However, there is a lot of heat loss in the boiler and the steam piping, and the energy consumption is high. It is also often utilized in vapor compression systems to control the temperature and humidity of the air, but the SA (supply air) is cooled to the dew point temperature, which requires air reheating. LDAC (liquid desiccant air-conditioner) is attracting attention as one of the most promising candidates to replace such inefficient air conditioning systems [1-4].

However, the present commercial LDAC uses an aqueous solution of LiCl (lithium chloride) as the humidity control liquid or desiccant. The LiCl is very caustic/corrosive to metals, in particular, iron or aluminum, both of which are popular materials in the air-conditioner system; this requires expensive special corrosion-resistance pipes and heat exchangers, which causes a critical problem that the manufacturing cost of the air-conditioning system is rather high.

ILs (ionic liquids) have gained strong interests due to their unique physical and chemical properties and their applied fields have been significantly expanding. ILs show a low volatility, unique solvation capability, and high stability and the liquids have thus been applied in various fields of electro-chemistry, organic and inorganic synthetic chemistry, catalysis, and gas absorption [5]. In particular, some ILs are non-crystalline and non-corrosive, and have extremely low vapor pressures.

Corresponding author: Hiroshi Nakayama, Dr.Eng, research engineer, research fields: development of commercial and industrial heat pump system.

As a result, it is a viable alternative to the traditional liquid desiccant, and is anticipated to be applied to liquid desiccant-based deep dehumidifier [6-8].

In these backgrounds, we have developed an inexpensive and compact LDAC by adopting a novel IL developed by Evonik Industries which does not corrode general-purpose metals such as iron and aluminum [9]. In this study, we evaluated the metal solubility and the sterilizing property of the IL. Based on the physical properties of the IL, we improved the heat exchanger and the humidity control module. Moreover, we conducted a performance evaluation of the LDAC in the environmental test room under the condition in the rated dehumidification condition and the transient condition.

2. Outline of LDAC

Fig. 1 shows an outline of LDAC in the case of dehumidification. LDAC is an air-conditioning unit that absorbs and releases water vapor in the air by bringing the outside air into direct contact with a gas-liquid contactor wetted with a liquid humidity control liquid to adjust the humidity and temperature of the air. The core components of the LDAC are the processor, regenerator, plate heat exchanger, and interchange heat exchanger. The processor plays a role of supplying the treated air to the room, and can create air of any temperature and humidity by adjusting the temperature and concentration of the humidity control liquid. Also, the temperature and concentration of the humidity control liquid can be independently controlled, and the temperature and humidity of the air can be freely set. On the other hand, the regenerator has a role of concentrating the liquid by heating the humidity control liquid, which has been diluted by absorbing the moisture in the air, and bringing it into contact with the outside air. Humidification is performed by switching between cooling and heating of a heat source such as a heat pump. Various heat sources such as heat pumps, groundwater, exhaust heat, and solar heat are used to cool or heat the liquid. In particular, a hybrid air conditioning system that combines a vapor compression heat pump and liquid desiccant air conditioning, which can heat and cool at the same time, improves the efficiency of the system [2].

3. Physical Properties of IL

As the key element, liquid desiccant materials play important roles in the overall performance of the desiccant cooling system. In general, humidity control liquids are required to have high humidity control performance, to be inexpensive, to have satisfy and high sterilization properties and so on. LiCl which is mainly used as a humidity control liquid for LDAC, satisfies such requirements, but has the problem of being highly corrosive to metals.

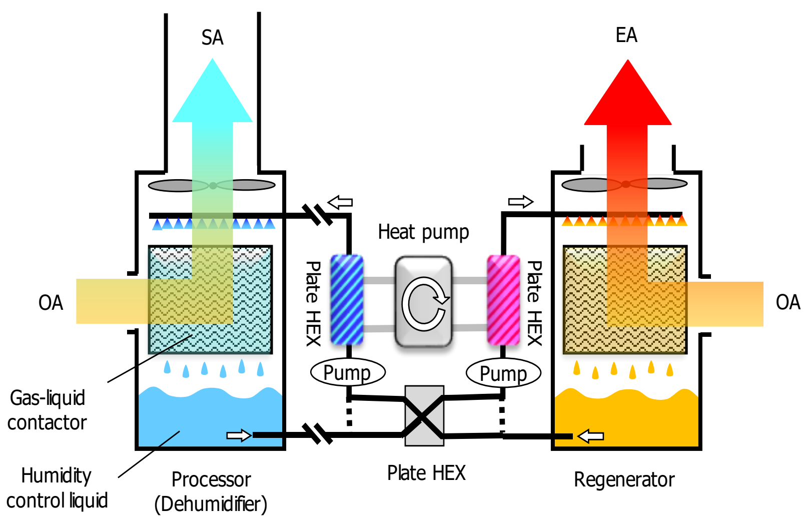

Fig. 1 Outline of LDAC (dehumidification case).

