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Modelling and Experimental Evaluation of an Open Cycle Liquid Desiccant Dehumidification Unit

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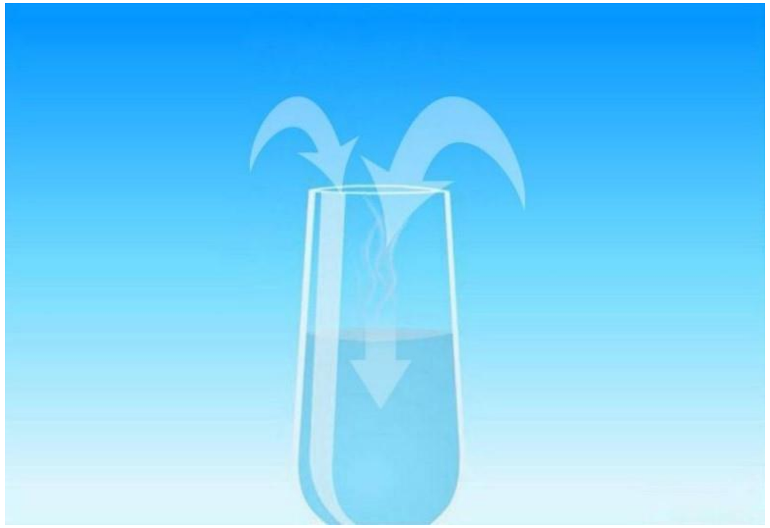
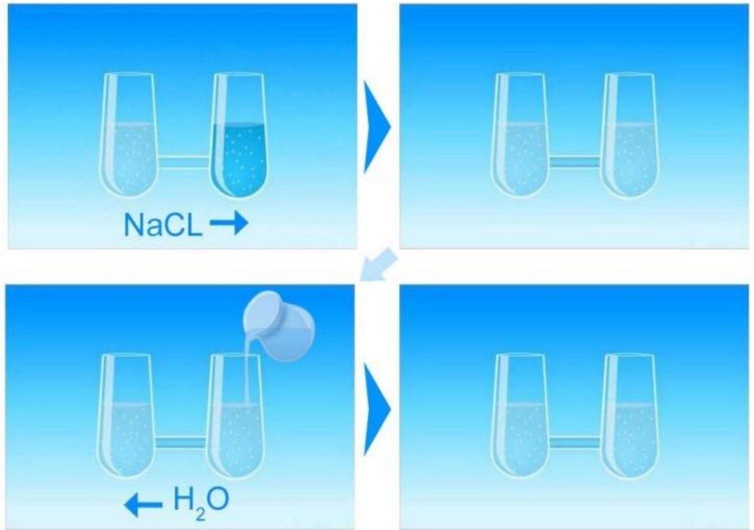
Basic Principle of the Absorption Process

A very strong salt solution will attract moisture with an almost like “magnetic” force



In a two part system, any concentration imbalance will cause “flow” to equilibrate the solutions

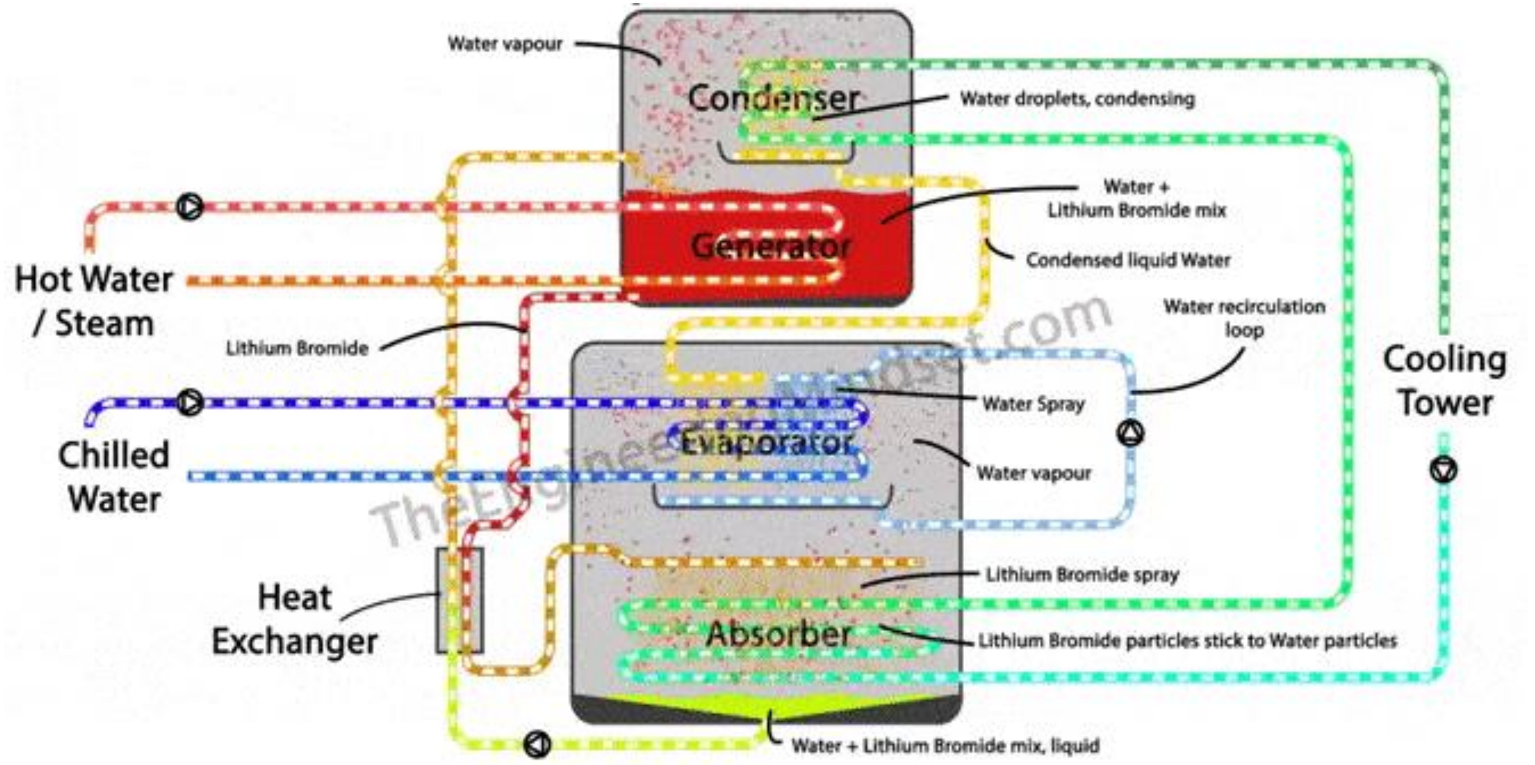


Adding a heat source to one part of the system, will cause water to evaporate from the solution, thus creating a continuous flow

