EUROSUN 2008
1st International Congress on Heating, Cooling, and Buildings
7th to 10th October, Lisbon - Portugal

444 - A Novel Generator Design for a Liquid Desiccant Air Conditioning System

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Abstract

Liquid desiccant systems are used for comfort and industrial air-conditioning and represent a promising alternative when driven by solar heat, to vapour compression machines usually employed in these applications. A novel design of the most important component, the internally heated regenerator, is presented and experimentally examined in this paper. The main focus for reengineering the regenerator is to avoid carry-over of the salt-solution to the air which is accompanied with both, corrosion and environmental impact problems. Furthermore, an important issue is to realize an even distribution of the liquid desiccant inside the regenerator.

The experiments presented here will therefore concentrate on the liquid desiccant (LD) distribution system inside the regenerator which consists of perforated plexiglass tubes with different, equally spaced, throttling-points and a wick material attached to the transfer area between the desiccant solution and the air stream. In order to determine the evenness of distribution, experiments were conducted with different combinations of the throttling-points diameters with a range between 0.5 mm-0.9 mm, varying the LD volume flow in different ranges between 0.3 l/min-1.2 l/min. A second set of experiments concentrated on the distribution behaviour of different types of textiles (cotton, viscose, polyamide, polyester and wood-pulp based textiles). Each type of the textiles has been tested to measure the absorption capacity and the diffusion speed by simply pouring a quantity of lithium chloride (LiCl) onto the upper surface of a taut piece of textile, and measuring the time needed for the LiCl droplets to be completely absorbed by the textile fibers. Each type has been tested in both, dry and wet state. Then polycarbonate plates were coated with these textiles and exposed to the salt solution throttled through the perforated tube. A violet fluorescent light has been used to support the visual inspection of the LD diffusion through the textile fibers.

A factorial design analysis was carried out for the results gained by testing the perforated tube. The analysis shows the optimal throttling-points diameter and the optimal spacing that will give the optimal conditions for an even distribution over the whole length of the tube. Furthermore, the analysis shows the minimum volume flow rate that might be obtained and fulfils a fairly evenness distribution. The second set of experiments revealed that new fibres have the best absorption and diffusion characteristics among the tested textiles compared to the traditional textiles currently in use such as cotton. The obtained results are implemented to build a LD regenerator that will be used for air conditioning applications.

Keywords: Desiccant, carryover, factorial design analysis, throttling-points.

1. Introduction

Conventional vapour-compression air-conditioning systems are completely powered by electricity, which is often accompanied by peak load charges, carbon dioxide emissions into the atmosphere, since the generation of electricity involves most often the utilization of fossil fuelled power plants, as well as high operational costs.

The main disadvantage of vapour-compression air-conditioning systems is that it is considered as an inefficient thermodynamic process. The handling of the latent load part requires cooling the air below its dew point which leads to an air temperature that is colder than the temperature needed to meet the sensible load. Thus, reheating the air is necessary.

Liquid desiccant air-conditioning systems remove the latent load directly from the air by absorbing the moisture by a hygroscopic salt solution e.g. lithium chloride (LiCl), calcium chloride ($CaCl_2$). The main components of an open-loop liquid desiccant air-conditioning system are the absorber (dehumidifier) and the desorber (regenerator) shown in Fig. 1.

