2018

Experimental Study on a Finned-tube Internally Cooled Contactor for Liquid Desiccant air conditioning systems with Ionic Liquid

Takahiro Sato
Graduate School of Fundamental Science and Engineering, Waseda University, Shinjuku-ku, Tokyo, 169-8555, Japan, waseda.tkhr-s986@akane.waseda.jp

Richard Jayson Varela
Graduate School of Fundamental Science and Engineering, Waseda University, Shinjuku-ku, Tokyo, 169-8555, Japan, rjvarela_2014@fuji.waseda.jp

Seiichi Yamaguchi
Waseda University, Department of Applied Mechanics and Aerospace Engineering, 3-4-1 Okubo, Shinjuku-ku, Tokyo 169-8555, Japan, sei_yamaguchi@aoni.waseda.jp

Kiyoshi Saito
Department of Applied Mechanics and Aerospace Engineering, Waseda University, Shinjuku-ku, Tokyo, 169-8555, Japan, saito@waseda.jp

Hiroshi Nakayama
Chubu Electric Power Co.,Inc.,Nagoya-shi, Aichi, 459-8522, Japan, Nakayama.Hiroshi2@chuden.co.jp

See next page for additional authors

Authors
Takahiro Sato, Richard Jayson Varela, Seiichi Yamaguchi, Kiyoshi Saito, Hiroshi Nakayama, and Xinming Wang

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Takahiro SATO[1]*, Richard Jayson VARELA[1], Seiichi YAMAGUCHI[2], Kiyoshi SAITO[2]
Hiroshi NAKAYAMA[3], Xinming WANG[4]

[1]Graduate School of Fundamental Science and Engineering, Waseda University,
Shinjuku-ku, Tokyo, 169-8555, Japan
(Phone: +81 03 5286 3259, Fax: +81 03 5285 3259, E-mail: waseda.tkhr-s986@akane.waseda.jp)

[2]Interdisciplinary Institute for Thermal Energy Conversion Engineering and Mathematics,
Waseda University, Shinjuku-ku, Tokyo, 169-8555, Japan

[3]Chubu Electric Power Co., Inc.,
Nagoya-shi, Aichi, 459-8522, Japan

[4]Evonik Japan Co., Ltd.,
Shinjuku-ku, Tokyo, 163-0938, Japan

ABSTRACT

This paper presents an experimental study on the dehumidification performance of a finned-tube internally cooled contactor in comparison to that of an adiabatic contactor in liquid desiccant air conditioning systems with an ionic liquid. The contactor is the most significant component in liquid desiccant systems because it is the component responsible for the dehumidification and regeneration processes. When the absorptive solution is in contact with the air in the contactor, the absorption/desorption of the solution occurs because of the difference in vapor pressure. This results in the transfer of heat and mass between the air and the solution.

Conventionally, adiabatic contactors that only entail air and solution interactions are used for the dehumidification/regeneration process of liquid desiccant systems. On the contrary, internally cooled contactors are recommended because they can realize a more efficient dehumidification process. This is possible because internally cooled contactors can maintain the dehumidification ability of the absorptive solution by utilizing cooling water as the third fluid in the contactor to remove the heat of absorption. In other words, internally cooled contactors can reduce the circulating solution mass flux and hence the power consumption of the solution pumps.

In this study, the dehumidification ability of a finned-tube internally cooled contactor was investigated experimentally. To increase heat transfer in cooling water, aluminum, which has a high thermal conductivity, was used as the contactor material. Although lithium chloride solution is a conventional absorptive solution, it is corrosive to aluminum; therefore, an ionic liquid was used as the absorptive solution in this experiment because it does not cause any corrosive action on aluminum. Currently, research activities on this new combination of contactor and absorptive solution are not extensive. This study provides new and valuable information for future work. Moreover, the results were compared to those of an adiabatic contactor to analyze the difference in the dehumidification ability between the two contactors.

