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Modeling and experimental validation of the desiccant wheel in a hybrid desiccant air conditioning system

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HIGHLIGHTS

► The desiccant wheel as core component of a highly efficient HVAC pilot installation based on renewable energies.
► Modeling and experimental validation of a desiccant wheel.
► Using a validated physical model to build a simplified model.
► Modeling and validation used from the same source.

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ABSTRACT

Modeling can be strong asset to the operation of air conditioning plants taking into account e.g. the strong dependency of local climate conditions for the operation of HVAC systems. This paper presents a validated physical model and a simplified model based on the results of the physical model for a desiccant wheel, which is the central part of a hybrid air conditioning system. The two models offer different advantages: While the physical model is complex and can be adapted flexibly to different wheel dimensions, desiccant materials or climatic conditions; the simplified model requires no knowledge of underlying equations and modeling language utilized and can be used for a first assessment of the potential of a desiccant cooling system in a certain location or for the use within online control systems. The coexistence of both models ensures that information tailored to the users' needs are made available. The validity of the physical model, and therewith the simplified model, is ensured through comparison with measurement obtained from a hybrid air conditioning system situated in northern Europe. The demonstration plant combines the advantages of a dedicated outdoor air system (DOAS) with the advantages of the common hybrid desiccant system to allow for energy efficient air conditioning in one installation. The availability of primary measurement data is extremely valuable to the process of model validation because knowledge about uncertainties and bias in measurement data unlikely to be known for secondary data can be used to understand and validate model results. A comparison of simulation results from the physical model to measurement data from the demonstration plant shows good compliance for a typical day of wheel operation after adjusting relevant model parameters.

1. Introduction

While air conditioning was restricted to hot climates in the past, a steep increase in its usage is now seen in moderate and even mild climates due to improved air tightness and better insulation of buildings. For the future, further growth in cooling demand can be expected as a consequence from global warming [25] and higher comfort standards [5,12]. According to [6] there is potential for increasing the efficiency of air conditioning systems and therewith reducing total energy consumption. To further reduce the energy consumption of buildings, active solar thermal systems can be a key technology [37].

In conventional systems the outdoor air (ODA) or a mix of outdoor and exhaust air are mainly cooled in electrically driven chiller to meet the space cooling demand. Dehumidification of the air is achieved with simple technological means through condensation of the contained water by underrunning the dew point temperature. But the simple and robust set-up has its price: in conventional HVAC systems the dehumidification of the outside air is very energy intensive. The specific enthalpy of the moisture removal is significantly higher as for the cooling process because of

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Nomenclature

Latin symbols

a	half width
A	measured value
A_e	area in equilibrium
c	specific heat capacity, J kg^{-1} K^{-1}
h	specific enthalpy, J kg^{-1}
k	inclusion factor
K	loss coefficient
$\dot{m}$	mass flow, kg s^{-1}
M	mass, kg
N	number of values
p	pressure, N m^{-2}
pT	coefficient for simplified model
pX	coefficient for simplified model
q	moisture content in desiccant wheel, kg kg^{-1}
$\dot{Q}$	heat flux, W
t	time
u	uncertainty
U	internal energy, J
v	velocity ms^{-1}
$\dot{V}$	air flow, m s^{-3}
X	value

Greek symbols

β	mass transfer, m^2 s^{-1}
γ	liquid fraction,
ψ	volume fraction,
φ	relative humidity
ϑ	temperature, °C
ρ	density, kg m^{-3}
ω	humidity ratio, kg kg^{-1}
χ	mass fraction of desiccant material, kg kg^{-1}

Indices

b	type B evaluation of standard uncertainty
c	combined standard uncertainty
i	control volume
j	coefficient
s	saturation
S	simulated
tr	triple point
w	water

the high evaporation enthalpy of the water ($r_0 = 2500$ k J kg^{-1}). Also, heat sinks with temperatures below the dew point are needed meaning natural heat sinks with temperatures over 17 °C e.g. shallow geothermal energy are mostly not sufficient [24,28].

A more energy efficient solution for HVAC systems are dedicated outdoor air systems (DOAS) or hybrid systems where sensible and latent space loads can be decoupled [29,41]. Desiccant cooling systems are one way to do so, using a desiccant material for moisture removal and a cooling unit for temperature control. Parmar and Hindoliya [30] offer a good overview of studies investigating the operation of desiccant cooling systems and their technological applications. Currently, several test facilities are operated in Mediterranean climates such as Italy [1,4] and Turkey [19].

An additional advantage of desiccant cooling systems is that refrigerant temperatures in the cooling unit can be higher than in conventional chillers, enabling the use of natural heat sinks. For a continuous operation, the desiccant material has to be regenerated driving the water vapor absorbed/adsorbed out of the wheel. Here again, natural heat sources e.g. solar thermal or waste heat can be used because low temperature heat is sufficient for the regeneration process. Wrobel and Schmitz [41] show that decoupling of heat and moisture removal in combination with renewable heat sinks and heat sources can save up to 58% of non-renewable primary energy compared to conventional cooling systems because the over-cooling of the supply air to achieve condensation is omitted.

Modeling can be a strong asset to plant operation because it permits the analysis of non-existing system configurations or extensions to the plant which do not exist yet. Also, parametric studies as well as sensitivity analysis are easily possible once a model of the existing plant has been implemented. However, little seems to have been written on simultaneously operating and modeling desiccant cooling systems. Ruivo et al. [18], Heidarinejad and Pasdarshahri [36], Zheng and Worek [42] present promising ideas on how to model different set-ups of desiccant cooling systems, but all of them rely on secondary data to validate their models.

The use of secondary data has several disadvantages, mainly a possible mismatch between the purpose of the original data collection and the current research objectives and some uncertainty about measurement validity, bias and deliberate distortion within the data. The mentioned risks can only be avoided by the use of primary data, therefore experimental and simulation results out of one hand are of great value. Consequently, this paper will present both experimental and simulation results for a desiccant wheel, which is the central part of a desiccant assisted air conditioning system in a geothermal and desiccant assisted air conditioning (GDAC) pilot plant.

