Enhancement of a Modelica Model of a Desiccant Wheel

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Abstract

This paper presents a MODELICA model for a desiccant wheel. Desiccant wheels are used in new concepts for air conditioning systems, which can save primary energy in contrast to conventional systems. This model is based on a model, which was presented at the MODELICA Conference 2005 [2], however in this study the model is improved with a new modeling approach to represent the wheels rotation. This structural change made the model faster and able to produce continuous output in contrast to the one of *Casas et al.*, [1, 2]. This was an essential step to enhance long term simulations of desiccant systems and control strategies. These simulations are necessary to optimize such systems and to evaluate their primary energy consumption.

Keywords: Modelica; Simulation; Desiccant Wheel; Air Conditioning; Sorption

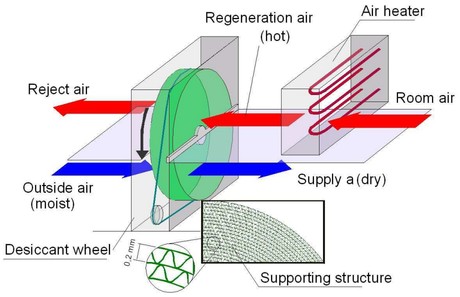

Figure 1: Example of an air-conditioning using a desiccant wheel

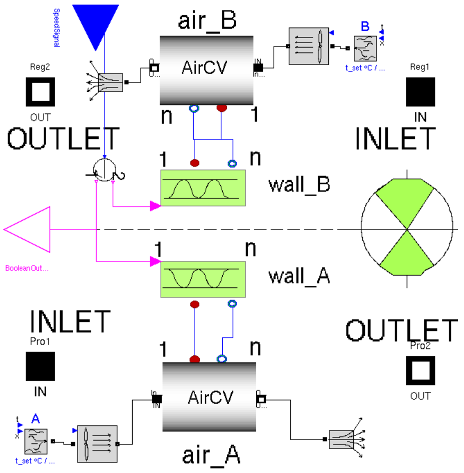

Figure 2: Schema of the old modeling approach [2]

1 Introduction

In desiccant air conditioning systems, moist air is dehumidified by means of a desiccant wheel, see figure 1. Water vapor is absorbed by desiccant material as humid air passes through the wheel. Using this technology, considerable energy savings can be obtained compared to conventional air conditioning systems. In [1] a model library has been developed to evaluate the performance of the desiccant assisted air conditioning process, so that different configurations and system concepts can be easily realized. Because it is necessary to simulate a period of a year to evaluate an air-conditioning concept, fast, dynamic models with a good accuracy are required. All these requirements argue for MODELICA as modeling language. The main and most complex component of this library is the model of the desiccant wheel.

Early approaches for numerical models can be found in [3, 7, 8]. These model formulations have the disadvantage in that they can not handle desiccant materials with discontinuities in their sorption isotherm (e.g. lithium chloride, LiCl). In [2] a MODELICA model is introduced to overcome those limitations, see figure 2 for an overview.

This model is discretized in such a way, that a system of ordinary differential and algebraic equations is generated, which can be easily re-configured for different set-up's. Also new relations for further sorption

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isotherms can be provided without much effort. But due to the modeling approach of the rotation movement of the desiccant wheel through the two airflows, every half revolution time a state event in the numerical solver is caused. Thereby the maximal step size of the solver is restricted. This approach is also only valid, if the change of the boundary conditions of the desiccant wheel is insignificant in half a revolution cycle. Considering the field of application, this is a rather academic aspect. Although the user should be aware of this fact. Another disadvantage is that the model produces discrete output variables from a continuous process. To overcome these handicaps a new model approach of the coated wheel's movement through the airflow was developed, implemented and tested. This approach was developed during the work on [4].

2 Modelica Model of *Casas et al.*

The model of *Casas et al.* is described in detail in [2]. This section will only give a short overview of the model and highlight the structural criteria that were changed in this work. As shown in figure 2 the implementation in Modelica is based on control volumes for air (AirCV) and for the desiccant material (wall_A/B), which can exchange heat and moisture.

Modelica can only handle ordinary differential equations with respect to time. Therefore the basic idea of the first approach was a variable transformation to express the position of the rotating wheel with respect to the airflows in terms of time instead of angular position. Among the assumptions made in [2], three are elementary in this approach:

1. The states are not a function of the wheel's radius: $\vartheta, x \neq f_{(R)}$.
2. The variation of boundary conditions during half a rotation is negligible: $\left.\frac{\partial BC}{\partial t}\right|_{\frac{T}{2}} \approx 0$.
3. The angular velocity of the wheel ω is constant during half a period: $\left.\frac{\partial \omega}{\partial t}\right|_{\frac{T}{2}} \approx 0$.