As a result, outlet air dew point temperatures lower than the cooling water temperature were achieved, and this is indicative of the advantage of a liquid desiccant air conditioning system over conventional vapor compression air conditioning system. Furthermore, the outlet air dew point temperatures of the internally cooled contactor were lower than those of the adiabatic contactor at low mass fluxes, and converged at a higher solution mass flux. This suggests the significant effect of cooling water on the dehumidification ability of the absorptive solution. The experimental data regarding the dehumidification ability of this new combination of an aluminum finned-tube contactor and ionic liquid solution are promising in terms of further investigating the structure of contactors. Moreover, these results provide significant information for the improvement of liquid desiccant air conditioning system design.

1. INTRODUCTION

Regulating humidity is essential in maintaining comfort and health in our everyday lives. However, dehumidification by a conventional vapor compression air conditioning system requires cooling the air temperature below the dew point temperature, which leads to excessive energy consumption. Furthermore, this dehumidification method causes condensed water to form mold on the heat exchangers and duct surfaces.

As a potential solution to these problems, this study focused on a liquid type desiccant air conditioning system. In this system, absorptive solution or liquid desiccant is utilized to perform air dehumidification/humidification. The difference in the water vapor pressure between the liquid desiccant and air causes the vapor in the air to become absorbed or desorbed by the liquid desiccant. Dehumidification by using this phenomenon does not include the condensation of water. Therefore, it is hygienic as mold does not form. Moreover, this system can save energy by replacing the energy source from electricity to unused energy such as waste heat from factories and solar energy.

In this liquid desiccant air conditioning system, the most significant component is called the gas-liquid contactor. This gas-liquid contactor is where the air and liquid desiccant come in direct contact and perform dehumidification/humidification. More specifically, the gas-liquid contactor that performs dehumidification is called absorber or dehumidifier, while that performing humidification is called desorber or regenerator.

There are several types of gas-liquid contactors, such as an adiabatic contactor and internally cooled/heated contactor. **Figure 1** shows a typical gas-liquid contactor called adiabatic contactor. In this contactor, the absorption solution that is cooled/heated beforehand is trickled into the contactor, where it comes in direct contact with air. Aqueous lithium chloride is a commonly used absorptive solution for this type of contactor, and much research has been conducted on this working fluid. For example, Yamaguchi *et al*. (2012) conducted an experimental investigation into the effect of superficial air velocity and solution mass flux on the heat/mass transfer rate when lithium chloride is used. Furthermore, Zhang *et al*. (2010) investigated the mass transfer rate of an adiabatic contactor and lithium chloride solution combination both experimentally and theoretically. However, a decrease in the dehumidification ability of the liquid desiccant, which resulted from the increase in temperature by the absorption heat, has been a problem for adiabatic contactors.

Therefore, another type of gas-liquid contactor, called the internally cooled/heated contactor, is recommended as it may solve the problems of adiabatic contactors. Unlike an adiabatic contactor, this contactor has a third fluid, refrigerant/cooling water, flowing through with the air and liquid desiccant. The trickled desiccant is cooled/heated by exchanging heat with the refrigerant. In other words, the absorption heat caused by dehumidification can be removed by the refrigerant, thus allowing the preservation of the liquid desiccant's dehumidification ability. Liu *et al*. (2016) reviewed three different types of internally cooled/heated contactors and compared their heat/mass transfer rates. Moreover, Chen *et al*. (2009) experimentally tested a fin-tube heat exchanger particular to liquid desiccant air conditioning system use. This heat exchanger was made of plastic, which does not indicate corrosiveness.

Many studies have also been conducted on the working fluids of a liquid desiccant air conditioning system. Conventional liquid desiccants, such as aqueous lithium chloride, are corrosive; therefore, an aqueous ionic liquid is proposed as an alternative liquid desiccant. An ionic liquid is defined as a liquid salt under atmospheric pressure and temperature. Owing to some of its characteristics, such as not crystallizing and being involatile, a wide range of possible uses is expected. Furthermore, corrosivity corrosion tests have indicated that an aqueous ionic liquid does not indicate corrosiveness for some metals. Various studies, although not too many, have used an ionic liquid as a liquid desiccant. For example, Luo and Shao (2012) measured the vapor pressure and analyzed the dehumidification ability of ionic liquid. Zegenhagen *et al*. (2015) experimentally investigated the effect of inlet air humidity, cooling water temperature, and solution mass flux on the outlet air when using an internally cooled/heated contactor with an ionic liquid.

