THERMODYNAMIC STUDY OF A DESICCANT AIR-HANDLING UNIT USING THERMOPSYCHRO SOFTWARE

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Summary: *The exergy analysis of thermal systems is a methodology whose principles are clear. However, its application to air conditioning systems has not been sufficiently extended, perhaps due to the difficult understanding of the exergy concept in these cycles and the diversity of criteria for the definition of the reference temperature for the calculation of the irreversibilities in the different elements that compose the installation. In this work the thermodynamic study of an air conditioning cycle with dehumidification by rotary desiccant is presented, using the THERMOPsychro software. The energy and exergy diagrams of the global installation are obtained, identifying the elements where the highest exergy destruction and the lowest exergy efficiency are obtained, indicating the possible improvement actions necessary to try to reduce these losses due to irreversibilities and to contribute to their optimization and to a more rational use of energy.*

Key words: THERMOPsychro, air conditioning, air handling unit, exergy, desiccant, desiccant.

1. INTRODUCTION

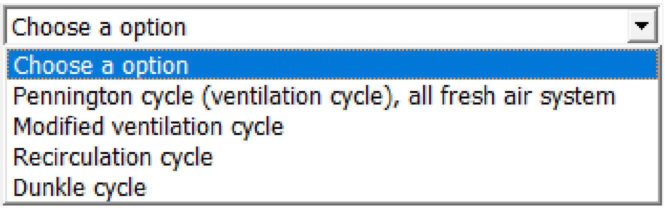
Currently, the desiccant air conditioning system is an alternative to use surplus energy from industrial facilities and/or solar energy and try to solve environmental and energy problems resulting from the use of conventional vapor compression in air conditioning systems. These systems can maintain the thermal comfort of a room with the optimization of solar thermal energy and minimal use of electrical energy [1]. A typical system combines a dehumidification system using a rotating desiccant wheel, with direct or indirect evaporative systems, which allow filtered and cooled air providing temperature and humidity conditions conducive to ambient thermal comfort, even in equatorial and tropical climates [2].

Energy analysis is a powerful tool to optimize the efficiency of processes and systems, with the objective of reducing the consumption of resources, increasing their use, with a lower emission of pollutants into the environment, and seeking to detect inefficiencies in design, operation and maintenance. [3] developed a procedure for energy and exergy analysis of open cycle desiccant refrigeration systems applied to an experimental unit operating in ventilation mode with natural zeolite as desiccant. The desiccant rotary exchanger has the highest percentage of total exergy destruction at 33.8%, followed by the heating system at 31.2 %. The rotary regenerator and evaporative coolers account for the rest of the exergy destruction. [4] performed an energy and exergy analysis of a desiccant cooling system integrated with an air-based thermal energy storage unit using phase change materials and a photovoltaic/thermosolar air collector. [5] developed a matlabt/simulink model of a desiccant liquid evaporative cooling system and analyzed it using the exergy analysis method, verifying that this is a very useful tool for the design, analysis and optimization of these systems.

In this work a desiccant air conditioning system is studied and analyzed from the thermodynamic point of view, under the perspective of the first and second principles. By means of the software called THERMOPsychro developed by the author of the work, the thermodynamic study of the system is carried out.

2. SOFTWARE THERMOPSYCHRO

The software provides a detailed solution, both numerical and graphical, of the thermodynamic states, as well as the main variables for thermal design, allowing the user to choose the input variables, which makes the software a very versatile tool. THERMOPsychro (www.thermosuite.com) provides the energy and exergy diagrams, presenting the losses due to irreversibilities in each equipment of the installation, which is key for the improvement and optimization of the air handling units. The information provided by these diagrams is very valuable, providing the efficiencies of each process, sensible and latent heats, thermodynamic properties of all states, most relevant design factors, water flow rates, exergy destroyed in each process, psychrometric diagram, summary of results, etc. It is a tool for teaching and industrial use, facilitating the student to acquire knowledge in a dynamic way, which improves the learning experience and helps the engineer or technician of a company to design and/or improve this type of installations.



ThermoPsychro

Figure 1. Desiccant psychrometric units.

