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Research Article

Experimental Investigation of a New Enthalpy Exchanger with Low Absorbent Carryover Designed for Liquid Desiccant Dehumidification System

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ABSTRACT

In this paper, the absorbent carryover effect in a designed counter-flow enthalpy exchanger is investigated. In a built prototype of the liquid desiccant dehumidifier, air and the absorbent solution are in contact and flow through a packed multi-channel polymer tower in a counter-flow pattern. To avoid the absorbent carryover, the tower is equipped with an eliminator. Experimental measurements show that applying wick of hydrophilic type material to the channels' surfaces of the eliminator and the enthalpy exchanger, while increasing the rate of dehumidification, reduces the solution carryover effect, however, it does not eliminate it. To eliminate the effect, pumping the solution into the tower is interrupted periodically. It was found that by adjusting the pump switching frequency, the carryover effect can be eliminated. The best result is achieved when the period of switching on state is about a quarter of the off state one and the total period is about 25 seconds. Since the solution pump is turned off frequently, the cost of electrical power is reduced significantly. Also, the measurements show that while the dehumidification ability of the tower is improved in a steady state operation its regeneration performance is not.

1. INTRODUCTION

Enthalpy exchangers play a key role in liquid desiccant air conditioners (LDAC). Much work has so far been conducted in air dehumidification using liquid desiccant, however less attention has been paid to elimination of the carryover phenomenon in these systems [1, 2]. Crossflow plate or packed-bed type heat and mass exchangers are widely used as the dehumidifier and solution regenerator. They can be used in parallel or counter flow patterns [3, 4, 5]. Considerable laboratory experiments, computational analysis and design work were carried out on cross flow polymer plate heat and mass exchangers (PPHE) at the Sustainable Energy Centre of the University of South Australia [6, 7] and the Queensland University of Technology [8, 9]. These involved modelling and experimental work on the PPHE, used as the enthalpy exchanger, and attempts have been made to reduce and eliminate the desiccant carryover in these air conditioners.

In the packed-bed enthalpy exchangers packing of polymer materials are used to increase the contact surface area between the air and the desiccant solution, while simultaneously reducing the carryover phenomenon in these systems. To further reduce the carryover of the desiccant particles into the conditioned space, a layer of wick is sometimes applied to the heat exchanger surfaces, which also increases the dehumidification efficiency of the air conditioning unit. In such a case the liquid desiccant is absorbed by the wick resulting in considerable reduction of solution mass flow rate. This would, subsequently, reduce the costs involved to operate the air conditioner.

In another research work at Materials and Energy Research Centre (MERC) of Iran, a solar LDAC pilot plant has been developed, installed and tested on a commercial building located in the north of the country on the Caspian Sea [10]. In this system cross-flow honeycomb enthalpy exchangers were used as packing materials in both the absorber unit and the regenerator, while utilizing eliminators to prevent the desiccant particles from being entrained by the process airflow. In a theoretical work conducted by John McNab [11] he suggested a LDAC in which the process air did not contact the liquid desiccant but was dehumidified indirectly by the return air from the conditioned space. The return air had been dehumidified by the desiccant solution and cooled by water spray below the dew point temperature of the process air prior to entering the

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*Corresponding Author's Email: shahab_alizadeh@hotmail.com (S. Alizadeh) absorber unit. In his system the polymer plate heat exchangers (PPHE) were used as the enthalpy exchangers in the absorber unit and the regenerator.

In an attempt by Andrew Lowenstein [12] a LDAC system known as the “zero carryover liquid desiccant air conditioner” was developed in which the low flow liquid desiccant technic was incorporated within the enthalpy exchangers. In his design he used counter flow plate heat and mass exchanger as the absorber unit with a layer of wick applied on the heat exchanger surfaces. He is currently in the commercializing phase of the air conditioners used with solar energy.

For conventional direct-contact liquid desiccant devices (e.g. packed towers or packed beds) entrainment of liquid desiccant droplets into the downstream air will cause corrosion of air ducts and exposed metal components [13,14]. As well, the overflow of liquid desiccant droplets at high quantities will negatively impact the indoor air quality. This problem largely limits the use of direct-contact exchangers to a few types of commercial and industrial applications and precludes their use for some other applications such as health care services [15, 16, 17].

The carry-over of liquid desiccant with air can also be eliminated by using a semi-permeable micro-porous membrane-based contactor in place of direct air–liquid contact or deploying a liquid desiccant to flow along porous mesh sheets forming a layer of liquid falling film instead of spraying [18, 19, 20].