In this study, the combination of an internally cooled/heated contactor with an aqueous ionic liquid as the working fluid was investigated. The objective of this research was to experimentally evaluate the potential of a metallic internally cooled contactor by using an ionic liquid. To this end, this study compared the experimental results of an internally cooled contactor's dehumidification ability to those of an adiabatic contactor.

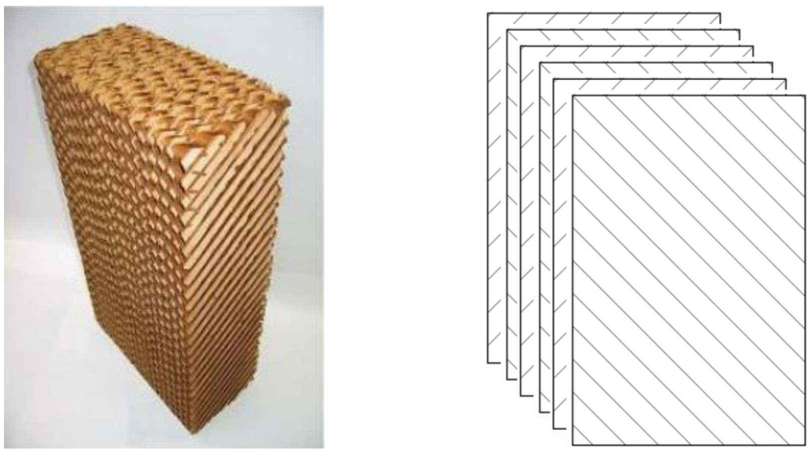


Figure 1. Adiabatic contactor

2. EXPERIMENT

2.1 Internally cooled/heated contactor

Although there exist many structures of internally cooled/heated contactors, this research focused on the fin-tube contactor shown in **Figure 2**. This contactor was made of aluminum and had the same structure as a typical fin-tube heat exchanger. It consisted of numerous fins with tubes going through them. All dimensions of the fin-tube contactor are listed in **Table 1**.

The solution trickled from the upper face of this fin-tube contactor formed a liquid film that flowed down along the surface of fins. The air flowed in between the fins of the fin-tube contactor at a right angle to the solution flow. Consequently, the air came in direct contact with the solution and the exchange of heat, mass, and momentum occurred. The refrigerant flowed through the tubes and exchanged heat with the solution and air. The heat was exchanged with the solution where the liquid film formed, while the heat was exchanged with air where the fin was dry.

Air is cooled and dehumidified when the liquid desiccant has a lower temperature and lower equilibrium vapor pressure. Furthermore, the refrigerant can remove the sensible and latent heat transferred from the air to the solution to maintain the ability of cooling and dehumidification. However, the air is heated and humidified when the liquid desiccant has a higher temperature and higher equilibrium vapor pressure. Then, the refrigerant heats the desiccant to maintain its heating and humidifying ability.

