EVALUATION OF LIQUID DESICCANT AND WATER MEMBRANE SYSTEMS FOR HEATING AND HUMIDIFICATION IN COLD-DRY CLIMATES

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ABSTRACT

Significant progress has been achieved in liquid desiccant technologies during the last decade. Although mainly investigated when used in cooling and dehumidification applications, a liquid desiccant system can be used to provide heating and humidification in cold-dry climates. It is well-documented in the scientific literature that a liquid desiccant system can be more energy efficient than a conventional vapor compression system in cooling and dehumidification applications. However, there is no clear information about the feasibility of using a liquid desiccant system for heating and humidification applications. The performance of a liquid desiccant heating and humidification (LDHH) system is studied in this paper using TRNSYS simulations. In addition, a water membrane heating and humidification (WMHH) system is proposed and investigated. The thermodynamic processes of the LDHH and WMHH systems are presented, and their thermal energy requirements are compared to that used in adiabatic humidification system. Results show that the thermal energy consumption of the LDHH system is higher than an adiabatic humidification system, while the WMHH system can achieve thermal energy savings compared to an adiabatic humidification system.

Keywords: Humidification; LAMEE; Liquid desiccant; Water; TRNSYS.

1. INTRODUCTION

Space heating and humidification makes up a significant percentage (up to 60%) of the total energy consumed by buildings in cold-dry climates (NRCan, 2009). In order to decrease both capital and operating costs, humidification equipment is sometimes not installed in HVAC systems. This results that indoor humidity levels are not maintained within recommended ranges, which may increase the risk of respiratory infections, asthma, and growth of bacteria (Sterling et al., 1985). Thus, it is necessary to develop humidification technologies that are capable of maintaining acceptable indoor humidity levels at low costs to improve the energy efficiency of buildings in cold-dry climates.

Previous studies have shown that significant energy savings can be achieved when liquid desiccant systems are used in cooling and dehumidification applications (Abdel-Salam and Simonson, 2016, 2014a, 2014b; Abdel-Salam et al., 2016; Abdel-Salam, 2015; Andrusiak and Harrison, 2009; Bergero and Chiara, 2011; Crofoot and Harrison, 2012; Crofoot, 2012; Mesquita et al., 2006; McNevin and Harrison, 2014; Jones, 2008; Zhang, 2012). The same liquid desiccant system can be used to achieve heating and humidification, instead of cooling and dehumidification, by reversing its operating cycle. Zhang et al. (2010) investigated the integration of a liquid desiccant cycle with an air-source heat pump located in a cold-dry climate in order to eliminate the frost formation on the external exchanger of the heat pump. It was concluded that the coefficient of performance of the hybrid system (the liquid desiccant cycle integrated with the air source heat pump) is around 100% higher than the coefficient of performance of a traditional heat pump with an electric humidifier. The hybrid system studied by Zhang et al. (2010) includes two heat pumps and a liquid desiccant cycle, which makes it quite complex for practical applications.

The focus of this paper is to investigate the performance of the liquid desiccant cycle, commonly used for cooling and dehumidification, when it is reversed to provide heating and humidification. This means that no additional components are added to the basic system used in cooling and dehumidification applications. Another objective of this paper is to propose and evaluate the performance of a water membrane humidification system. TRNSYS software is used in this paper to evaluate the performance of the systems studied.

2. SYSTEMS DESCRIPTION

2.1. Liquid Desiccant Heating and Humidification (LDHH) System

A schematic diagram for the liquid desiccant heating and humidification (LDHH) system is presented in Figure 1. The core components of the system are as follows: air humidifier, solution regenerator, and cooling and heating equipment. The LDHH system has the same core components as a liquid desiccant cooling and dehumidification system, and the only difference between the two systems is that the operating processes are reversed. This is similar to a vapor compression system which can be operated under either cooling or heating mode.

As shown in Figure 1, the ambient air stream is heated and humidified in the air humidifier using a desiccant solution stream. The solution stream leaves the air humidifier at lower moisture content than its inlet condition, and thus it has to be regenerated before re-entering the air humidifier. The regeneration process takes place in the solution regenerator, where moisture is transferred from the ambient air to the solution stream. The continuous operation of the liquid desiccant cycle is activated using heating and cooling coils. Heating the solution prior entering the air humidifier ensures that the vapor pressure of the solution stream is higher than the air vapor pressure, and thus moisture transfers from the solution to the air stream. While, cooling the solution before entering the solution regenerator ensures that the vapor pressure of the solution is lower than the air vapor pressure, and thus the moisture transfers from the air to the solution stream.