The pilot plant uses a lithium chloride (LiCl) desiccant wheel for dehumidification of the outdoor air, while natural heat sinks and heat sources allow for temperature control of the air and regeneration of the wheel. This set-up allows for an energy efficient and demand orientated air conditioning of an office room as shown in Section 2 of this paper. The desiccant wheel model is written in the language Modelica and was created by Casas [8] and further developed by Joos [21] and Morgenstern [27]. Details on a simplified wheel model are presented in Section 3 of this paper.

2. Desiccant aided air conditioning system

2.1. Pilot installations

The main part of the pilot installation is the desiccant assisted air conditioning system. The use of desiccant wheels for dehumidification in combination with low caloric heat sources e.g. solar thermal energy for wheel regeneration is an established technique and its use reaches back to the 1960s [33]. Because the dehumidification is done in a first step, it is possible to use heat sinks at higher temperature levels, thus saving energy. Dedicated outdoor air systems (DOAS) develop this effect further and remove sensible and latent space loads in two different systems [24,28,35].

The pilot installation described in this paper combines the advantages of desiccant hybrid systems and DOAS to an HVAC system based on renewable heat sources and heat sinks. An additional bypass system allows for a demand oriented air conditioning process in order to reduce pressure loss and save additional energy. Sensible space loads are removed by radiant cooling systems e.g. floor cooling and radiant beams. This allows the desiccant aided air conditioning system to focus on the reduction of latent loads as

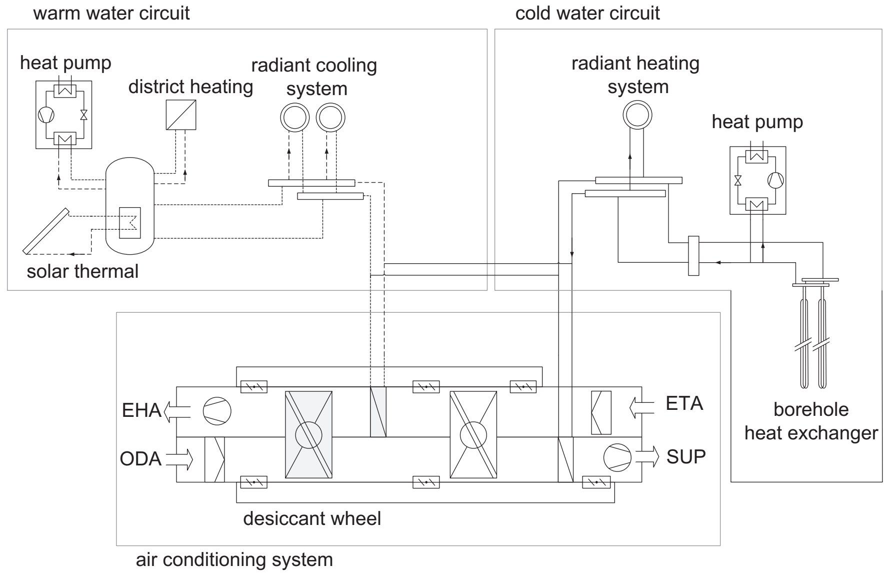

Fig. 1. Pilot installation of a desiccant aided air conditioning system with geothermal heat sink and solar thermal heat source.

well as on the supply of fresh air. The air flow through the desiccant assisted air conditioning system can consequently be reduced to the minimum hygienic air rate, making space heating and cooling very energy efficient.

Fig. 1 shows the presented pilot installation. A flat panel solar thermal system is used as primary heat source and borehole heat exchangers as well as energy piles is the primary heat sink. Additionally, the heat supply side includes a district heating connection with a primary energy ratio (PER) of 0.568 [13]. It is connected to the condensing side of a heat pump, which can be used to provide additional heating services. During summer, the heat pump can provide additional cooling and its evaporative side is therefore connected to the cold water circuit of the plant.

2.2. Description of the desiccant wheel

The pilot installation shown in Fig. 1 can be a very energy efficient solution for heating and cooling. However, the efficiency of the whole system is highly influenced by the performance of the desiccant wheel, its central component. Some experience with the rotating desiccant wheel used in the presented pilot installation will be reported in this paper.

The desiccant of this specific wheel is embedded in supporting material with honeycomb structure as shown in Fig. 2a. The path taken by the dehumidified within the desiccant process as well as the condensing process in the psychometric chart can be seen in Fig. 2b. In the condensing process, the air is chilled below its dew point by a cooling system to remove moisture. In contrast, in desiccant aided dehumidification processes, the water in the air is attracted by desiccant materials e.g. lithium chloride. In some desiccants the water is held on the surface, these desiccants are called adsorbents and they are mostly solids. Other desiccants, so called absorbents, undergo a chemical or physical change while interacting with the water from the moist air stream. Absorbents are usually liquids, or solids which become liquids [17].