Introduction to Absorption Refrigeration

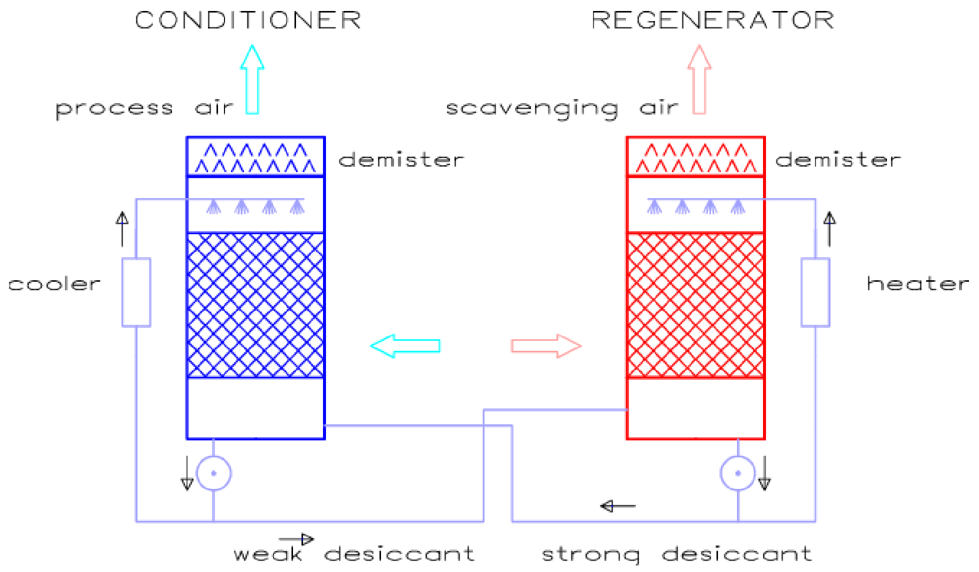
Absorption Chillers

- Provides chilled water that can be used for cooling purposes
- Basic Parts that comprise the Chiller
- Evaporator
- Absorber
- Regenerator
- Heat source
- Condenser
- Solution Heat Exchanger
- Cooling Tower



Liquid Desiccant Dehumidifiers

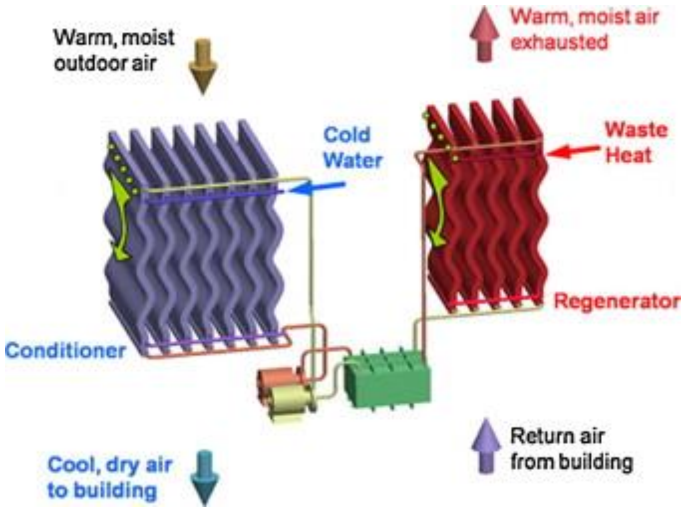
- Used mainly in the industrial sector where eco-friendly approaches for air conditioning are prioritized and enhanced
- Similar to absorption chillers, LDD units consist of the following parts:
  - Absorber
  - Regenerator
  - Heat source
  - Cooling Source

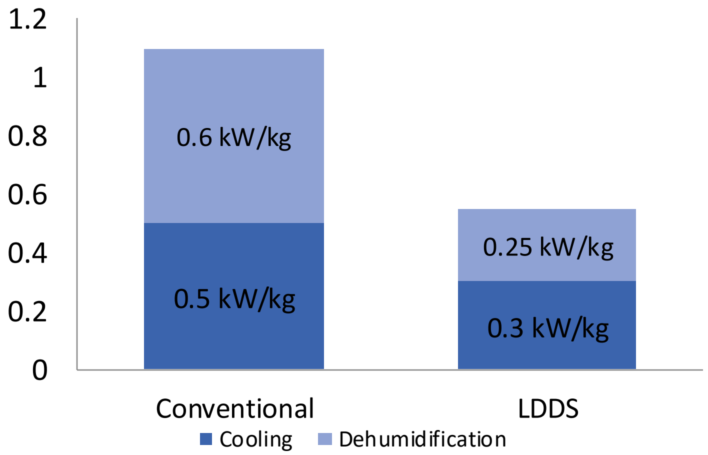


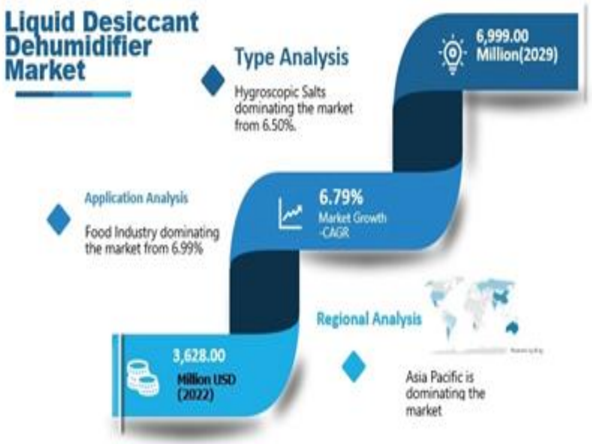
Liquid Desiccant Dehumidifiers

Advantages

- ✓ Unlike conventional AC systems, they provide both temperature and humidity control without overcooling the air past the condensation point
- ✓ Energy efficiency
- ✓ Ability to handle large amounts of air
- ✓ Low environmental impact
- ✓ Renewable source integration
- ✓ Despite the higher initial installation cost, the investment in a LDDS can typically be recouped within one or two years of operation