3. ROTARY DESICCANT DEHUMIDIFICATION

A rotary desiccant-based air conditioning system combines different technologies, such as desiccant dehumidification, evaporative cooling, refrigeration and regeneration. Desiccant air conditioning systems are heat-driven refrigeration units that can be used as an alternative to conventional mechanical vapor compression and absorption refrigeration systems. Their operation is based on the use of a rotary dehumidifier in which air is dehumidified. Subsequently, this dry air is first cooled in a sensible heat exchanger (rotary regenerator) and then further cooled in an evaporative cooler. The resulting cooled air is sent to the room. The system can be operated in closed cycle or more commonly in open cycle in ventilation or recirculation modes. In this system, an external heat source is required to regenerate the desiccant, so waste heat at a temperature between 60°C and 95°C can be used.

The cycle analyzed is shown in Fig. 2, the Pennington cycle, for which a patent was filed in 1955. To obtain state 8, a flow of water (0.5 kg/s) heated to 70 ºC is used. This heat is supplied to the unit by a heat source, which could also be a gas burner, a solar collector, geothermal energy or waste heat from conventional fossil fuel systems. The type of heat source must be known to determine the exergy destruction and exergy efficiency of the exchanger. This figure presents the remaining values of the input variables, comfort levels of T_5=25 °C and Φ_5=60 % RH, outdoor conditions of T_1=31.5 °C and Φ_1=32.9 % RH, air flow rate of 0.8 kg/s, etc.

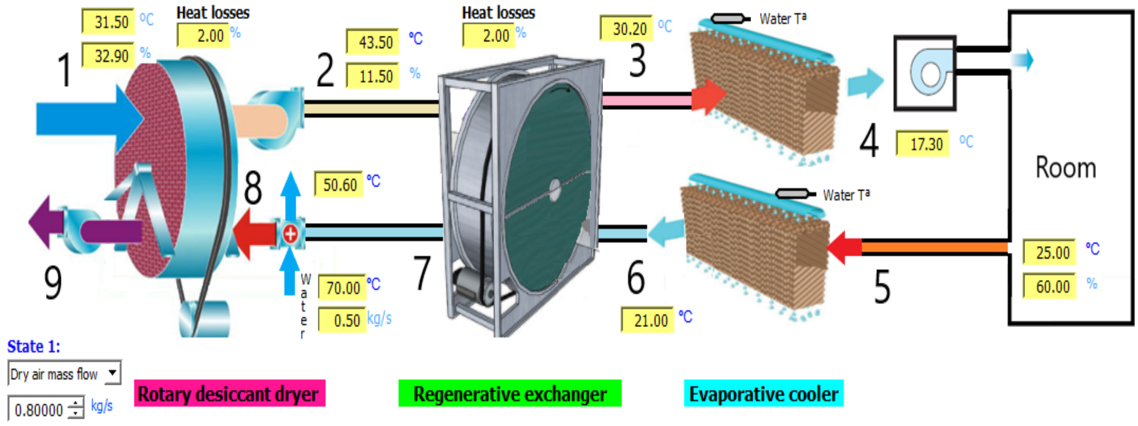


Figure 2. Pennington cycle (ventilation cycle).

Ambient air (state 1) is fresh process air that initially passes through a desiccant wheel, where moisture is removed and the temperature is increased due to the adsorption heat effect. This hot, dry air is then cooled significantly in a regenerative heat exchanger. The process air is then evaporatively cooled to supply air condition by passing it through a direct evaporative cooler. On the recirculated air side, the air in state 5 is cooled and humidified in another direct evaporative cooler. This air is then sensitively heated in the regenerative heat exchanger with the process air. The resulting air stream is then heated from state 7-8 by the external heat source. After regeneration in the desiccant wheel, the air is discharged in state 9.

