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DESICCANT DEWPOINT COOLING SYSTEM INDEPENDENT OF EXTERNAL WATER SOURCES

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ABSTRACT

This paper presents a patent pending technical solution aiming to make desiccant cooling systems independent of external water sources, hence solving problems of water availability, cost and treatment that can decrease the system attractiveness. The solution consists in condensing water from the air that regenerates the desiccant dehumidifier, and using it for running the evaporative coolers in the system. A closed regeneration circuit is used for maximizing the amount of condensed water. This solution is applied to a system with a desiccant wheel dehumidifier and a dew point cooler, termed desiccant dew-point cooling system, for demonstrating its function and applicability. Simulations are carried out for varying outdoor conditions under constant supply conditions. The results show that the system is independent of external water supply for the majority of simulated conditions. In comparison to the desiccant dew-point system without water recovery, the required regeneration temperature increases and the system thermal efficiency decreases.

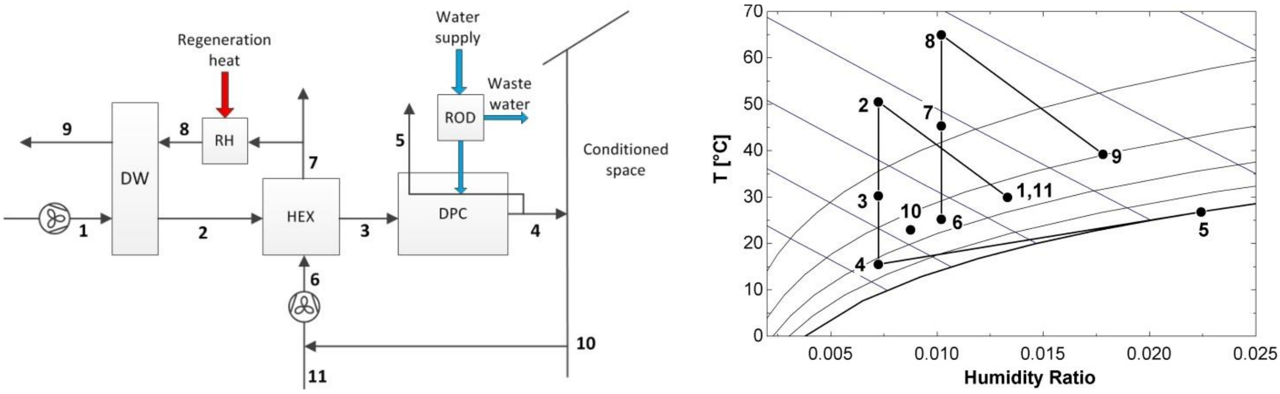
1. INTRODUCTION

Desiccant Cooling (DEC) systems can be employed in air conditioning applications requiring both dehumidification and cooling as an alternative to cooling-based dehumidification technologies. DEC systems consume heat for regenerating desiccant dehumidifiers, water for running evaporative coolers, and electricity for running auxiliaries such as fans and pumps. DEC systems have potential for reducing energy consumption and environmental impact in comparison to cooling-based dehumidification technologies. In fact, DEC systems handle latent loads more efficiently, do not use harmful refrigerants and can run on heat from cheap and clean renewable heat sources or waste heat as explained by Daou et al. (2006).

However water for running evaporative coolers is not available in all locations worldwide, limiting the applicability of DEC systems. If available, water has a cost and needs to be demineralized for ensuring a correct operation of evaporative coolers, resulting in increased operational costs and level of maintenance. This paper presents a patent pending technical solution to these problems that generates from the idea of recovering the moisture removed from the air by the adsorption process and using it to feed the evaporative coolers in the system. This solution is applied to a specific desiccant cooling system, termed Desiccant Dew-point Cooling (DDC) system.

