SOLAR DESICCANT AIR-CONDITIONING IN AN INDUSTRIAL APPLICATION: OPTIMISATION APPROACHES FOR SOLAR-THERMAL INTEGRATION AND AIR-HANDLING UNIT

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Abstract

Solar-driven air-conditioning with DEC-systems (Desiccant and Evaporative Cooling) is a renewable solution and promising alternative to nowadays´ electricity based compression type refrigerating. While this conventional technology, with its consumption of fossil primary energy affects the depletion of resources and contributes to the global warming through CO_2-emissions, solar air-conditioning is an approach, which uses solar-thermal heat, in contrary to electricity, to drive air-conditioning systems. Against this background, the *Centre of Excellence for Renewable Energy Research* at *Ingolstadt University of Applied Sciences* (Germany) investigates a solar-driven desiccant and evaporative cooling system in a multipurpose building, operated with two large arrays of solar-thermal flat-plate collectors. This paper initially describes the system layout and the measurement equipment integrated in the solar DEC-system. Subsequently, the measurement results of 2009 cooling period are summarised, which showed a considerably low refrigeration capacity of the system. Operational optimisations that were realised prior to the 2010 cooling period are described and consequently, the measurement results of the solar DEC-system in the 2010/11 cooling periods are analysed. For this purpose, first the air-handling components desiccant wheel and heat recovery wheel are analysed, which repeatedly showed considerable deficiencies in efficiency. Combined with the results of a process water analysis, the impact of an insufficient water treatment (causing severe calcification in the air ducts) on the efficiency of components and system is discussed. Secondly, as a main part of this paper, the analysis focuses on the operation of the two large solar collector arrays and its integration in the DEC-process. Intensive experiences on the operation of such a large complex system are discussed and the importance of self control mechanisms as well as the enforcement of quality assurance processes are argued, in order guarantee an energy efficient operation of the overall system. An outlook on the further proceeding in the current research project particularly with regard to the system simulation concludes the paper.

1. Introduction

The market for air-conditioning in buildings is growing worldwide due to increased thermal loads, increased living standards and architectural concepts with an increasing ratio of glass facades (Henning, 2007). Today, the commonly used technology for air-conditioning is electrically driven compression-type refrigeration. However, this technology comes along with disadvantages of high energy consumption and CO_2-emissions as well as a refrigerating medium increasing the greenhouse effect. Due to decreasing energy resources and an increasing awareness for the environment and costs, ecologic and economic aspects are gaining more importance within purchasing and operating an air-conditioning system. Furthermore, the commonly used chillers are frequently leading to peaks in the electrical demand during summer periods, especially in cooling dominated climates.

Against that background, the use of solar-thermal energy for the air-conditioning of buildings carries a huge but undeveloped potential. Especially when regarding the fact that cooling loads and availability of solar radiation are approximately in phase. The open-cycle solar DEC-process uses the cooling effect of evaporating water to regulate the air temperature through controlled dehumidification, sensible heat recovery and humidification of the supplied air whereupon the process is driven by low temperature solar heat instead of electricity (Bader et al., 2010).

The *CENTRE OF EXCELLENCE FOR RENEWABLE ENERGY RESEARCH* at *Ingolstadt University of Applied Sciences* investigates a renewable-only based HVAC-system of a multipurpose building in Ingolstadt as illustrated in fig. 1. The 10,000 m^2 gross floor area building is part of the biggest logistic centre in the region. The investigated building provides space for a training centre (ground floor), an office environment, a film studio (first floor) and a hotel (second floor). The floor plan shows an area of 4,100 m^2, the building has a capacity of approx. 45,000 m^3. Next to a ground source heat pump for base-load heating and cooling, the building is equipped with two arrays of solar-thermal flat-plate collectors and a DEC-system. Due to high internal and external thermal loads, active cooling is required. While base-load cooling is supplied by the heat pumps via the thermo-active building structure, peak-load cooling is realised by solar-driven DEC-technology (Haller, 2007).

Fig. 1: Solar-driven DEC-system in Ingolstadt

On the one hand, this investigation is supposed to demonstrate the potential of solar-assisted cooling, on the other hand, the research project focuses on the analysis and optimisation of the solar-driven cooling system as well as the deduction of planning criteria for design, operation and control of solar-driven DEC-systems particularly with respect to the multipurpose use of solar energy. The project is supported by the *Bavarian State Ministry of Sciences, Research and the Arts*.

2. System Layout and Measurement Equipment

2.1. Description of the overall system

The DEC-system consists of two separate plants with a nominal air flow of 8,000 $m^3 h^{-1}$ and a nominal cooling capacity of 35 kW each, however, only one of the plants is investigated in detail. The overall design data of the investigated solar DEC-system are summarized in tab. 1.

Tab. 1: Design data of the solar-driven DEC-System

Design Data		
Geographic position of the building	48.78 °N	11.40 °E
Solar collector aperture area	262.5	[m^2]
Active area air-conditioned (both plants)	2,040	[m^2]
Nominal ventilation air flow rate	2 x 8,000	[$m^3 h^{-1}$]
Max. nominal cooling capacity	2 x 35	[kW]
Nominal capacity regeneration air heat exchanger	87	[kW]

The plant in Ingolstadt, as illustrated in fig. 2, uses a lithium chloride desiccant wheel based on a cellulose matrix with a diameter of 1.41 m and a depth of 0.45 m. The wheel is operating as dehumidifier wheel in cooling mode (20 h^{-1}) and as enthalpy changer in heating mode (600 h^{-1}). The heat recovery wheel is approximately of the same size with a diameter of 1.42 m and consists of a seawater resistant aluminium alloy (AlMg3). The spray nozzle humidifiers in the supply air duct and the return air duct are both driven with decalcified (ion exchange) water and a pressure of 3 MPa (30 bar) to 7 MPa (70 bar) and are completed with the integration of a droplet separator. The regeneration heat to dehumidify the desiccant wheel on the return air side with a temperature of up to 70 °C is provided by the regeneration air heat exchanger with a nominal capacity of 87 kW. The regeneration air heat exchanger is directly supplied by heat from the solar collector arrays as described in section 2.2. The mass flow of the regeneration air heater is regulated depending on the inlet temperature of the regeneration air heater.