Equation (1a) gives the average outlet temperature of one airstream. To calculate the integral, the tangential outlet temperature distribution must be known. This leads to a tangential discretization of the wheel and a modeling of the the motion of the discrete pieces through one airflow into the other. To display this movement the variable transformation from the angle ϕ to the time t is introduced, which leads to equation (1b).

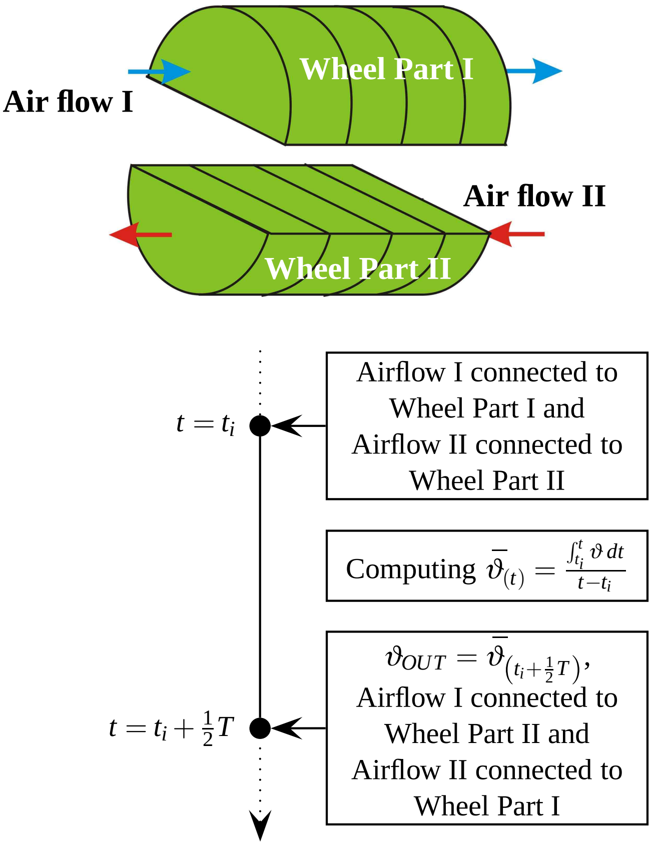


Figure 3: Function principle of the model from *Casas et al.*

$$\bar{\vartheta}_{\text{Air,out}} = \frac{1}{\pi}\int_{0}^{\pi} \vartheta_{\left(\phi,t,BC_{(t)}\right)}\, d\phi \tag{1a}$$

with

$$t = \frac{\phi}{\omega} = \frac{\phi \cdot T}{2\pi} \text{ and } dt = d\phi$$

leads to

$$\bar{\vartheta}_{\text{Air,out}} = \frac{2}{T}\int_{t_0}^{t_0+\frac{T}{2}} \vartheta_{\left(t,BC_{(t)}\right)}\, dt \tag{1b}$$

The advantage of this formulation is, that the wheel has only to be split in two halves; one for each air flow. At the end of half a rotation period, the boundary conditions of the two pieces are switched; the wheel has performed half a revolution. Figure 3 illustrate this behavior.

Another more process engineering oriented point of view is that the continuous process of the turning wheel is represented by batch processes, which each last half a revolution period.

Among the application restrictions mentioned, this model has two other drawbacks. First it produces discrete output variables from continuous input values in contrast to the physical process. And second, as will be pointed out in section 4.2 the models computing time is quite large, because it causes every $\frac{T}{2}$ a state event.

3 Structure of the new MODELICA Model

Based on the restriction of applicability and the large computing times mentioned in section 2, a new modeling structure has been developed. The basic idea in this approach is not to perform the variable transformation, but to use equation (1a). To reach this aim, another way to describe the motion of the wheel through the air flows had to be introduced.

The construct of the air and desiccant material control volumes is no longer virtually moved through the air flow by switching the air connectors every half rotation period. Instead the control volume are locally fixed and a *desiccant fluid* was introduced, which flows through the *desiccant CV*'s in cross flow to air flow direction.