1.1. Desiccant Dew-point Cooling system

The considered DDC system refers to the work by Bellemo (2011) and it is constituted by a Desiccant Wheel (DW), a Regeneration Heater (RH), an air-to-air Heat Exchanger (HEX), a Dew Point Cooler (DPC), a Reverse Osmosis Device (ROD) for water demineralization, and the required auxiliaries. Similar DEC systems were proposed by Jain et al. (1995) and Goldsworthy and White (2011). A schematic diagram and a psychrometric description of the DDC system are shown in Figure 1.



a) Schematic diagram b) Psychrometric description

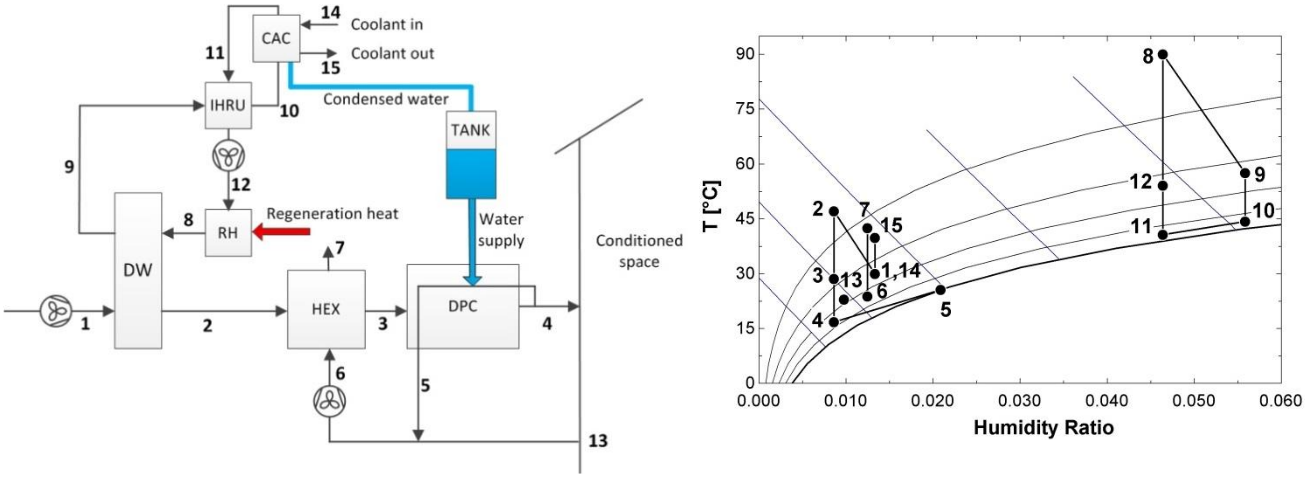
Figure 1. DDC system

Referring to Figure 1, outdoor air (1) is dehumidified in the DW to (2), pre-cooled in the HEX to (3), and further cooled in the DPC to the supply conditions (4). The DPC is an indirect evaporative cooler that uses a fraction of the cooled primary airstream as its secondary airstream. Thus the DPC cools the dehumidified air without adding moisture to it, and the lowest achievable temperature is the dew point of the primary airstream. As a drawback, the fraction of primary airstream recirculated into the DPC as secondary air also has to be dehumidified and pre-cooled in the system. The water supplied to the DPC is demineralized in the ROD, which wastes part of the water supplied in the reverse osmosis process. The secondary airstream in the DPC is simultaneously heated and humidified to (5) and exhausted to the outdoor. The airflow exhausted from the conditioned space (10) and some outdoor air (11) are mixed (6) in order to obtain an airflow rate equal to the process airflow rate, and heated in the HEX to (7). Depending on the airflow rate required for regenerating the DW, a part of the airflow in (7) can be exhausted to the outdoor, while the remaining part is heated to (8) in the RH and, after regenerating the DW, is exhausted to the outdoor (9).

A previous study by Bellemo et al. (2013) showed that the DDC system can have lower energy consumption and environmental impact than electric and absorption chillers for increasing latent loads, and when cheap and clean heat sources are available. However the DDC system consumes a high amount of demineralized water.