Duong et al. [21] described a liquid desiccant regeneration process by thermal packed-bed evaporation, which can result in considerable desiccant loss due to carryover. They revealed that desiccant carryover did not only result in the need to replenish desiccating agents (hence a cost increase), but also caused potential long-term health concerns [22, 23]. To address the issue of desiccant carryover, several membrane separation processes, including reverse osmosis (RO) [24] and electro-dialysis (ED) [25], have recently been investigated for regenerating liquid desiccants. However, the high electricity demand of RO and ED renders them less attractive for LDAC applications.

To improve the supply air quality, it is necessary to prevent the desiccant carryover. The present research introduced a new solution to overcome the carryover problem in direct-contact enthalpy exchangers, while simultaneously gaining a significant energy savings in the system. Elimination of the carryover in a counter-flow air to liquid enthalpy exchanger, composed of polypropylene materials has been considered. The outcome is empirically tested and is accomplished in three steps of design development. Following the experimental setup description below, the three technical enhancements, which aimed to overcome the liquid desiccant carryover, will be introduced and their consequences will be investigated.

2. DESCRIPTION OF THE LIQUID DESICCANT EXPERIMENTAL SETUP

The key divisions of a LDAC system is composed of two enthalpy exchanger devices, which makes possible the mass and heat transfer between the air and liquid desiccant. They are the air dehumidification and solution regeneration towers. The dehumidifier operation is used to dry the supply air. During this process, as the desiccant solution absorbs moisture from the airflow it becomes diluted. The diluted solution is then concentrated by means of a low-grade energy such as solar or waste heat in a regeneration process. This suggests that LDAC is an energy saving air conditioner and energy can be saved as concentrated liquid desiccant and used when required.

The experimental setup is designed as a counter-flow system using LiCl-H_2O as the absorbent solution. A schematic of the liquid desiccant system is given in Figure 1. As revealed in the figure, the system consists of a pre-cooling coil, 3 electrical heater units, a desiccant solution tank, an enthalpy exchanger, an eliminator, 5 spray nozzles, a centrifugal pump and a suction fan. To avoid the corrosion effect of the absorbent solution, the liquid passageway is well protected by polymer material and the enthalpy exchanger and the eliminator are composed of multi-channel polymer blocks made of polypropylene material. In this design, the enthalpy exchanger is an assembly of 5 multi-channel blocks, each spaced by a 10 mm gap. The eliminator, however, is made of only one block.

To satisfy all conditions required in this research, the system is so designed that it can operate in dehumidification as well as regeneration mode just by switching from cooling to heating of the process air. As a result, when the heater is turned on and the pre-cooling coil is switched off, the relative humidity of the heated air can be so decreased that it regenerates the liquid desiccant by absorbing the water vapor from the solution. The hot and humid air is then exhausted from the system. In dehumidification mode, by turning off the heater and switching on the pre-cooling coil, the relative humidity of the cooled air can be so increased that is appropriate to air drying using humidity absorption process.

As shown in Figure 2, a prototype of the above enthalpy exchanger is designed and built. During the enthalpy exchange operation, the absorbent solution is distributed from the nozzles, which are located at the top of the exchanger unit and flowing through the channels. In the opposite direction the airstream from the bottom of the system flows up in a counter flow manner.

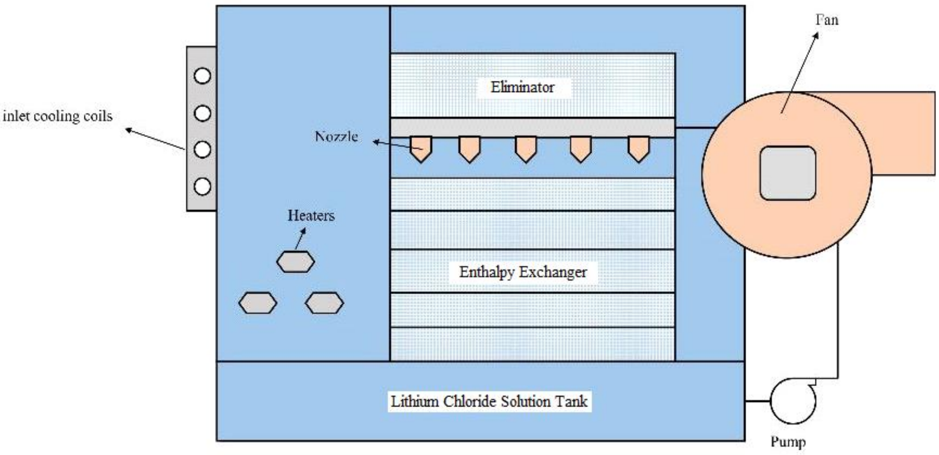

Figure 1. Schematic description of the liquid desiccant system.