Therefore the existing control volumes for air and the desiccant material were used to build a wheel model with a discretization in axial and tangential direction. This modeling approach is sketched in figure 4(a). The black lines on the wheel should hint to the discretization. In contrast to figure 3 the air connectors of the *Air CV* are attached to the in- and outlet connectors of the wheel model. Also the desiccant material models are connected in series to model the rotation by keeping the *desiccant fluid* in a continuously circulating flow.

Figure 4(b) illustrates how the *air* and the *desiccant CV*'s interact by exchanging heat and moisture for modeling the (de-)humidifying the air by the sorbens. These flows are sketched by the double headed arrows between the two CV's. Air flows along the cylinder axis while the solid passes its CV's in tangential direction. These two streams are indicated in figure 4(b) by the arrows near the two CV's.

For these purposes a *desiccant fluid* flow had to be introduced in the *desiccant CV* and set in relation to the revolution speed. This mass flow is computed by equation (2d), which results of the wheel's mean circumferential velocity (2a), the conservation of mass (2b) and the radial passage area (2c). The area is obtained by dividing the longitudinal half section $R \cdot L$ by the axial discretization n.

$$v_{DF} = \frac{R}{2} \cdot \omega \tag{2a}$$

with

$$\dot{m} = A \cdot \rho \cdot v \tag{2b}$$

and

$$A = \frac{L \cdot R}{n} \tag{2c}$$

leads to

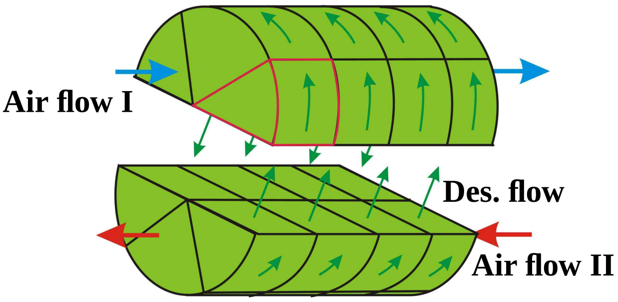
$$\dot{m}_{DF,i} = \frac{L \cdot R^2 \cdot \omega \cdot \rho_{DF}}{2 \cdot n} \tag{2d}$$

The density ρ_{DF} represents the mass of the carrier material for the sorbent divided by the volume of the wheel, thus including its porosity. This definition was chosen, because the phase equilibrium calculation uses the loading of the carrier material with the sorbens and the loading of the sorbens with water.

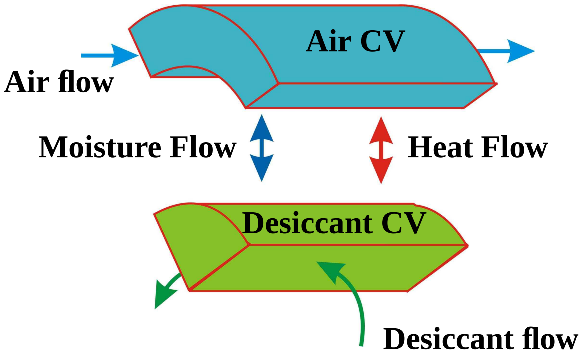
As mentioned before, the new wheel model was constructed by control volumes for air and desiccant material. *Casas et al.* used for their model *Air CV*'s with an axial discretization n in flow direction. To include as much of the existing code as possible m of the *air CV*'s are put side by side to get a control volume, which is discretized in two dimensions. Each stream tube in this construct can not directly interact with its neighbors. Listing 1 gives some code snippets to illustrate the implementation in MODELICA.

There are m instances of the model `AirCV`, which are n times discretized *Air CV*. Each `AirCV` has an `HeatConnector` and `HumidityConnector` in order to couple it with the *Desiccant CV*. These connectors are united in the two models `Heat1Dto2D` and `Humidity1Dto2D`. The function of these two models is to provide a $n \times m$ matrix of heat and humidity flows respectively, so that an Air2D model can easily be connected to a two dimensional desiccant material model to form half a desiccant wheel. Figure 5 shows the two *Air CV*'s connected to two *Desiccant CV*'s, which form a closed loop with a circular flow of the *desiccant fluid*.

The *Desiccant CV* is constructed using an analog method. Its model name in the library is `SMCV_2D`.