1.2. Desiccant Dew-point Cooling system with Desorbed Water Recovery

The Desiccant Dew-point Cooling with Desorbed Water Recovery (DDC-DWR) system uses a closed regeneration circuit where the regeneration air is cooled below its dew point for condensing the moisture desorbed from the DW. The regeneration air is cooled in an air-to-air Condensation Air Cooler (CAC) that uses outdoor air as coolant. The condensed water is collected into a tank and it can be directly used to run the DPC. In fact, the condensed water is equivalent to distilled water, hence does not need any further demineralization process. When the amount of condensed water exceeds the amount of consumed water, the remaining condensed water is stored in the tank, acting as a buffer in the opposite situation. An additional Internal Heat Recovery Unit (IHRU) is added in the closed regeneration circuit. A schematic diagram and a psychrometric description of the DDC-DWR system are shown in Figure 2.



a) Schematic diagram b) Psychrometric description

Figure 2. DDC-DWR system

Referring to Figure 2, the regeneration air is cyclically heated in the RH to (8), used to regenerate the DW to (9), pre-cooled in the IHRU to (10), dehumidified in the CAC to (11), and pre-heated in the IHRU to (12). The IHRU allows reducing the amount of sensible heat to be removed from the regeneration air in the CAC for achieving condensation, and also reducing the amount of regeneration heat required in the RH. Point (10) should approach saturation with no condensation occurring in the IHRU.

Figure 2b shows the regeneration air has very high moisture contents in comparison to the DDC system in Figure 1b, the reason being that the temperature and type of coolant used in the CAC (here being outdoor air) sets the working conditions of the regeneration air. Increased humidity of the regeneration air requires a higher regeneration temperature for achieving the same amount of dehumidification in the DW. For the same reason, in the DDC-DWR system, the cold side of the HEX is a mix of the airflow exhausted from the conditioned space (13) and the exhaust DPC secondary airflow (5). The use of the exhaust DPC secondary airstream leads to lower temperatures but higher humidity contents in (6) than mixing with outdoor air, thus enhancing the pre-cooling of the process airstream without increasing the regeneration temperature.

2. MODEL FORMULATION

2.1. Model formulation

The components in the DDC system are modelled defining their effectiveness. Pressure drops in the components and the corresponding auxiliary power consumption are neglected. The models are implemented in Engineering Equation Solver (EES), which is used for simulations. In the following, the numbering of the state points adopted in Figure 2 is used in the reported equations.

2.1.1. Desiccant wheel

A DW operates with two airstreams flowing from opposite directions across two separate sections. The process airstream is dehumidified via the adsorption process, while the regeneration airstream removes moisture from the desiccant via the desorption process. The inlet relative humidity and enthalpy of the two airstreams determine the theoretical physical limits of their outlet conditions as indicated by Goldsworthy and White (2012). Adsorption is an exothermic process, hence the process air enthalpy increases, while during desorption the regeneration air enthalpy decreases.

The DW model assumes the process airstream outlet enthalpy increases linearly by 10% of the inlet value at the lowest possible relative humidity, i.e. the regeneration air inlet relative humidity. Energy and mass balances around the whole component are:

$$(h_2 - h_1) + f_{reg}(h_8 - h_9) = 0 \quad (1)$$

$$(x_2 - x_1) + f_{reg}(x_8 - x_9) = 0 \quad (2)$$

and the regeneration fraction and dehumidification effectiveness are defines as:

$$f_{reg} = \frac{\dot{m}_{a,8}}{\dot{m}_{a,1}} \tag{3}$$

$$\varepsilon_{DW,process} = \frac{x_2 - x_1}{x_2^* - x_1} \tag{4}$$

The superscript * is used to indicate the lowest achievable humidity ratio in the model.