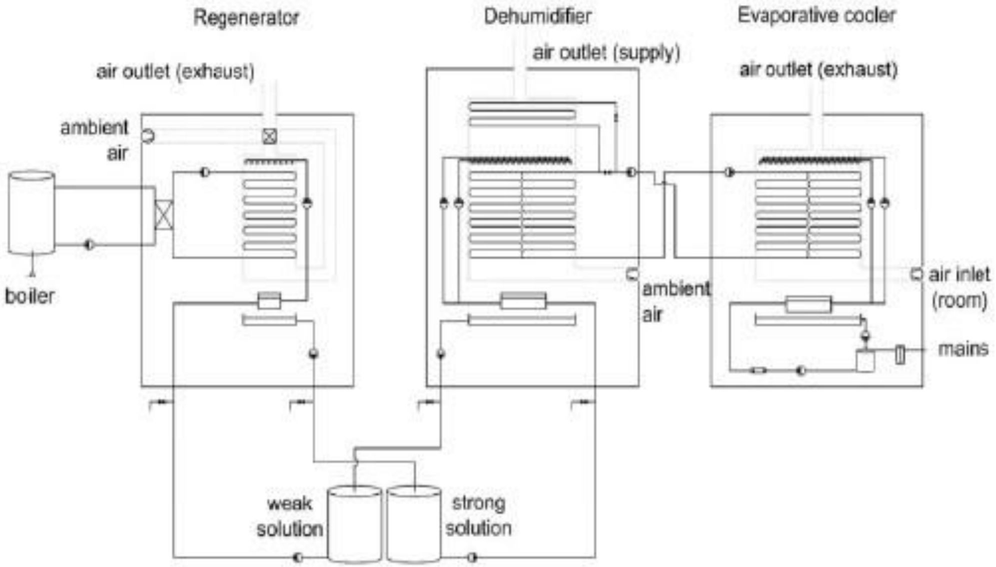


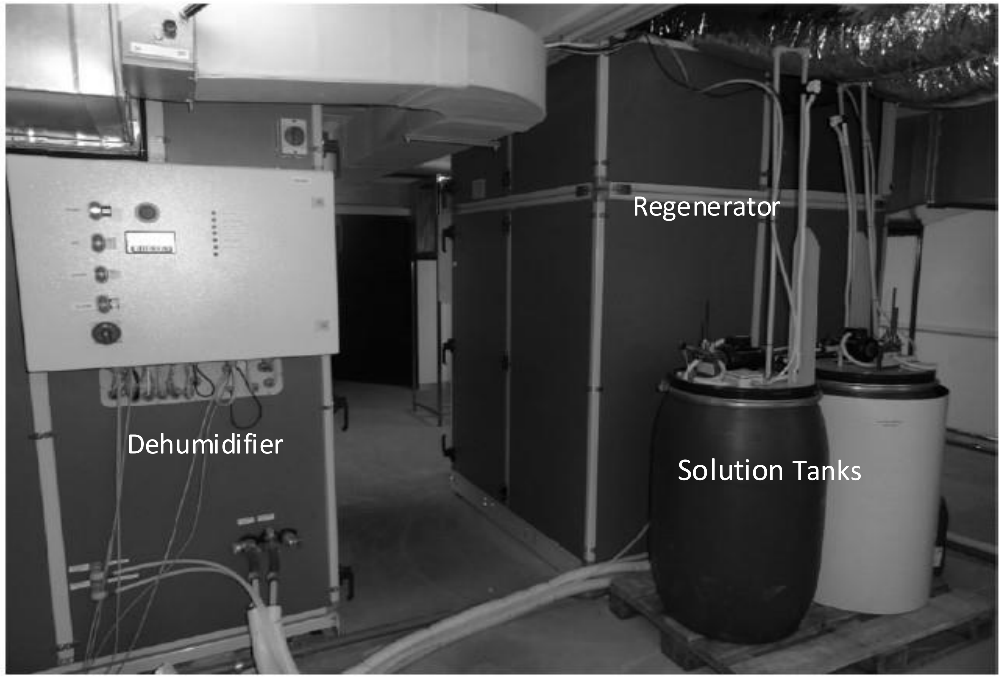
Open vs Closed Cycle LDDS

	Closed Cycle Systems	**Open Cycle Systems**
Process	Air is conditioned in a closed loop, with no direct exchange between desiccant and outdoor air	Desiccant directly interacts with ambient air to absorb moisture
Applications	Used in buildings and areas where air recirculation is needed	Common in the industrial sector and areas needing “high-capacity” dehumidification
Advantages	Better indoor air quality	Can handle large air volumes Low operational cost
Disadvantages	Lower efficiency Complex design concerning the “air side” High maintenance cost	High initial installation cost High maintenance cost

LDD Experimental Unit

- Installed in the Laboratory of Applied Thermodynamics laboratory , Thermal Section, School of Mechanical Engineering
- It is an open cycle cooling and dehumidifying system using Lithium Chloride as a liquid desiccant medium.
- Integrated with an evaporative cooler and a heating source for continuous operation

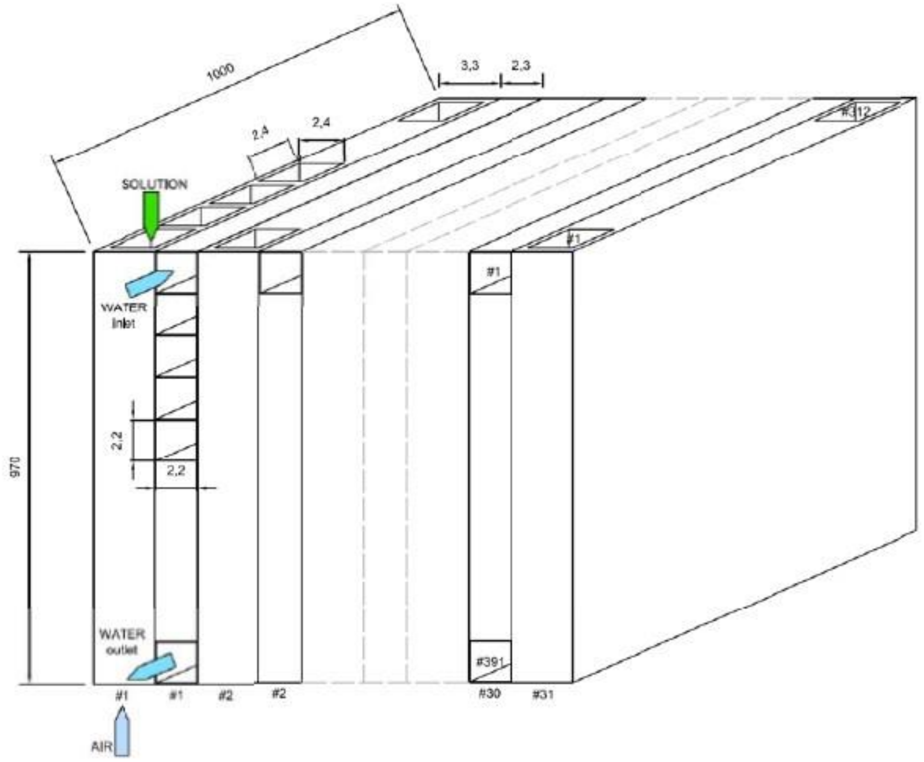




LDD Experimental Unit

Absorber

- **Absorber Packing Geometry**
- The absorber unit consists of a counter-flow plate heat exchanger.
- The heat exchanger is constructed from 62 white polypropylene sheets with vertical ducts, which serve the solution and air flow, along with 60 black sheets with horizontal ducts, which enable the simultaneous flow of water inside the heat exchanger.
- The length, depth and height are 2.3*1000*970mm for the black sheets and 3.3*1000*970 for the white sheets.
- Each black sheet has 391 ducts of 2.2*2.2 mm and each white sheet has 312 ducts of 2.4*2.4 mm.