Both the air humidifier and solution regenerator in this study are liquid-to-air membrane energy exchangers (LAMEEs). Semi-permeable membranes are used to separate between the air and solution streams in LAMEEs, as can be seen from Figure 2, which eliminate the desiccant droplets carryover in air streams. The air flow rates in the air humidifier and solution regenerator are maintained constant at 0.31 kg/s. The specifications of the LAMEEs used in this paper are presented in a previous study by Abdel-Salam and Simonson (2014a).

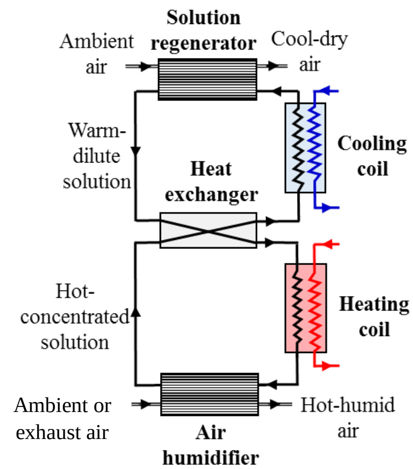

Figure 1. A schematic diagram for the liquid desiccant heating and humidification (LDHH) system. The air and solution flow rates in the solution regenerator and air humidifier are equal.

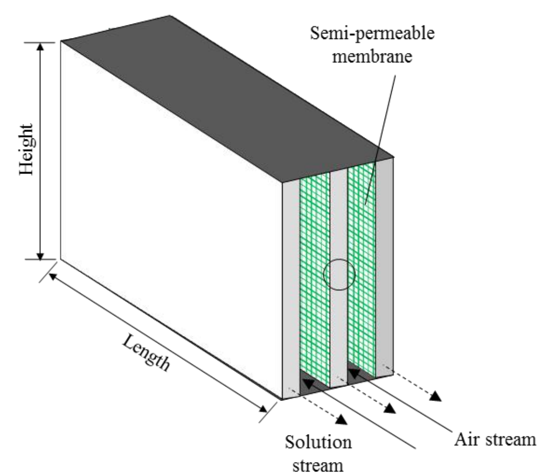

Figure 2. A schematic diagram for the liquid-to-air membrane energy exchanger (LAMEE).

2.2. Water Membrane Heating and Humidification (WMHH) System

Figure 3 shows a schematic diagram for the water membrane heating and humidification (WMHH) system. The cold-dry air stream is simultaneously heated and humidified in the LAMEE using a hot water stream. The air leaves the LAMEE at the specified set point humidity ratio, and it is then heated using an air heating coil until it reaches the required set point temperature.

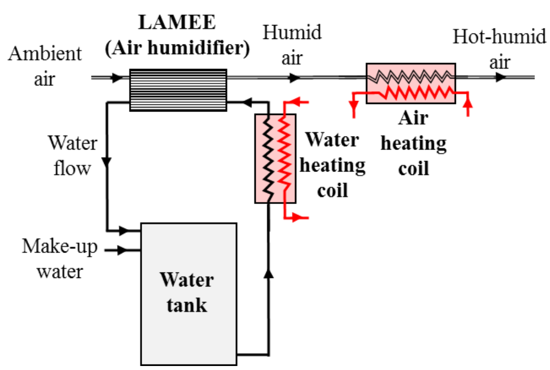

Figure 3. A schematic diagram for the water-membrane heating and humidification (WMHH) system.

3. MODELLING

The performances of the systems studied in this paper are evaluated using the TRNSYS software (TRNSYS, 2010). A model that was developed for a liquid desiccant cooling and dehumidification system in a study by Abdel-Salam and Simonson (2014b) is used in this paper. Some modifications were implemented on the model to evaluate the performance of the WMHH system, while no modifications were required to simulate the LDHH system. A detailed description for the TRNSYS model is presented in Abdel-Salam and Simonson (2014b).