2.1.2. Dew point cooler

The DPC is modelled applying energy and mass balances around the whole component and introducing a dew point effectiveness:

$$(h_4 - h_3) + f_{rec}(h_4 - h_5) = 0 \tag{5}$$

$$\dot{m}_{w,DPC} + \dot{m}_{a,5}(x_4 - x_5) = 0 \tag{6}$$

$$f_{rec} = \frac{\dot{m}_{a,5}}{\dot{m}_{a,3}} \tag{7}$$

$$\varepsilon_{DPC} = \frac{T_3 - T_4}{T_3 - T_{3,dewpoint}} \tag{8}$$

The amount of water consumed by the DDC system is calculated taking into account the water wasted during the reverse osmosis process introducing a water waste factor:

$$f_{w,waste} = \frac{\dot{m}_{w,DPC}}{\dot{m}_{w,consumed}} \tag{9}$$

It is assumed that the secondary airstream leaves the cooler at saturated conditions.

2.1.3. Condensation air cooler

The CAC is used to condense water from the regeneration air with outdoor air. The regeneration air can at best leave the CAC saturated at the wall temperature. The model considers an average wall temperature, assuming the convective thermal resistances to be the same for both airflows. A by-pass factor is introduced to consider a part of the regeneration airflow does not change conditions flowing across the CAC, ranging from 0, i.e. no regeneration air is bypassed, to 1. The resulting equations for modelling the CAC are:

$$\bar{T}_{surface} = \frac{\left((T_{10}+T_{11})/2 + (T_{coolant,in}+T_{coolant,out})/2\right)}{2} \tag{10}$$

$$h_{11} = (1 - BF)h_{a,reg}\big|_{\bar{T}_{surf,\phi=1}} + BF \cdot h_{10} \tag{11}$$

$$x_{11} = (1 - BF)x_{a,reg}\big|_{\bar{T}_{surf,\phi=1}} + BF \cdot x_{10} \tag{12}$$

$$BF = \frac{\dot{m}_{a,bypass}}{\dot{m}_{a,10}} \tag{13}$$

The amount of water condensed is calculated as:

$$\dot{m}_{w,CAC} = \dot{m}_{a,10}(x_{10} - x_{11}) \tag{14}$$

The system independency from any external water source is expressed through a water recovery factor:

$$f_{wr} = \frac{\dot{m}_{w,CAC}}{\dot{m}_{w,DPC}} \tag{15}$$

which can range from 0, i.e. no water recovery, to infinite, i.e. no water consumption. The DDC-DWR system is independent from external water sources when $f_{wr} \geq 1$.

2.1.4. HEX, IHRU and RH heat exchangers

The HEX, IHRU and RH exchange only sensible heat. The effectiveness definition for the HEX is:

$$\varepsilon_{HEX} = \frac{\dot{C}_2(T_2-T_3)}{\dot{C}_{min}(T_2-T_6)} = \frac{\dot{C}_6(T_7-T_6)}{\dot{C}_{min}(T_2-T_6)} \tag{16}$$

The IHRU effectiveness is defined analogously.

The RH effectiveness is not defined since its hot side can be of different nature, e.g. direct contact with the heat source or using secondary hot water or air circuits. The RH is characterized by the amount of regeneration heat it provides to the regeneration air:

$$\dot{Q}_{reg} = \dot{m}_{a,12}(h_8 - h_{12}) \tag{17}$$

The system thermal COP is defined as:

$$COP_{th} = \frac{\dot{m}_{a,4}(h_1-h_4)}{\dot{Q}_{reg}} \tag{18}$$

3. RESULTS

The simulations are carried out at constant indoor conditions of 23°C and ϕ=0.5, while an airflow rate of 1 kg/s is constantly supplied at 18°C and ϕ=0.64, corresponding to a total indoor load of 6.4 kW and a Sensible Heat Ratio of 0.8. The remaining constant input values for the simulations are reported in Table 1.