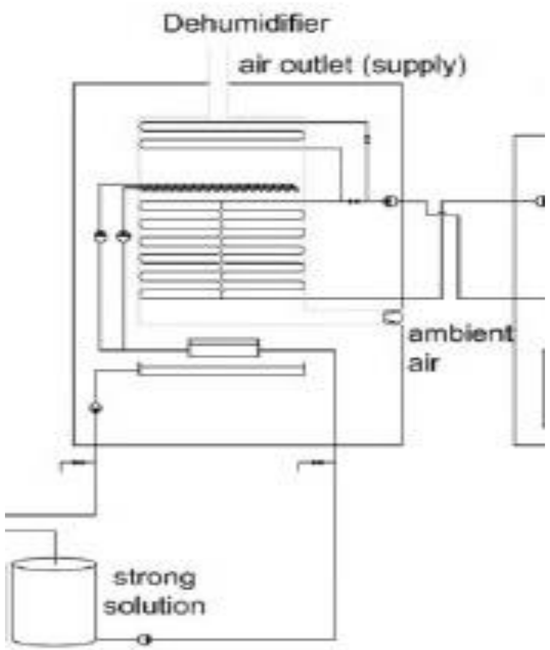


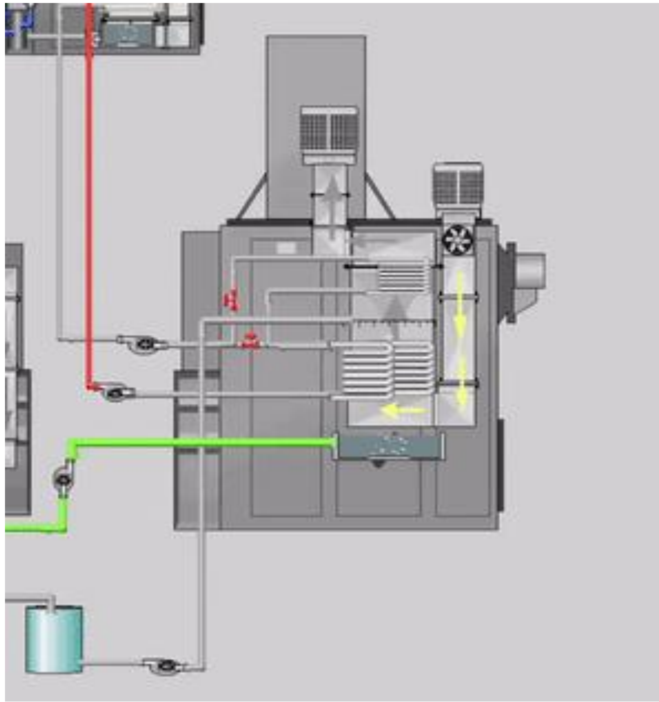
LDD Experimental Unit

Absorber

Dehumidification Process Description

- LiCl solution from the strong solution tank is pumped to the dehumidifier, sprinkled from the 2/3 of the height of the heat exchanger and collected at the bottom of the unit.
- Concurrently, humid air from the room is blown from the bottom to the top of the unit and comes in direct contact with the desiccant medium, which absorbs moisture from the air.
- Due to condensation and the mixing of water vapor with the aqueous solution, latent heat is released, decreasing the ability to remove water vapor from the air, thus inducing the need of simultaneous cooling water flow inside the heat exchanger in order to absorb that unnecessary heat load.
- The cooling water not only increases the dehumidification capacity, by restricting the temperature changes for both the desiccant and air, but it is also used for further cooling of the air exiting from the unit (at 2/3 of the height to the top of the heat exchanger).
- At the end of the process, the diluted desiccant solution is pumped to the weak solution tank and the air, cooled and dehumidified, is supplied back to the room.





LDD Experimental Unit

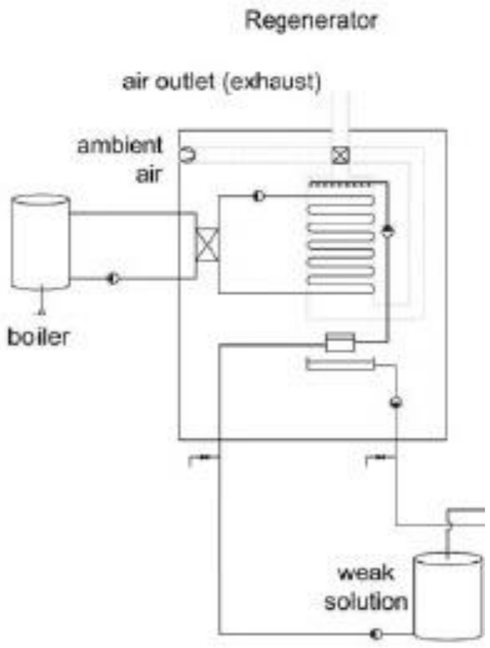
Regenerator

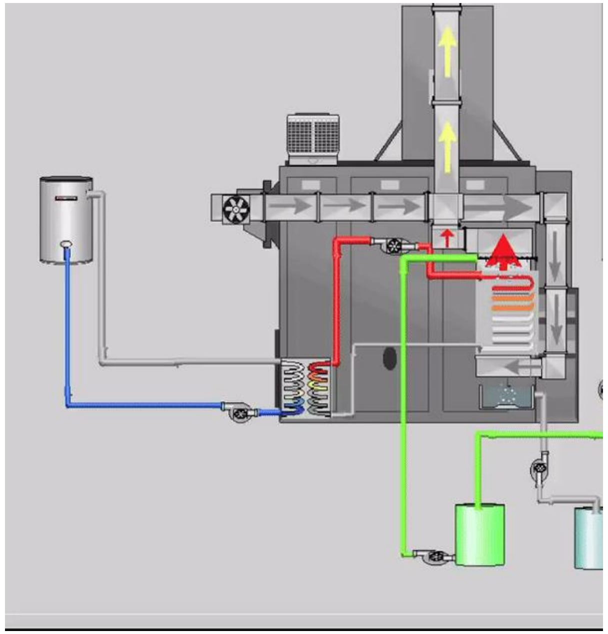
- **Geometry**

- The Regenerator’s heat exchanger consists of 25 and 24 black and white polypropylene sheets respectively.

- **Regeneration Process Description**

- Ambient air is blown to the bottom and flows from bottom to the top
- The air comes in direct contact with the aqueous solution, which is pumped from the weak solution tank and sprayed from the top of the counter flow heat exchanger.
- Through the concurrent circulation of heated water in the horizontal tubes, water vapor is released from the solution and is carried away by the air stream.
- At the outlet of the regenerator there is an additional air to air heat exchanger in order to preheat the air and reduce the amount of heat needed for the regeneration process.
- At the end of the process, the desiccant has gained its initial concentration, and it is pumped into the strong solution tank as the air is exhausted into the atmosphere.

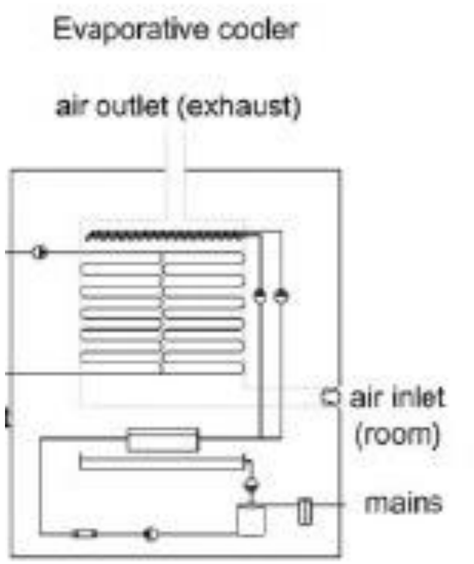


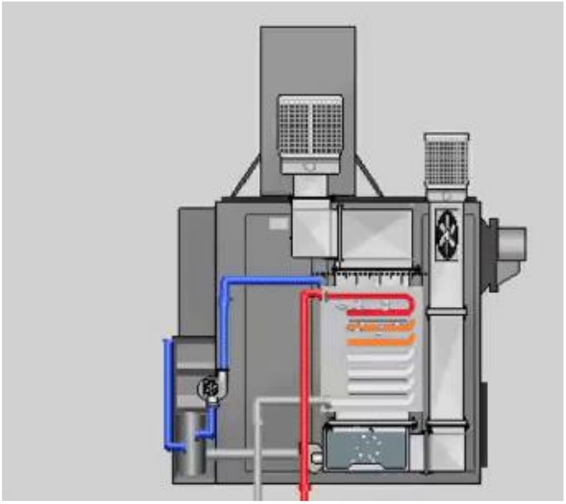


LDD Experimental Unit

Evaporative Cooler

- **Evaporative Cooler’s Role**
- Water containing the unwanted heat load from the dehumidifier is circulated in the cooler’s heat exchanger through the horizontal tubes and needs to be cooled in order to be reused in the next dehumidification cycle.
- With the same geometry as the absorber its main role is the constant supply of the necessary amount of cooling water that is used during the absorption process.
- **Evaporative Cooling Process Description**
- To achieve this, the evaporative cooler uses exhaust air from the room and mains water.
- The water is sprinkled at the top of the heat exchanger and evaporates as it comes in direct contact with the air, flowing from the opposite direction, thus creating the cooling effect.
- The air, as it has become humid, is exhausted into the exterior.
- The mains water circulation system consists of a buffer tank, to ensure immediate water supply, and another tank, that collects any unvaporized water droplets, which are then redirected to the sprinklers.
- **Main Advantage**
- Theoretically, the process described determines the minimum temperature of the cooling water as the wet bulb temperature of the room’s air but requires no additional refrigerant, thus minimizing the environmental impact of the unit.