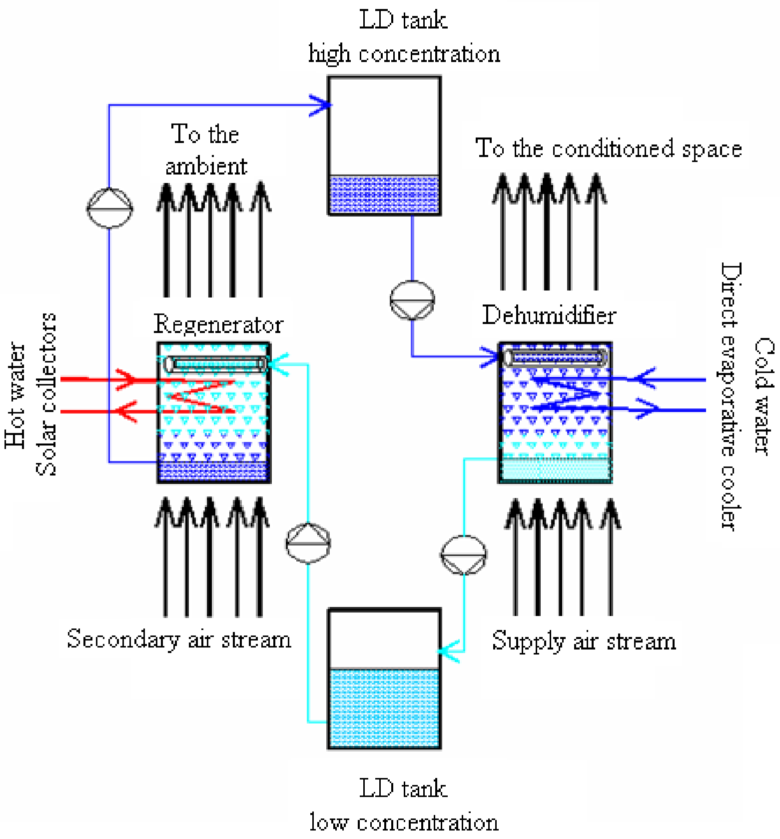

Fig. 1. Schematic of an open-loop liquid desiccant air-conditioning system

In the absorber, moisture absorbed from the conditioned air stream dilutes the desiccant solution loading the desiccant with water vapour. The dilute solution is reconcentrated in the regenerator, where it is heated to elevate its water vapor pressure. A scavenging air stream, usually ambient air, contacts the heated solution in the regenerator. There, water evaporates from the desiccant solution into the air and the solution is reconcentrated. A high impact on the system's performance results from the design of the regenerator as the driving heat is consumed in this component.

In the literature concerning liquid desiccant systems, the most examined type of both, the absorber and the regenerator is the adiabatic heat and mass exchanger. A typical representative of an adiabatic heat and mass exchanger is a packed bed with both, regular and random structures. The history of packed bed heat and mass exchangers used in liquid desiccant systems dates back to

1930's when Kathabar Inc. [1] produced the first LiCl system, primarily for industrial applications. Despite the intensive research that has been conducted to develop these systems, there are still disadvantages of packed bed structures in absorbers and regenerators, the main ones are high pressure drop, high auxiliary energy consumption, high liquid to air ratio, flooding risks and the entrainment of desiccant mists into the air stream are the main disadvantages of packed bed structures in absorbers and regenerators.

Newer studies [2-4] favoured internally heated regenerators designed with a parallel plate structure to obtain regular cross-sections for the air flow to prevent carry-over and to reduce essentially the desiccant flow rate. Out of this design the need for a sophisticated distribution system emerges as the low desiccant flow rate needs to be equally distributed over a large area. Bi-sectional or nozzle distributors have been proposed so far. They promised good results in the investigated prototypes but had problems during longer operation as crystallization of salt particles in the distribution channels occurred or air entered the distribution system.

Uneven horizontal distribution of the liquid desiccant as it enters the generator is undesirable because it reduces the effective area of contact between the liquid desiccant and air and thus decreases the mass transfer and heat exchange between the liquid and vapour. To ensure proper operation of the generator, it is also important to ensure that the ratio of liquid to vapour is constant over the cross-section of the plates. For this reason, it is important to have an even distribution of liquid as it enters the generator. A need has thus developed in this paper for a liquid distributor that is capable of facilitating uniform LD distribution at low flow rates.

A further part of the distribution system consists of textiles which are attached to the plate. Former studies revealed the necessity for closer investigations as the used materials e.g. cotton fleece did not distribute the desiccant as a uniform film over the vertical plate but formed runlets on the surface.

2. Description of the novel generator design

In this heat and mass transfer prototype, the desiccant solution and the air stream is brought into contact with each other in a cross flow configuration. The regenerator consists of a stack of polycarbonate (PC) twin wall plates. Each plate has an internal heating water circuit. The plates are covered with a wick fibre to facilitate intimate contact between the liquid desiccant and air. This is done to increase the exposure time over the plates and thereby enhance the desired mass transfer and heat exchange. The general design is shown in the left part of Fig. 2.

