DESIGN, SIMULATION AND TESTING OF A HYBRID LIQUID DESICCANT FOR INDEPENDENT CONTROL OF TEMPERATURE AND HUMIDITY

L. Alonso[1], X. Peña[1], C. Pascual[1], J. Prieto[2], J. Ortiga[2], K. Gommed[3]

1: Tecnalia Research & Innovation, Thermal Energy Area, Energy and Environment Division. Area Anardi 5, 20730 Azpeitia (Gipuzkoa), Spain

2: Universitat Rovira i Virgili, CREVER, Mechanical Engineering Department. Avda Països Catalans 26, 43007 Tarragona, Spain

3: Technion – Israel Institute of Technology, Faculty of Mechanical Engineering. Haifa 32000 Israel

ABSTRACT

In this paper the design, simulation and testing of a hybrid liquid desiccant system for a case study in Taiwan is presented, in the scope of the European project nanoCOOL. The designed system has been constructed and is being tested at laboratory scale. After the set-up of the system, it will be sent to Taipei for demonstration in real scale conditions, in the Taiwan Building Technology Center. The demonstration site comprises two locker rooms in a swimming pool of the university, with high internal humidity generation, low sensible heat ratio, and high external humidity levels due to sub-tropical humid climate present in Taiwan.

Keywords: hybrid liquid desiccant system, simulation, temperature and humidity control

INTRODUCTION

The treatment of humidity on HVAC systems is crucial when a satisfactory indoor air quality needs to be reached. Traditional HVAC systems meet the latent cooling load by reducing the air temperature until its dew point, heating subsequently the air in order to reach the supply temperature for user comfort, with the energy waste this entails. Hybrid liquid desiccant systems (HLDS) combine the liquid desiccant technology for dehumidification of air with conventional compression cycle technology for cooling.

The demo site comprises two locker rooms in a swimming pool of the National Taiwan University of Science and Technology, with high internal humidity generation, low sensible heat ratio, and high external humidity levels due to sub-tropical humid climate present in Taiwan. Based on the design conditions, the internal sensible and latent heat generation, and the ventilation requirements according to international standards; the design conditions and the cooling and dehumidification loads have been calculated:

Outdoor design conditions	30ºC / 21,5 g/kg dry air
Comfort design conditions	24ºC / 7,5 g/kg dry air
Ventilation rate	2.500 m³/h
Internal sensible heat load	3,5 kW
Ventilation sensible heat load	5 kW
Total sensible heat load	8,5 kW
Internal latent heat load	8,8 kW
Ventilation latent heat load	21,3 kW
Total latent heat load	30,1 kW

Table 1: Design conditions and cooling/dehumidification loads

DESIGN AND SIMULATION

The designed hybrid liquid desiccant system (HLDS) is comprised by a liquid desiccant system (LDS) whose main components are the absorber, regenerator and liquid-liquid heat exchanger; and a conventional Air Handling Unit (AHU) with a cooling coil and a cross-plate heat exchanger for ventilation heat recovery. A polyvalent unit able to simultaneously provide cooling and heating, feeds the absorber and the cooling coil with cold water at 15ºC, and the regenerator with hot water at 55ºC.

Models of the individual components of the Liquid Desiccant System (absorber, regenerator and liquid-liquid heat exchanger) and the Air Handling Unit (cooling coil, air-air plates heat exchanger) have been implemented in EES (Engineering Equation Solver) [1]. By combining the separate models of each component, a versatile mathematical model has been developed, which can be used for both the design and simulation of the HLDS.

Liquid Desiccant System

The absorber and the regenerator are falling film type, internally cooled and heated respectively. They are comprised by a polypropylene tube bundle, a liquid distributor system with spray nozzles, and a demister inside a fiber glass tower. Tube bundles are formed of individual modules of 97 tubes, which are linked horizontally in threes, and then vertically to form 14 passes, with a total area of 53,2 m^2. A proper wettability of the tubes is key for obtaining good performance in the liquid desiccant cycle, for that reason the polypropylene tubes have received a plasma treatment in order to improve their wettability [2]. The air flows from bottom to top getting in contact with the descendent lithium chloride solution, which forms a falling film outside the tubes. The rich LiCl solution absorbs humidity from air in the absorber, and the poor LiCl solution desorbs humidity enriching the solution in the regenerator. Cold water (15ºC) and hot water (55ºC) flows inside the tubes, cooling the solution and the air in the absorber, and heating the solution and the air in the regenerator.