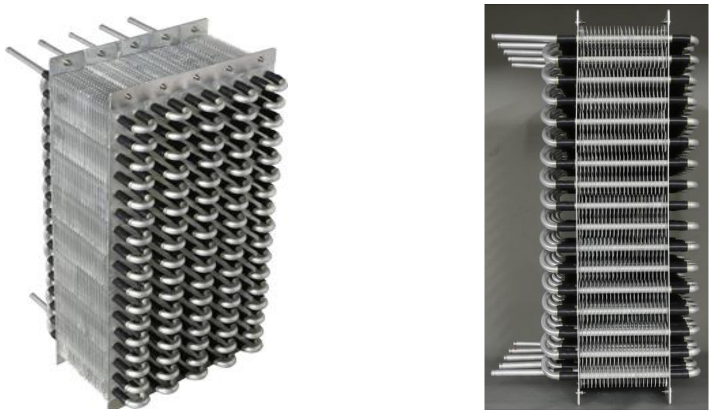


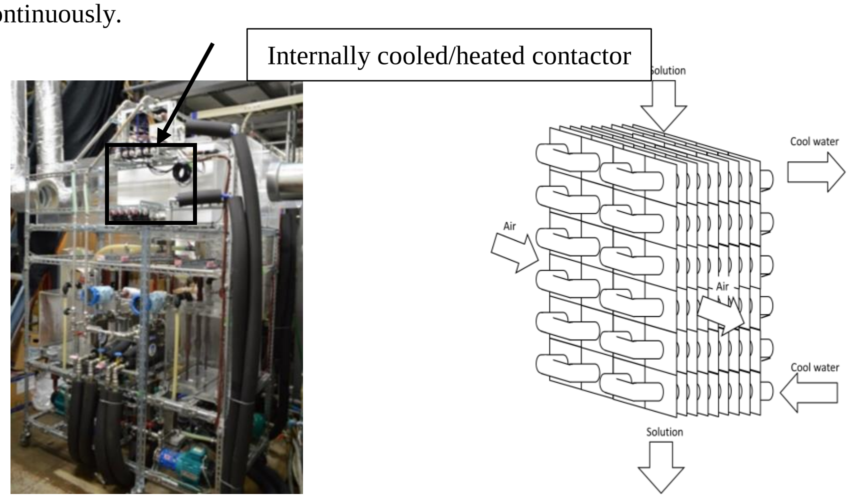
Figure 2. Finned-tube-type internally cooled/heated contactor

Table 1. Specifications of finned-tube-type internally cooled/heated contactor

Height of structure	H	mm	408
Width of structure	W	mm	104
Length of structure	L	mm	200
Specific surface area	C_{sv}	$m^2 \cdot m^{-3}$	451
Outer tube diameter	D	mm	7.38
Horizontal tube pitch	P_h	mm	24.0
Vertical tube pitch	P_v	mm	20.0
Fin thickness	τ	mm	0.10
Fin pitch	l	mm	4.42

2.2 Experimental apparatus

Figure 3 shows the liquid desiccant system used in the experiment. **Figure 4** shows a schematic of the system where the measurement points are indicated. The liquid desiccant system that was used consisted mainly of four parts: the process section, regeneration section, air control unit, and chiller unit. The chiller unit was used as a cooling source, while the boiler was used as a heat source. This system was designed to carry out dehumidification and regeneration simultaneously and continuously.



(a) Experimental apparatus (b) Finned-tube internally cooled/heated contactor

Figure 3. Pictures of experimental apparatus for the performance evaluation test of finned-tube-type internally cooled/heated contactor

In this experiment, the air, solution, and cooling water were measured. The air measurements consisted of the inlet/outlet temperature, dew point temperature, flow rate, and pressure drop. The air temperature was measured with a Type T thermocouple that was corrected using a quartz thermometer. The dew point temperature was measured with a chilled mirror hygrometer, and the flow rate was measured with a thermal anemometer. The solution measurements included the inlet/outlet temperature, refractive index, and mass flux. The solution temperature was measured with a platinum resistance temperature detector, the refractive index was measured with a process refractometer, and the mass flux was measured with a Coriolis flow meter. Typically, the concentration of a desiccant is calculated using its temperature and density; however, as the change in density with temperature was small, this study used the refractive index and temperature to calculate the concentration of the solution. Finally, the cooling water measurements included the inlet/outlet temperature, total flow rate, and flow rate per tube of gas-liquid contactor. The temperature was measured with a Type T thermocouple, while the flow rate was measured with a Coriolis flow meter. The flow rate per tube was adjusted by using the valves such that the cooling water would be distributed equally among the tubes.