(a) Complete Wheel



(b) Detail scheme of one element from the wheel in fig. 4(a)

Figure 4: Scheme of the new modeling approach

It has *n* stream tubes, which are discretized *m* times. The mass flow of the virtual fluid is computed in both SMCV_2D models by equation (2d). The connectors between the *Desiccant CV* only contain the temperature and the water loading of the *desiccant fluid*. The reason for this is to avoid initialization problems with a circular incompressible flow. The disadvantage of this approach is, that the wheel's rotation direction is fixed. But this restriction is also true for the real desiccant wheel, which was used for the experimental part. Another simplification of this model is that the entrainment of air from one air flow to the other is not modeled. So the simulation of fast rotating wheels will lead to errors. But in their application the wheel's circumferential speed is small in comparison to the velocity of the air flows.

Listing 1: Excerpt from the Air CV 2D Matrix model

```
model Air2D
  parameter Integer n = 1 "Axial
     Discretization";
  parameter Integer m = 1 "Tangential
     Discretization";
   ⋮
  AirCV[m] Air(
    each n=n,
       ⋮
  );
  MeanValues Mean(m=m);
  Heat1Dto2D HeatMatrix(n=n,m=m);
  Humidity1Dto2D HumidityMatrix(n=n,m=m
     );
  AirSplit Split(m=m);
equation
  for j in 1:m loop
    connect(Split.Outlet[j], Air[j]
       .Inlet);
    connect(Air[j].Outlet, Mittel.Inlet
       [j]);
    connect(Air[j].HeatConnector,
       HeatMatrix.Heat1D[j]);
    connect(Air[j].HumidityConnector,
       HumidityMatrix.Hum1D[j]);
  end for;
    ⋮
end Air2D;
```

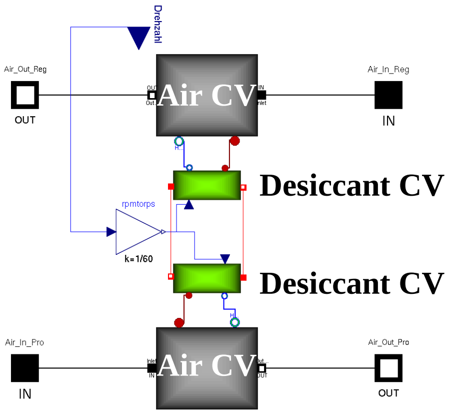


Figure 5: Dymola representation of the new modeling approach

4 Comparison of the two Models

4.1 Results

The model of *Casas et al.* contains sorption isotherms in the medium model for LiCl, which where validated with measured values. The steady state results of the whole wheel were checked against the manufacturer's data and the transient simulations against the model of *Rau et al.* [5]. These isotherms were also implemented in the *desiccant material CV* of the new model. To validate the implementation the test model shown in figure 6 was used. This model consists of a *desiccant material CV* which is connected to an *Air CV*. The des-

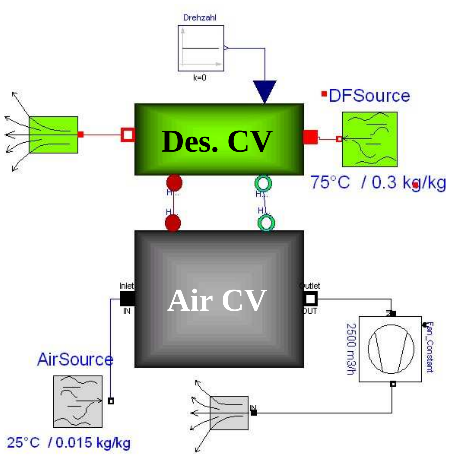


Figure 6: Test model for the comparison with the isotherm data of *Rau et al.*

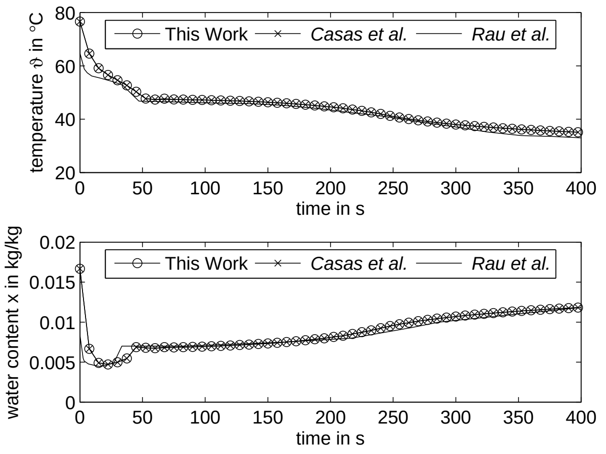


Figure 7: Comparison of a single element of the model from *Casas et al.* and the new one

iccant fluid flow is set to zero in this model, so that the results can be compared to the single blow simulations done by *Rau et al.* [5] and *Casas et al.* [1, 2]. Figure 7 shows the results of the three models. It is obvious that the sorption isotherms implementation in the new model is equivalent to the model of *Casas et al.*. In this aspect it is adequate, because the mathematical implementation of those isotherms was already adapted to the use in MODELICA.