The advancement of the distribution system consists of:

- a separation between the liquid desiccant distributor and the contact area between air and desiccant. The LiCl solution is distributed over the textile separately in an advance stage i.e. before coming in contact with the air stream. A separator is used to split the generator into two chambers. In the upper small chamber LiCl throttled through perforated plexiglass tubes, completely diffused through the textile fibres and trickles down to come in contact with the horizontal air stream in the lower large chamber. This separator will prevent LiCl particles to drift into the air stream, resulting in a zero carryover regenerator.
- the employment of promising fibres, a new natural man made fibre produced from wood pulp. This fiber can absorb 50% more moisture than cotton did, it has a lower sorption index than cotton, which means higher transport speed of the liquid.
- the employment of perforated plastic tubes with different tested throttling-points diameters.

The LD distributor in this design uses a plurality of parallel plexiglass tubes to horizontally distribute the LD over the wick. The parallel tubes extend outwardly from openings in the lower edge of one of the sides of a LD feed box and are closed from the free end. The tubes penetrate the PC plates horizontally and deliver the desiccant solution over the coated plates at a number of equally spaced-apart locations (discharge-holes). The distributor is shown on the right part of Fig. 2.

The discharge holes are preferably formed on the plexiglass tubes by using a CNC machine to make the fine drip points with high precision. The size and number of the discharge holes are selected to provide the desired liquid flow. The throttling-point density determines the flow into the wick material covering the PC twin-wall plates. Likewise, the distance between the discharge-holes is selected to accommodate the desired LD flow rate with the maximum even distribution.

The regenerator consists of an upper and a lower hot water-feeder box. Each water feeder box consists of four equal chambers separated by baffles. Hot water will pass through the internal passages of the PC twin-wall plate in a 3-loop serpentine path. It will enter the first chamber from a primary opening in the upper wall of the chamber, and it collides with a liquid spreading surface that faces the internal PC passages. The spreading surface will also disrupt the downward flow of water and will direct it equally to the channels.