The system is accomplished with an additional surface radiator with a nominal cooling power of 40 kW and a supply air heater with a nominal capacity of 34 kW in the supply air duct. The surface radiator is integrated for back-up reasons. The cooling capacity of one of both DEC-plants is approximately 35 kW. However, currently only one plant is in operation with an expected cooling capacity of around 24 kW due to a reduced air volume flow set by the plant operator.

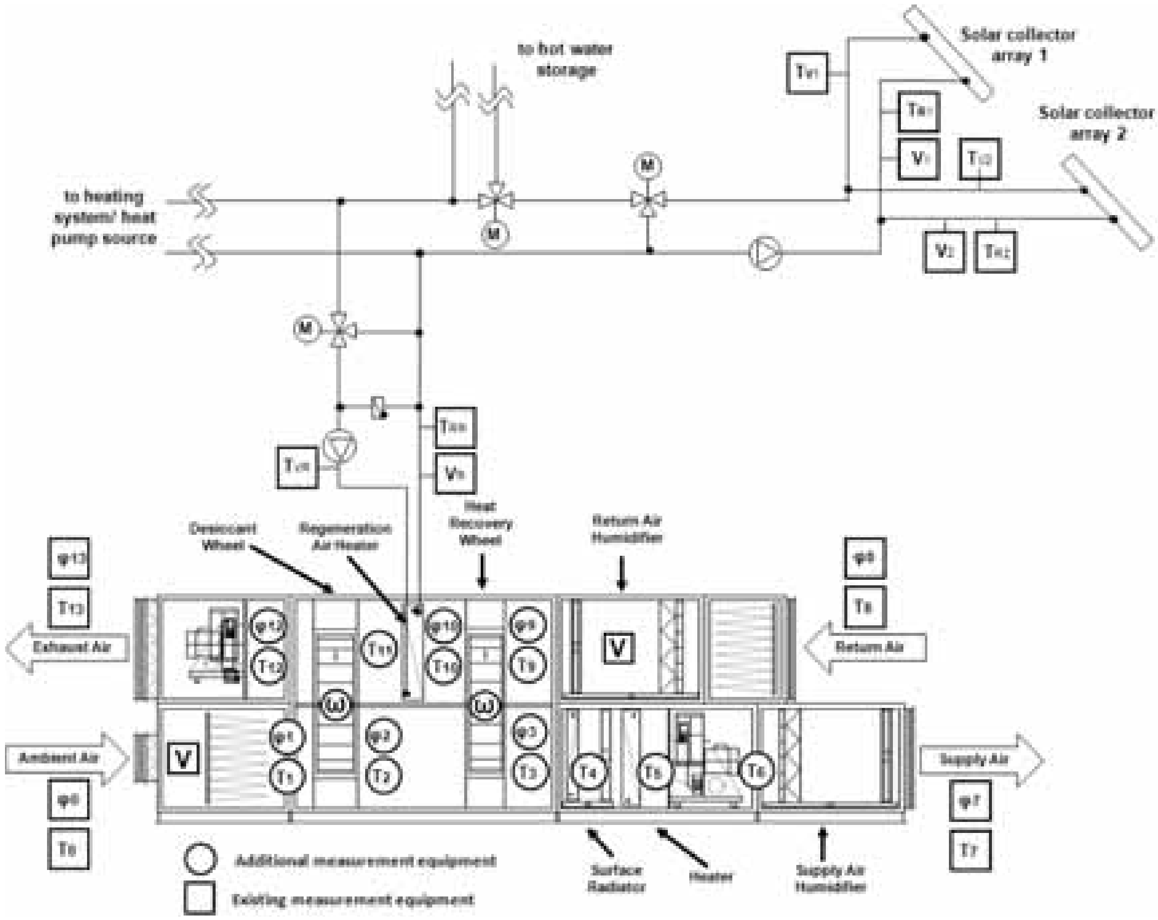

Fig. 2: Solar DEC-system layout with measurement equipment
(T_i: temperature, φ_i: relative humidity, V_i: volume flow, ω: frequency)

Prior to the 2009 cooling period, additional measurement equipment was installed within the DEC-plant, as illustrated in fig. 2, to closely monitor the solar DEC-process and to evaluate the performance of its single components. Thereby an inhomogeneous air-distribution within the ducts was approached with the integration of special measurement devices as described by Bader et al. (2009, 2010a). Altogether, the entire building energy system is equipped with extensive measurement equipment consisting of 121 measuring points.

2.2. Description Solar System

Two arrays of solar-thermal high-performance flat-plate collectors (262.50 m²) are installed on the flat roof of the building. The collectors are mainly supposed to supply the regeneration heat for the DEC-plant. Additionally, they supply heat to the hot water stores, heating in winter as well as for the regeneration of the heat pump energy source in the ground storage.

According to the planning documentation, the circulation pump in the solar circuit is controlled depending on the absorber temperature and the collector volume flow is varied depending on the collector flow temperature.

Due to leakages, the plant operator decided to bridge two collectors which therefore results in a total aperture area of 258.65 m^2 in use. Tab. 2 summarises key information figures on the two collector arrays.