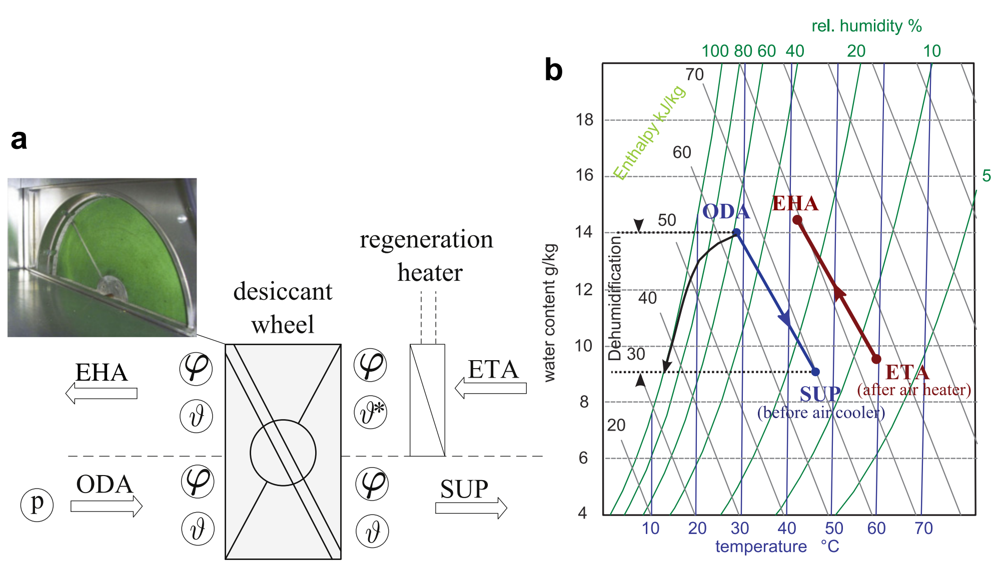

Fig. 2. Air dehumidification in the desiccant process (a) Scheme of the desiccant wheel with outdoor air (ODA), supply air (SUP), extract air (ETA) and exhaust air (EHA), (b) Enthalpy diagram of the desiccant process.

Casas [8] describes the desiccant process using lithium chloride as desiccant as a combination of adsorption and absorption. The process can be described as following: Outside air is dried in the desiccant wheel which is continuously regenerated by warm regeneration air. The water in the warm and humid outdoor air is adsorbed and/or absorbed by the desiccant of the wheel. The enthalpy of evaporation as well as the free enthalpy is set free and transferred to the supply air. The air behind the desiccant wheel is drier but warmer than the outdoor air (ODA). In general, a rotating heat exchanger reduces the temperature before the dry air is cooled with the air cooler unit. For the regeneration warm air has to be passed through the wheel to desorb the bound water.

The geometric parameters for the wheel used in the presented pilot installation as well as some physical parameters can be found in Table 1. Other parameters, especially the total density and the overall heat capacity depend strongly on supporting material, the installation situation and the surrounding of the wheel, e.g. the casing. They can therefore hardly be generalized.

2.3. Data acquisition and measurement data evaluation

Analysis of uncertainty in measurement is an important part in the evaluation of any measurement results as well as for the evaluation of the system models. Table 2 shows a selection of sensors used within the pilot installation with focus on the uncertainty of temperatures and water contents. While temperatures are measured directly, water contents and therewith the uncertainty of water contents depend on several input parameters and has to be calculated [11,23].

The water content of air is defined as

$$\omega = 0.622 \cdot \frac{p_W^s(\vartheta)}{\frac{p}{\phi} - p_W^s(\vartheta)} \tag{1}$$

With the saturation pressure based on the Antoine approximation ($A = 17.2799$, $B = 4102.99$, $C = 237.431$ [3])

$$p_W^s = \exp\left(A - \frac{B}{\vartheta + C}\right) \cdot p_{tr} \tag{2}$$

and p_{tr} as the triple point of water, the water content of air ω results as following.

$$\omega(\vartheta, \phi, p, p_{tr}) = 0.622 \frac{\exp\left(A - \frac{B}{\vartheta + C}\right) \cdot p_{tr}}{\frac{p}{\phi} - \exp\left(A - \frac{B}{\vartheta + C}\right) \cdot p_{tr}}. \tag{3}$$

The water content based on equation (1) depends on the temperature, the relative humidity, the pressure and the triple point. Due to the very low uncertainty of the triple point $p_{tr} = 611.657$ Pa with $u = 0.010$ Pa the uncertainty of the triple point will be neglected.

With the half-width a calculated using the uncertainty of the measurement equipment, the standard uncertainty results in

Table 1
Specifications of the desiccant wheel.

Wheel parameter	
Desiccant media	Lithium chloride (LiCl)
Density LiCl	2068 kg m^{-3} [32]
Heat capacity LiCl	1132 J kg^{-1} K [32]
Wheel diameter	0.65 m
Wheel depth	0.2 m
Wheel speed	0.33 rpm

Table 2
Uncertainty of the measurement devices of the pilot installation.

Sensor	Measure variable	Uncertainty
Easytemp®TMR31	Temperature (ϑ)	$\pm(0.15 + 0.002 \cdot \lvert\vartheta\rvert)$ (class A)
Type 405	Temperature (ϑ^*)	$\pm 1/3 \cdot (0.30 + 0.005 \cdot \lvert\vartheta\rvert)$ (class 1/3B)
PC52-Series	Humidity (φ)	±(2% relative humidity)
Wireless Vantage Pro2™	Absolute pressure (p)	±(1.0 hPa)

$$u_B = \frac{\Delta a}{\sqrt{3}} \tag{4}$$

The uncertainty $u_c(\omega)$ of the water content can be described as the combination of uncertainties u_B calculated before.

$$u_c(\omega) = \sqrt{\left(\frac{\partial \omega}{\partial \vartheta}\right)^2 \cdot u_B^2(t) + \left(\frac{\partial \omega}{\partial \phi}\right)^2 \cdot u_B^2(\phi) + \left(\frac{\partial \omega}{\partial p}\right)^2 \cdot u_B^2(p)}. \tag{5}$$

The extended uncertainty U can be calculated with the inclusion factor k as multiplicator. To take into account the distribution of measurement uncertainty, the extended uncertainty U can be calculated from u using the inclusion factor k [10].

$$U = k \cdot u_c \tag{6}$$

It is importance to notice, that the uncertainty calculated does not include any systematic error. The bias in measurement, especially the temperature measurement behind the desiccant wheel in only one point, can lead to even a higher uncertainties as calculated.