4. RESULTS AND DISCUSSION

The dead state is defined for P_0=101325 Pa, T_0=4 ºC and Φ_0=70 % RH. Fig. 3 shows the thermodynamic variables of each state, including thermal, mechanical, chemical and total exergy. While Fig. 4 shows the change of the most relevant properties in each process, entropy generated, exergy destroyed, sensible and latent heats, energy and exergy efficiency, water temperature and flow rate, humidifier efficiency, CSHF, HSHF and exchanger efficiency. The properties of moist air and water are based on ASHRAE-RP1485 from ASHRAE, Hermann et al [7]. A heat loss in both heat exchangers of 2 % has been considered, incorporating (in the Grassmann diagram) the exergy destruction due to this reason to losses due to internal irreversibilities in each device. Fig. 5 shows the psychrometric diagram of the installation. Figs. 6 and 7 show the results of the applied thermodynamic, energy and exergy balances, respectively. In the energy analysis, the sensible and latent heats in the evaporative coolers are almost identical (they are processes at constant wet bulb temperature, almost isoenthalpic), but one incoming and one outgoing.

Properties	State 1	State 2	State 3	State 4	State 5	State 6	State 7	State 8	State 9	Units
Dry bulb temperature	31.5	43.5	30.2	17.3	25	21	34.0946	83.1913	70.9366	ºC
Relative humidity	32.9	11.5	23.6601	94.3666	60	86.9539	40.2258	3.99319	8.14702	%
Humidity at saturation	29.7523	59.7257	27.5318	12.3652	20.0822	15.6547	34.6853	706.384	293.49	g/kg air
Specific humidity	9.48408	6.33045	6.33045	11.6555	11.8957	13.5678	13.5678	13.5678	16.7858	g/kg air
Degree of saturation	0.318768	0.105992	0.229933	0.94261	0.592349	0.866693	0.39117	0.0192075	0.0571939	
Dew temperature	13.2412	7.27181	7.20468	16.3841	16.6986	18.7429	18.6672	18.6571	22.0075	ºC
Wet bulb temperature	19.6853	21.0035	16.7089	16.7089	19.4698	19.4698	23.3228	33.9997	33.2059	ºC
Density	1.14156	1.10371	1.15229	1.19344	1.16208	1.17483	1.12473	0.969458	0.998999	kg/m³
Specific volume	0.875992	0.906031	0.867839	0.837916	0.860526	0.851187	0.889106	1.0315	1.001	m³/kg
Saturation pressure	4625.85	8877.76	4295.24	1975.22	3169.38	2487.79	5352.31	53883	32485	Pa
Vapor pressure	1521.9	1020.94	1016.26	1863.95	1901.63	2163.23	2153.01	2151.65	2646.56	Pa
Enthalpy	56.0715	60.1981	46.565	47.0388	55.5757	55.7204	69.0809	119.828	115.617	kJ/kg
Entropy	0.1994	0.210172	0.16619	0.169706	0.198727	0.199506	0.243892	0.397022	0.38964	kJ/kg K
Air pressure	99803.1	100304	100309	99461.1	99423.4	99161.8	99172	99173.4	98678.4	Pa
Total exergy	1.7479	2.73709	1.30218	1.05624	1.55426	1.5636	2.62021	10.9185	8.90108	kJ/kg
Thermal exergy	1.31148	2.62179	1.18688	0.317977	0.779315	0.516968	1.57357	9.87185	7.26144	kJ/kg
Mechanical exergy	0	0	0	0	0	0	0	0	0	kJ/kg
Chemical exergy	0.436428	0.115304	0.115304	0.738261	0.774945	1.04663	1.04663	1.04663	1.63964	kJ/kg
Dry air mass flow	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	kg/s
Volume flow	0.700794	0.724825	0.694271	0.670332	0.688421	0.680949	0.711285	0.825203	0.800801	m³/s

Figure 3. Thermodynamic variables.