Tab. 2: Key figures of the solar flat-plate collector arrays

Design Data				
Total aperture area (designed)			262.50	[m²]
Total aperture area (currently in operation)			258.65	[m²]
Azimuth of solar array (South=0°, East=90°)			-20	[°]
Slope of solar arrays			30	[°]
	Array 1		**Array 2**	
Aperture area (currently in operation)	91.25	[m²]	167.40	[m²]
per module	1.901	[m²]	1.860	[m²]
Optical efficiency η_0	0.841	[-]	0.801	[-]
Linear heat loss coefficient a_1	3.430	[W $m^{-2}K^{-1}$]	3.858	[W/$m^{-2}K^{-1}$]
Quadratic heat loss coefficient a_2	0.0185	[W/$m^{-2}K^{-2}$]	0.0100	[W/$m^{-2}K^{-2}$]

Regarding the hydraulic collector circuit design, five collectors are connected in series, whereas the series circuits of each collector array are connected in parallel. Downstream the circuits, both collector arrays are jointing in a common point of transfer.

3. Previous Monitoring Experiences

The solar DEC-system in Ingolstadt showed massive problems during the first year of operation (2006). While the degree of comfort in the building was found to be satisfying during the cooling period, the solar-driven DEC-plant showed major deficiencies in cooling performance, hydraulics and control. Especially, a too high rotational speed of the desiccant wheel and an inadequate adjustment of solar collector arrays, DEC-plants and building structure were identified. Therefore, in an overhaul of the system several problems in the hardware were identified and corrected such as blocked spray nozzles due to calcifications, leakages in the sealing of the desiccant wheel and an incorrect installation of a non-return valve in the hydraulic system of the regeneration air heater. Moreover, the control strategy regarding the cooling power of the plant and the speed of the desiccant wheel were checked. Detailed results of cooling period 2006 are described by Haller (2007).

In the second year of operation (2007), some deficiencies of the first year were found to be removed, but still the plant did not work according to its capacity. Insufficient dehumidification by the desiccant wheel was identified as a major problem. Based on a detailed analysis of the desiccant wheel, one-sided displacement of the sorbent was assumed to be the reason for insufficient cooling capacity. Obviously, control or mechanical malfunctions during operation led to a one-sided oversaturation and thus to a one-sided damage of the desiccant wheel as described by Haller et al. (2007). Consequently, the damaged wheel was removed prior to the 2008 cooling period.

During the third year of operation (2008), the DEC-plant was not permanently in operation throughout the cooling period due to organisational complicacies. However, analyses on exemplary days proved that the one-sided damage of the desiccant wheel in 2007 could be solved by replacing the desiccant wheel during maintenance in spring 2008. Considering the plant settings of a reduced volume flow, a maximum refrigeration capacity of around 24 kW was expected, when the plant was operating in DEC-mode. However, with an analysed refrigeration capacity (ambient air to supply air) of around 15 kW (including the surface radiator) this value was by far not reached. The reason for this malfunction was supposed to be a limited dehumidification capacity of the desiccant wheel as described by Bader et al. (2009). Since the DEC-plant was until then regarded as a black box, these kinds of in-process problems could hardly be analysed with the existing measurement equipment (fig. 2; only temperature and humidity of ambient air, supply air, return air and exhaust air were measured).

4. Monitoring and Operational Analysis of the DEC-system

4.1. Solar DEC-System Analysis in 2009 Cooling Period

The analysis of the thermal comfort in an exemplary selected hotel room in the entire month of August 2009 showed a "comfortable" or "still comfortable" room condition. Only approximately two percent of the measured values could be ranked as "uncomfortable warm". The temperatures within this time period rank from minimum 20.92 °C to maximum 25.92 °C. The relative humidity measures its lowest value at 47.1 % and reaches its maximum value at 67.94 %.

However, when regarding the thermal comfort in the same hotel room only during DEC-operation on exemplary days, e.g. August 20th, 2009, 68 % of the measured values were "uncomfortable warm". The temperatures range between values of 25.88 °C and 24.94 °C while the relative humidity reaches values between 63.35 % and 60.08 %. This phenomenon mainly occurred, since within the entire month of August also air conditions of cooler days and nights were influencing the thermal comfort, while the comfort during DEC-operation exclusively reflected the thermal comfort of the room on a hot summer day.

The analysis of the thermal comfort therefore shows that the DEC-plant obviously sets the room temperature to certain conditions however these conditions do not locate within the comfort area according to EN 15251:2007. A probable reason for that might be an insufficient refrigeration capacity of the DEC-plant, which therefore cannot reach the set supply air conditions. Hence, the refrigeration capacity of the solar DEC-system is analysed in the following.

The monitoring of the DEC-plant in cooling period 2009 as described by Bader et al. (2010b) showed that the expected refrigeration capacity of around 24 kW (reduced nominal capacity due to a reduced air-flow rate) was not reached. The DEC-plant, which was supposed to supply peak-load cooling, only shortly reached a maximum refrigeration capacity of 15 kW on one day (July 27th, 2009) while, as fig. 3 shows for an representative exemplary day (August 20th, 2009), the average refrigeration capacity measured around 6 to 8 kW.