Figure 2. A side photograph of the designed liquid desiccant system.

Figure 3 shows the path of the absorbent solution in the system. As shown in Figure 4, the airstream enters the system through the pre-cooling coil and after passing through the electrical heater units and the enthalpy exchanger tower it leaves the system through a centrifugal suction fan. A photograph of the dehumidification tower used in the enthalpy exchanger is also demonstrated in Figure 5. Based on the planned research requirements, to introduce the minimum carryover, modifications have been carried out on the setup. The chronological development of the design is summarized in 3 consecutive steps as follows:

- All channels of the eliminator are threaded by means of cotton strings, which function as a wick. As a result, more droplets are adsorbed, which improves the contact between the air and the desiccant solution.
- Besides the eliminator block, all the channels of the enthalpy exchanger are threaded by means of cotton strings. As a result, more droplets are still adsorbed through the channels, further improving the contact between the air and the solution.

Following the above changes, a programmable timer switch is used to interrupt periodically the liquid desiccant pumping. As the pump is activated, the sprayed liquid wets the channels and the wicks, causing the enthalpy exchange between the solution and the airflow.

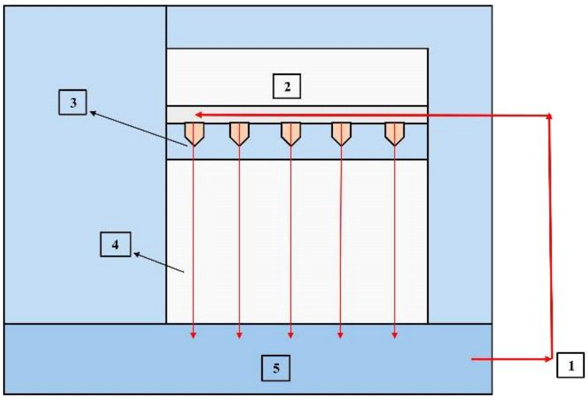

Figure 3. Path of the liquid desiccant in the system: 1-Suction line; 2-Distribution line; 3- Solution spray; 4-Air-solution contact; 5-Return to solution tank.

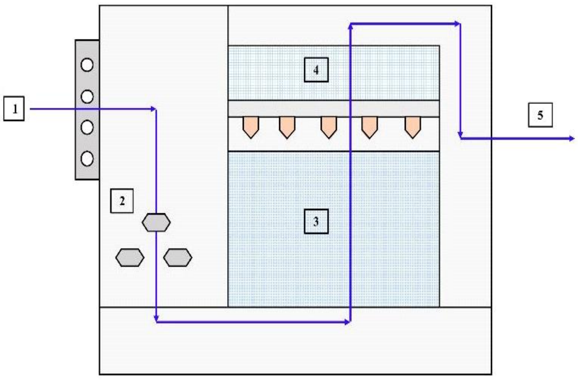

Figure 4. Path of the air in the system: 1-Air is cooled down (in dehumidification); 2- Air is warmed up (in regeneration); 3-Air in contact with the desiccant solution; 4-Moisture is removed from air in the eliminator; 5- Exhaust air.

Figure 5. A photograph of the dehumidification tower used in the enthalpy exchanger.

3. EXPERIMENTAL PROCEDURE

The main implemented methods to achieve the research goals are detailed as follows:

3.1. The system has been set up in regeneration mode

- Turning on the liquid pump to circulate the solution in the enthalpy exchanger and wetting the walls of the channels. Some of the experiments are so planned that the solution pump is interrupted periodically at a well-defined frequency.
- Turning on the heater, while the cooling cycle is idle, and preheating the inlet air up to about 80 °C.
- Regularly measuring the temperature and relative humidity of the process air prior to and after passing through the enthalpy exchanger. The experiment continues for about 1 hour and the measurements are carried out at 10-minute time intervals.

3.2. The system has been set up in dehumidification mode

- Turning on the liquid pump to circulate the solution in the enthalpy exchanger and wetting the walls of its channels. Experiments are so planned that the solution pump is interrupted periodically at a well-defined frequency.
- Turning on the cooling cycle, while the electrical heaters have been turned off and cooling the inlet air down to 18 °C.
- Regularly measuring the temperature and relative humidity of the process air prior and after passing through the enthalpy exchanger. The experiment takes about 1 hour, and the measurements are carried out every10 minutes.