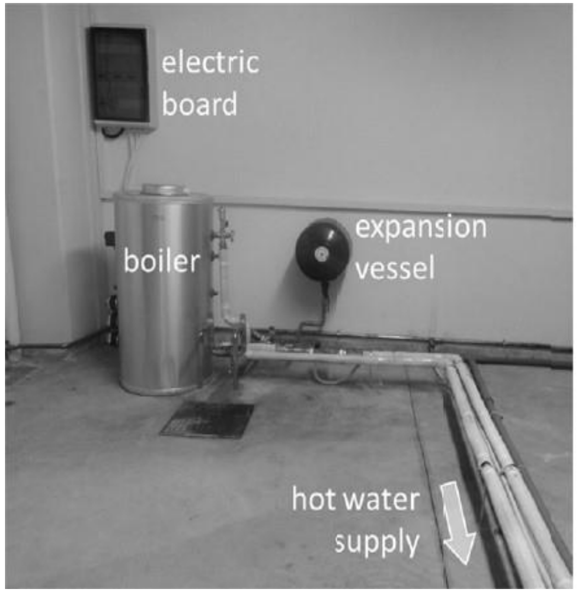




LDD Experimental Unit

Heating Source and Storage Tanks

- **Heating Source.**
- The heating source required for the supply of heated water into the regenerator consists of a 24kW boiler, equipped with an automatic thermostat which adapts to the heating demands of the system.
- The water from the boiler flows into a plate heat exchanger which comprises the thermal exchange bus between the water circulating inside the regenerator and the water from the boiler.
- **Storage Tanks**
- The two solution tanks serve to make the dehumidification and regeneration processes independent from each other, while also enabling the storage of the necessary energy for air conditioning over any desired period, in the form of a concentrated salt solution without any energy losses.
- Overflow protection, consisting of mechanical overflow switches operated by a rod mounted to a float, has also been installed in the tanks. Should the desiccant level exceed the permitted maximum level , the switch is triggered, the power supply for the subsystem gets interrupted and all pump circuits are switched off.



Data Acquisition System

DA Hardware

- The system consists of temperature pt100 sensors, relative humidity th100 sensors and various pressure or ΔP sensors (Tpmc 131,Dsg 500, Dcxl10ds, Scx15an).
- In addition, 4 data acquisition modules are also integrated.
- The system is completed with one data collector module.
- The data exchange between the modules and the collector is achieved through a serial RS485 configuration.
- Then, the collector, using an RS232 cable, sends the data through a RS232 -Usb converter to the control pc.
- All modules and sensors require a Vdc supply, thus implying the need to install a 24 Vdc as well as a 12 Vdc supplier.
- The data acquisition modules provide 7 data channels, which are differentially configured, providing the ability to measure voltage or current changes from the sensors.
- Most of the sensors use a two-wire configuration, providing either a 0-10 V or a 4-20 mA signal, except some pressure sensors which are connected accordingly to their pinout schematic.
- The communication protocol used for the system comprises a custom but simple request-reply protocol based on ASCII code and it is configured according to the manuals of the DA modules.

Table 1. Sensor Connection and Calibration Details

Unit	Sensor Type	Tag Name	Module Name (Address)	Channel	Operating Voltage	Output Signal	Gain/Offset
Absorber	Temperature	T_ABS_OUT_WATER	I7018 (30)	1	-	4-20 mA	553.191/ -263.021
		T_ABS_IN_AIR		2	-		
		T_ABS_OUT_AIR		3	-		
		T_ABS_IN_CONC		4	-		
		T_ABS_IN_DIL		5	-		
		T_ABS_IN_WATER		6	-		
	Humidity	RH_ABS_OUT	I7019R (24)	0	24Vdc	0-10 V	18.764/19.7835
		RH_ABS_IN		1			
	Pressure	P_AMBIENT		3	12Vdc		-44.333/0.202
	Differential Pressure	ΔP_ABS_AIR		4	24Vdc		0.0116/-0.0011
		ΔP_ABS_PACK		5			0.0121/-0.0018
	Pressure	P_ABS_WATER_BOT		6			0.1116/-0.6343
		P_ABS_WATER_TOP		7			0.0991/-0.4443
Regenerator	Temperature	T_REG_OUT_WATER	I7018 (21)	1	-	4-20 mA	-553.191/ -263.021
		T_REG_OUT_AIR_1		2	-		
		T_REG_IN_AIR		4	-		
		T_REG_OUT_AIR_2		5	-		
		T_REG_IN_DIL		6	-		553.191/ -263.021
		T_REG_OUT_CONC		7	-		
	Humidity	RH_REG_OUT	I7019 (23)	0	24Vdc		18.7640/19.784
	Differential Pressure	ΔP_REG_AIR		1	12Vdc		-15.294/208.87
	Humidity	RH_REG_IN		6	24Vdc		18.7640/19.784

Data Acquisition System

Sensor Positions

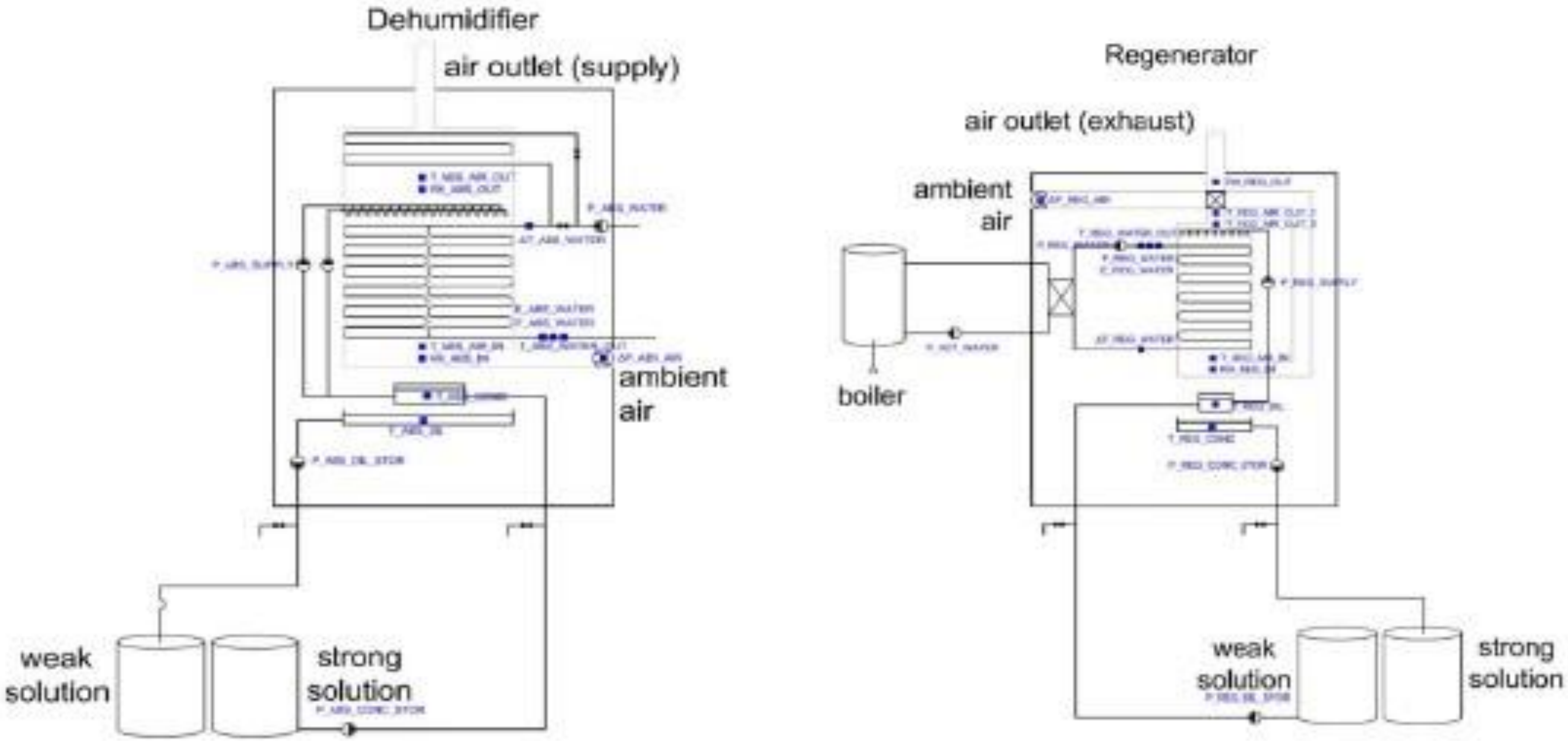
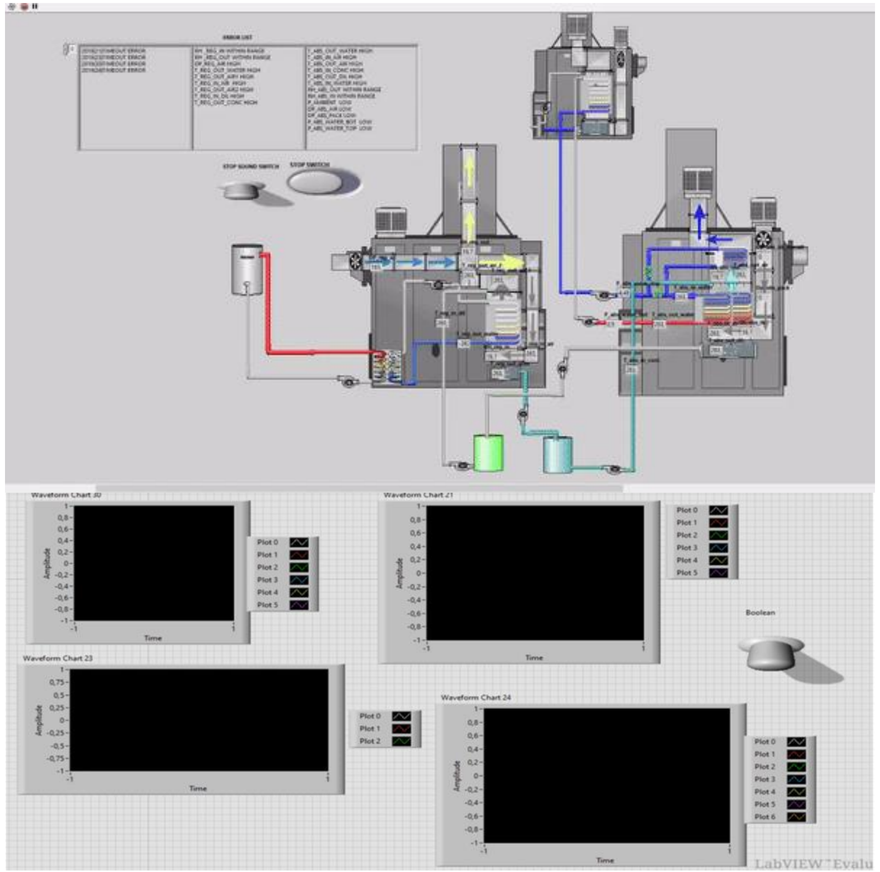