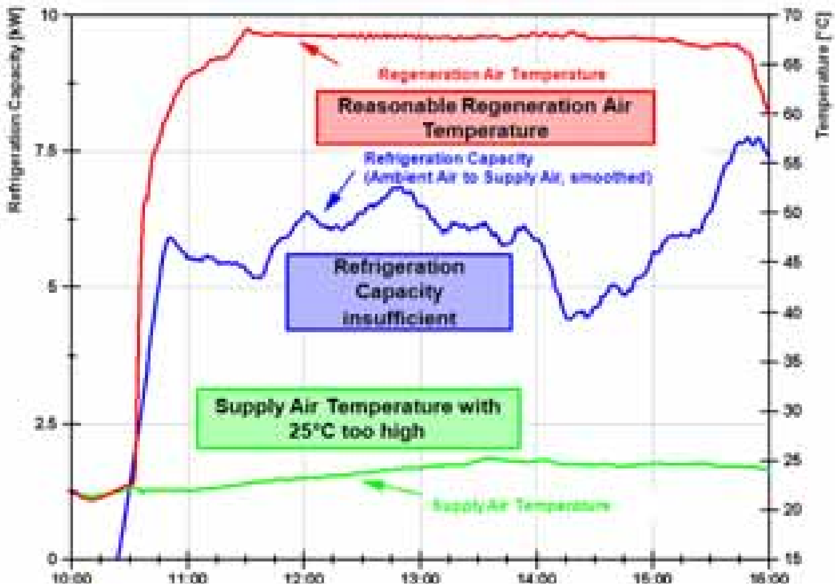

Fig. 3: Solar DEC-plant performance for an exemplary day (August 20th, 2009)

However, the regeneration air temperature measures around 68 °C throughout the entire DEC-process and therefore provides appropriate conditions for the DEC-process. To solely analyse the solar DEC-process, the surface radiator has been deactivated in cooling period 2009. On the exemplary day August 20th, 2009, the supply air temperature of up to 25 °C during DEC-operation can be evaluated as too high, as illustrated in fig. 3. Especially the described uncomfortably high room temperature indicates a higher available cooling demand.

To analyse the cause for the considerably low refrigeration capacity in spite of a sufficient regeneration air temperature, the operation of the critical components in the DEC-process, such as desiccant wheel and heat recovery wheel was investigated. The numbers in brackets in the following diagrams thereby refer to the corresponding sensors in the system (cf. fig. 2).

The analysis of the desiccant wheel on the same exemplary day (August 20th, 2009) shows that the regeneration air heater heated the return air in front of the desiccant wheel to around 68 °C (fig. 4, upper diagram). Therefore, sufficient solar regeneration conditions for the dehumidification of the desiccant wheel were available throughout the entire duration of the DEC-operation. A closer investigation of the desiccant wheel's dehumidification capacity (fig. 4, lower diagram) at a volume flow ratio of 1.14 (supply air to return air), shows that the desiccant wheel initially dehumidified the process air by around 4.3 g kg^{-1} dry air. Thus, at the beginning of the process the dehumidification capacity reached a value as it would be expected according to manufacturer information. However, the dehumidification capacity steadily decreased with ongoing DEC-process to around 2.5 g kg^{-1} dry air, even though the boundary conditions like the regeneration air temperature were measured as stable. Further daily analyses reveal a dehumidification capacity permanently measured around 2 g kg^{-1} dry air (e.g. July 27th, 2009) and therefore below the expected level.

A temporary adjustment of the volume flow ratio from 1.14 to 1.05, as suggested by the manufacturer of the desiccant wheel, did not result in an improved dehumidification capacity. Hence, the results gained by Schürger (2007) in laboratory tests could be approved under in-situ conditions. The insufficient dehumidification of the supply air did not create optimal conditions for the subsequent air-conditioning processes within the DEC-plant. Cause for the decreasing dehumidification capacity could for instance be an unexpectedly varying rotational speed of the desiccant wheel, which was subject to investigations in 2010 cooling period.

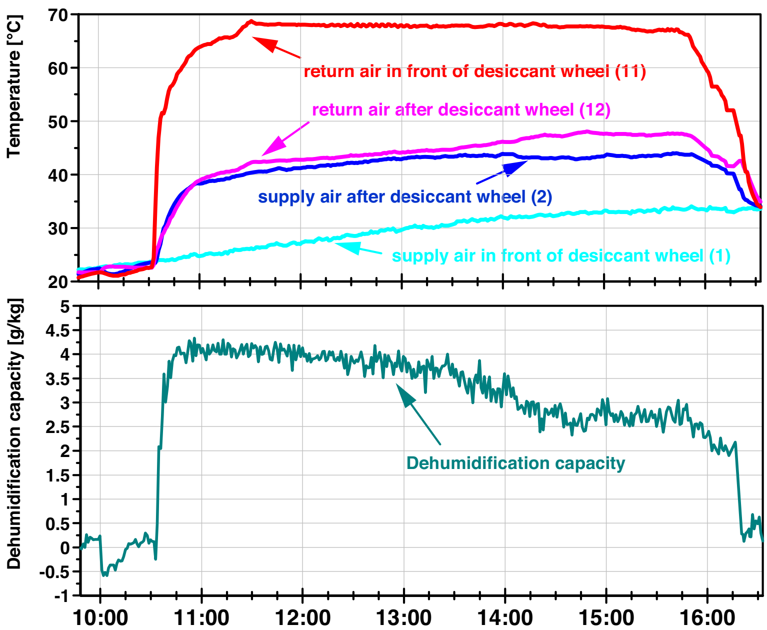

Fig. 4: Desiccant wheel analysis (August 20th, 2009)

The behaviour of the heat recovery wheel as another core element of the DEC-process was also analysed in detail. Fig. 5 illustrates the process conditions for the heat recovery on the exemplary day August 20th, 2009. It was found that the heat recovery ratio only reached 58 % at a rotational speed of 600 h^{-1} and a volume flow ratio (supply air to return air) of 1.14. According to information of the component manufacturer, a heat recovery ratio of 75 % however, would be expected under the given conditions. Therefore, also this component did not reach the planned efficiency. Comparable in-situ measurements carried out by Eicker et al. (2002) at the DEC-plant in Althengstett (Germany) showed a similar difference between the measured heat recovery ratio and the expected value.