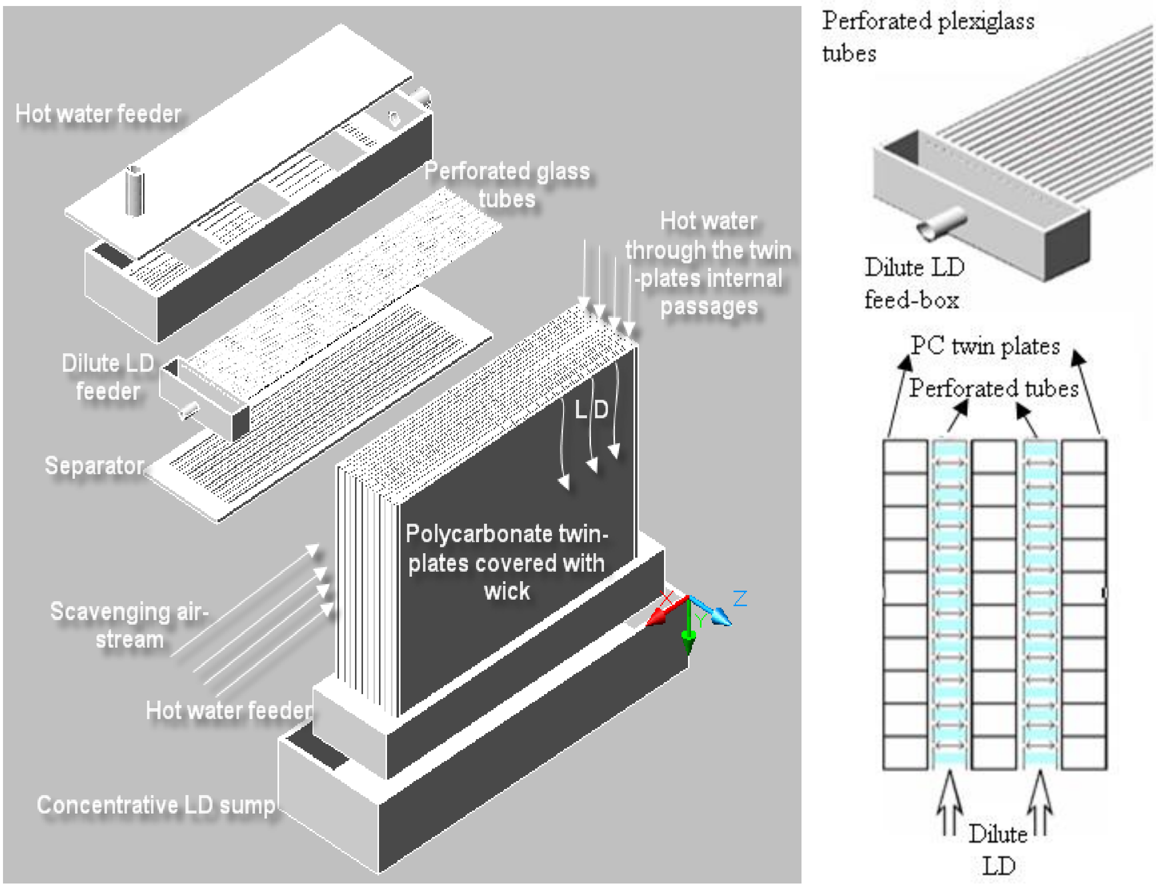

Fig. 2. Exploded view of generator design along with the illustration of flow directions of heating water, LD and air (upper left), an isometric enlargement of the LD distribution system and a top-view of how the glass tubes penetrate the polycarbonate twin-plates (upper right).

3. Experimental setup

Two different sets of experiments were carried out to prove the advancements on the distribution system.

1. The objective of the first test is to determine the optimal size and number of discharge points distributed along the plastic tube. The optimized tube will serve the LD flow rate required by the application and ensure fairly equal amounts of the LD throttled-out through each discharge bore. Five perforated plastic tubes are tested. Each tube is perforated by a CNC machine in equally-spaced positions. H_2O/LiCl (30% salt concentration by weight) is used as the liquid desiccant with three volume flow rate values. In order to investigate the effect of the distance between the LiCl feed-box and the discharge-point location, different positions along the tube are selected. Transparent PVC hoses are used to enclose the discharge-bores, without affecting the throttled LiCl. The free ends of the PVC hoses are connected to plastic bottles in order to collect the LiCl throttled out of the intended discharge-bore. Fig. 3 shows the experimental setup.

Fig. 3. Experimental setup to determine the optimum size and number of discharge points for the distributor (upper), and to check the LiCl diffusion through the textile (lower).

2. The second test is a comparison between different types of textiles (100% cotton, 100% viscose, 100% polyester, 100% polyamide and wood pulp based textiles) with different thicknesses and different weaving. Each type of the mentioned textiles has been tested to measure the absorption capacity and the diffusion speed by simply pouring a quantity of LiCl onto the upper surface of a taut piece of textile, and measuring the needed time for the LiCl droplets to be completely absorbed by the textile fibers. Each type has been tested in both, dry and wet state. Then PC plates were coated with the textiles which show the best absorption and diffusion speed, and exposed to a LiCl solution throttled through the perforated plexiglass tube. A violet fluorescent light and dyes have been used to support the visual inspection of LiCl distribution through the textile fibers. Fig. 3.

4. Analysis of the results

The first set of experimental data for the distribution tube was analyzed by the factorial design analysis using MINITAB version 15.

Factorial design analysis is a statistical method in which every level of one factor is tested in combination with every level of another factor. In general, in a factorial analysis, all possible combinations of factor levels are tested [5].

Four variables (factors) were considered to have the highest influence on the distribution test. The first factor is the LiCl volume flow rate with three treatments (levels) with a range between 0.3 l/min-1.2 l/min. The second factor is the bore size with five levels, ranges between 0.5 mm- 0.9 mm. The third factor is the distance for each throttling-bore from the LD feed-box entrance with ten levels, ranges between 4 cm-58 cm. The forth factor is the run time for each test with two levels (10 min and 15 min). Two replicates were taken for each trial in order to get an unbiased estimation. Since the number of levels for the studied factors is not equal, general full factorial design was used to analyze the measured data. The significance level α of the test is 0.05.