3. Modeling of the desiccant wheel

Generally, modeling and simulation are of high value whenever real experiments are too complicated, too expensive, dangerous or unethical [14]. For HVAC system in particular, as they strongly depend on local climate conditions which cannot be changed arbitrarily, modeling and simulation of existing pilot installation are an important part of their global evaluation.

In this work, Modelica was chosen as modeling language for the GDAC-plant. It is an object-oriented equation-based language for the modeling of large, complex and heterogeneous physical systems. The basic idea behind Modelica was "to create a language that could express the behavior of models from a wide range of engineering domains without limiting those models to a particular commercial tool [38]". Therefore Modelica is often referred to as a multi-domain modeling language.

One of Modelica's merits when modeling the GDAC-plant is its strength in handling time dependent variables. Because it is ultimately necessary to simulate year-long periods to evaluate air-conditioning concepts, dynamic models with a good accuracy are required.

3.1. Physical modeling

This paper presents the model of the desiccant wheel which is a vital part of the HVAC_Lib model library developed at the Institute of Thermo-Fluid Dynamics, Technical Thermodynamic. The structure of the library is shown in Fig. 3a. The desiccant wheel is the most complex model within the library due to the interaction of the chemical process of ab-/adsorption with the thermodynamical processes of heating (cooling) and humidification (dehumidification) of the moist air stream.

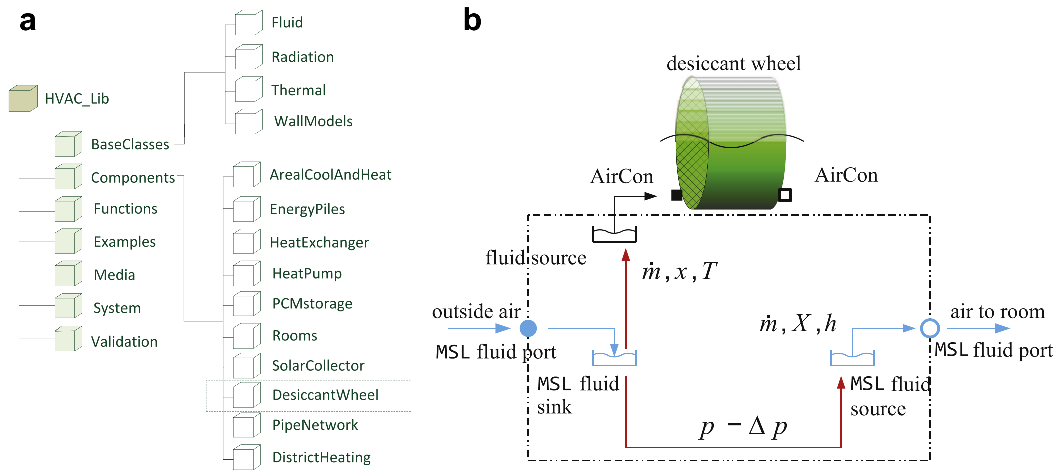

Fig. 3. Desiccant wheel as part of the HVAC_Lib (a) Structure of the HVAC_Lib model library (b) Structure of the wheel model within HVAC_Lib.

The absorption/adsorption process of water from moist air in the desiccant wheel is described using partial differential equations. It is driven by coupled heat and mass transfer between the moist air and the desiccant material used for its dehumidification (see Fig. 4). Therewith is the desiccant material assumed to be laid on a uniform supporting material such as cellulose forming a homogeneous wheel.

Consequently, energy and mass balances for each of the two materials have to be formulated. For both, an approach using lumped transfer coefficients is chosen. Assuming humid air to be incompressible and an ideal mixture according to Dalton's Law of Partial Pressures as well as neglecting heat conduction in the direction of the flow, the discretised energy balance for any element i of moist air can be written as

$$\frac{\partial U_\mathrm{i}}{\partial t} = \dot{Q}_\mathrm{i} + \dot{m}_{\mathrm{i}-1} \cdot h_{\mathrm{i}-1} - \dot{m}_\mathrm{i} \cdot h_\mathrm{i} + \dot{m}_\mathrm{w,i} \cdot h_\mathrm{w,i} \tag{7}$$

with

- $\dot{m}_{\mathrm{i}-1}$ – mass flow of (moist) air entering the element i,
- $\dot{m}_\mathrm{i}$ – mass flow of (moist) air leaving the element i,
- $h_{\mathrm{i}-1}$ – enthalpy of (moist) air entering the element i,
- h_i – enthalpy of (moist) air leaving the element i.

$\dot{Q}_\mathrm{i}$ is the sensible heat flux and $h_\mathrm{w,i}$ denotes the enthalpy of the exchanged moisture making $\dot{m}_\mathrm{w,i} \cdot h_\mathrm{w,i}$ the latent heat flux. The energy balance for the desiccant material results in

$$\frac{\partial U_\mathrm{i}}{\partial t} = \dot{Q}_\mathrm{i} + \dot{m}_\mathrm{w,i} \cdot h_\mathrm{w,i}. \tag{8}$$

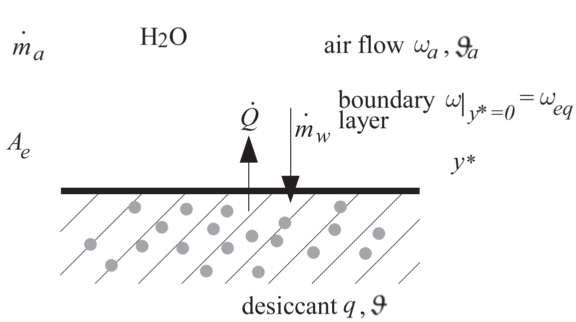

Fig. 4. Convective heat and moisture transfer.

neglecting axial heat conduction. As for the air side, $\dot{Q}_\mathrm{i}$ is the sensible heat transferred between air and desiccant material by convection and can be described according to Newton's Law of Cooling using a numerically determined heat transfer coefficient for laminar flow. $\dot{m}_\mathrm{w,i} \cdot h_\mathrm{w,i}$ is again the latent heat transferred with the moisture and is subject to heat of vaporization and binding enthalpy.