Results	1-2	2-3	3-4	5-6	6-7	7-8	8-9	Room	Net	Units
Delta-RH	-21.4	12.1601	70.7065	26.9539	-46.728	-36.2326	4.15383	-34.3666	-24.7529	%
Delta-Tdb	12	-13.3	-12.9	-4	13.0946	49.0967	-12.2547	7.70001	39.4366	°C
Delta-Twb	1.31815	-4.29456	0	0	3.85306	10.6768	-0.793793	2.76086	13.5205	°C
Delta-v	0.0300391	-0.0381926	-0.0299232	-0.00933975	0.037919	0.142398	-0.0305021	0.0226108	0.125009	m³/kg
Delta-h	4.12659	-13.6331	0.473824	0.14473	13.3605	50.747	-4.2108	8.5369	59.5456	kJ/kg
Delta-s	0.0107724	-0.0439822	0.00351563	0.000778481	0.0443858	0.153131	-0.00738192	0.0290215	0.190241	kJ/kg °
Sensible heat	9.84737	-10.9065	-10.5074	-3.4019	10.6884	40.5976	-10.1455	6.23046	32.4025	KW
Latent heat	-6.5461	0	10.8864	3.51769	0	0	6.77682	0.599054	15.2339	kW
Total heat	3.30127	-10.9065	0.379059	0.115784	10.6884	40.5976	-3.36864	6.82952	47.6365	kW
Energy efficiency	98	98	100	100		100				%
Generated entropy	0.00296796	0.00109198	0.00295951	0.000680659		0.000745881	(Inc. at 1-2)	0.000545086	0.00899108	kW/°C
Irreversibility	0.822569	0.302643	0.820228	0.188645		0.206721	(Inc. at 1-2)	0.15107	2.49188	kW
Exergy efficiency	91.8824	91.2037	50.7435	86.8954		99.7244		82.1216		%
Water mass flow			0.00426007	0.00133775						kg/s
Water temperature			16.7089	19.4698						°C
Humidifier efficiency			95.6188	72.3299						%
Coil sensible HF (CSHF)			0.491141	0.491634						
Room sensible HF (RSHF)								0.912285		
Heat exchanger effectiveness	23.2147	59.1111				44.4678				%

Figure 4. Results obtained.

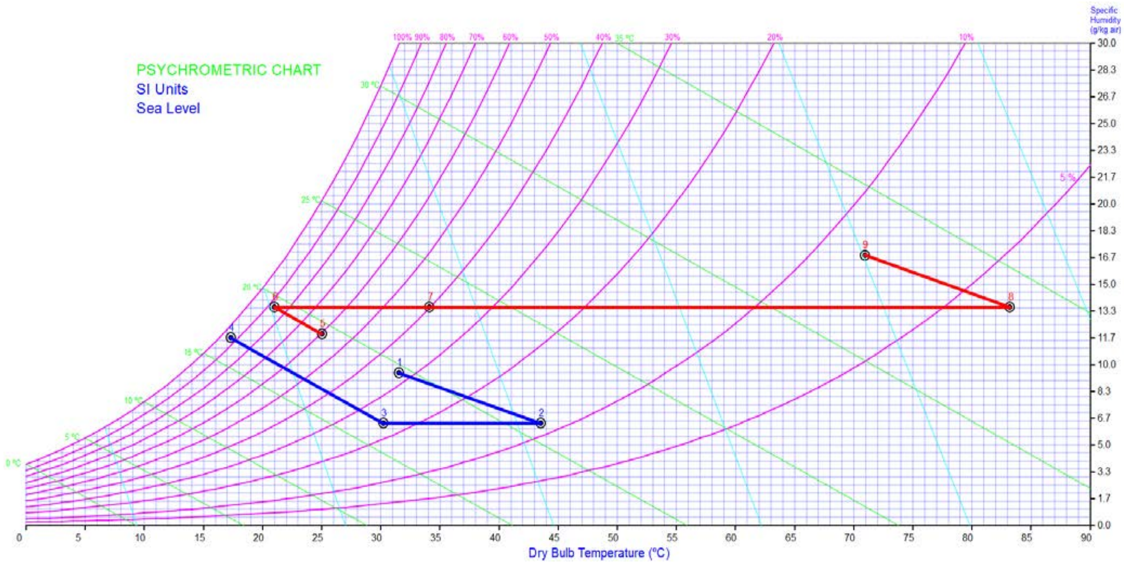


Figure 5. Psychrometric diagram of the process.