Table 1. Parameter values used for simulations

Parameter	Values
$\varepsilon_{DW,process}$	0.85
ε_{HEX}	0.8
ε_{IHRU}	0.8
BF	0.1
$\dot{m}_{coolant}$ $[kg/s]$	2
f_{reg}	0.7
f_{rec}	0.3
$f_{w,waste}$	0.5

Both the DDC-DWR and the DDC systems are simulated for varying outdoor conditions, in the outdoor temperature range 25-40°C and for outdoor humidity ratios as low as 8.5 g/kg. The resulting water recoveries/consumptions, regeneration temperatures, regeneration heat consumptions and thermal COPs are reported in Figure 3 for the DDC-DWR system and in Figure 4 for the DDC system.

In Figure 3 and Figure 4 both systems present limits on the outdoor conditions for covering the required indoor load. These limits are due to the DPC effectiveness that is an output from the simulations: the maximum allowable DPC effectiveness is set to 70%, so the systems are considered not applicable when higher values are needed for reaching the required supply temperature. The DDC-DWR has a wider range of applicability because of the composition of the airstream at the cold side of the HEX: mixing exhaust indoor air with exhaust DPC secondary air provides a colder airstream than with outdoor air, thus the required DPC effectiveness is reduced and less water is needed for providing the cooling effect.

Figure 3a shows the DDC-DWR system can be independent of any external water source in the majority of its range of applicability. For higher outdoor humidity ratios, which correspond to higher dehumidification rates in the DW, the DDC-DWR operates with f_{wr}>1, so the excess condensed water is stored in the tank. Figure 4a shows that the DDC system consumes a large amount of water: only half of it is evaporated in the DPC, while the other half is wasted during the reverse osmosis process. The amount of water condensed in the DDC-DWR system can be estimated from Figure 4a. As an example, for T_{out}=30°C and ϕ_{out}=0.5 it is found that f_{wr} ≈1.5 and the water evaporated in the DPC of the DDC system is approximately 18 kg/h; hence in the DDC-DWR the amount of water evaporated in the DPC can be assumed 15 kg/h, as the pre-cooling in HEX is more effective (same reason for which the DDC-DWR has a wider range of applicability). The corresponding amount of water condensed in the DDC-DWR system is approximately 22.5 kg/h.

The comparison between Figure 3b and Figure 4b shows that the DDC-DWR requires considerably higher regeneration temperatures than the DDC system. Considering again T_{out}=30°C and ϕ_{out}=0.5, the DDC-DWR requires T_{reg} ≈95°C, while the DDC system requires T_{reg} ≈60°C. Regeneration temperatures even below 50°C are computed for the DDC system when low dehumidification rates are needed.