For all results, which are discussed below, models were used, which contain an instance of a whole desiccant wheel model and sources and sinks for the air flows. One of those test configurations is presented in figure 8, in this case with the new model.

The accuracy of the new model depends on the tangential discretization m. The behavior of the *desiccant material CV* approaches that of the real wheel as the computational grid is refined, viz. the more dis-

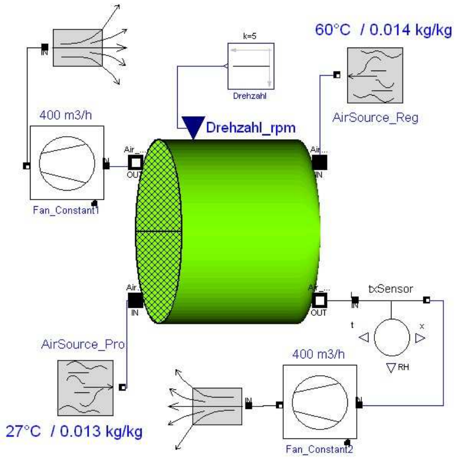


Figure 8: Test model for comparisons of the whole wheel model, here with the model form this work

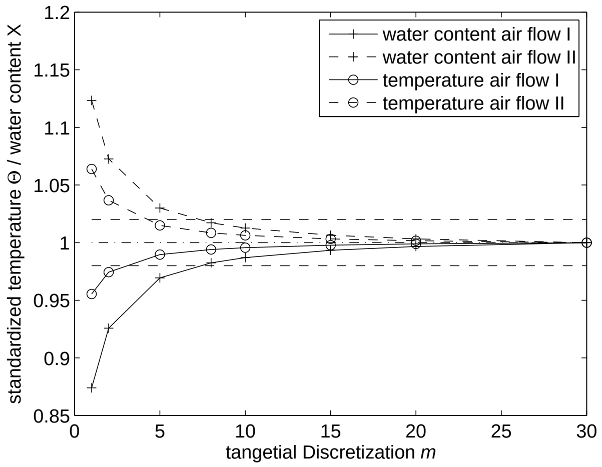


Figure 9: Influence of the tangential discretization to the accuracy

crete control volumes are instantiated in flow direction of the *desiccant fluid*. Figure 9 shows standardized outlet temperatures Θ and water contents X of the two air flow through the desiccant wheel model. They are plotted against the tangential discretization m. The reference value is the corresponding simulation result from a calculation with $m = 50$. The values were computed from the steady state results from a step response after 5000 s. It can be seen, that at $m = 8$ the relative error is smaller ±2%. Later the consequences on the CPU time will be discussed, but it can be seem from table 1, that depending on the required accuracy m should be chosen as 5 or 8.

Figure 10 shows a detail view on the step response of an outlet temperature of three test models, one with the desiccant wheel form *Casas et al.* and two with wheel models from this work with different numbers of tangential CV's. The complete simulation time was

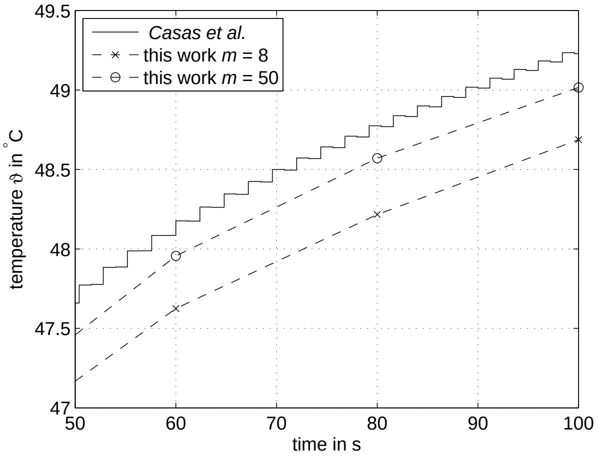


Figure 10: Comparison of complete the model from *Casas et al.* and the new one

5000 s. The new model produces continuous output variables in respect to the solver step-size in contrast to the discrete output of the old one. The model with the tangential discretization of $m = 8$ has a slightly larger deviation from the one with $m = 50$ than the model of *Casas et al.*. But as will be shown in the next section, it has a remarkable advantage concerning computing times. And compared with measurement errors, the accuracy is sufficient.