3.3. Carryover inspection method

The experimental results indicate that the carryover droplets are too small to be sensed visually. Therefore, to detect these droplets based on a known standard, a white paper of A4 size is held in front of the air passage at 20 cm distance from the fan outlet. The exposed face of the paper is then illuminated, and the solution droplets are appeared as bright dots on it. Counting these shining points gives a measure of the carryover magnitude.

Following are the instrumentations used for measurement in the experiments:

- Relative humidity and temperature of the process airflow is measured by a humidity and temperature meter, namely Lutron IDR-RH101, as a trade mark with an accuracy of ± 0.1 % for RH and ± 0.1 ºC for temperature.
- Airflow velocity at fan outlet is measured by an anemometer marked as Omega HHF11A with an accuracy of ± 0.1 m/s.
- Desiccant solution concentration is measured by measuring the solution conductivity using a conductivity meter sensor with an accuracy of ± 0.1 ms/cm [msimense/cm].

The measuring stations considered in the experimental setup are indicated in Figure 6.

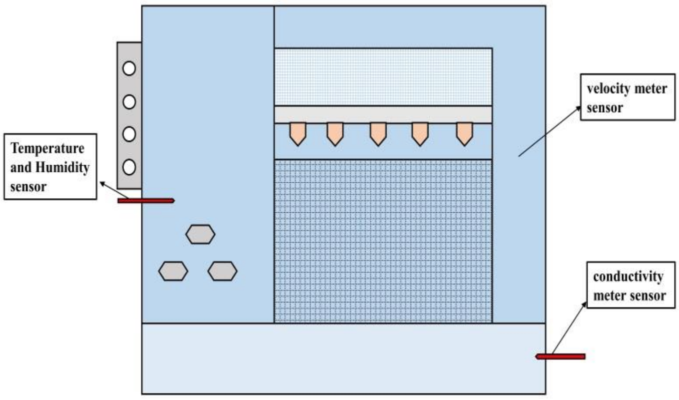

Figure 6. Measuring stations in the experimental setup.

In the context of the research subject, 7 series of experiments are planned as follows:

- Study of the setup performance in the regeneration mode, while only the eliminator is wicked.
- Study of the setup performance in dehumidification mode, while only the eliminator is wicked.
- Study of the setup performance in regeneration mode, while the eliminator and the enthalpy exchanger are both wicked.
- Study of the setup performance in dehumidification mode, while the eliminator and enthalpy exchanger are both wicked.

- Study of the optimal pump switching frequency, which minimizes the carryover of the solution droplets while the eliminator and the enthalpy exchanger are both wicked. During this experiment the heating and cooling equipment are turned off.
- Study of the setup performance in regeneration mode, while the eliminator and the enthalpy exchanger are wicked as well as the pump switcher is in use at optimal frequency.
- Study of the setup performance in dehumidification mode, while the eliminator and the enthalpy exchanger are both wicked as well as the pump switcher is in use at optimal frequency.

4. EXPERIMENTAL RESULTS

Providing the above detailed conditions for testing the enthalpy exchanger, the experiments were successfully carried out and their results are as follows:

Experiment 1:

The device works at regeneration mode while its eliminator is wicked. Variation of the air relative and absolute humidity during the test is measured and plotted versus time as shown in Figures 7 and 8, respectively. Also, the average airflow velocity at the outlet of the fan is measured as 6.94 m/s. Therefore, considering the opening dimensions of the fan outlet and referring to the airflow density, the water mass removed from the desiccant solution is calculated to be about 6.85 Kg/h. Implementation of the carryover inspection method indicates that the amount of carryover in this case is considerable.

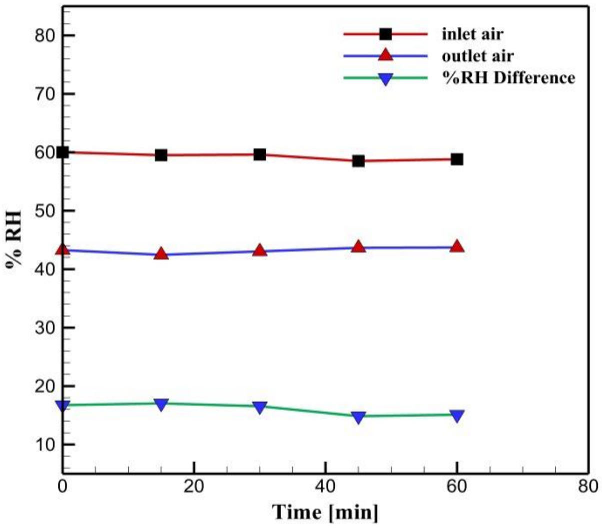

Figure 7. Air relative humidity versus time in the 1st test.