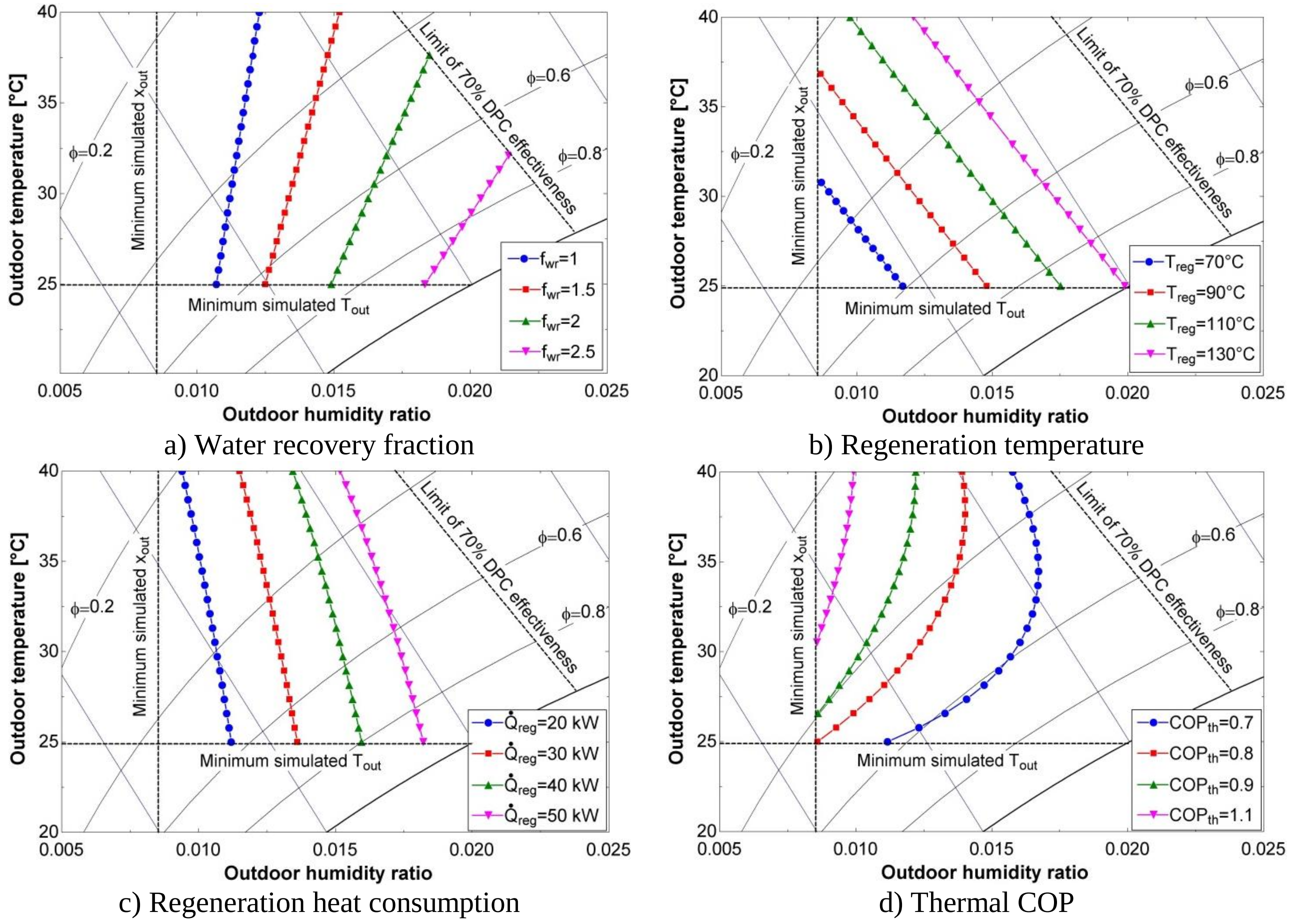
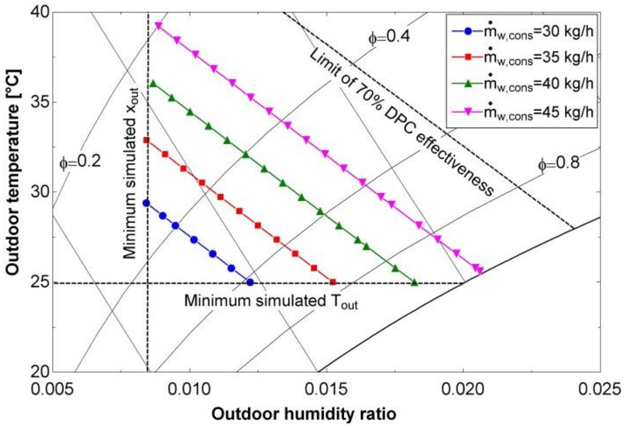