Figure 2. a) *Absorber sensors* b) *Regenerator sensors*

Data Acquisition System

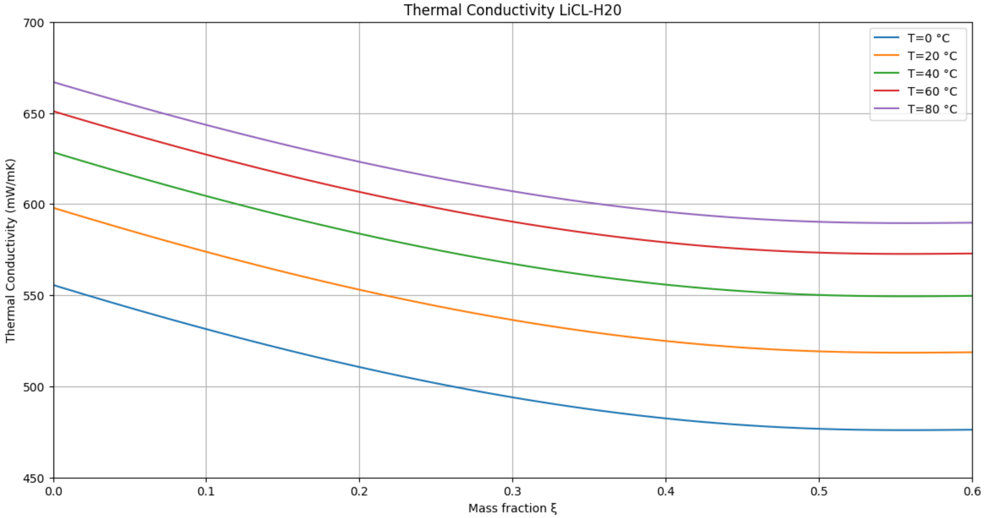
DA Software

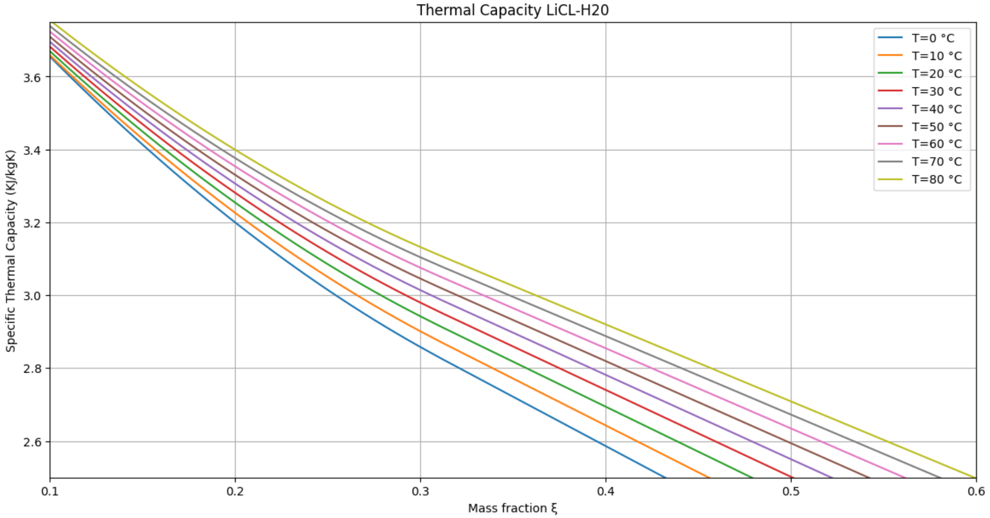
- A data parsing method has been also programmed in order to display the data in a readable number format.
- In addition, an alarm program has been created, containing high, low and timeout alarms.
- It is important to leave a gap of 300ms between each iteration for the program to function correctly.
- The final control screen program displays the functioning of the unit, using an animation for an easier understanding of the process.
- The measurements and the alarm status are also displayed in the final control screen. Should a malfunction occur, an alarm sound will be produced along with the appropriate alarm status.
- In a different program the data are displayed in a configurable chart format and exported in a spreadsheet format.



THE NON-ADIABATIC MODEL

- Based on energy and mass conversation laws, the non-adiabatic model describes coherently the coupled heat and mass transfer processes taking place inside an internally cooled, parallel plate liquid desiccant dehumidifier and regenerator.
- Specific thermodynamic libraries (such iapws and coolprops) are powerful tools that provide accurate results for properties of dry and humid air, liquid water and saturated water vapor and are therefore used in the current model.
- Additionally, basic thermodynamic parameters of the inlet desiccant solution and heat or mass transfer coefficients should be calculated from empirical equations as a function of the desiccant's temperature and concentration.