The change of water mass in any discrete element $\dot{m}_\mathrm{w,i}$ can be calculated from

$$\dot{m}_\mathrm{w,i} = \frac{\partial M_\mathrm{w,i}}{\partial t} = M_\mathrm{i} \cdot \chi \cdot \frac{\partial q_\mathrm{i}}{\partial t}, \tag{9}$$

whereby q_i is the moisture content in the desiccant material and χ is the mass fraction of the desiccant material.

$$q_\mathrm{i} = \frac{M_\mathrm{w,i}}{\chi \cdot M_\mathrm{i}}. \tag{10}$$

Analog to the description of heat transfer using a heat transfer coefficient and a temperature gradient, convective mass transfer can be described by

$$\dot{m}_\mathrm{w,i} = \beta_\mathrm{i} \cdot \rho_\mathrm{a,i} \cdot A_\mathrm{e,i} \cdot \left(\omega_\mathrm{a,i} - \omega|_{y^*=0} \right). \tag{11}$$

neglecting humidity transport and diffusion into the wheel. β_i denotes the mass transfer coefficient and a moisture gradient between the air flow and the boundary layer of the desiccant surface is the driving force $\omega_\mathrm{a,i} - \omega|_{y^*=0}$. It is assumed that the boundary layer is everywhere in equilibrium with the wall with respect to temperature and moisture content. It is important to note that these relationships can only be used if convective mass transfer at the surface dominates the overall mass transfer resistance as other moisture transport mechanisms (e.g. pore diffusion in the material) are neglected.

The sorption isotherm describes the equilibrium moisture content of a desiccant for a constant temperature depending on vapor partial pressure and needs to be determined experimentally.

$$\omega_\mathrm{eq} = \omega(p_\mathrm{w}, \vartheta) \tag{12}$$

In the literature, several experiments investigating the sorption isotherm of lithium chloride are reported [16,20,34]. While the sorption isotherm of most solid desiccants (e.g. silicagel) is continuous over a wide range of temperatures, the slope of lithium chloride's sorption isotherm changes discontinuously due to phase changes of the system (LiCl hydrate formation). For the implementation in Modelica, appropriate crossing functions are used to avoid numerical instabilities during simulation and to reduce computation time.

3.2. Object-orientated structure

Casas models the sorption wheel as slowly rotating desiccant wheel according to reality. His sorption wheel is discretised both in tangential and in longitudinal direction [9]. During validation the model provides accurate results for the absorptive capacity of the wheel, but proves to need high computation time. Consequently, the wheel model is refined by Joos and its structure is altered fundamentally to overcome restrictions in applicability and to reduce computing time. The approach is described in detail in Ref. [22].

Now, air and desiccant material control volumes (CVs) are fixed locally and a virtual desiccant fluid is introduced which flows through the desiccant control volumes in cross flow to the direction of the air flow (Fig. 5a. The black lines on the wheel indicate the discretization. Benefiting from the flexibility of an object orientated modeling language, the existing control volumina models by Casas can be used and are simply rearranged. Fig. 5b illustrates how the air control volume and the desiccant material control volume interact by exchanging heat and moisture modeling (de-)humidification of the air by the sorbens. Air flows along the cylinder axis while the virtual desiccant fluid passes in tangential direction through its control volume.

The desiccant wheel model is further refined and included into the library by Morgenstern [27] as shown in Fig. 3b. Some changes to physical and object structure of the model are made (e.g. updates in used Modelica version and changes of connector variables) and including a pressure loss over the wheel is made an option in the model. This becomes extremely relevant when the wheel model is incorporated into models of the entire pilot plant as especially in highly energy efficient systems pressure loss is of major interest. Within the air handling unit of the GDAC-plant, the pressure loss over the desiccant wheel has a significant influence of the total pressure loss. In consequence, including a constant pressure loss or a more complex pressure loss expression into the desiccant wheel model is necessary to accurately predict plant efficiency.

4. Results and discussion

Mathematical models always are at fault to demonstrate how closely their results resemble reality. In science, two methods have developed for this purpose: verification and validation.

Verification is making sure that "the software is an adequate representation of the documented behavior [14] or in easier words: making sure the model was built right [7]". For the Modelica model library HVAC_Lib and the desiccant wheel model presented here, this means that all models are built according to the Modelica syntax, that all units are correctly declared, etc. The compiler of Dymola, the simulation environment used, contributes highly to the process of verification, performing various checks on the model during the process of translation.

In contrast, validation answers a different question: "Is the right behavior evident in the system [14]?" or easier: was the right thing built into a model [7]? As Fischer puts it: "The source code may be built adequately but if it doesn't operate as the user needs it to then what's the point in building the system?" Therefore validation is a crucial step during model development. In this work, the validation of the desiccant wheel model by comparison with measurement data from the GDAC-plant is presented.

4.1. Validation

The aim of the sorption wheel model is to predict both changes in water load and in temperature of supply and exhaust air. Measurement data and simulation results for the temperature and the water content of the supply air at the outlet of the sorption wheel for two 2.5 h sample runs of the pilot plant can be seen in Fig. 6. The mathematical analysis of measurement data and simulation results is done using mean absolute percentage error (MAPE) and root mean squared percentage error (RMSPE) [2,40].

$$\mathrm{MAPE} = \frac{\sum\left|\frac{X_S - A}{A}\right|}{N}\cdot 100 \tag{13}$$

$$\mathrm{RMSPE} = \sqrt{\frac{\sum\left(\frac{X_S - A}{A}\right)^2}{N}}\cdot 100 \tag{14}$$

With X_S being the simulated value, A the actual measured value and N as the number of values analyzed.