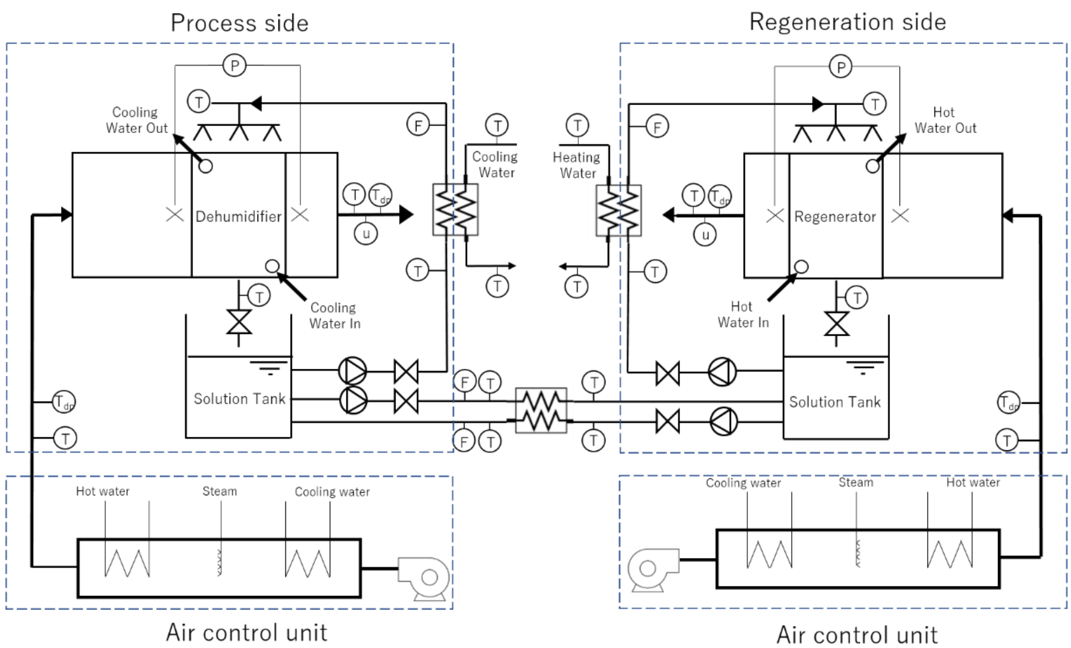


Figure 4. Flow diagram of experimental apparatus and measuring points

2.4 Experimental conditions

In this experiment, the effect of the solution mass flux on heat/mass transfer was investigated. The experimental conditions are listed in Table 2. As a reference, the experimental conditions for the adiabatic contactor with lithium chloride solution, reported by Yamaguchi *et al*. (2012), and those of the adiabatic contactor and an ionic liquid, are listed in Table 2. The fin-tube contactor used in this experiment had the same dimensions and surface area per volume as those in the experiments conducted by Yamaguchi *et al*. (2012). Therefore, a direct comparison of the experimental results can be made.

The air inlet conditions were set according to the average Tokyo summer air temperature and humidity, while the air inlet conditions and superficial air velocity were set to a standard value. The solution inlet temperature was set to 17 °C and the use of a hybrid desiccant system (combination of liquid desiccant system and vapor compression cycle) was assumed, where the solution is cooled by the evaporator of a vapor compression cycle. The solution inlet concentration was set such that the equilibrium humidity ratio would be the same as that of the lithium chloride solution used in experiment conducted by Yamaguchi *et al*. (2012). The cooling water inlet temperature was set by assuming the evaporation temperature of the vapor compression cycle. The ionic liquid used in this experiment was provided by Evonik Industries.

Table 2. Experimental conditions

Air inlet	Temperature	℃	34.0	
	Humidity ratio	g/kg(D.A.)	19.5	
	Specific velocity	m/s	1.5	
Solution inlet	Absorbent	-	Ionic liquid	LiCl (Yamaguchi)
	Temperature	℃	17.0	17.0
	Concentration	wt%	75.0	30.0
	Mass flux	m/s	0.0-3.1	1.9-10.3
Water inlet	Temperature	℃	17.0	-
	Volume flow rate	L/min	6.0	-