From the output a large F-statistic and a low p-value is seen, indicating strong evidence of a correlation between the four factors and the LiCl throttled through each discharge-point. It is also shown that p-values for all terms in the test are less than the significance level. This confirms the quality of the test.

Fig.4 depicts the normal probability plot of LiCl mass throttled through the perforated plastic tubes. The normal probability plot is a graphical technique for assessing whether or not a data set is approximately normally distributed. The data are plotted against a theoretical normal distribution in such a way that the points should form an approximate straight line. Departures from this straight line indicate departures from normality. The figure shows a little bit lower tail that do not fall exactly along a straight line passing through the centre of the plot. This indicates some potential problem with the normality assumption. However, no severe deviations from normality are obvious apparent. It is clearly shown that the minimum mass flow rate that could be used to ensure normal probability assumption corresponds to a bottle content with a total mass of 230 g.

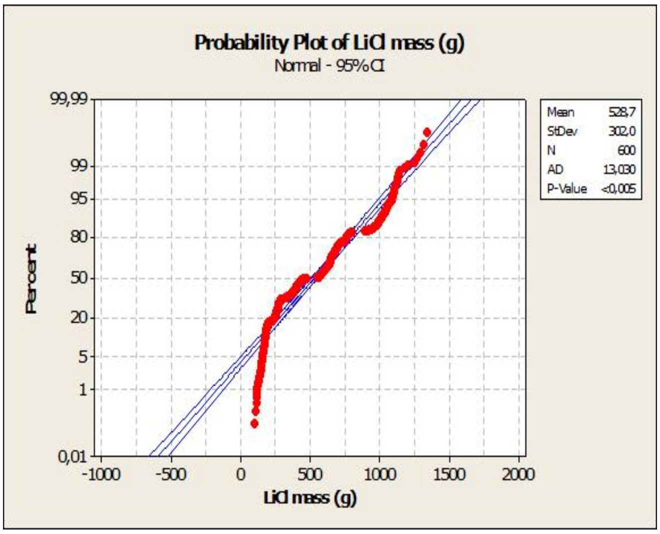

Fig. 4. Normal probability plot of the response (LiCl mass)

Fig.5 shows the residual versus the experimental response (LiCl mass). The residual is the difference between an observed value of the response variable and the value predicted by the regression line. Analysis of the residuals is frequently helpful in checking the assumption that the errors are approximately normally distributed with constant variance if the regression line catches the overall pattern of the data. It can be conducted that the variance appears to be constant, which is an important assumption for a regression model to meet. The figure shows also that the variance becomes larger as the LiCl mass increases, but there is no serious model inadequacies since the data points are uniformly distributed.

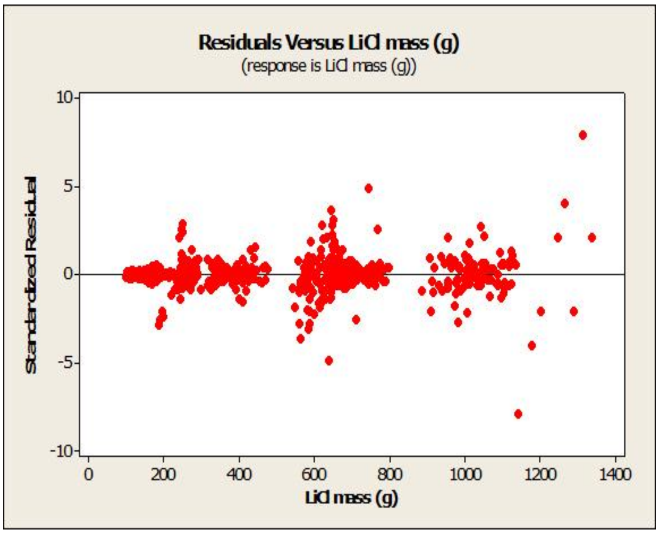

Fig. 5. Residual versus the response (LiCl mass)

The second set of tests focused on the absorption capacity and diffusivity of different textiles. A probe of lithium chloride solution (45% salt concentration by weight) was poured on a taut piece of textile. Then the needed time for the LiCl droplets to be completely adsorbed by the textile fibers were measured. The tests were carried out for the textiles in dry and wet state. Fig. 6 shows the adsorption speed for probes of one of the promising wood-pulp based textiles, polyamide, viscose, cotton, polyester and polystyrene fibers.