As described previously, the desiccant wheel and in consequence the desiccant wheel model are characterized by a number of geometrical and material parameters. For the simulation the material parameters i.e. heat capacity and density of the desiccant wheel as well as the mass fraction of desiccant among supporting material in the wheel are modified within a realistic range to fit the measurement data. This approach is reasonable due to significant uncertainties about the true value of these parameters as they are hard to measure in the first place and also strongly influenced by installation and commissioning of the pilot plant.

The sample runs for the parameter modification are performed on a typical sunny day under controlled operation of the pilot plant. The general outdoor conditions during summer for the location of the pilot installation can be seen in Fig. 7a and b. Fig. 7a and b shows

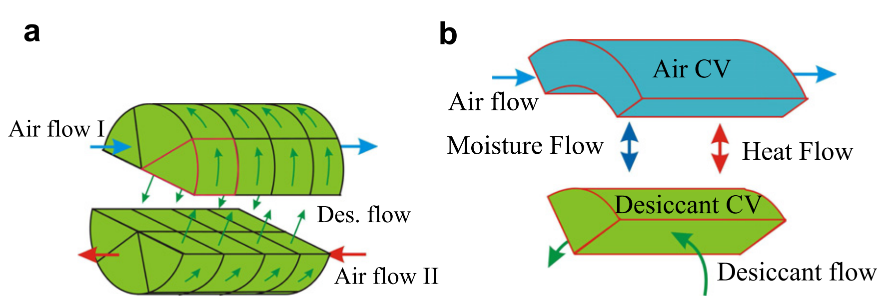

Fig. 5. The desiccant wheel as part of the air conditioning process according to Joos et al. [22] (a) Complete wheel (b) Detail scheme of one element from the wheel.

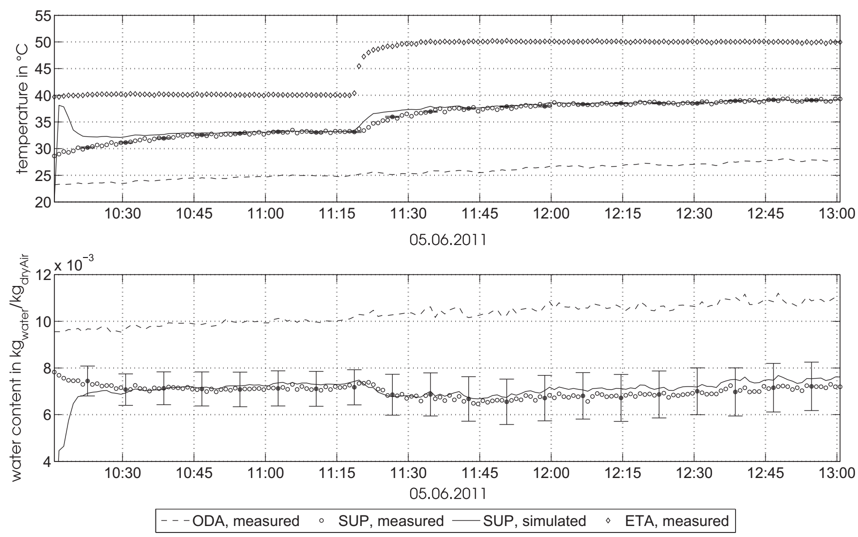

Fig. 6. Performance of the desiccant wheel compared to the simulation results of the desiccant wheel ($L = 0.25$ m, $D = 0.65$ m, LiCl, $\dot{V} = 900\ m^3\ h^{-1}$) with supply air (SUP) behind the desiccant wheel and extract air (ETA) behind the regeneration air heater.

for how long certain outdoor air conditions prevailed during the period from 09.10.2009 to 06.01.2012. The outdoor conditions for the day of the sample runs are indicated.

Adopting the model to the data measured during the first sample run, the density of the desiccant wheel model results $\rho = 18$ kg m^{-3}, its heat capacity is $c_p = 2200$ J kg^{-1} K and the mass fraction of desiccant is $\chi = 0.06$ kg kg^{-1}. The MAPE of the temperature for this runs is 2.07% (RMSPE 4.98%). For the water content the MAPE is 4.44% (RMSPE 9.70%). Table 3 also shows errors for the second sample run using the same model parameters.

Both model parameters and deviations between measurement data and simulations results appear to be reasonable given the range of material parameters reported in the literature [15,31] and the significant uncertainties about the accuracy of the measurement data. This holds especially true for the MAPE of the water content, which might at first appear high but needs to be contrasted with relative measurement uncertainties as big as 20% resulting from equation (5) with inclusion factor $k = 2$ for normal distributed measurement uncertainty. The uncertainty of the indirect measured water content at the wheel outlet is indicated by error bars in Fig. 6.

It has to be taken into account that the presented parameters and errors are only strictly valid for plant operation under comparable climate conditions. However, the use of desiccant wheels is especially beneficial in humid climates (more than

Table 3
MAPE and RMSPE in % for temperature and water content.

	05-06-2011		06-06-2011	
	M/S	M/A	M/S	M/A
RMSPE (ϑ)	4.98	4.77	4.62	3.91
RMSPE (ω)	9.70	3.47	9.66	5.86
MAPE (ϑ)	2.07	4.04	1.85	3.40
MAPE (ω)	4.44	2.88	5.54	4.75

10 g kg^{-1}) and cannot be fully exhausted in Germany where their use is restricted to few days during summer. With a maximum dehumidification of $\Delta\omega = 8$ g kg^{-1} a pre-cooling for fully humid climate is necessary [9,26]. The desiccant wheel model can offer valuable indications toward the plant performance in different climates, but growing uncertainty about the deviation between simulation and actual results has to be considered.