4. RESULTS AND DISCUSSIONS

A psychrometric chart is presented in Figure 4, which shows the air and solution operating conditions in the liquid desiccant heating and humidification (LDHH) system under the AHRI winter test conditions (1.7°C and 3.5 g/kg). The inlet solution temperatures to the air humidifier and solution regenerator are set at 35°C and 0°C, respectively. It can be seen from Figure 4 that the cold-dry air is simultaneously heated and humidified to approximately 34ºC and 6 g/kg.

A sensitivity study is conducted to investigate if there is a potential to increase the humidity ratio of the air leaving the humidifier by either increasing the solution set point temperature at the air humidifier inlet or decreasing it at the solution regenerator inlet. Results are presented in Figure 5, where it is found that regulating solution inlet temperatures does not result in significant improvement in the amount of moisture transfer in liquid desiccant heating and humidification systems, unlike liquid desiccant cooling and dehumidification systems. This is because the humidity ratio of the air leaving the humidifier is constrained by the moisture content of the air stream used in the solution regenerator, which is assumed to be the ambient air in this paper. It can be seen from Figure 6 that the humidity ratio of the air leaving the humidifier significantly increases with the increase of the ambient air humidity ratio. In addition, if the return air from the building is used in the solution regenerator instead of using the ambient air, the humidity ratio of air leaving the humidifier increases as presented in Figure 7.

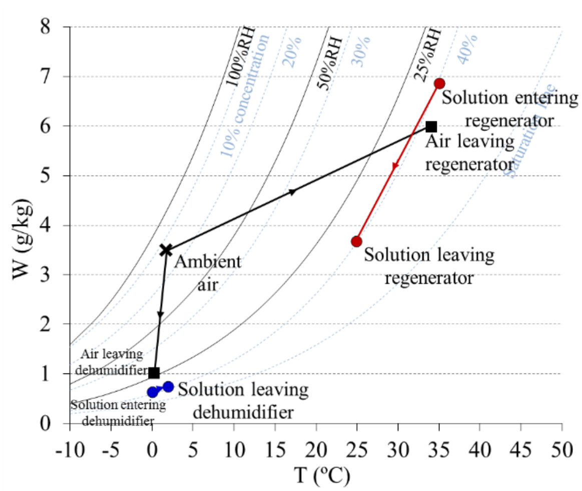

Figure 4. A psychrometric chart shows the operating conditions of the liquid desiccant heating and humidification (LDHH) system under AHRI winter test conditions.

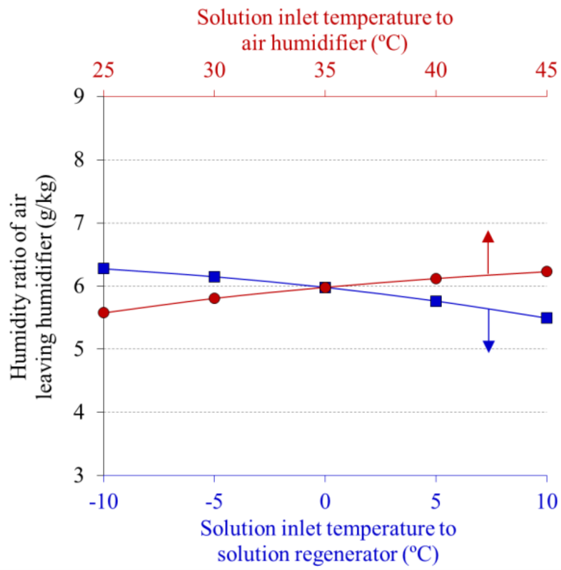

Figure 5. The influence of solution inlet temperatures to air humidifier and solution regenerator on the humidity ratio of air leaving the humidifier.

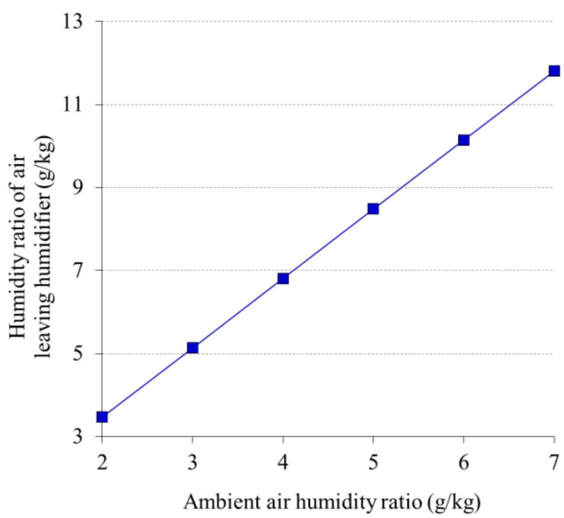

Figure 6. Regeneration with ambient air. The air inlet conditions to both humidifier and regenerator are the same, and they are at 10ºC and the humidity ratio given in the horizontal axis.