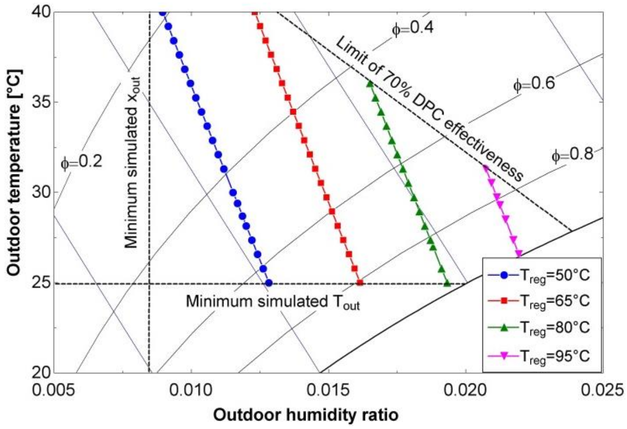
Figure 3. DDC-DWR system performance for varying outdoor conditions

Figure 3c and Figure 4c show the corresponding regeneration heat consumptions. It is noticed that the DDC-DWR system consumes almost double the amount of regeneration heat than the DDC system. This is due to the higher regeneration temperatures, as the regeneration fraction is the same for both systems.

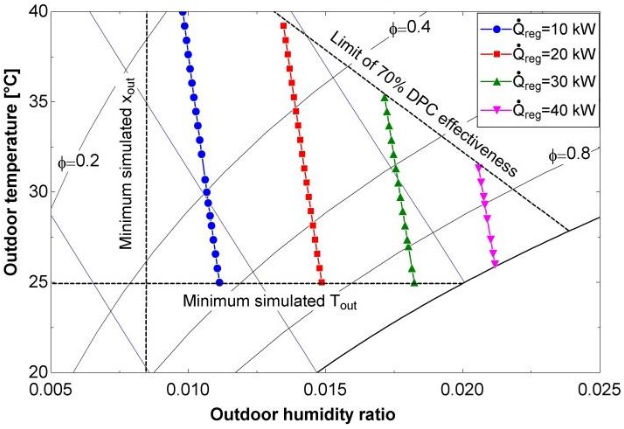
Analogous considerations can be done comparing Figure 3d and Figure 4d. Moreover these figures are useful to compare the systems to a single effect LiBr-H_2O absorption chiller, whose average thermal COP can be assumed equal to 0.7 with regeneration temperature of 90°C, see Duffie and Beckman (2006). The DDC system is clearly more efficient than an absorption chiller, while the DDC-DWR system performs better for not too humid outdoor conditions, i.e. limited dehumidification rates. The DDC-DWR system can still be independent from external water sources and even store excess condensed water with a COP_{th} higher than 0.7, e.g. at T_{out}=30°C and ϕ_{out}=0.5 it is found that f_{wr} ≈1.5 and COP_{th} ≈0.78.



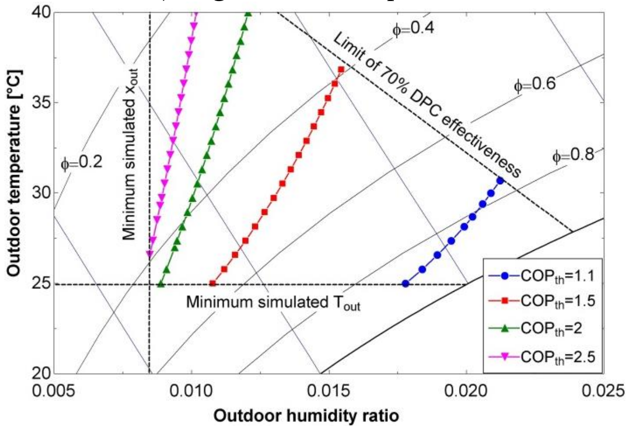
a) Water consumption



b) Regeneration temperature



c) Regeneration heat consumption



d) Thermal COP

Figure 4. DDC system performance for varying outdoor conditions

4. DISCUSSION

The results have demonstrated that the DDC-DWR is capable of running independently from external water sources, which allows for deploying this type of DEC systems in locations with no water availability. However the range of applicability of the DDC-DWR system should also take into account the maximum allowable regeneration temperature, depending on the considered heat source. The coupling between DEC systems and solar energy systems is already proven to be an attractive solution compared to both absorption and electric chillers, but it might not always be possible to run the DDC-DWR system with solar energy as the required regeneration temperature gets too high.