Models for the absorber and regenerator are based on the theoretical model described by Gommed and Grossman [3]. Water and salt mass balances, energy balances, thermodynamic equilibrium and heat and mass transfer equations are included in the model.
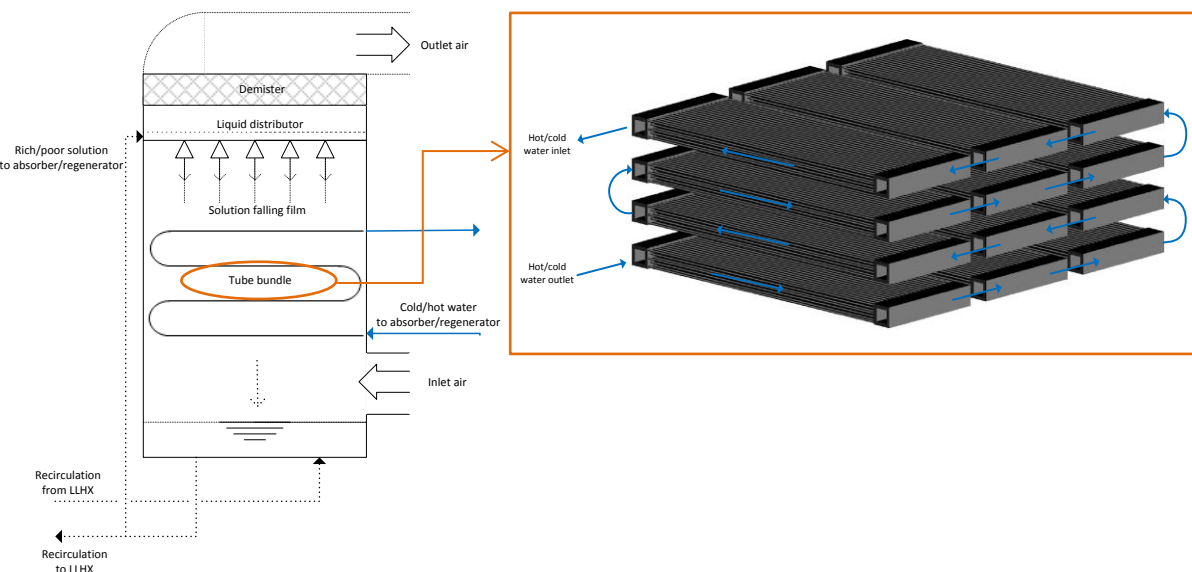

Figure 1: Scheme of the absorber/regenerator units, and the tube bundle layout.

Heat and mass transfer coefficients involved in the modelling are the global heat transfer coefficient between external medium and the solution (U), the heat and mass transfer coefficients between air-solution interface and the air stream (σ_a, β_a), and the heat and mass transfer coefficients between air-solution interface and the solution stream (σ_s, β_s).

The heat transfer coefficient between external medium and solution stream is calculated as:

$$U = \frac{1}{\frac{\emptyset_{ext}}{\emptyset_{int}}\frac{1}{h_{wt}} + R_t + \frac{1}{h_{ts}}} \tag{1}$$

The water-tube heat transfer coefficient (h_{wt}) has been calculated depending on the flow regime by using correlations described by Nellis & Klein [4]; using the following correlation for Re<2300,

$$Nu = \frac{\left[0{,}1156 + \frac{0{,}08569}{Pr^{0{,}4}}\right]Gz}{[1 + 0{,}1158Gz^{0{,}6}]} \tag{2}$$

The Gnielinski equation for fully developed flow for 2300<Re<10000,

$$Nu = \frac{\left(\frac{f_{fd}}{8}\right)(Re - 1000)Pr}{1 + 12{,}7(Pr^{2/3} - 1)\sqrt{\frac{f_{fd}}{8}}} \tag{3}$$

$$Nu = \frac{1}{[0{,}790\ln(Re) - 1{,}64]^2} \tag{4}$$

And the Dittus-Boelter equation for Re>10000,

$$Nu = 0{,}023Re^{0{,}8}Pr^n \tag{5}$$

N=0,4 for heating of the fluid (absorber)

N=0,3 for cooling of the fluid (regenerator)

The tube-solution heat transfer coefficient (h_{ts}) and the mass transfer coefficient between air-solution interface and the air stream (β_a) have been obtained from experimental results of the field tests developed in Technion (Israel Institute of Technology) in Haifa [5]. In the field tests a Liquid Desiccant System was experimentally tested using different types of tubes in absorber mode. The performance with plastic tubes, which showed poor wettability, was lower than with the titanium tubes, which presented good wettability. The designed HLDS will be using polypropylene tubes which have received a plasma treatment in order to increase their wettability [2]. Therefore, the experimental values used for the modelling correspond to the experiments carried out with titanium tubes.