THE NON-ADIABATIC MODEL
Assumptions

- Basic geometric characteristics of the absorber packing
- Plate height equal to 0.5 m
- Plate length equal to 1m
- Plate thickness is 4.87 mm
- Wall thickness is 0.35 mm
- Distance between two consecutive plates equal to 3.3mm
- Additional assumptions for model simplification and model convergence.
- Heat and mass transfers occur only in the flow direction
- Temperature of the liquid desiccant is equal to the temperature of the plates
- Heat and mass transfer area equal to the specific surface of the packing
- Vapor pressure equilibrium between the vapor and the liquid at the interface
- Negligible heat transfer from liquid to vapor or from radiation, viscous dissipation, pressure gradients, concentration gradients or gravitational effects.

THE NON-ADIABATIC MODEL
Equations

- The following set of differential equations represents the gradients of air, solution and water temperatures inside the packing as well as the air absolute humidity, solution mass flow rate and concentration gradients for the absorber and regenerator respectively.

$$\left\{\begin{array}{l}
\dfrac{dT_a}{dA} = \dfrac{T_a - T_s}{C_{p,ma}}\left(\dfrac{a_a}{\dot{m}_a} - C_{p,st}{}^{sat}\dfrac{dW}{dA}\right) \\
\dfrac{dT_s}{dA} = -\dfrac{1}{\dot{m}_s C_{p,s}}\left[\begin{array}{l}\dot{m}_a\left[C_{p,s}(T_s - T_{s,in}) + C_{p,st}{}^{sat}T_s + \Delta h_{abs}\right]\dfrac{dW}{dA} + \\ a_a(T_s - T_a) + U(T_w - T_s)\end{array}\right] \\
\dfrac{dT_w}{dA} = \dfrac{U(T_s - T_w)}{\dot{m}_w C_{p,w}} \\
\dfrac{dW}{dA} = -\dfrac{K_G}{\dot{m}_a}\left(W^{sat} - W_{in}\right) \\
\dfrac{d\dot{m}_s}{dA} = \dot{m}_a\dfrac{dW}{dA} \\
\dfrac{dX}{dA} = -\dfrac{\dot{m}_a}{\dot{m}_s}X\dfrac{dW}{dA}
\end{array}\right\}$$

Dehumidifier

$$\left\{\begin{array}{l}
\dfrac{dT_a}{dA} = \dfrac{T_s - T_a}{C_{p,ma}}\left(\dfrac{a_a}{m_a} + C_{p,st}{}^{sat}\dfrac{dW}{dA}\right) \\
\dfrac{dT_s}{dA} = -\dfrac{1}{\dot{m}_s C_{p,s}}\left[\begin{array}{l}m_a\dfrac{dW}{dA}\left[-C_{p,s}(T_s - T_{s,in}) + C_{p,st}{}^{sat}T_s + \Delta h_{evap}\right] + \\ +a_a(T_a - T_s) + U(T_s - T_w)\end{array}\right] \\
\dfrac{dT_w}{dA} = \dfrac{U(T_w - T_s)}{\dot{m}_w C_{p,w}} \\
\dfrac{dW}{dA} = \dfrac{K_a}{m_a}\left(W^{sat} - W_{in}\right) \\
\dfrac{d\dot{m}_s}{dA} = \dot{m}_a\dfrac{dW}{dA} \\
\dfrac{dX}{dA} = -\dfrac{m_a}{m_s}X\dfrac{dW}{dA}
\end{array}\right\}$$

Regenerator

The system can be solved as a boundary equation problem using the appropriate library with the following boundary conditions

$$\left\{\begin{array}{l}
\left(T_a\right)_{z=0} = T_{a,in} \\
\left(T_s\right)_{z=L} = T_{s,in} \\
\left(T_w\right)_{z=L} = T_{w,in} \\
\left(W\right)_{z=0} = W_{in} \\
\left(\dot{m}_s\right)_{z=L} = \dot{m}_{s,in} \\
\left(X\right)_{z=L} = X_{in}
\end{array}\right\}$$

Experimental Validation of the Model

- The required duration for the stable functioning of the unit is 3 hours.
- All measurements of relative humidity are transformed into absolute humidity, using the appropriate library, for an easier comparison of the experimental and theoretical results.
- The tables contain all the results for the absorber and regenerator respectively.