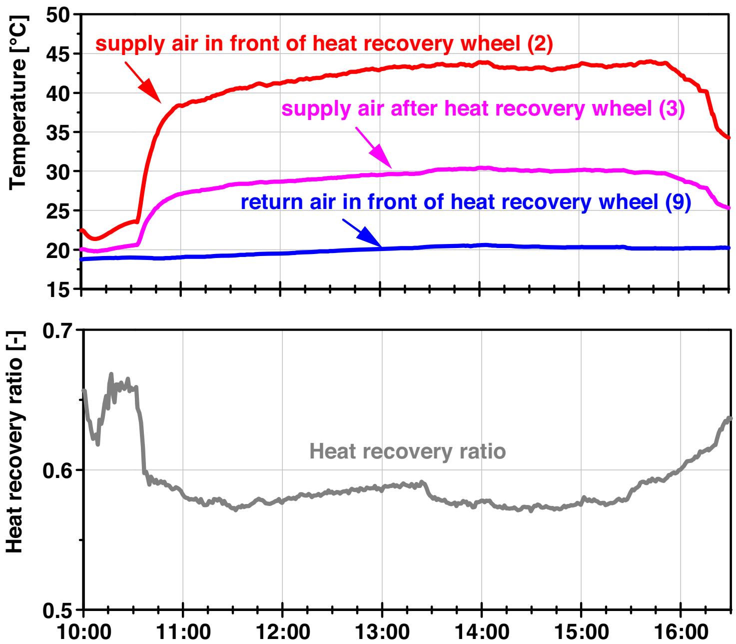

Fig. 5: Heat recovery wheel analysis (August 20th, 2009)

A close visual inspection of the DEC-plant revealed that calcification has not only been a major problem of the humidifier spray nozzles but proved that it affects the complete plant. Although the whole system has been cleaned and renewed during maintenance in May prior to 2009 cooling period, already in July 2009 severe deposits of calcification were observed as shown in fig. 6.

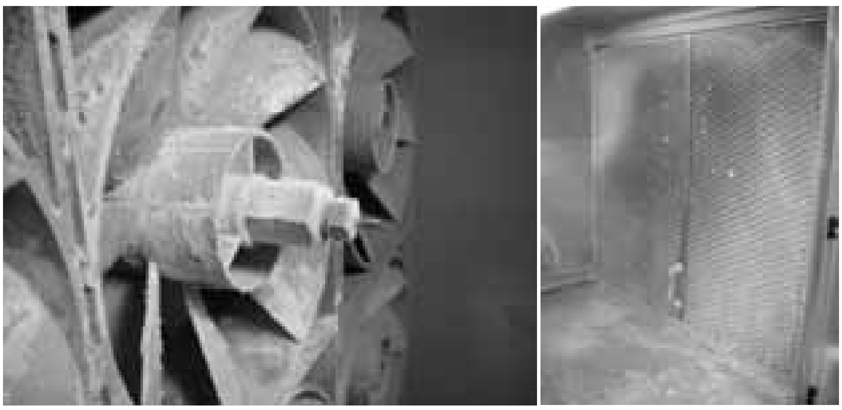

Fig. 6: Calcification of the DEC-plant

Therefore, a significant reason for the noticeable, insufficient low heat recovery rate might be founded in the discovered immense calcification, lowering the heat transfer characteristics of the heat recovery wheels aluminium alloy matrix.

Consequently, the humidifier process water was analysed regarding its water hardness to evaluate the effectiveness of the currently realised water treatment installation of an ion-exchanger. According to standard VDI 3803, a general hardness of the humidifier process water of max. 7 °dH German degrees (~ 8.87°e, English degrees) is acceptable in the investigated case. The manufacturer of the humidifier unit even demands treated water with a general hardness of 3°dH (~ 3.8 °e) and a maximum electrical conductivity of 20 µS cm^{-1}. The analysis of the supplied water, however showed a general hardness of 16°dH (~ 20 °e) and the analysis of the process water directly upstream the humidifiers disclosed a general hardness of 11 °dH (~ 13.8°e). This denotes that the realised water treatment is insufficient for the operation of a DEC-process. (Bader et al., 2011)

4.2. Solar DEC-System Analysis in 2010 cooling period

Prior to 2010 cooling period several operational optimisations have been realised. The heat recovery wheel aluminium alloy matrix was cleaned with high pressure hot water as shown in fig. 7 in order to remove calcification deposits from the wheel and therefore improving its heat recovery ratio.

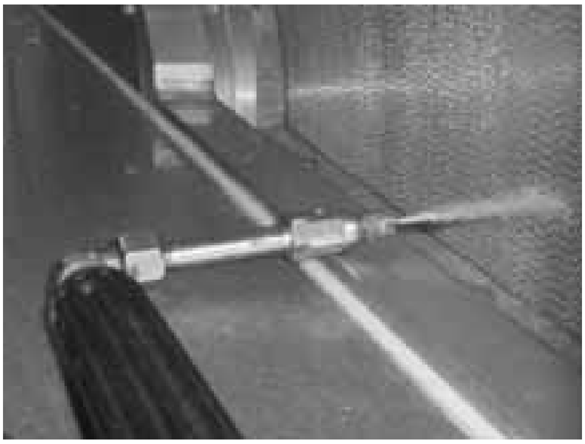

Fig. 7: Cleaning of the heat recovery wheel in May 2010

Additionally, the calcified steel droplet separators at the humidifier unit were changed into new fibrous web droplet separators to filter calcifications from the air and therefore minimize its impact on further components within the DEC-process, such as the cleaned heat recovery wheel. Furthermore, sealings at both, the heat recovery wheel and the desiccant wheel were thoroughly adjusted in order to reduce leakages to a minimum and the desiccant wheel's flat drive belt was shortened in order to minimize the probability that its rotational speed varies due to a loose belt.