Assumption of a Lewis factor equal to one is considered, which is applicable for air.

$$Le = \frac{\sigma_a}{\beta_a Cp_{air}} \tag{6}$$

The liquid-liquid heat exchanger is a plate heat exchanger made of a polymeric matrix composite including graphene nanoparticles, from SGL company. It is used to precool the solution going to the absorber, and to preheat the solution going to the regenerator. Its model is based on the ε-NTU method with correlations for heat transfer in plate heat exchangers described by H. Martin [6]. The model has been contrasted with the design data from SGL. Heat exchanger effectiveness for design working conditions is 0,85.

Air Handling Unit and polyvalent unit

The air handling unit comprises the air plate heat exchanger for heat recovery of ventilation, the cooling coil, and the corresponding fans, dampers and filters for the system. The casing and the arrangement of the different elements is specially designed for its optimal connection with the LDS.

The air heat exchanger is a compact plate heat exchanger, with cross-flow configuration, made of aluminum and with internal fins to increase the heat transfer between both air streams. The use of such equipment enables considerable savings to be achieved in the operating costs of air-conditioning plants, and thus the saving of energy that would otherwise be lost. In the HLDS it is used for preheating the air entering the regenerator. It is modelled by using the ε-NTU method.

The cooling coil has been modelled by using the model described in [7]. This model is based on epsilon-NTU and LMTD and LMHD equations and uses Braun's hypothesis to simulate the behaviour of the cooling coil in an AHU (air handling unit). Normally, cooling coils in Air Handling Units deal with sensible and latent cooling loads, condensing water from air in the surface of the tubes. In this case, the cooling coil serves for dealing only with sensible cooling loads; no condensation will occur in the surface of the tubes, so in theory the dry cooling coil approach could be used for the modelling. However, the model includes also the wet coil approach, in case the cooling coil may be used for dehumidification as well. In that case, the cooling coil should be oversized respect to the actual size. For the air side the correlation proposed by Wang et al.[8] is selected and the HTC validated against a reference HX calculation software; on the other hand for the calculation of the tube side coefficient the correlation proposed by Gnielinski [9] for turbulent region and the described on Nellis & Klein [4] for the laminar one as in the case of the absorber and regenerator have been used.

The polyvalent unit is a heat pump able to provide heating and cooling simultaneously, by recovering heat from a water condenser when the machine is working on dual mode, and by condensing with air when the machine is working on cooling mode. Therefore, it will be used in cooling mode when the LDS is only dehumidifying and cooling (regenerator off), or in dual mode when the system is regenerating LiCl solution as well, with no need from another external source of heat.

WHOLE CYCLE MODELLING AND RESULTS

The individual models of the LDS and the AHU have been combined to develop the complete model of the HLDS. A split system is included at the solution outlet of the absorber and regenerator, so that the amount of solution which is recirculated to the absorber and regenerator from the bottom of each tower is set to 0,9 of the outlet solution from each component; sending 10% of the solution through the liquid-liquid heat exchanger. The figure below shows the results from the modelling of the whole HLDS.