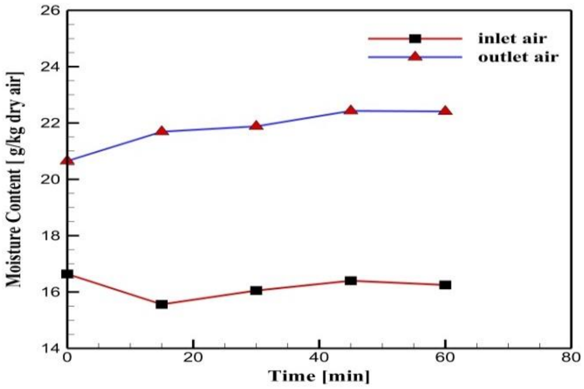

Figure 8. Air absolute humidity versus time in the 1st test.

Experiment 2:

The device works at dehumidification mode while the eliminator is wicked. Variation of the relative and absolute humidity during the test is measured as shown in Figures 9 and 10, respectively. The average airflow velocity at the outlet of the fan is measured as 6.94 m/s. Therefore, considering the opening dimensions of the fan outlet and referring to the airflow density, the water mass removed from the air is calculated to be about 1.38 Kg/h.

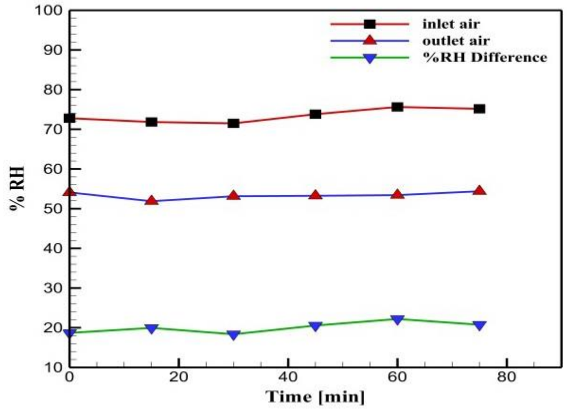

Figure 9. Air relative humidity versus time at the 2nd test.

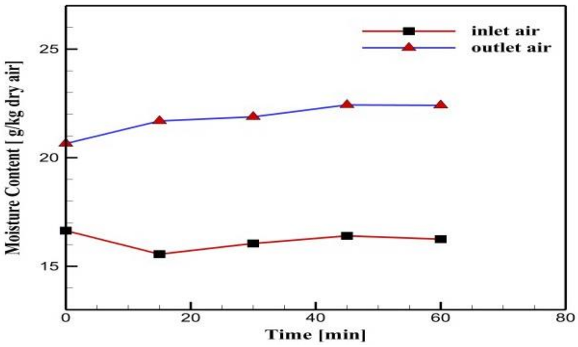

Figure 10. Air absolute humidity versus time in the 2nd test.

Experiment 3:

The device works at regeneration mode, while both the exchanger and the eliminator are wicked. Variation of the air relative and absolute humidity during the test are measured as a function of time as shown in Figures 11 and 12, respectively. Also, the average airflow velocity at the outlet of the fan is measured to be about 6.425 m/s. Considering the opening dimensions of the fan outlet and referring to the air density, the water mass removed from the desiccant solution is calculated to be about 5.6 Kg/h. Implementing the carryover inspection method described earlier, a reduction in the amount of carryover compared to the previous tests has been determined.

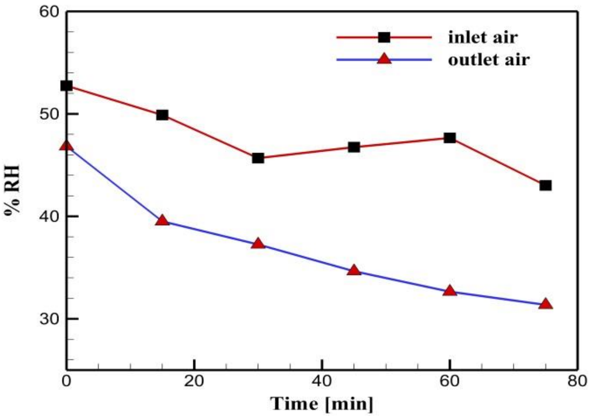

Figure 11. Air relative humidity versus time in the 3rd test.