An interesting alternative is to integrate the DDC-DWR and DDC systems in the same system. This can be achieved with a switch between a closed and an open regeneration circuit (i.e. the two systems are used as different operational modes), or with a hybrid solution that uses a variable amount of fresh outdoor air to replace part of the regeneration air flowing in an analogous circuit to the one used in the DDC-DWR system. The combination of the two systems allows for recovering water when possible, storing the excess water, and using it at other times for lowering the regeneration temperature and increasing the thermal performance. This solution would further extend the applicability of the system.

Further calculations should take into consideration the electricity consumption in the DDC-DWR system too. The DDC and DDC-DWR systems are unlikely to have higher electricity consumptions than electric chillers, but they might have higher electricity consumptions than absorption chillers as found by Bellemo et al. (2013), even though the overall energy (heat and electricity) consumption remains lower. These differences should be quantified by dimensioning the system components.

5. CONCLUSION

A technical solution for making DEC systems independent of external water sources is introduced and applied to the DDC system for demonstrating its functioning and applicability. The resulting DDC-DWR system is simulated for a generic load case and varying outdoor conditions. The DDC-DWR system is found independent from any external water supply for the majority of the simulated conditions, meaning it can be employed in areas with limited or even absent water availability. The available temperature level of the heat source used for regenerating the desiccant dehumidifier can limit the applicability of the proposed solution, as the computed regeneration temperature increases significantly in comparison to the simple DDC system. The electricity consumption for running the system auxiliaries should be evaluated for a more comprehensive comparison with both electric and absorption chillers. Finally, the possibility of designing a system for exploiting the characteristics of both the DDC-DWR and DDC systems is a promising solution for increasing further the applicability of this technology, and it should be evaluated in a future study.

6. REFERENCES

Bellemo L. 2011, *New desiccant cooling system using the regenerative indirect evaporative process*, MSc thesis, Department of Mechanical Engineering, Technical University of Denmark, 160 p.

Bellemo L, Elmegaard B, Reinholdt L, Kærn M, Jakobsen A, Markussen W. 2013, Modelling and analysis of a desiccant cooling system using the regenerative indirect evaporative cooling process, *ECOS conference*, Guilin, China.

Daou K, Wang R, Xia Z. 2006, Desiccant cooling air conditioning: A review. *Renewable and Sustainable Energy Reviews* 10(2): 55-77.

Duffie JA, Beckman WA. 2006, *Solar Engineering of Thermal Processes*, Wiley, Hoboken, 928 p.

Goldsworthy M, White S. 2011, Optimisation of a desiccant cooling system design with indirect evaporative cooler. *Internal Journal of Refrigeration* 34(1): 148-158.

Goldsworthy M, White S. 2012, Limiting performance mechanisms in desiccant wheel dehumidification. *Applied Thermal Engineering* 44: 21-28.

Jain S, Dhar P, Kaushik S. 1995, Evaluation of solid-desiccant-based evaporative cooling cycles for typical hot and humid climates. *Internal Journal of Refrigeration* 18(5): 287-296.

7. NOMENCLATURE

$\dot{C}$	thermal capacity flow	[kJ/kg-s]
f_{rec}	recirculation mass flow rate fraction	[-]
f_{reg}	regeneration mass flow rate fraction	[-]
h	specific enthalpy	[kW/kg]
$\dot{m}$	mass flow rate	[kg/s]
$\dot{Q}$	heat flow rate	[kW]
T	temperature	[°C]
ϕ	relative humidity	[-]

Subscripts

a	dry air
w	water