4.2. Simplified model

For some purposes e.g. a first assessment of a possible application of a desiccant cooling system in a certain location or for the use as within an online control system, the physical model of the desiccant wheel may be too complex and exceed a users computation power available [22]. For this purpose, characteristic

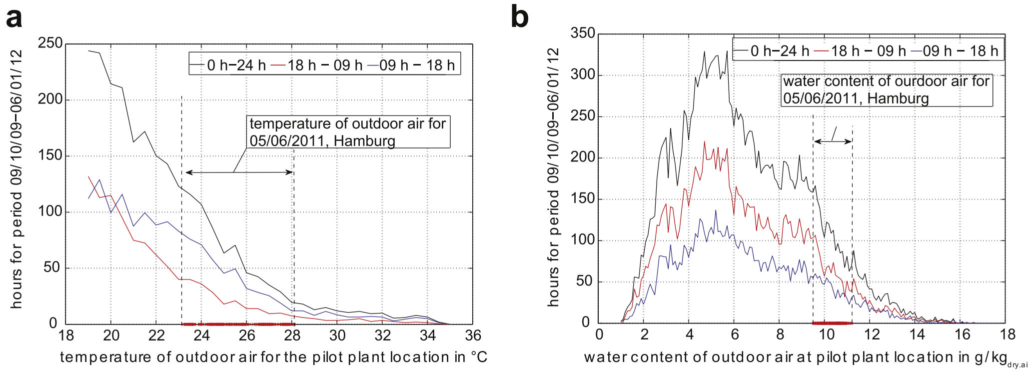

Fig. 7. Temperature and water content of the outdoor air (ODA) for 05/06/2011, Hamburg. (a) Temperatures of outdoor air (ODA) (b) Water content of outdoor air (ODA).

Table 4
Coefficients for simple approximation of the desiccant wheel, validated with measurement data for: $\omega_{ODA} = [8.5 \text{ g kg}^{-1}_{dryair} - 13\text{g kg}^{-1}_{dryair}]$, $\vartheta_{ODA} = [20\ ^\circ C–30\ ^\circ C]$, $\vartheta_{RHE} = [45\ ^\circ C–50\ ^\circ C]$.

j	$pT(RHE)_j$			$pX(RHE)_j$		
00	[4.0136×10^{-2}	-4.7338×10^{0}	1.2104×10^{2}]	[-2.6155×10^{-2}	2.6123×10^{0}	-5.9110×10^{1}]
10	[9.3524×10^{-4}	-8.3906×10^{-2}	3.8056×10^{0}]	[8.2691×10^{-4}	-8.7388×10^{-2}	2.1593×10^{0}]
01	[-2.9531×10^{-3}	3.6530×10^{-1}	-8.5401×10^{0}]	[1.7125×10^{-3}	-1.7441×10^{-1}	4.2265×10^{0}]
20	[-2.8017×10^{-5}	2.7851×10^{-3}	-1.0583×10^{-1}]	[-3.5617×10^{-5}	3.7957×10^{-3}	-7.6326×10^{-2}]
11	[1.5452×10^{-5}	-1.7507×10^{-3}	3.5048×10^{-2}]	[-1.4435×10^{-5}	1.2705×10^{-3}	-2.3106×10^{-2}]
02	[4.5132×10^{-5}	-5.6535×10^{-3}	1.4085×10^{-1}]	[-2.5269×10^{-5}	2.6026×10^{-3}	-6.1609×10^{-2}]

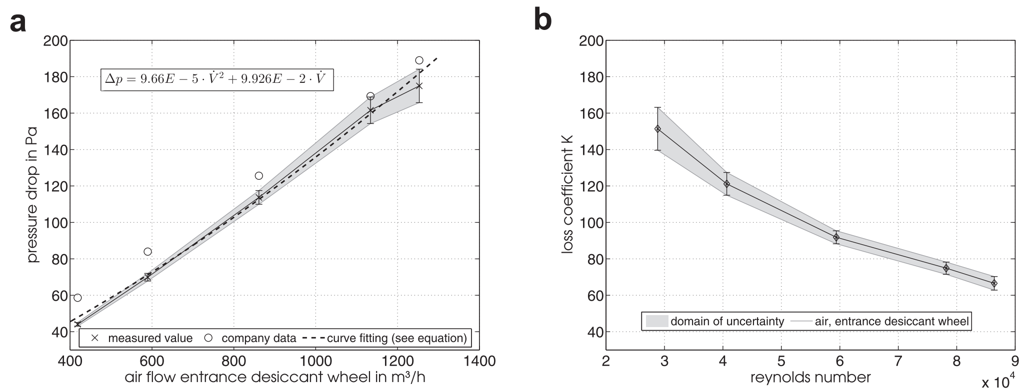

Fig. 8. Pressure drop and loss coefficient for the supply air flow of the desiccant wheel ($D = 0.65$ m) based on 50–80 samples each point. (a) Measurement data and company data for the pressure drop in the desiccant wheel (b) Loss coefficient K against the Reynolds number.

functions of temperature and humidity for a desiccant wheel with specifications as used in the GDAC-plant are generated based on the simulation results of the validated Modelica wheel model. The functions are limited to the approximation of desiccant wheels with nearly the same dimensions and desiccant material, but can offer a benchmark for plant dimensioning if the more variable physical model, adaptable to any dimensions and desiccant materials, is too complex for an application for example yearly calculations or control models.