Table 1 Thermophysical properties of humidity control liquid (25 ℃) [9].

	Unit	IL	LiCl
Mass fraction	%	0-80	0-35
Density	kg/m^3	1,000-1,150	1,000-1,215
Viscosity	Pa s	0.001-0.03	0.001-0.005
Surface tension	N/m	0.072-0.039	0.072-0.091
Thermal conductivity	W/mK	0.607-0.271	0.607-0.539
Specific heat capacity	kJ/kg K	4.2-2.2	4.2-2.8

ILs are molten salt at room temperature, consisting of organic cation and inorganic or organic anion. ILs are generally nonflammable, have good thermal and chemical stability, and do not evaporate under normal conditions. Compared to the inorganic salts, ILs have good fluidity over a wide temperature range and have no or very low corrosion to metals.

In this study, a novel IL developed by Evonik Industries was used as the humidity control liquid. This IL exhibits high dehumidification performance, thermal and chemical stability, low volatility, comparable heat mass transfer properties [9] and is suitable for LDAC. Table 1 shows comparison of thermophysical properties of humidity control liquid. At the same temperature and the equivalent liquid desiccant mass fraction at which the saturated vapor pressure is identical, the aqueous IL exhibits lower density and surface tension than aqueous LiCl. On the other hand, the viscosity of aqueous IL is higher than that of aqueous LiCl.

3.1 Level of Metal Ions into the IL

Figs. 2 and 3 show the metal ions of stainless steel and aluminum dissolved into the IL. The test period is 3 weeks and the temperature of the solution is heated up to 70 ℃. The amount of metal ions dissolved in the IL is measured by ICP-MS (inductively coupled plasma-mass spectrometry). The mass fraction of IL and LiCl is 80 wt% and 35 wt%, respectively. Saturated vapor pressure at these mass fractions is close to the value when dehumidifying the outside air in summer. The size of the metal sample is 40 mm × 10 mm × 3 mm. The amount of metal ions of SUS (steel use stainless) and aluminum dissolved into the IL is much less than into the LiCl solution and is at a practically acceptable level. This result suggests that commonly used tubes and heat exchangers can be used, which is a great advantage in reducing the manufacturing cost of air conditioners.

3.2 Sterilization Performance

In the COVID-19 pandemic, the air cleaning performance of air conditioners is also required as an additional factor. Therefore, we investigated the sterilization and virus inactivation performance of the IL. As an example, Figs. 4 and 5 show the results of the sterilization effect against *Legionella* and *Aspergillus niger* of the IL in comparison with LiCl solution. When each bacterium is brought into contact with the IL, it dies after 1 min, which demonstrates that the sterilization performance is higher than that of LiCl.

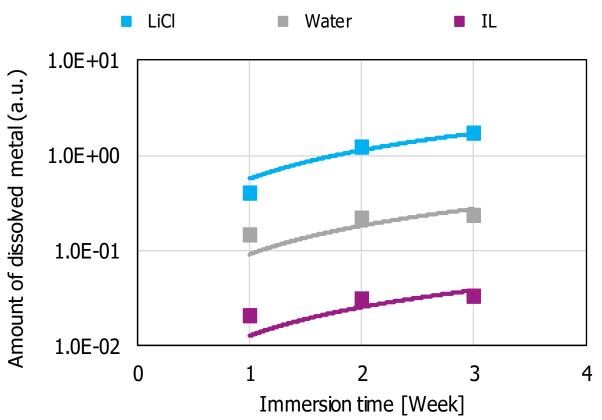

Fig. 2 Amount of dissolved metal (aluminum).

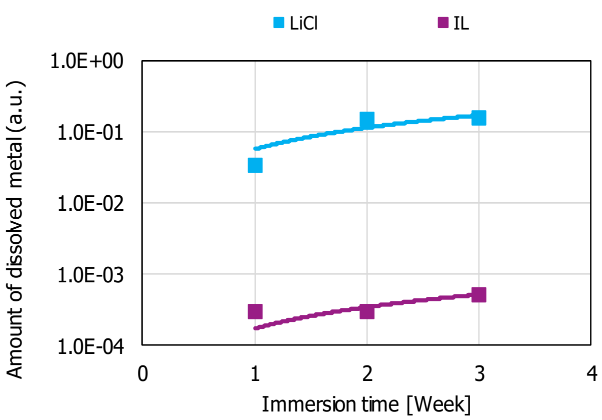

Fig. 3 Amount of dissolved metal (SUS304).