Calculated impulsion air conditions are 19,8ºC and a humidity ratio of 6,8 g/kg dry air. In order to achieve these conditions, the required capacity of the absorber and regenerator is 40,3 kW and 40,8 kW respectively, with a 13,5 kW capacity liquid-liquid heat exchanger. The air plate heat exchanger has a capacity of 13,3 kW. The cooling coil needs to provide 1,4 kW in the design conditions, however for the construction of the prototype it will be oversized in order to be able to deliver the necessary cooling to meet the sensible cooling load, which leads to 8,5 kW. Considering the electrical consumption of the polyvalent unit, the HLDS has a COP of 2,7.
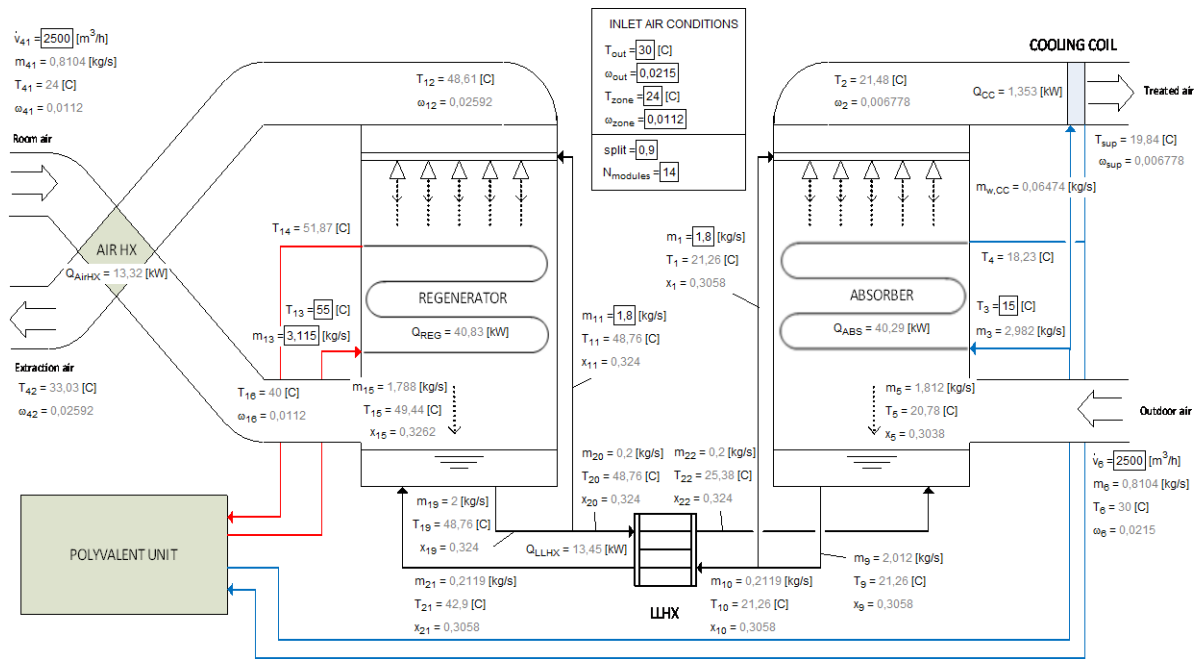
Figure 2: Results from simulation of the HLDS

COP of the HLDS and conventional system are calculated as:

$$COP_{HLDS} = \frac{Cooling\ effect}{Energy\ consumed\ by\ polivalent\ unit} \tag{7}$$

$$COP_{conv}\ \frac{Cooling\ effect}{\dfrac{Q_{CC}}{COP_{heat\ pump}} + Q_{reheat}} \tag{8}$$

A representation of the HLDS process in a psychrometric chart is shown below, as well as the corresponding process to the treatment of air with a conventional system. In the conventional system, the air needs to be cooled down to a high extent in the cooling coil to reach the required dehumidification. In order to achieve comfort indoor conditions, the air needs to be reheated in a reheating coil. With the HLDS process, the need for reheating is eliminated, which leads to important energy savings. Taking into account the reheating consumption in the conventional system, an improvement of around 45% in COP is achieved.
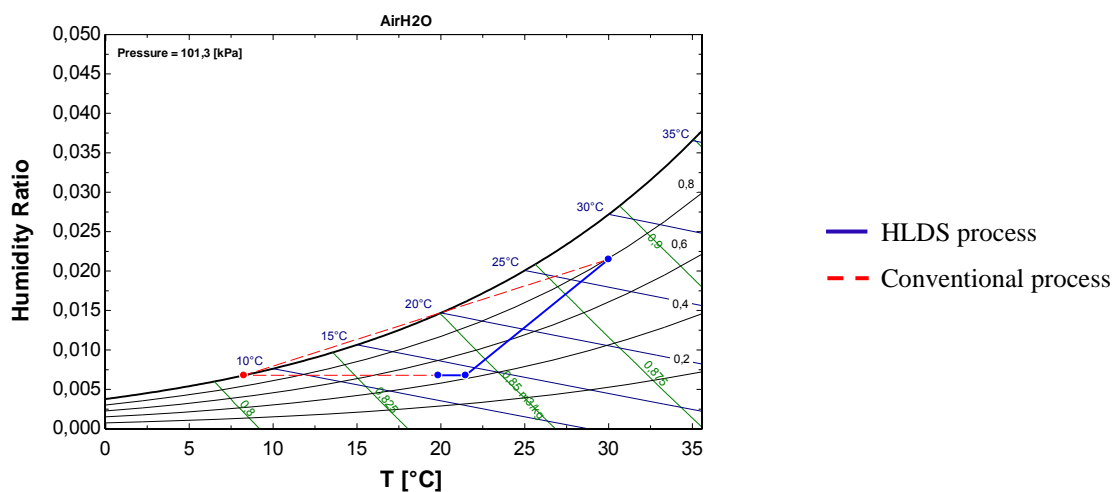