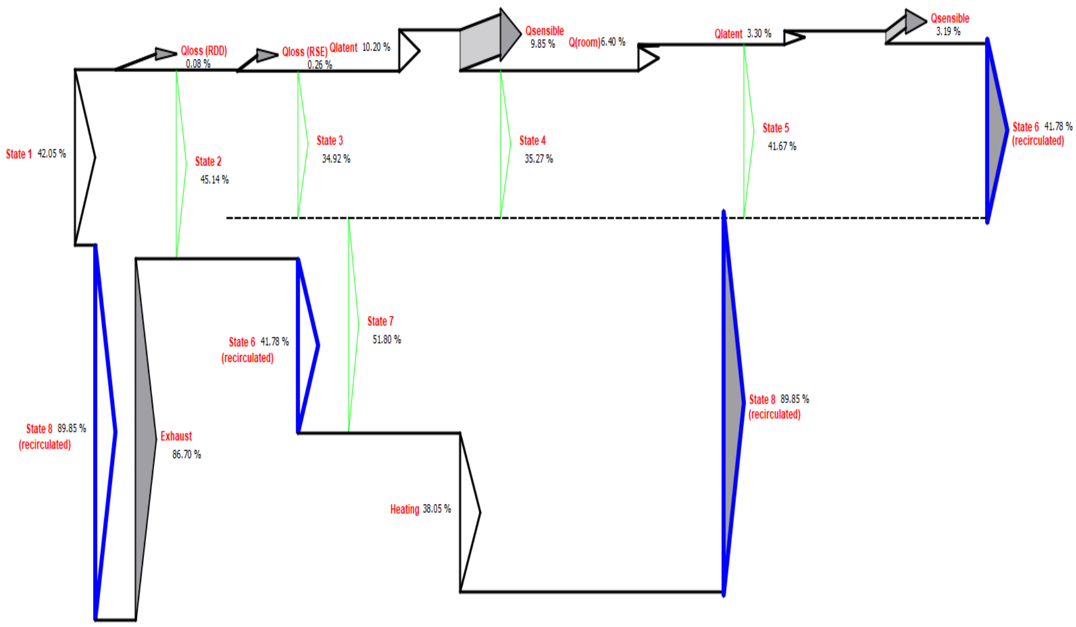


Figure 6. Energy diagram.

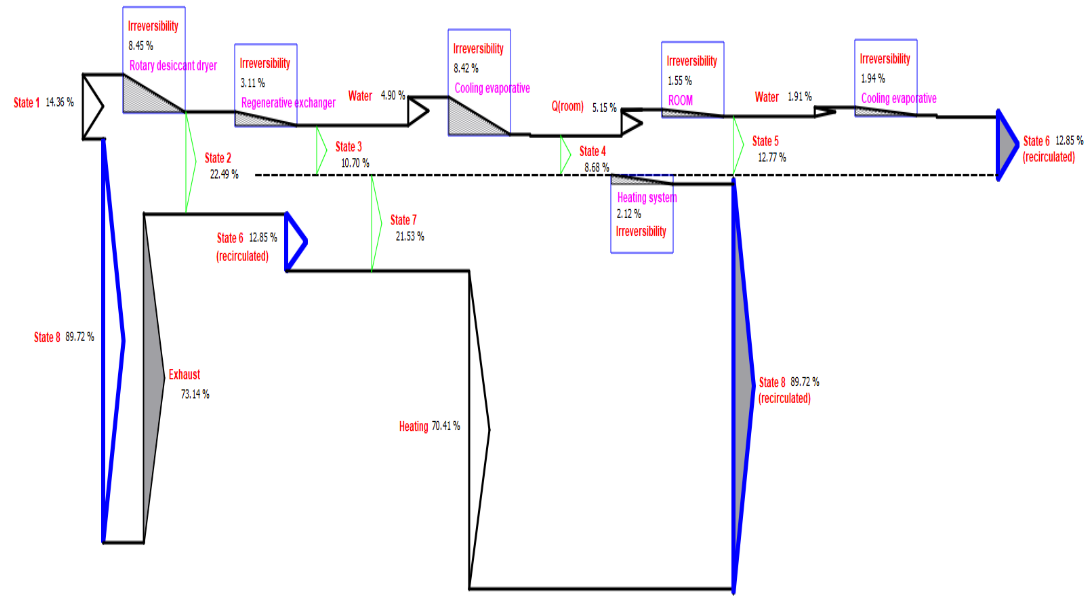


Figure 7. Grassmann's exergy diagram.