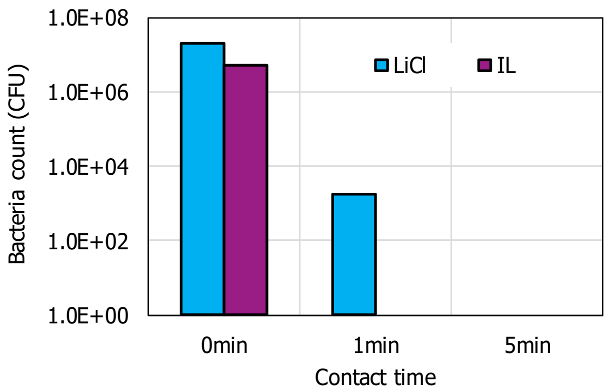

Fig. 4 Bacteria count (*Legionera*).

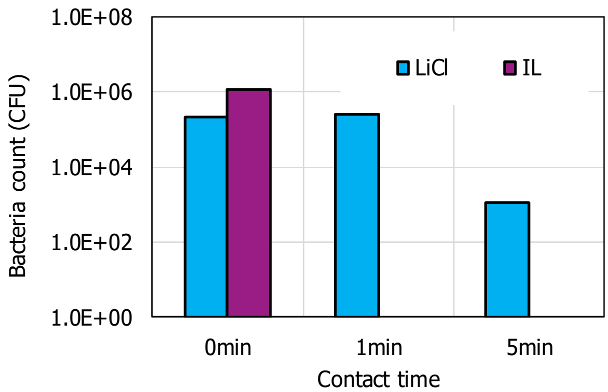

Fig. 5 Bacteria count (*Aspergillus niger*).

Table 2 Virus inactivation performance result of IL.

	Value of virus infectious dose (TCID50/mL)			
	Feline coronavirus		Influenza virus	
	IL	Water	IL	Water
0 min	1.7×10^5	1.7×10^5	1.0×10^5	1.0×10^6
1 min	No count	—	No count	—
5 min	No count	—	No count	—
60 min	No count	1.1×10^5	No count	3.1×10^6

Table 2 shows the inactivation effect of the IL on two types of viruses (feline coronavirus and influenza virus). The IL was added to the liquid containing the virus cell line, and after a predetermined period of time, the amount of virus infection to the cell line was measured. In the case of the purified water for comparison, the amount of viral infection hardly changed after 60 min, but with the IL, the amount of viral infection decreased sharply down to the detection limit even after only 1 min, demonstrating a remarkable viral inactivation effect.

Regarding the hazards of this IL, we conducted acute dermal and inhalation toxicity test using mice in accordance with the OECD (Organisation for Economic Co-operation and Development) guidelines (TG 402 and TG 436), and confirmed that the classification of hazards to health (GHS: Globally Harmonized System of classification and labelling of chemicals) is beyond the most mild class.

4. Configuration of Humidity Control Module

In LDAC, the SA temperature is determined by controlling the temperature of the humidity control liquid, and the air humidity is determined by controlling the concentration of the humidity control liquid. In a typical LDAC, as shown in Fig. 6, the humidity control liquid is first cooled in a plate heat exchanger and then directly contacted with the outside air in an air-liquid contactor. The temperature and humidity of the outside air are regulated by direct contact with this liquid.

In the conventional LDAC systems using LiCl, as the humidity control liquid generates heat when it absorbs moisture, the temperature gradually rises in the downstream direction of the gas-liquid contactor. Since the dehumidification ability of the humidity control liquid decreases as the temperature rises, a large amount of liquid needs to be circulated to prevent this, which requires large capacity solution pumps and solution tanks. Therefore, from the perspective of cost reduction and compactness, it was necessary to minimize the liquid flow rate and tank size.