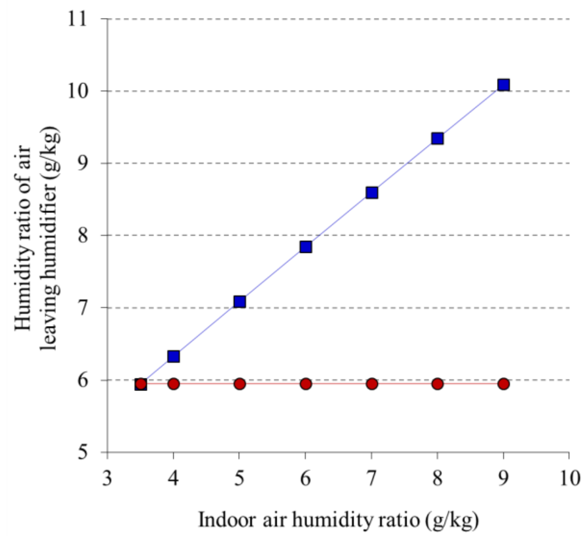

Figure 7. Regeneration with indoor air (exhaust air).
[■] Air inlet conditions to the humidifier are under AHRI winter conditions, while air inlet conditions to the regenerator are at 22ºC and the humidity ratio given in the horizontal axis.
[●] Air inlet conditions to both humidifier and regenerator are under AHRI winter conditions

The inability of the liquid desiccant heating and humidification (LDHH) system to humidify the cold-dry air above a maximum supply humidity set point can be eliminated by decreasing the concentration of the solution stream entering the air humidifier, which can be achieved by simply adding water to the desiccant solution. The lower the concentration of the desiccant solution, the higher its moisture content and ability to humidify the air stream to a higher humidity ratio set point. Thus, it is concluded that more efficient air humidification can be achieved by using water in the LAMEE rather than a desiccant solution. In this case only one LAMEE will be required as shown in the water membrane heating and humidification (WMHH) system presented in Figure 3. A psychrometric chart is presented in Figure 8 to show the thermodynamic processes occur in the WMHH system. The cold-dry air stream is simultaneously heated and humidified using a water stream in the LAMEE until the air reaches a desired humidity set point, and then the air stream is sensibly heated until it reaches a given set point temperature.

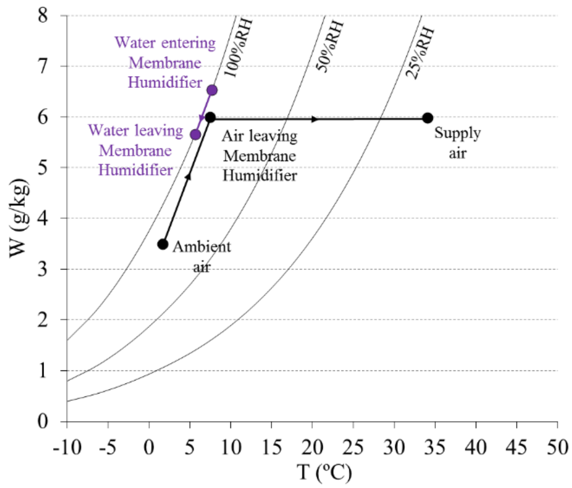

Figure 8. A psychrometric chart shows the operating conditions of the WMHH system under AHRI winter test conditions.

The air humidification rate in the WMHH system can be controlled by changing the water set point temperature or bypassing the air stream. The influence of water inlet temperature on the humidity ratio of air leaving the water membrane humidifier is presented in Figure 9. It can be seen that significant increase can be achieved in the supply air humidity ratio by increasing the water set point temperature.