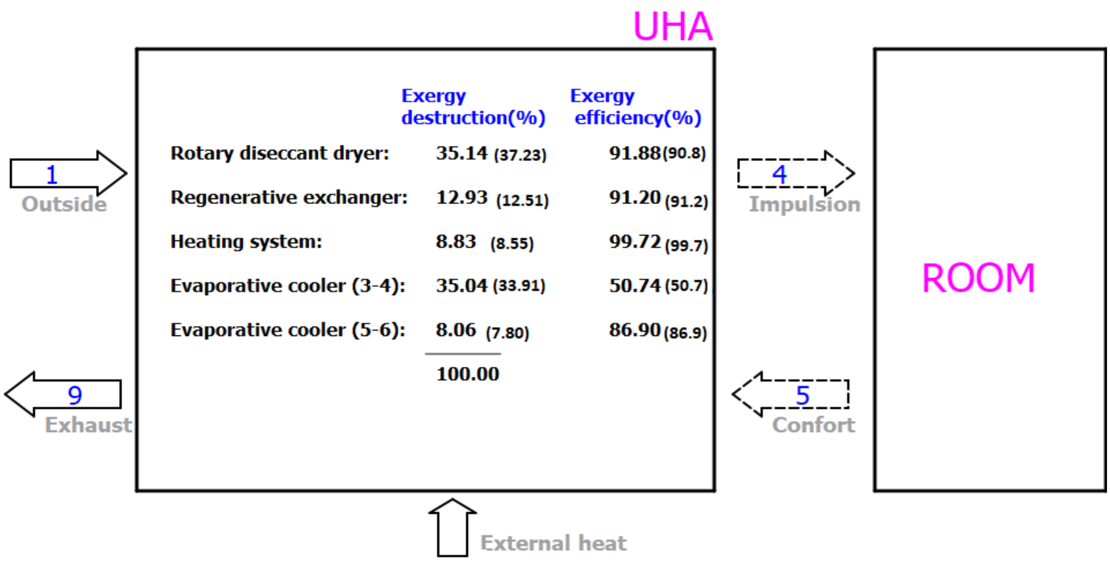


Figure 8. Summary of exergy destruction in the elements of the installation.

Fig. 8 shows a summary of the losses due to irreversibilities of only the five essential devices (not including the fan, nor the losses due to air exhaust, nor in the room), for the case of the present work and in parentheses for the case of a drier and warmer climate (T_1=32.5 ºC and Φ_1=22.9 % RH). It is observed that when the climate is drier and warmer, the exergy destroyed of the dissecting rotary heat exchanger increases, and with it also its exergy efficiency. While in the other elements the exergy destroyed decreases less markedly than the increase in the rotary heat exchanger, although their exergy efficiencies are not altered, since the ratio between the outgoing exergy and the incoming exergy remains constant. The device with the highest losses due to irreversibilities is the Rotary Desiccant Dryer (35.14 %), mainly due to the mixing of the process and regeneration air streams, the transfer of energy and mass at a finite temperature difference and the difference in pressures between the desiccant matrix and the regeneration air. To minimize irreversibilities in this equipment, one possible strategy could be to pursue isothermal dehumidification. If the air were to flow alternately through infinite and intercooled desiccant wheels, the process would more closely resemble an isothermal process. It is known by different authors that among the parameters that influence the performance of the dehumidifier are the desiccant material, its own geometry, the regeneration temperature, the ratio between the process air and regeneration air flows and the rotational speed of the dehumidifier.

On the other hand, in the evaporative cooler (3-4) there are also losses due to irreversibilities of 35.04 % which are justified by the large mass transfer involved at a finite temperature difference. The regenerative heat exchanger also contributes significantly to exergy destruction, (12.92 %) which means that these heat exchange mechanisms (without mass exchange) energy efficient heating methods, such as heat pumps, could further improve the exergy performance of such systems. In the heating system, the generation of irreversibilities (8.83 %) is justified by the temperature difference between the streams involved. This is equipment in which the margin for improvement in terms of irreversibilities is much more limited than in the rotary dehumidifier. Finally, the evaporative cooler (5-6) with a lower humidity variation than the previous one, suffers an 8.06 % exergy destruction.

5. CONCLUSIONS

The analysis presented in this paper shows how the use of THERMOPsychro and exergy analysis provide valuable information in the analysis of desiccant air conditioning systems, on the devices where the greatest exergy losses occur, pointing out where efforts should be directed for their minimization and consequent improvement.

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