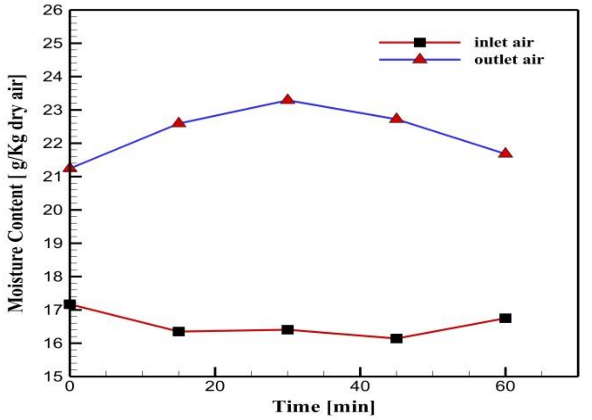

Figure 12. Air absolute humidity versus time in the 3rd test.

Experiment 4:

The device works at dehumidification mode while both the exchanger and the eliminator are wicked. Variation of the relative and absolute humidity during the test are measured as a function of time as shown in Figures 13 and 14, respectively.

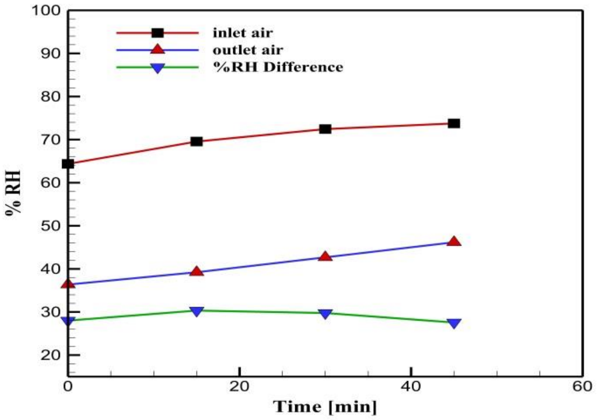

Figure 13. Air relative humidity versus time in the 4th test.

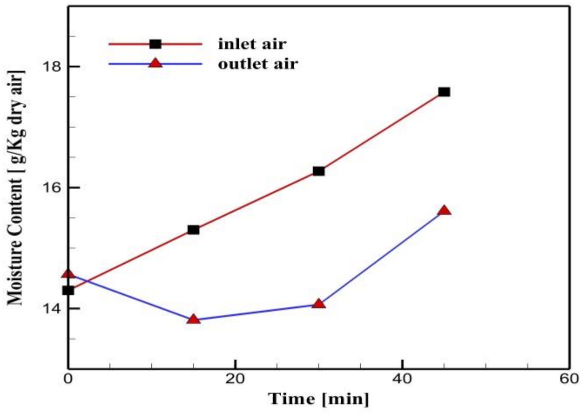

Figure 14. Air absolute humidity versus time in the 4th test.

There has apparently been an initial error in measuring the air moisture content in Figure 14, however, as the test continues a considerable reduction in the air absolute humidity can be observed in this figure as a result of wicking the enthalpy exchanger as well as the eliminator.

The average airflow velocity at the outlet of the fan is measured to be about 6.425 m/s. Therefore, considering the opening dimensions of the fan outlet and referring to the airflow density, the water mass removed from the airflow is calculated to be about 2.06 Kg/h.

Experiment 5:

If the liquid pump operates continuously, the channel wicks will be saturated of the desiccant solution, which will cause to strengthen the overflow effect. To overcome this problem, it is necessary to switch off the pump periodically. To estimate the optimum time cycle of the pumping interruption, the setup overflow is evaluated at different switching periods. The best result is obtained when the pump works for 5 seconds and rests for 20 seconds. During this investigation all the heating and cooling equipment are turned off.

Experiment 6:

The device works at regeneration test condition while both the eliminator and the exchanger are wicked, and the interruption frequency of the solution pump is set on the optimal value. Variation of the relative and absolute humidity during the test is measured as a function of time and demonstrated in Figures 15 and 16, respectively. Also, the average airflow velocity at the outlet of the fan is measured to be about 6 m/s. Therefore, considering the opening dimensions of the fan outlet and referring to the airflow density, the water mass removed from the desiccant solution is calculated to be about 4.22 Kg/h.