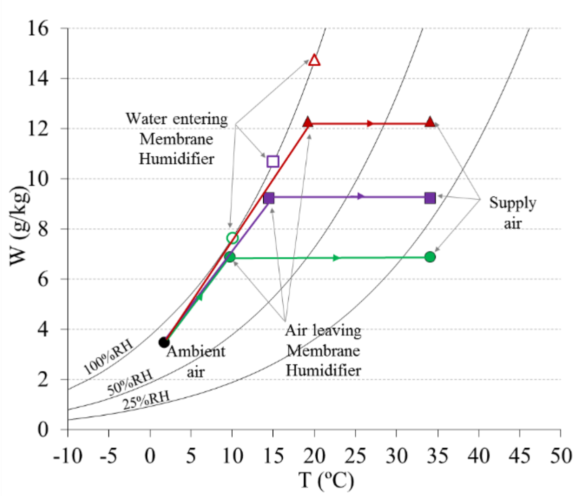

Figure 9. A psychrometric chart shows the operating conditions of the WMHH system under different water inlet temperatures.

Figure 10(a) shows a summary for the thermodynamic processes followed in the LDHH and WMHH systems, compared to an adiabatic humidification system. The thermal energy requirements for the three systems are presented in Figure 10(b). Results show that the thermal energy requirements in the LDHH system is higher than the heating energy requirements for either the WMHH system or the adiabatic humidification system. Also, cooling energy is required in the LDHH system to cool the solution prior entering the solution regenerator. The thermal energy required to operate the water membrane heating and humidification system is found to be nearly equal to that of the adiabatic humidification system.

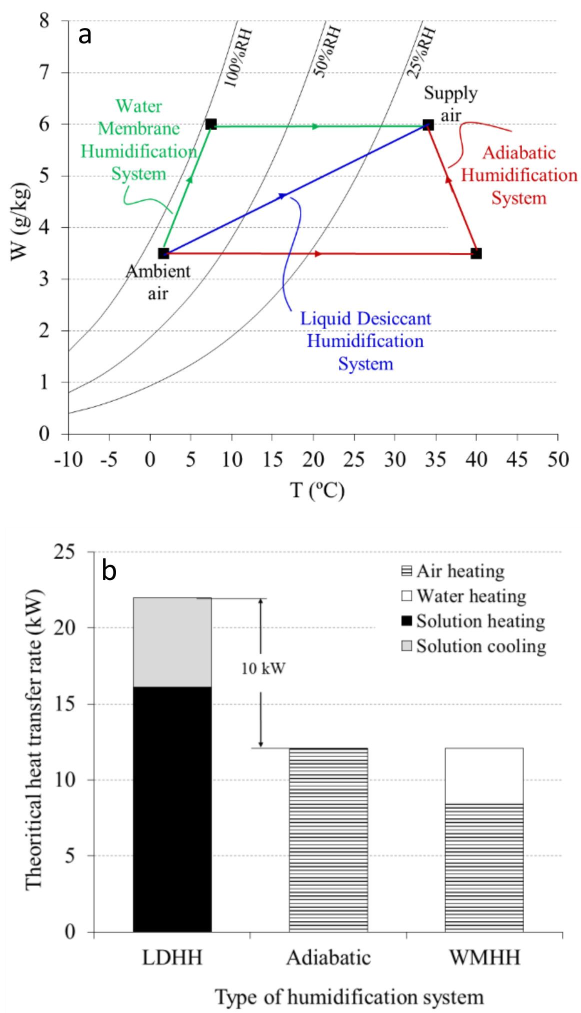

Figure 10. The (a) thermodynamic processes and (b) thermal energy requirements for the LDHH, WMHH and adiabatic systems under AHRI winter test conditions and supply air conditions of 35°C and 6 g/kg.

Besides the lower thermal energy requirements, there are other advantages for the WMHH system compared to the LDHH system as follows:

- Water has lower cost than liquid desiccant.
- Only one LAMEE is required to be installed in the WMHH system, compared to two LAMEEs in the LDHH system.
- No need to use expensive anti-corrosive materials and apply special coatings to surfaces, which is the case when liquid desiccant is used.

Moreover, there are could be potential advantages for the WMHH system compared to contact-humidification technologies (e.g. adiabatic, steam injection, ultrasonic) such as the following.

- Air and water streams are not in direct-contact with one another in the WMHH system, which could result in improved air quality.
- Waste heat can be used in the WMHH system to provide humidification, which is not possible in contact-humidification technologies.