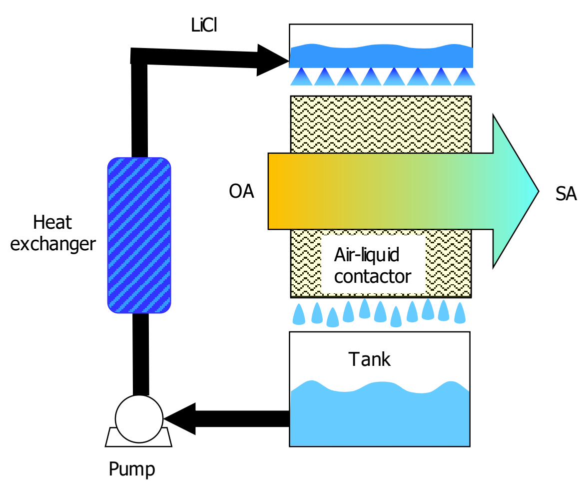

Fig. 6 Conventional humidity control module.

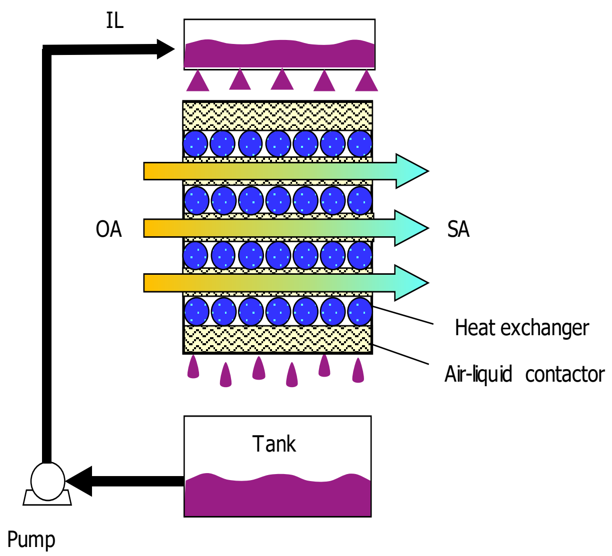

Fig. 7 Developed humidity control module.

In this study, a sandwich structure was adopted in which tube heat exchangers and gas-liquid contactors were alternately arranged as shown in Fig. 7, and dehumidification was performed while cooling the humidity control liquid. Tests were conducted under various conditions with different tube heat exchanger arrangements and different types of gas-liquid contactors.

As a result, it became possible to maintain conditioning performance while suppressing the temperature rise of the humidity control liquid in the downstream direction under conditions where the liquid flow rate was reduced compared to conventional methods, and a compact integrated humidity control module was developed. This reduced the circulation flow rate (liquid volume) by approximately 90% compared to conventional models, and also significantly reduced the tank size.

As shown in Table 1, at high concentration, IL has a lower surface tension and a higher viscosity than LiCl. Therefore, even at low flow rates, a stable thin liquid film is formed, which tends to facilitate heat and mass exchange [10].

5. Specifications

The appearance of the developed LDAC is shown in Fig. 8, and its specifications are shown in Table 3. The processor and regenerator have the same shape. Inside the housing, the gas-liquid contactor, tank, pump, and fan are arranged. The heat source can be not only hot and cold water from the heat pump chiller, but also hot water discharged from the factory and well water. In particular, if hot waste water of 40 to 50 ℃ can be used, significant energy savings can be expected. Compared to the lineup of conventional models, this LDAC has achieved a reduction of about 20% in manufacturing costs, about 25% in installation area, and about 90% in the amount of humidity control liquid used.

The LDAC shown in Fig. 8 has a rated air volume of 4,500 m^3/h, but industrial customers (e.g., paint booths and clean rooms) require a wide range of treatment air volumes. Therefore, as shown in Fig. 9, the gas-liquid contactor module can be incorporated into the AHU (air handling unit) used for air conditioning. This makes it possible to handle a wide range of treatment with air volumes up to 20,000 m^3/h according to customer needs.

Fig. 8 Outside appearance of the LDAC.

Table 3 Specifications of the LDAC.

Dimensions (W × D × H)	1,600×1,830×2,000
Weight (kg)	1,620
Pump power supply (W)	200
Rated dehumidification capacity (kg/h)	67.5
Rated humidification capacity (kg/h)	68.6
Rated air flow rate (m^3/h)	4,500

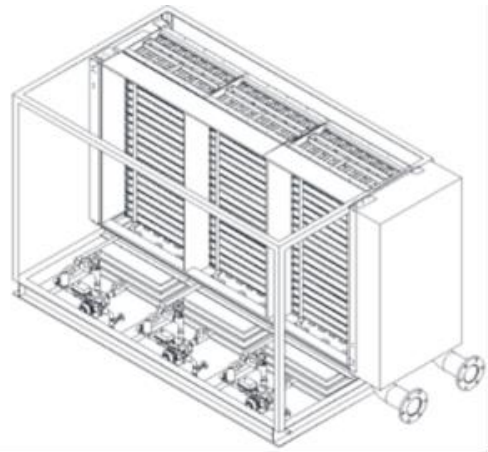

Fig. 9 Module type of LDAC.