3. RESULTS AND DISCUSSION

The effect of the solution mass flux on the outlet air temperature, humidity ratio, dew point temperature, and pressure drop is shown in **Figure 5**. For comparison, the experimental results obtained by Yamaguchi *et al*. (2012) are shown in the same figure. Several observations can be made based on these results. First, when a comparison was made with the same solution mass flux, a lower air outlet temperature and humidity were obtained by using an internally cooled contactor rather than an adiabatic contactor. Furthermore, to achieve the same outlet air humidity, the internally cooled contactor required less solution mass flux. For example, to obtain an air outlet humidity ratio of 12.7 g/kg (D.A.), the internally cooled contactor requires 0.77 $\text{kg/(m}^2\cdot\text{s)}$, while the adiabatic contactor requires 2.1 $\text{kg/(m}^2\cdot\text{s)}$. In other words, the use of an internally cooled contactor can lead to a reduction in the solution mass flux. Additionally, the outlet air dew point temperature reached below the temperature of the cooling water. The occurrence of dehumidification because of absorption was indicated because the dehumidification of air by cooling was not able to reach the air dew point temperature below the cooling water temperature.

The pressure drop decreased when the solution mass flux increased from $0\ \text{kg/(m}^2\cdot\text{s)}$ to $0.7\ \text{kg/(m}^2\cdot\text{s)}$ but increased when the solution mass flux increased over $0.7\ \text{kg/(m}^2\cdot\text{s)}$. Normally, when the solution is trickled, the film thickness of the solution causes the air passage to narrow, which causes the pressure drop to increase. However, these results reveal a different pattern because the pressure drop decreased at a low solution mass flux. This may have been caused by the difference in friction between the air/aluminum fin and air/solution because the friction between the air and the solution may have been smaller than that of the air and aluminum fin. Accordingly, this may also be the reason for the decrease of pressure drop when the solution is trickled at a low mass flux. However, as the solution mass flux increases, the pressure drop increases because the narrowing air passage overcomes the pressure drop decrease by the smaller friction of the solution and, thus, it causes the pressure drop to increase.