5. CONCLUSIONS

The performances of a liquid desiccant heating and humidification system and a water membrane heating and humidification system are investigated in this paper. The performances of the systems are evaluated using TRNSYS modelling, and compared to an adiabaiatic humidification system. Results show that the humidification capacity of a liquid desiccant system is limited by the moisture content of the air stream used in the solution regenerator. The thermal energy requirements of a liquid desiccant heating and humidification system is around 45% higher than adiabatic humidification under AHRI winter test conditions.

To eliminate the drawbacks associated with liquid desiccant heating and humidification, a water-membrane heating and humidification system is proposed and investigated in this paper. Water is used in a liquid-to-air membrane energy exchagner (LAMEE) to heat and humidify the cool-dry outdoor air, where the water is separated from the air stream using semi-permeable membranes. Results show that the water-membrane heating and humidification system can achieve the desired control over the humidity ratio of supply air stream. The thermal energy requirements for the water-membrane heating and humidification system is found to be nearly the same as the adiabatic humidification system.

In conclusion, results presented in this paper shows that it is not feasible to use the same liquid desiccant system commonly used for cooling and dehumidification to provide heating and humidification. A promising performance can be achieved using a water-membrane heating and humidification system, and thus it is recommended to be further investigated in future studies when installed in residential/commercial applications located in cold-dry climates.

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REFERENCES

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 1152-1183.

Abdel-Salam A.H. McNevin C., Crofoot L., Harrison S. and Simonson C.J. (2016), 'A field study of a liquid desiccant air conditioning system: Quasi-steady and transient performance' ASME Solar Energy Engineering Journal, in press.

Abdel-Salam A.H. (2015), 'A novel liquid desiccant air conditioning system with membrane exchangers and various heat sources', Ph.D. thesis, University of Saskatchewan; Saskatoon, Canada.

Abdel-Salam A.H. and Simonson C.J. (2014a), 'Capacity Matching in Heat-Pump Membrane Liquid Desiccant Air Conditioning Systems' International Journal of Refrigeration 48 166-177.

Abdel-Salam A.H. and Simonson C.J. (2014b), 'Annual Evaluation of Technical, Environmental and Economic Performance of a Membrane Liquid Desiccant Air

Conditioning System with/without ERV', Applied Energy, 116 134-148.

Andrusiak M. and Harrison S.J. (2009), 'The modeling of a solar thermally-driven liquid desiccant air conditioning system' In: Proceedings of the ASES national conference, Buffalo, USA.

Bergero S. and Chiari A. (2011), 'On the Performances of a Hybrid Air-Conditioning System in Different Climatic Conditions', Energy 36 5261-5273.

Crofoot L. (2012), 'Experimental evaluation and modeling of a solar liquid desiccant air conditioner', M.A.Sc. Thesis, Queen's University, Kingston, Canada.

Crofoot L. and Harrison S. (2012), 'Performance Evaluation of a Liquid Desiccant Solar Air Conditioning System', Energy Procedia 30 542-550.

Mesquita L.C.S., Harrison S.J. and Thomey D. (2006), 'Modeling of heat and mass transfer in parallel plate liquid-desiccant dehumidifiers', Solar Energy 80 1475-1482.

McNevin C. and Harrison S. (2014), 'Performance improvements on a solar thermally driven liquid desiccant air-conditioner', In: Proceedings of CSME International Congress, Toronto, Canada.

Jones B.M. (2008), 'Field evaluation and analysis of a liquid desiccant air handling system', M.A.Sc. Thesis, Queen's University, Kingston, Canada.

Natural Resources Canada (NRCan), 2009. Energy Efficiency Trends in Canada 1990 to 2007. Ottawa, ON, Canada. Retrieved from: <http://oee.nrcan.gc.ca/publications/statistics/trends/2009/pdf/trends.pdf>

Sterling E.M., Arundel A. and Sterling, T.D. (1985), 'Criteria for human exposure to humidity in occupied buildings', ASHRAE Transactions 91 611-622.

TRNSYS-version 17 (2010), Solar Energy Laboratory, University of Wisconsin, Madison, Wisconsin.

Zhang L.-Z. (2012), 'Progress on Heat and Moisture Recovery with Membranes: From Fundamentals to Engineering Applications', Energy Conversion and Management 63 173–195.

Zhang L., Dang C. and Hihara E. (2010), 'Performance Analysis of a No-Frost Hybrid Air Conditioning System with Integrated Liquid Desiccant Dehumidification', International Journal of Refrigeration, 33 116-124.