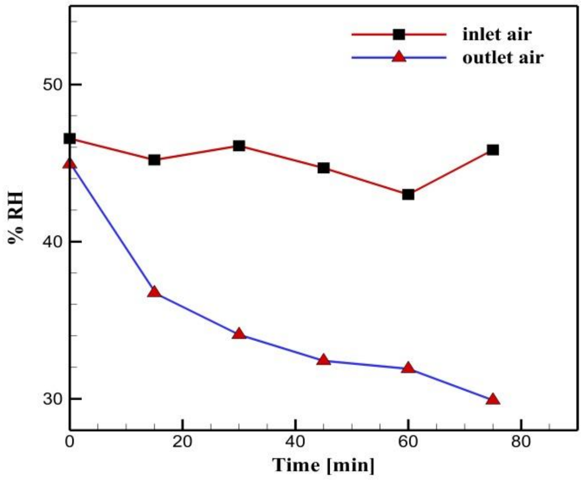

Figure 15. Air relative humidity versus time in the 6th test.

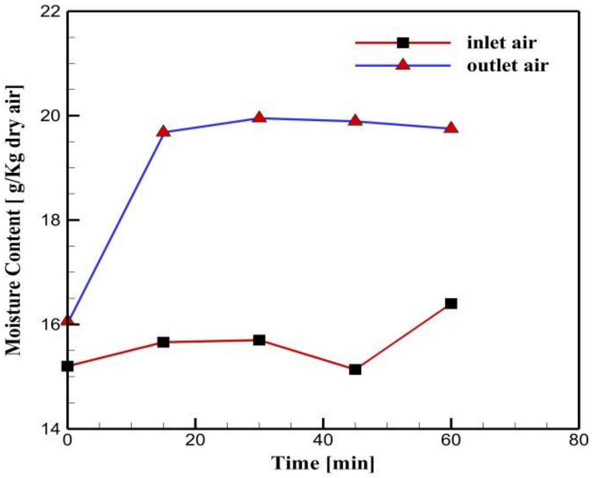

Figure 16. Air absolute humidity versus time in the 6th test.

Experiment 7:

The device works in the dehumidification test condition while both the eliminator and the exchanger are wicked and interruption frequency of the desiccant pump is set on the optimal value. Variation of the relative and absolute humidity with respect to time during the test is measured and plotted as shown in Figures 17 and 18, respectively.

A further error has possibly occurred in Figure 18 when recording the test results just as the experimental test started. This could also be due to either a visual error or a sudden change in the environmental air conditions (temperature and humidity), which again improves as the test continues and the air absolute humidity remarkably reduces due to setting the solution pump interruption frequency on the optimal value.

Also, the average airflow velocity at the outlet of the fan is measured to be about 6 m/s. Therefore, considering the opening dimensions of the fan outlet and referring to the airflow density, the water mass removed from the airflow is calculated to be about 1.85 Kg/h.

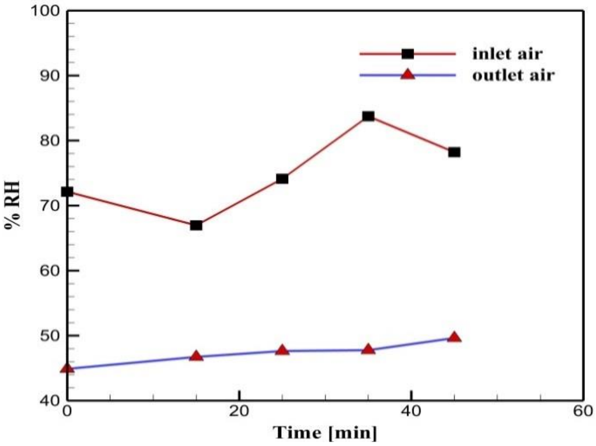

Figure 17. Air relative humidity versus time in the 7th test.

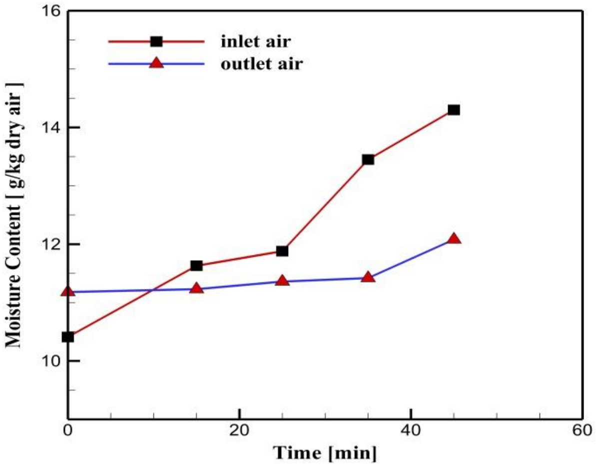

Figure 18. Air absolute humidity versus time in the7th test.