6. Performance Tests of the LDAC

The performance test of the developed LDAC was carried out in the climatic environment test room of the Research and Development Department of Chubu Electric Power Co., Inc., as shown in Fig. 10, where the rated humidification performance and dehumidification transient performance were measured. This test room can measure the heating and cooling capacity by the air enthalpy method [11]. A heat pump chiller with a rated heating and cooling capacity of 100 kW was used as the heat source.

Table 4 shows the results of the rated performance test. This test was conducted under typical Japanese summer OA (outdoor air) conditions, assuming application to a commercial building. The measured value of the dehumidification capacity was close to the target value, confirming that stable performances were obtained.

6.1 Dehumidification Transient Performance Test

This test was conducted for the purpose of verifying the humidity control during sudden weather changes. In manufacturing processes such as pharmaceutical and painting processes, it is important to maintain a stable state even under drastic change in OA conditions.

Fig. 11 shows the temperature and humidity changes processed by the developed LDAC in a situation simulating a situation where the temperature and humidity of the OA change rapidly in a short time, such as a summer rain shower. In this case, the OA temperature is decreased by 10 ℃ and the humidity is increased by 60% during 1 h. The test results showed that the treated air was supplied at a very stable level. The average SA temperature and relative humidity during the test were 26 ℃ and 44%, respectively. The SA temperature change was within ±0.6 ℃ and humidity change was within ±1%.

7. Primary Energy Consumption

Table 5 shows the result of estimating primary energy consumption and CO_2 emission of the conventional system and that of the developed LDAC system when the system is introduced to a hospital in Japan. The conventional system consists of a gas steam boiler and an air-cooled heat pump chiller. A substantial reduction in energy consumption of 72% and CO_2 emission of 49% from that of the conventional system can be expected when the new system is introduced.

Fig. 10 LDAC performance test.

Table 4 Results of rated performance test.

		Target value	Measured value
Flow rate (m^3/h)		4,500	4,474
Temperature of cold water (℃)		10.0	9.6
Temperature of hot water (℃)		45.0	45.5
OA	Temperature (℃)	34.3	34.3
	Humidity ratio (g/kgDA)	19.5	19.2
SA	Temperature (℃)	20.0	18.4
	Humidity ratio (g/kgDA)	7.0	6.4
Cooling capacity (kW)		70.3	72.9
Dehumidification capacity (kg/h)		67.5	68.7

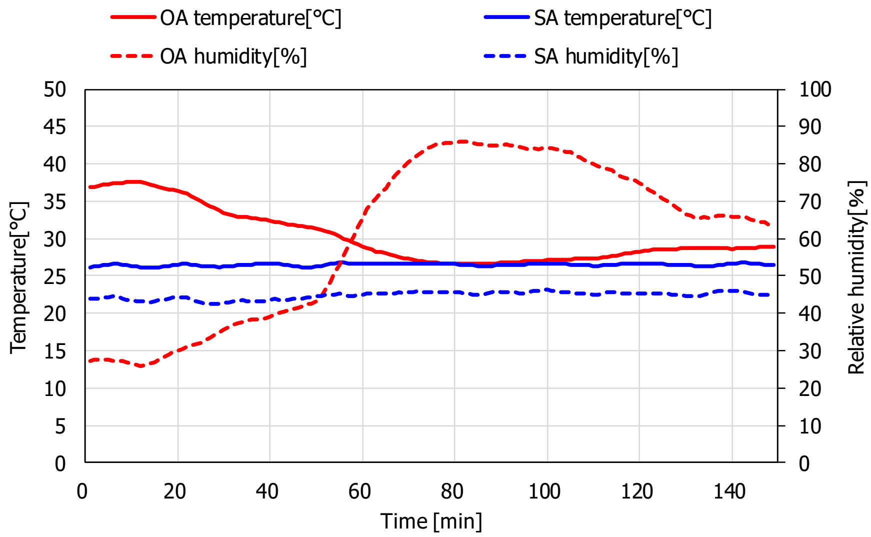

Fig. 11 SA temperature and humidity characteristics when a shower is assumed.