In 2010 cooling period, despite of the described implemented operational optimisations the refrigeration capacity of the Solar DEC-system has been again measured beyond its expectations, as it could be proven by investigating diverse exemplary days, when the system was operating in DEC-mode (e.g. July 22nd, 2010 and August 01st, 2010).

The analysis of the desiccant wheel performance shows results comparable to 2009 cooling period. The dehumidification capacity decreases with ongoing DEC-process and does not reach the expected values according to manufacturer data. However it could be proven, that this is not caused due to an inadequate wheel speed, as the newly integrated frequency measurements showed an appropriate constant wheel speed of 21 h^{-1} throughout the entire operation of the DEC-process on various days. According to results of Schürger (2007) the dehumidification capacity of the lithium chloride desiccant wheel only decreases with rotational speeds of above 25 h^{-1}. Therefore the wheel speed cannot be regarded as cause for the decreasing dehumidification capacity. The decrease in dehumidification capacity could be partly explained by a decreasing absolute humidity of the ambient air upstream the desiccant wheel as there is a trend of a higher dehumidification capacity with a higher water content of air in front of the desiccant wheel (Schürger, 2007). However this trend does not explain the appearing decrease in dehumidification capacity in periods when the absolute humidity of the ambient air upstream the desiccant wheel increases conspicuously. The phenomenon rather must be explained with the oversaturation of the desiccant wheel matrix. While on the one hand, the manufacturer recommends as possible solution raising the regeneration temperature up to 80 °C, Schürger (2007), on the other hand argues that temperatures significantly above 70 °C may damage the desiccants wheel matrix.

Concerning the disproportionately low refrigeration capacity of the DEC-plant, the calcified heat recovery wheel (cf. 4.1.) was identified as critical cause in 2009 cooling period. In 2010 cooling period the investigations of the thoroughly purified wheel however, still resulted in measured heat recovery ratios below 60 % on different analysed exemplary days with DEC-operation and therefore the heat recovery wheel did again not reach its expected efficiency. Fig. 8 shows the heat recovery ratio on the exemplary day, August 01st, 2010.

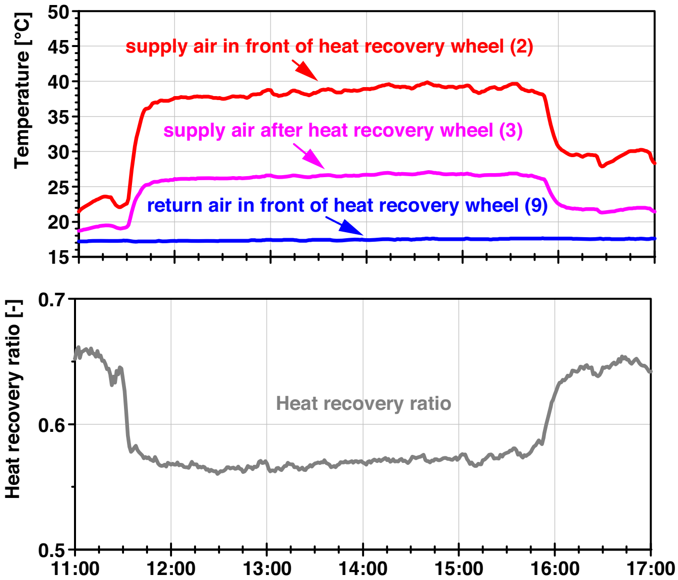

Fig. 8: Heat recovery wheel analysis during DEC-operation (August 01st, 2010)

Further investigating the reasons for this deficit and verifying the effectiveness of the hot water cleaning process, the pressure drop across the wheel was measured in the supply air duct and the return air duct during operation. At design conditions of a supply and return air flow rate of $\dot{V}$=8000 m^3 h^{-1} a pressure drop across the wheel of Δp_{sup}= 122 Pa is expected in the supply air stream and a pressure drop of Δp_{ret}= 106 Pa can be anticipated in the return air duct. As the volume flow rate in operation significantly deviates from the design flow rate ($\dot{V}_{sup}$=4600 m^3 h^{-1}, $\dot{V}_{ret}$=4060 m^3 h^{-1}) the pressure drop was expected to be Δp_{sup}= 40.3 Pa in the supply air and Δp_{ret}= 27.3 Pa in the return air. The real concurrent decrease in pressure across the wheel, however measures Δp_{sup}= 85 Pa in the supply air stream and Δp_{ret}= 62 Pa in the return air stream and therefore appears more than two times higher than expected. According to these results, the calcification deposits in the wheel could obviously not be reduced by hot water cleaning. In fact the calcification might still reduce the cross section of the heat recovery wheels aluminium alloy matrix and therefore cause a higher pressure drop. This is obviously not only the effect of reduced heat transfer characteristics due to declined material properties but also because of a reduced cross section that leads to an increased air velocity reducing the heat transfer through convection.

A new epoxy coated heat recovery wheel has consequently been recommended to be implemented together with a reverse osmosis system for improved water conditions. Both optimisation measures are currently being processed.

5. Solar System Analysis

5.1. Solar Integration Analysis

Both solar-thermal flat-plate collector arrays have originally been designed for the operation of a solar air-conditioning system including two DEC-plants with a nominal refrigeration capacity of 35 kW each. When evaluating the solar integration, it must be considered that only one of both DEC-plants is in operation at a reduced air flow (cf. section 2.2.). According to available design information, the currently realised hydraulics and the control strategy allow the use of the solar heat either for the preparation of hot water for the hotel or alternatively for the supply of regeneration heat for the DEC-plant. As a third option, the solar heat can be used for the regeneration of the heat pump source in the building's base plate or for the heating support if required. At present, a simultaneous utilisation of the solar heat for diverse consumers is not possible with the implemented hydraulics and control strategy. Due to the dimensioning of the collector array for originally two DEC-plants, however, this would in principle be interesting from an energetic and operational point of view.