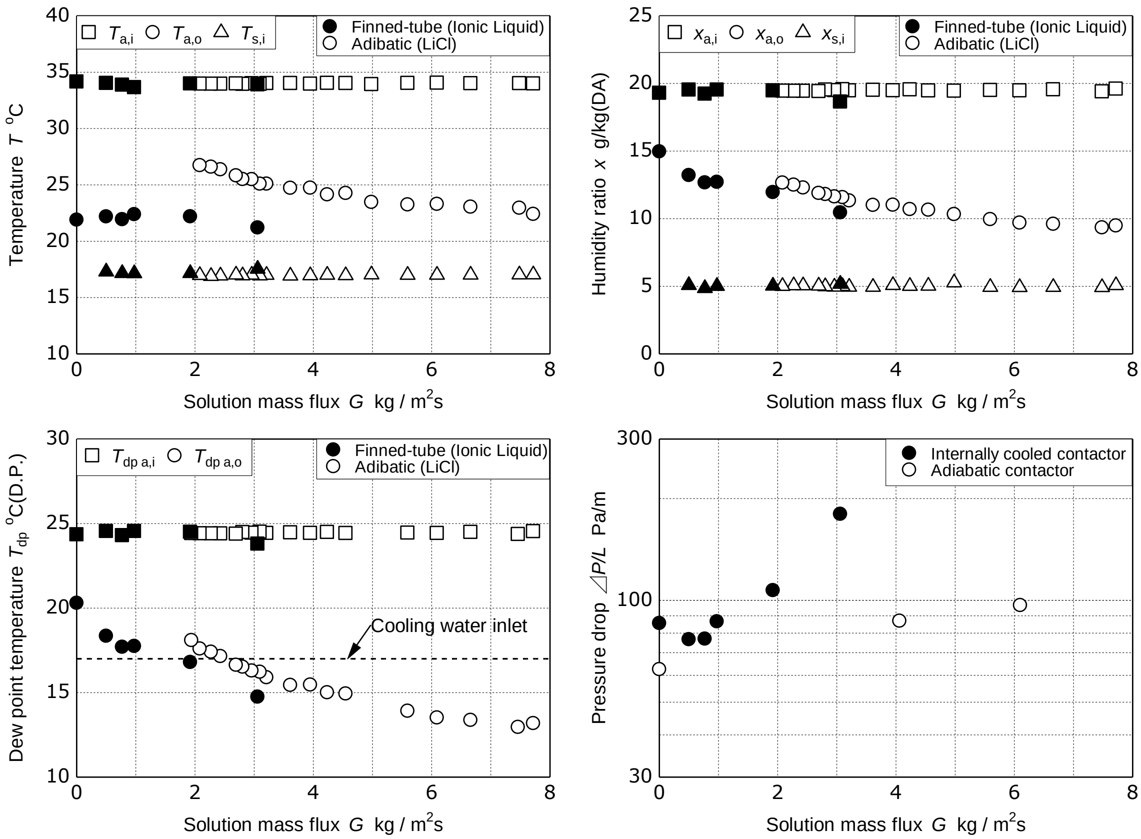


Figure 5. Experimental results of solution flow rate effect

4. CONCLUSIONS

This study investigated the effect of solution mass flux on the outlet air when using a finned-tube internally cooled contactor with an aqueous ionic liquid as the working fluid. This study demonstrated that the finned-tube internally cooled contactor with an ionic liquid had higher dehumidification performance than the adiabatic contactor with lithium chloride. This most likely occurred because of the removal of absorption heat by the cooling water, which maintained the temperature and dehumidification ability of the solution throughout the contactor.

To develop high efficiency liquid desiccant air conditioning systems for industrial application, optimal design of the internally cooled/heated contactor is necessary. Further investigation on the solution mass flux and air superficial velocity effects on the heat and mass transfer rates will provide with valuable information for the design optimization.

In future work, data on heat and mass transfer regarding internally cooled contactors will be collected. Those data will help us to build a correlation modelling by which heat and mass transfer rates of the contactor at different values of solution mass flux and air superficial velocity can be calculated.

NOMENCLATURE

H	Height of structure	(mm)
W	Width of structure	(mm)
L	Length of structure	(mm)
C_{sv}	Specific surface area	$(\mathrm{m}^2 \cdot \mathrm{m}^{-3})$
d	Tube outer diameter	(mm)
Ph	Horizontal tube pitch	(mm)
Pv	Vertical tube pitch	(mm)
τ	Fin thickness	(mm)
l	Fin pitch	(mm)

REFERENCES

Jun, L., Xiaohua, L., & Tao, Z. (2016). Performance comparison of three typical types of internally-cooled liquid desicant dehumidifiers. *Building and Environment*. 103, 134-145.

Li, Z., Eiji, H., Fumio, M., & Chaobin, D. (2010). Experimental analysis of mass transfer in adiabatic structured packing dehumidifier/regenerator with liquid desiccant. *International Journal of Heat and Mass Transfer*. 53, 2856-2863.

Lin, C., Zhen, L., & Zeng-Yuan, G. (2009). Experimental investigation of plastic finned-tube heat exchangers, with emphasis on material thermal conductivity. *Experimental Thermal and Fluid Science*. 33, 922-928.

Seiichi, Y., Kiyoshi, S., Hikoo, M., & Masatoshi, H. (2012). Heat and mass transfer of packed bed absorber for liquid desiccant air-conditioning system: 1st Report: Experimental Study. *Transactions of the Japan Society of Refrigerating and Air Conditioning Engineers*. 29(1). 229-236.

Yimo, L., Shuangquan, S., Fei, Q., Changqing, T., & Hongxing, Y. (2012). Investigation on feasibility of ionic liquids used in solar liquid desiccant air conditioning system. *Solar Energy*. 86, 2718-1724.

Zegenhagen, M., Ricart, C., Meyer, T., Kuhn, R., & Ziegler, F. (2015). International Conference on Solar Heating and Cooling for Buildings and Industry, *SHC 2014*: *Energy Procedia,* (544).