4.2 Computing Time

The computing times discussed in this section correspond to calculations on one core of an Genuine Intel(R) CPU T2300 @ 1.66 GHz on a laptop with 1 GB RAM.

Figure 11 shows a comparison in computing time between the previous approach and the new model. The old model has no tangential discretization, but has to modify the `connect` statement between the air flows an the wheel's control volumes every half period. Whereas the new one needs to be divided in at least five to eight parts (m in fig. 11) per control volume to produce good output values. This leads to the behavior presented in the plot. The old model produces at every half revolution time an event while switching the sides, which wastes computing time while reinitialization of the equation system. This leads to the nearly linear characteristic consisting of numerous small steps. The new model contains a multiple ($\sim m$ times) of equations compared the the old one, so the computing time for one step is much higher, but due to the model structure time steps larger than half the revolution time are possible. In highly dynamic regions, like the beginning of the plot in figure 11, the computational effort is high, but due to the large time steps in regions with small gradients, the overall computing time is lower for the new model with a tangential discretization of m = 5,8 and 10 for simulation times larger than 300 seconds in this example.

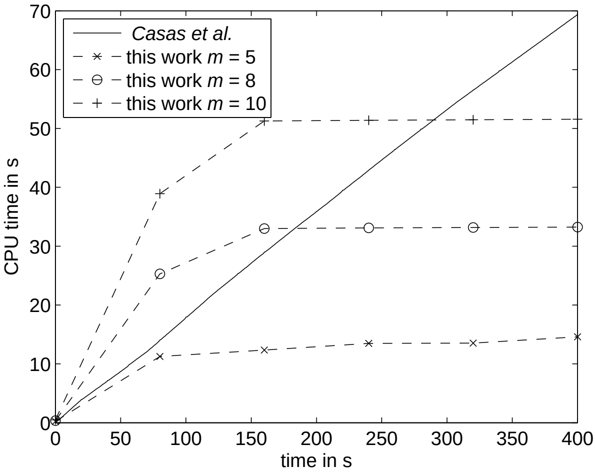


Figure 11: Impact of tangential discretization m on computing time, compared with the model from [2]

This behavior is expected to lead to a large decrease in computing time, especially at long time simulations of air-conditioning systems.

Table 1 gives an overview of the equations, which are created by the different test models, so the number of equations is a little larger than in the stand alone wheel model. The table also shows the computational time of the test model for a simulation time of 5000 s. Due to the above mentioned effect of the state events during the simulations of *Casas et al.*'s model, the new model with $m = 5$ is nearly 20 times faster even though it consists of about 10 times the number of equations. In this case with the old wheel's test model 4166 state events occurred during simulation time.

5 Summary and Outlook

Because of the enhancement of the desiccant wheel model from *Casas et al.* a MODELICA model could be created, which combines good accuracy with acceptable computing times. It was successfully used in further work of *Applied Thermodynamics*, like [4, 6], as the heart of a library for desiccant systems. Several simulation of complete climate periods were performed as well as studies concerning different control strategies of those systems. For the analysis of control strategies the models were exported to Matlab/Simulink to find and optimize control parameters.

Table 1: Number of equations and CPU time of the test model against the tangential discretization m

m	No. of equations	CPU time[a] in s
1	1681	~ 1
2	3043	~ 4
5	7129	20
8	11215	48
10	13939	78
15	20749	186
20	27559	289
30	41179	810
50	68419	2154
Casas et al.	1184	827

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[a] For a simulation time of 5000 s in Dymola using Dassl

Especially for this part it was very helpful, that the new model no longer produces discrete output. It was also possible to adapt the model parameters in such a way that data from existing air conditioning systems could be recomputed.

Nomenclature

Latin Symbols	
A	Area
L	Length
m	Tangential discretization
$\dot{m}$	Mass flow
n	Axial discretization
R	Radius
t	Time
T	Period
v	Velocity
x	Water content
X	Standardized water content
Greek Symbols	
ϑ	Temperature
Θ	Standardized temperature
ρ	Density
ϕ	Angle
ω	Angular Velocity
Abbreviations and Subscripts	
BC	Boundary condition
CV	Control Volume
DF	Index for *desiccant fluid*
i	Index for i-th element

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