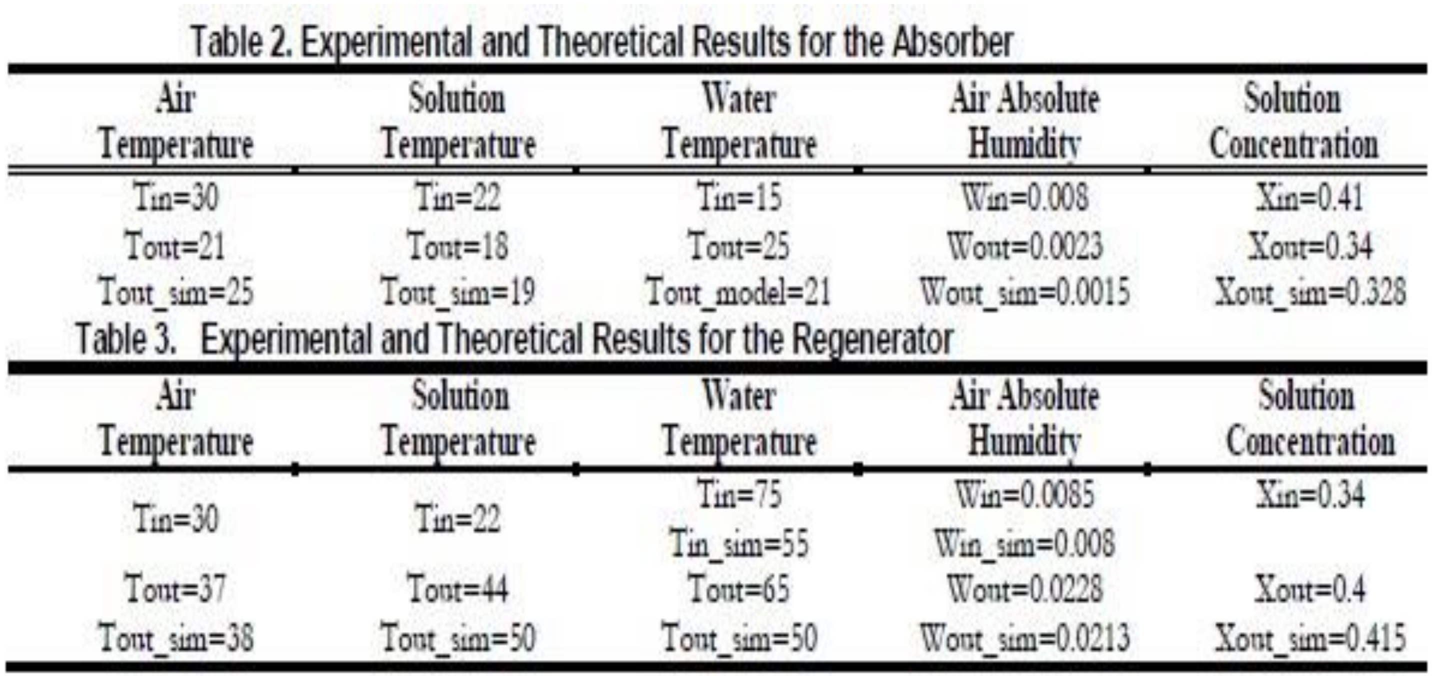


Table 2. Experimental and Theoretical Results for the Absorber

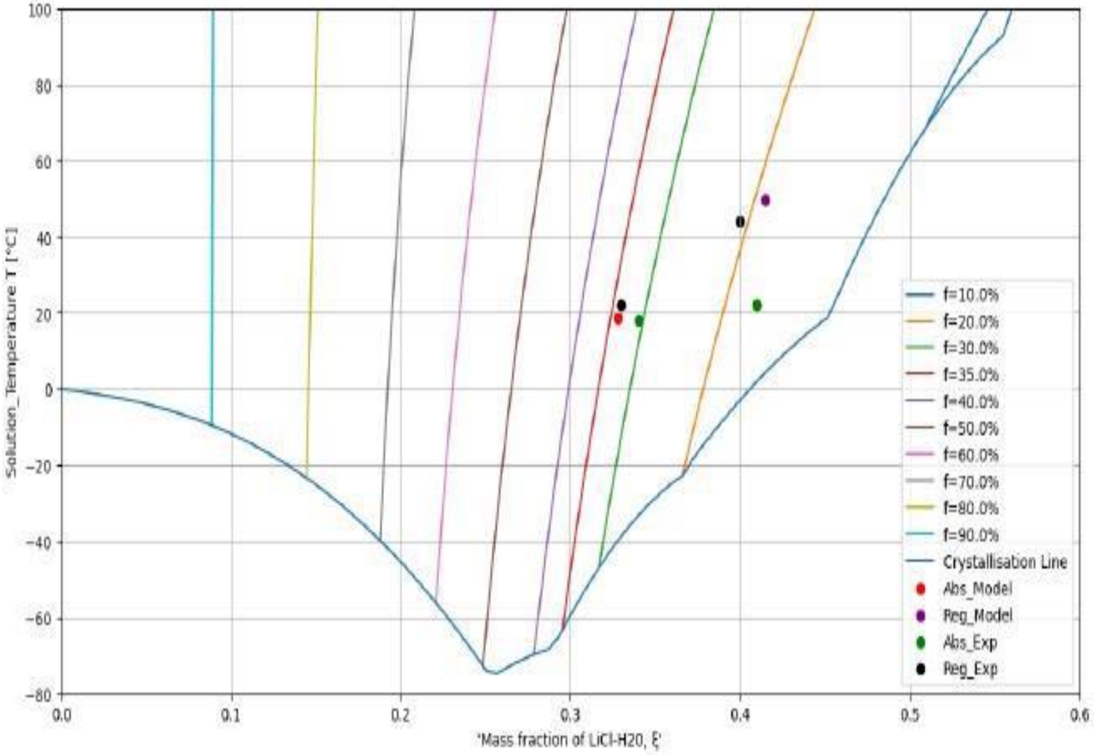
Air Temperature	Solution Temperature	Water Temperature	Air Absolute Humidity	Solution Concentration
Tin=30	Tin=22	Tin=15	Win=0.008	Xin=0.41
Tout=21	Tout=18	Tout=25	Wout=0.0023	Xout=0.34
Tout_sim=25	Tout_sim=19	Tout_model=21	Wout_sim=0.0015	Xout_sim=0.328

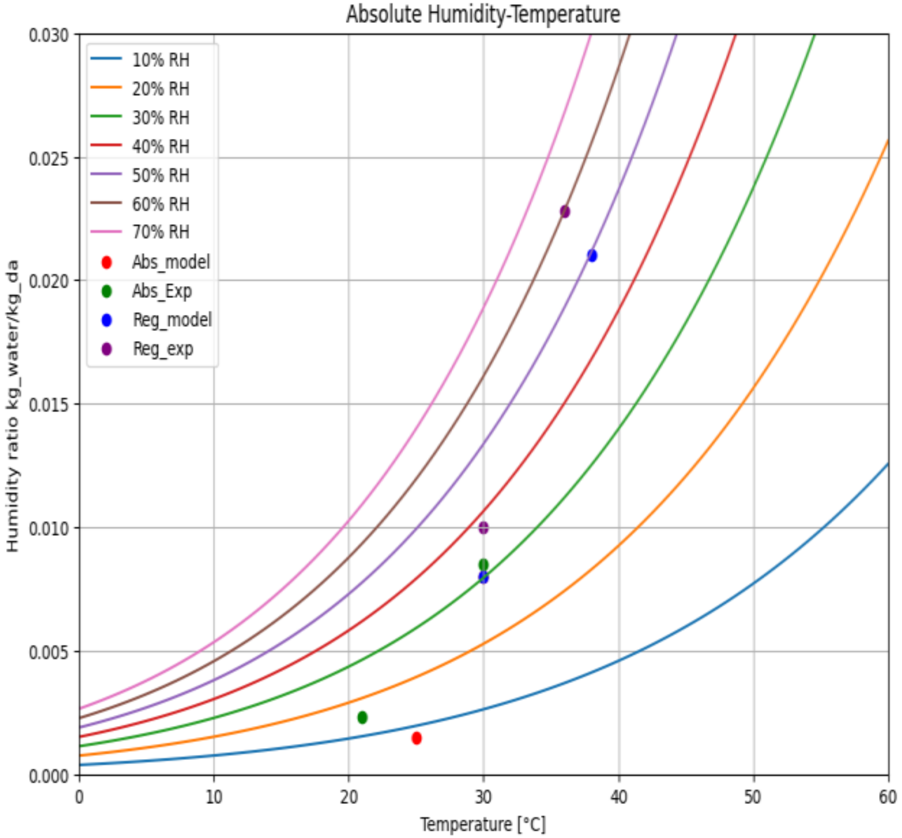
Table 3. Experimental and Theoretical Results for the Regenerator

Air Temperature	Solution Temperature	Water Temperature	Air Absolute Humidity	Solution Concentration
Tin=30	Tin=22	Tin=75	Win=0.0085	Xin=0.34
		Tin_sim=55	Win_sim=0.008	
Tout=37	Tout=44	Tout=65	Wout=0.0228	Xout=0.4
Tout_sim=38	Tout_sim=50	Tout_sim=50	Wout_sim=0.0213	Xout_sim=0.415

Experimental vs Theoretical Results

The figures ,derived from the data in Tables 2 and 3, show the variation of inlet and outlet absolute humidity (Win, Wout) in relation to air temperature (Tin, Tout).This includes data for both the experimental setup and the model simulated results (Woutsim, Toutsim). The variation in solution concentration (Xin, Xout) is also presented in relation to its temperature, comparing experimental results with theoretical model predictions for each unit.





Experimental vs Theoretical Results

Conclusions from the Comparison

- The model **underestimates the cooling ability** of the dehumidifier as it does not consider the further cooling of the air exiting the unit through the air-water heat exchanger installed at the top of the absorber.
- There seems to be a **difference between the liquid desiccant temperature of the model and the experiment**, which might indicate some **wrong calibration of the sensors**.
- The **difference between the simulated and experimental measurement of cooling water exit temperature** occurs due to possible **underestimation of the total heat exchange coefficient U**, which originates from **false assumptions about the plates' thermal conductivity and water's heat transfer coefficient**.
- The difference between the simulated and experimental value of outlet air's absolute humidity can be mitigated with appropriate temperature conversions.
- Inaccuracies concerning the solution concentration for both the absorber and regenerator, occur due to the lack of a constant solution mass flow meter in the current data acquisition system.

Conclusions and Further Research

Summary

- It is of vital importance to obtain data from measurements is essential for optimizing open cycle liquid desiccant dehumidification systems, which are distinguished by their exceptionally low environmental impact.
- The goal of this work was to validate the existing theoretical model, through experimental measurements obtained by a data acquisition system, for a liquid desiccant dehumidifier and regenerator that can be used for a future energy and exergy performance analysis.
- The data acquisition process encompasses sensor position, calibration and the creation of a control screen, where
- The validation process involved implementing the model using an advanced programming language, due to its plethora of libraries for thermodynamic analysis, and comparing the experimental data with theoretical results.

Conclusions and Further Research

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