Figure 3: Air treatment processes in the HLDS and in a conventional cooling system represented in the psychrometric chart

CONCLUSION

Based on the cooling loads calculation, a hybrid liquid desiccant system has been designed and simulated for a case study in Taiwan, sizing every component to match the sensible and latent cooling loads. The system achieves a reduction in energy consumption; as unlike conventional systems it does not need to reach the dew point to remove humidity, with the consequent improvement in the COP. The designed system has been constructed and is at the setting-up phase in the laboratory, in order to define the best control strategies for the system. Future work focuses on its performance monitoring in the real-site demonstration in Taiwan.
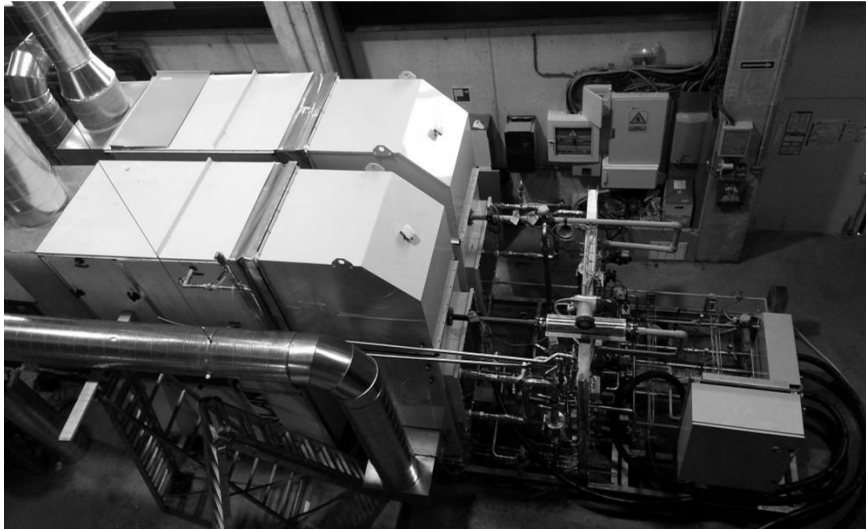

Figure 4: Nanocool system

REFERENCES

1. Engineering Equation Solver. F-Chart Software. http://www.fchart.com

2. A. Fina, A. Guerriero, S. Colonna, F. Carosio and G. Saracco. Polymer-based materials for the application in Liquid Dessicant heat exchangers. *V Congreso Iberoamericano de Ciencias y Técnicas del frío*. Tarragona, June 18-20 (2014).

3. K. Gommed, G. Grossman. Improved Simulation Model for Air-Liquid Contactors in Open Absorption Air Conditioning Systems. *Proceedings, the International Sorption Heat Pump Conference*, College Park, MD, USA, March 31-April 3 (2014).

4. G. Nellis, S. Klein. Heat Transfer. *Cambridge University Press* (2009), 661-671.

5. K. Gommed, G. Grossman, J. Prieto, J. Ortiga, A. Coronas. Experimental Comparison between Internally and Externally Cooled Air-Solution Contactors. *Proceedings, the International Sorption Heat Pump Conference*, College Park, MD, USA, March 31-April 3 (2014).

6. Holger Martin. Pressure Drop and Heat Transfer in Plate Heat Exchangers. *VDI Heat Atlas* (2010), 1515-1521.

7. Air-Braun, J.E., Klein, S.A., Mitchell, P.E., Effectiveness models for cooling towers and cooling coils. *ASHRAE Transactions Vol.92 part 2* (1989), p.164-174.

8. C. Wang, Y. Hsieh, Y. Lin. Performance of Plate finned Tube Heat Exchangers Under Dehumidifying Conditions, *Journal of Heat Transfer.* Vol.119 nº1 (1997), p109-117

9. V. Gnielinski, New equation for heat and mass transfer in turbulent pipe and channel flow, *International chemical engineering*, vol. 16 (1976) pp.359-368.