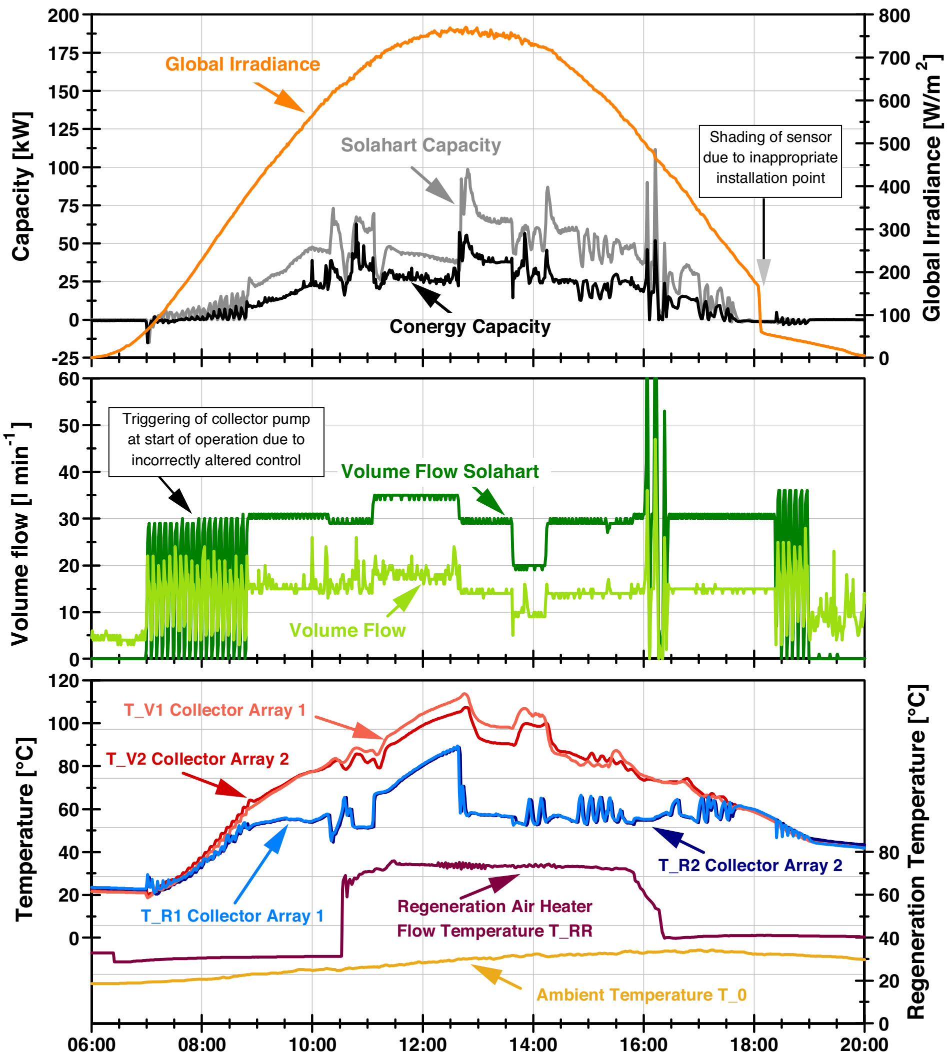

Fig. 9: Daily operation of solar collector arrays on a day with DEC-operation (August 20th, 2009)

As fig. 9 illustrates, the flow temperature of the regeneration air heater constantly reached a temperature of 72 °C to 73 °C during DEC-operation on the exemplary day August 20th, 2009. Therefore, the DEC-process was provided with an adequate regeneration temperature of around 68 °C (cf. fig. 4). The collector arrays, however, provided flow temperatures of up to 110 °C. As these temperatures are far too high for the DEC-process, they were consequently adjusted using the flow temperature mixer of the regeneration air heater, in order to reach reasonable temperatures for the DEC-process and to avoid a damage of the desiccant wheel. This indicates an existing potential of an integration of further heat sinks in the hydraulics and control of the overall solar system and furthermore approves the importance of a flow temperature control of the collectors was approved. However, as discussed in section 4.1. (cf. fig 4), it can be detected that there was obviously no interdependence between the insufficient refrigeration capacity of the DEC-plant and the integration of the solar collectors in the DEC-process in cooling period 2009, as solar regeneration heat was sufficiently available at a reasonable temperature level (fig. 9, lower diagram) during DEC-mode.

Regarding the collector arrays start of operation it becomes evident, that the collector pumps start is not anymore controlled depending on the absorber temperature of the hotter array. The pump starts at 07:00 and triggers switching on and off in 5 minute intervals until the flow temperature of collector array 2 T_{V2} (fig. 9, lower diagram) finally endurably exceeds a temperature of 60 °C at around 08:50. Analyses of various additional days in cooling periods 2009/10 showed a similar behaviour and therefore proved that the originally implemented control was obviously replaced by an insufficient time switch control. The collector arrays end of operation reveals a similar pattern of the volume flow when the collector pump is again triggering in five minute steps from 18:25 until 19:00. Due to this described control malfunction with its fixed initial time switch, it was observed that the pump triggers from 07:00 until 19:00 on days with little global irradiance without any permanent running. This control characteristic does not only contribute to the lifetime reduction of components but also causes unnecessary electricity consumption. The collector arrays end of operation is conspicuous for another reason. The approximation of the collector flow temperatures (T_{V1}, T_{V2}) and their corresponding return temperatures (T_{R1}, T_{R2}) at 17:40 prefigures that that the solar heat consumption of all available heat sinks stopped at a collector flow temperature of 60 °C. However the set point starting triggering the pump to switch off is only reached at 18:25. This evidences on the one hand, that the collector fluid was unnecessarily circulated through the solar collector system for 45 min and reveals on the other hand that the currently hydraulics and control cannot use these heat quantities, e.g. to regenerate the heat pump source in the ground storage. After end of operation at 19:00 the flow rate within collector array 1 remains at an average level of around 10 l min^{-1} (fig. 9, middle diagram) and therefore leads to negative collector capacities at night time.