Table 5 Estimated primary energy consumption and CO_2 emission.

	Conventional system	Developed system	Reduction rate
Primary energy consumption (GJ/year)	449	126	72% down
CO_2 emission (ton-CO_2/year)	111	56	49% down

Estimate condition:
Building: Hospital (floor area: 2,000 m^2)
Air conditioning operation: 24 h/day, 365 days, flow rate 10,000 m^3/h
System efficiency: Heat pump chiller (cooling COP (coefficient of performance): 4.07, heating COP: 4.06), gas boiler 70%
Calorific value: Electricity 9.70 MJ/kWh, Gas 45 MJ/m^3
CO_2 emission factor: Electric 0.449 kg-CO_2/kWh, Gas 2.29 kg-CO_2/m^3

8. Conclusions

We have developed an inexpensive and compact LDAC by using a novel IL that does not corrode general-purpose metals. The developed LDACs were already installed in hospitals, nursing homes, offices, food supermarkets, and beer factory as energy-saving and hygienic air conditioners. The results obtained during the research and development of this system are as follows:

The amount of SUS and aluminum dissolved in the IL is much lower than that in LiCl solution. In addition, the IL has a higher sterilization effect against bacteria and viruses than LiCl solution.

A sandwich structure in which tube heat exchangers and gas-liquid contactors are alternately arranged was developed for the direct contact of air to liquid. Consequently, the liquid flow rate can be reduced by 90% compared to the conventional unit.

By appropriately controlling the temperature and IL concentration, extremely stable processing air can be supplied even under conditions where the outside air conditions change rapidly.

It is expected that the energy consumed by conventional air conditioning system such as heat pump chiller and boiler, can be reduced 72% by introducing the new system.

References

[1] Lowenstein, A. 2008. "Review of Liquid Desiccant Technology of HVAC Applications." *HVAC&R Research* 14: 819-39.

[2] Yamaguchi, S., Jeong, J., Saito, K., Miyauchi, H., and Harada, M. 2011. "Hybrid Liquid Desiccant Air-Conditioning System: Experiments and Simulations." *Appl. Ther. Eng.* 31: 3741-7.

[3] Abdel-Salam, A. H., and Simonson, C. J. 2016. "State-of-

the-Art in Liquid Desiccant Air Conditioning Equipment and Systems." *Renewable and Sustainable Energy Reviews* 58: 1152-83.

[4] Kim, M., Park, J., and Jeong, J. 2013. "Energy Saving Potential of Liquid Desiccant in evaporative-Cooling-Assisted 100% Outdoor Air." *Energy* 59: 726-36.

[5] Itoh, T. 2017. "Ionic Liquids as Tool to Improve Enzymatic Organic Synthesis." *Chm. Rev.* 117: 10567-607.

[6] Luo, Y., Shao, S., Qin, F., Tian, C., and Yang, H. 2012. "Investigation on Feasibility of Ionic Liquids Used in Solar Liquid Desiccant Air Conditioning System." *Solar Energy* 86: 2718-24.

[7] Watanabe, H., Komura, T., Matsumoto, R., Ito, K., Nakayama, H., Nokami, T., and Itoh, T. 2019. "Design of Ionic Liquid as Liquid Desiccant for an Air Conditioning System." *Green Energy Env.* 4: 139-45.

[8] Maekawa, S., Matsumoto, R., Ito, K., Nokami, T., Li, J. X., Nakayama, H., and Itoh, T. 2020. "Design of Quaternary Ammonium Type-Ionic Liquids as Desiccants for an Air-Conditioning System." *Green Chemical Eng.* 1: 109-16.

[9] Cao, B., Yin, Y., Zhang, F., Tong, S., Che, C., Chen, W., Ji, Q., Xu, G., and Li, X. 2022. "Experimental Study on Heat and Mass Transfer Characteristics between a Novel Ionic Liquid and Air under Low-Humidity Conditions." *Int. J. Heat Mass Trans.* 198: 123373.

[10] Varela, R. J., Giannetti, N., Saito, K., Wang, X., and Nakayama, H. 2022. "Experimental Performance of a Three-Fluid Desiccant Contactor Using a Novel Ionic Liquid." *Appl. Ther. Eng.* 210: 118343.

[11] Watanabe, C., Ohashi, E., Hirota, M., Nagamatsu, K., and Nakayama, H. 2009. "Evaluation of Annual Performance of Multi-type Air-Conditioners for Buildings." *J. Ther. Sci. Tech.* 4: 483-93.