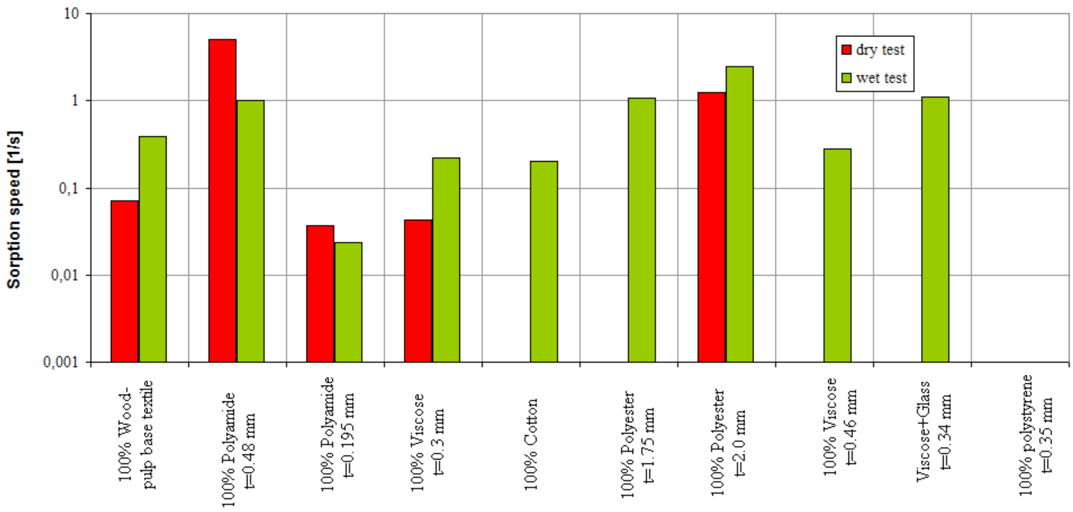

Fig. 6. LiCl adsorption-speed test for different textiles

The best results were obtained for pure wood-pulp, polyamide and polyester fibres. Different probes of polyester and polyamide fibres reveal essentially inferior adsorption speed. Therefore the material itself is not the only factor influencing the adsorption speed. During the tests a strong dependency was detected between the sorption speed and the material thickness, the pore size and the weaving structure. Further tests must be carried out to clarify these influences. A good LiCl diffusion behaviour through the pure wood-pulp fiber was proved in the experiments.

5. Conclusion and Outlook

This paper presents experimental tests and a factorial design analysis of a desiccant distributor system which will be used in the prototype of a LD regenerator. It shows the optimal conditions that will ensure even distribution and the applicability to serve a wide range of desiccant flow rates. Furthermore, it presents experimental investigations for different textiles in order to choose the best textile with the highest adsorption speed and the finest desiccant diffusion through the textile fibers.

The factorial design analysis shows the optimal diameter of the throttling-holes, and the optimal spacing between those throttling diameters. Those optimal values will ensure a fairly even distribution and it will serve a wide range of desiccant volume flow rates, which will make the LD distributor flexible to serve the requested volume flow rate requested by the air conditioning cooling load.

The experimental investigations related to textiles approved that new textiles such as pure wood-pulp fibers and polyamide perform much better than traditional textiles currently in use such as cotton.

Further investigations must be carried out to clarify the influence of the textile thickness, the pore size, the desiccant type and the weaving structure on the adsorption behaviour of textiles. Experimental investigations might be considered concerning: the durability of the throttling-bores against the desiccants corrosivity, the influence of the regenerator operating conditions (high temperatures and corrosivity) on the textile performance, the effect of using higher desiccant concentration e.g. 40% on the distribution through the perforated tubes (in case if the LD distributor will be used in a conditioner instead of a regenerator), the necessity to flush the distributor and the solution that might be used.

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