5. DISCUSSION OF THE TEST RESULTS

Figure 19 provides a comparison between the results obtained from the experiments 1, 3 and 6, which indicates that in the regeneration mode wicking the enthalpy exchanger reduces the regeneration rate. It can also be shown that there is a relative reduction in the air absolute humidity while the device operates in the regeneration mode. Figure 20 also indicates that although by iterative switching of the solution pump, the carryover can be decreased dramatically, but it also reduces the desiccant feeding rate and as a result there will be a reduction in the regeneration ability.

As shown in Figure 20, a comparison between the results obtained from the experiments 2, 4 and 7 reveal that by wicking the enthalpy exchanger in the dehumidification mode the drying rate of the process air is initially reduced, however it is improved in a steady state operation of the system. Moreover, it can be shown that in the dehumidification mode there is a relative reduction in the process air absolute humidity. Although by iterative switching of the solution pump the carryover can be decreased dramatically, however, it reduces the desiccant feeding rate. This will cause an initial reduction in the air dehumidification ability, which improves as the system enters a steady state operation.

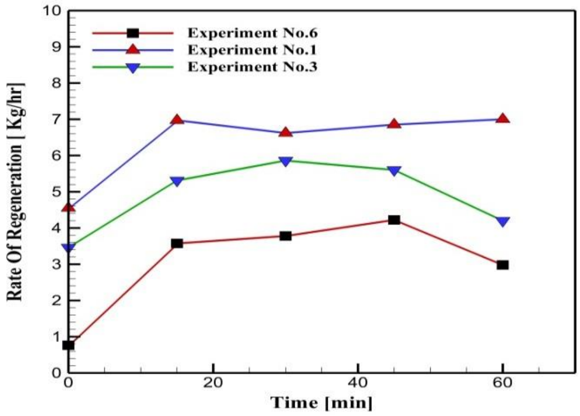

Figure 19. Comparing the rate of regeneration for the experiments 1, 3 and 6.

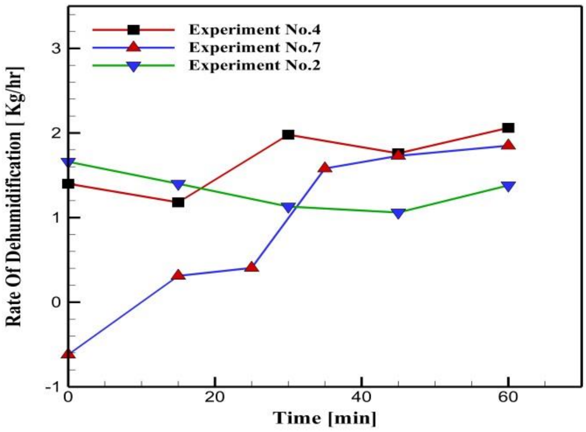

Figure 20. Comparing the rate of dehumidification for the experiments 2, 4 and 7.

In comparing the rate of reduction in the air absolute humidity in Figure 20, a decrease in the regeneration ability of the enthalpy exchanger (due to a decrease in the desiccant feeding rate) initially affects the air dehumidification rate. However, this short coming again improves as the system enters a steady state operation. As shown in Figure 20 the dehumidification rate of the process air sharply increases in the 7th test compared with the 2nd test and possibly the 1st test if the experimental test could continue further beyond the time interval shown in Figure 20.

6. CONCLUSIONS

The carryover phenomenon is investigated in a packed tower liquid desiccant dehumidifier, which is equipped with a counter flow enthalpy exchanger and an eliminator composed of polypropylene material. To overcome the carryover problem two technical solutions are proposed. In the first stage, threading of the exchanger channels and the eliminator is carried out using cotton string material (wick). As a result, more liquid desiccant droplets are adsorbed through the channels, which improves the contact between the air and the desiccant solution. By applying this modification, the experiments showed a reduction in the carryover of the desiccant droplets, however it was not eliminated. The modification has been accomplished by a new suggestion concerning the solution pumping to be interrupted periodically. A programmable timer switch is used for this purpose. As the pump is activated, the sprayed liquid wets the channels and the wicks, causing the enthalpy exchange between the solution and the airflow. To estimate the optimum frequency of this switching, a series of trials has been conducted, which reveals that for 25 seconds only 5 seconds operation of the pump is recommended. The final solution is tested in dehumidification as well as in regeneration mode of the system. The results show that the carryover is successfully eliminated. Since the solution pump is turned off frequently, the cost of electrical power utilized in the system is reduced significantly. The experimental data further indicates that the air dehumidification performance of the enthalpy exchanger is improved in a steady state operation. However, the solution regeneration ability of the system can either remain unchanged or is relatively declined under special conditions of the system operation.

7. ACKNOWLEDGEMENT

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