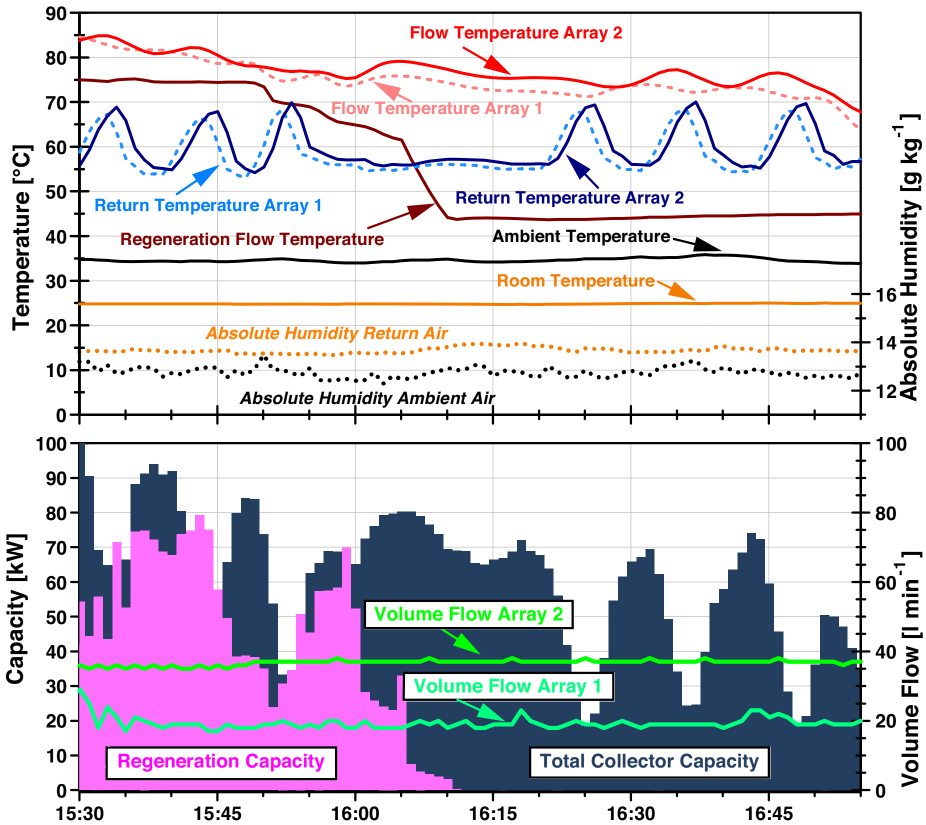

Fig. 10: Solar integration analysis at DEC-process end (July 22nd, 2010)

Fig. 10 illustrates the end of the DEC-process on July 22nd, 2009 which can be regarded as representative for this kind of system condition. At around 15:50 the DEC-process stops operating as the regeneration air heater flow temperature drops below its critical set point caused by insufficient collector flow temperatures. The room air conditions with a room temperature of T_{room}~ 25 °C and an absolute humidity of the room air (approximates return air condition due to mixed ventilation) x_{room}~ 13.7 g kg^{-1} at the end of the DEC-operation can be evaluated inappropriate for a conference room of building category II according to EN 15251:2007. Together with the unaltered high ambient air conditions (T_{amb}~ 25 °C; x_{room}~ 13.0 g kg^{-1}) within the same time period it becomes evident that the DEC-process stop was not actuated by the DEC-control due to a change of air-conditions respective cooling load but in fact by insufficiently provided regeneration conditions in form of heat at a reasonable temperature of above 75 °C.

The volume flows, as illustrated in fig. 10 lower diagram, of both collector arrays remain constant throughout the entire time span at levels of around 20 l min^{-1} (collector array 1) and 40 l min^{-1} (collector array 2). However, a decrease of collector volume flows by means of an intelligent solar DEC-integration control lowering the pump power would be expected in order to lengthen the DEC-systems duration in sorption mode. The total solar collector capacities of above 70 kW after 16:00 indicate a continuous availability of solar heat after end of DEC-operation, which then partly supply other heat sinks (e.g. hot water storage, ground storage) and cannot be utilised by the DEC-process.

6. Conclusions

The in-situ analysis of this solar DEC-system in Ingolstadt, with multipurpose use of solar heat, unveils considerable malfunctions on component level as well as on system control level. With this scientific analysis, diverse problems could be detected and solutions could be initiated. The various problems as described in this paper in detail would have been remained undiscovered and unremedied without this scientific analysis. This clearly demonstrates the indispensable implementation need of adequate self-control strategies especially regarding system efficiency of the overall system. The determination of the control for the entire system has to be of priority in the system planning phase. As unaware, manual interventions of the building operator into the hydraulic system of the overall system frequently caused additional malfunctions, new concepts with a minimum of interference possibilities paired with an intensive training of the system operator are highly recommended for these kind of complex systems. Obviously the planning reliability and quality control of such extensive renewable energy systems is not sufficiently guaranteed in state-of-the-art buildings as affirmed in a similar project by Häring et al. (2010). However, this is the requirement for a further, appreciable distribution of this promising DEC-technology.

Hence, the *Centre of Excellence for Renewable Energy Research* carries out an operation accompanying simulation to further optimise the system and develop advanced plant concepts and control strategies. The optimisations and gained technical expertise on the system will essentially influence planning criteria and strategies for construction, operation and control of solar-driven DEC-systems.

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