The function for the specific wheel described in Table 1 for a volume flow of $\dot{V} = 900\ \text{m}^3\ \text{h}^{-1}$ can be described with the following equations. The equations are polynomial functions of second degree in x- and y-direction which have previously been shown to deliver suitable approximations for this purposes [39].

$$\vartheta_{DEC} = pT_{00} + pT_{10} \cdot \omega_{ODA} + pT_{01} \cdot \vartheta_{ODA} + pT_{20} \cdot \omega_{ODA}^2 + pT_{11} \cdot \omega_{ODA} \cdot \vartheta_{ODA} + pT_{02} \cdot \vartheta_{ODA}^2 \tag{15}$$

$$\omega_{DEC} = pX_{00} + pX_{10} \cdot \omega_{ODA} + pX_{01} \cdot \vartheta_{ODA} + pX_{20} \cdot \omega_{ODA}^2 + pX_{11} \cdot \omega_{ODA} \cdot \vartheta_{ODA} + pX_{02} \cdot \vartheta_{ODA}^2 \tag{16}$$

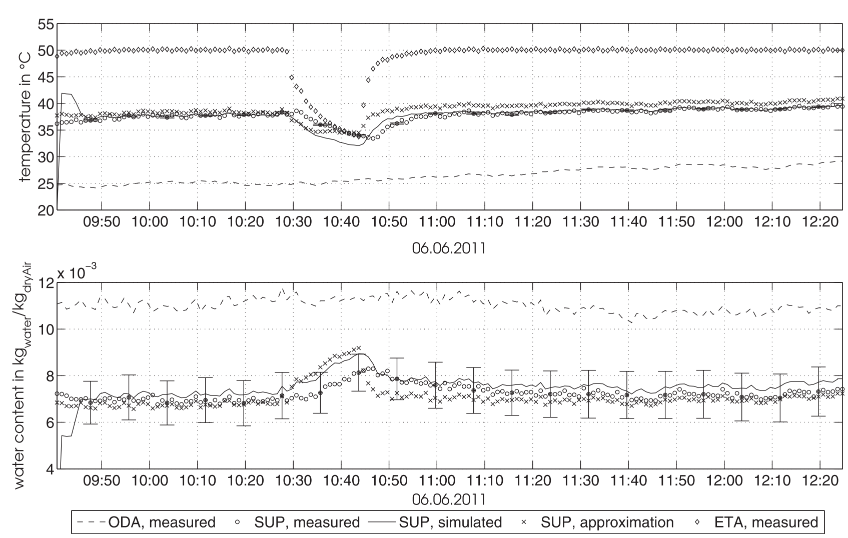

Fig. 9. Performance of the desiccant wheel compared to the simulation results of the physical and simplified desiccant wheel model ($L = 0.25$ m, $D = 0.65$ m, LiCl, $V = 900\ \text{m}^3\ \text{h}^{-1}$) with supply air (SUP) behind the desiccant wheel and extract air (ETA) after the regeneration air heater.

The coefficients for the approximation depending on the regeneration temperature can be found in Table 4. The coefficients can be calculated by a quadratic equation with the general form.

$$pT_{\mathrm{j}} = pT(\mathrm{RHE})_{\mathrm{j}}(1) + pT(\mathrm{RHE})_{\mathrm{j}}(2)\cdot\vartheta_{\mathrm{RHE}} + pT(\mathrm{RHE})_{\mathrm{j}}(3)\cdot\vartheta_{\mathrm{RHE}}^{2} \quad (17)$$

$$pX_{\mathrm{j}} = pX(\mathrm{RHE})_{\mathrm{j}}(1) + pX(\mathrm{RHE})_{\mathrm{j}}(2)\cdot\vartheta_{\mathrm{RHE}} + pX(\mathrm{RHE})_{\mathrm{j}}(3)\cdot\vartheta_{\mathrm{RHE}}^{2} \quad (18)$$

The pressure loss due to friction of laminar or turbulent flows can be calculated with equation (19).

$$\Delta p = K\cdot\frac{\rho\cdot v^2}{2} \quad (19)$$

where K is the loss coefficient and v the velocity at the corresponding location. Equation (20) approximates the pressure drop of the desiccant wheel based on measurement data. The deviation of the measurement data to the company data is shown in Fig. 8a has a MAPE of 9.6934% (RMSPE 11.6%). Fig. 8b shows the loss coefficient as used to compute the simplified model. It is based on measurement data and the Reynolds number calculated at the entrance of the desiccant wheel.

$$\Delta p = a\cdot\dot{V}^2 + b\dot{V}, \text{with } a = 3.66\mathrm{E}-05 \text{ and } b = 9.926\mathrm{E}-2. \quad (20)$$

The simulation results for both the physical Modelica model (S) and the approximation (A), compared to the measurement data (M) can be seen in Fig. 9. Table 3 shows the mathematical error expressions. It is clear that the approximation provides very good results which partly even exceed the quality of the simulation results while needing far less resources and computations power for this particular wheel configuration. But again, it has to be taken into account that the extrapolation of results outside the range of the measurement data may lead to significantly higher deviations for both temperature and water content.

5. Conclusion

This paper shows that detailed numerical models as well as simplified models can be valuable tools to analyze the performance of HVAC systems, for system control and to assess applicability in different climatic conditions. But is also becomes obvious that they can only be customized and validated if appropriate measurement data is available. Without repeated comparison to actual performance data, the worth of simulation results is highly questionable.

Experimental and simulation results from the same source are therefore extremely valuable. Unlike when using secondary data, measurement uncertainties and effects influencing the quality of measurements are well known and can be considered when evaluating simulation results. In secondary data confidence intervals for measurements are not always given, which aggravates conclusions about their accuracy and resulting error margins of simulation results.

On the other hand, the use of primary measurement data links the validation process for models to local climate conditions, in this case to Northern Germany. Measurement data from other locations could be beneficial to extend the reach of the desiccant wheel model and to further investigate its sensitivity to input data. However, for applications in desiccant cooling systems in moderate climates the presented model allows predictions with relative errors of less than 5% for temperature and less than 10% for humidity at the wheel outlet.

Using a validated physical model as starting point to build a simplified model has several advantages for the dimensioning of new desiccant assisted HVAC systems. While the physical model offers flexibility within wheel parameters and physical properties at the price of high complexity and demand for skills and computational capacity, the simplified model is less flexible but can be used in online controls systems or other simulation tools based on numerical approximations. The coexistence of both models ensures that information tailored to the users' needs are made available and a wide range of people can benefit from the results obtained through the pilot plant presented.

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