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Real-time diagnostic tool for hygienic and energy parameters of air handling components

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Abstract. Material and surface properties in air conditioning systems are subject to change, e.g. due to aging, wear or fouling. This is why regular inspections, maintenance or even cleaning measures are mandatory. In the course of quality assurance and the striving for sustainability and energy efficiency, heat- and mass-transferring air conditioning components particularly require permanent metrological monitoring. This goes beyond the conventional data recording in air conditioning components. With the aim of parameter-guided maintenance management, this means a comprehensive monitoring of function and properties based on design and process data. An extensive exchange of information throughout the entire value chain and life cycle (Industry 4.0) also is essential. ILK Dresden has developed a measurement-based diagnostic tool especially for a new type of membrane heat and mass transfer unit for air humidification and sorptive dehumidification. The aim was to process real-time measurement data, considering long-term data, and to apply it for statistical evaluations of changing material parameters, for target-performance comparisons and for risk assessments (e.g. mould growth). The central element of the tool was programmed in Python and is a script for the direct and simultaneous iterative calculation of the ideal reference process and the real characteristic values of the heat and mass transfer process in the membrane heat exchanger. In addition to the thermodynamic calculation, the mould growth risk can be determined with this algorithm. The basis for assessing the mould growth risk is based on a known algorithm comprising different thermodynamic parameters. This method in addition with a detection of special events (load curves, maintenance, faults, etc.), provided by machine learning algorithms is the basis for a process optimisation, quality assurance and sustainable system operation. This presentation will illustrate the technical parameters and the function of the diagnostic tool. Furthermore, the results of the initial test phase under laboratory conditions will be presented as well as an overview of further development steps and potential areas of application.

Keywords. liquid sorption, humidity recovery, enthalpy recovery, HVAC, textile heat exchangers, hygiene, energy efficiency, evaporative cooling, closed-loop-system.
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1. Introduction

Increasing energy efficiency requirements lead to higher demands on air conditioning systems, too. One approach to cope with this is the application of a desiccant cooling system with a lithium-chloride (LiCl)-brine [1]. Since open systems have disadvantages with regard to corrosion, enclosed heat exchangers e.g. with semipermeable membranes as diaphragms are the subject of ongoing research projects (e.g. Rosenbaum [2–4]). One of the most interesting possibilities is the combination of more than two different fluids within one heat exchanger. Applying such a heat exchanger provides the opportunity to e.g dehumidify an air stream with a LiCl-brine whilst the intrinsic solution enthalpy is balanced with a cooling water circuit. At the opposite, an air stream might be cooled and humidified at the same time by applying a cooling water circuit and a hot water circuit in combination.

All these different options suffer from the same problem: The heat exchanger performance cannot be solved explicitly by applying the known equations. Therefore the supervision and optimisation of an air conditioning system with such a heat exchanger is challenging.

Secondly, mould-growth is one of the major problems to be solved in air conditioning systems, especially under humid operation conditions. Mould can course severe health problems when spores or mycotoxins are transported as airborne particles to the occupants of rooms equipped with this problematic air conditioning system, leading to Upper Respiratory Tract symptoms, Cough, Wheeze or Asthma [5]. For this reason, strict regulations for design, installation, operation and maintenance of an air conditioning are state of the art (e.g. [6], [7][6]).

Nevertheless, a deeper insight into the actual conditions of an air conditioning system is of interest with respect to the reduction of maintenance work and correct handling of current issues, e.g. the replacement of filters in case of increased mould-growth risk [8].

The purpose of this article is to provide information on a proposal to manage the requirements of a modern air conditioning system in terms of implementation in IoT and cloud-based systems. The theoretical background and investigations at a heat exchanger with textile-based materials of a closed-loop circuit will be explained in the following sections.

2. Theoretical Background

2.1 Thermodynamic calculation of the heat exchanger

The thermodynamic calculation of the heat exchanger is based upon a numerical discretisation of several fluid layers with up to three different fluids species, as illustrated in Fig. 1. The fluid can be chosen as air, water or a brine of LiCl and water. Each of this layers allows a fluid a movement within the x,y-plane and each layer comprises a n_x,n_y-matrix of unit cells. The flow-direction is described as an initial boundary condition. The boundary of each flow normal to the flow direction at every x,y-plane is defined as adiabatic in terms of heat and mass transfer.

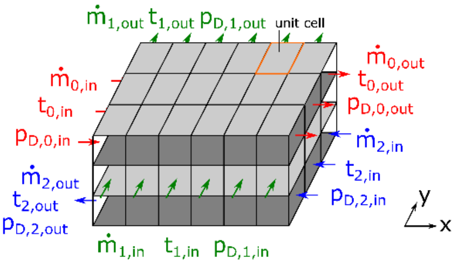

Fig. 1 – Model scheme

The contact conditions between two layers are defined separately. Thus, the outlet parameters of each layer are calculated referring to the very contact conditions and the inlet parameters by solving the heat and mass transfer equation (according to Fig. 2) with respect to the flow-direction, starting at the inlet and ending at the outlet.

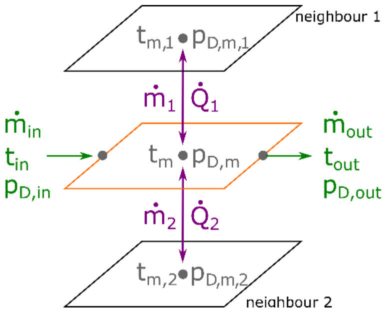

Fig. 2 – heat and mass transfer at single element

Each unit cell is divided into subsections in order to stabilise the numerical interpolation. As depicted in Fig. 3, a linear interpolation is applied to calculate the representative parameters. This avoids non-physical numerical effects like crossing temperature lines in neighbouring cells.

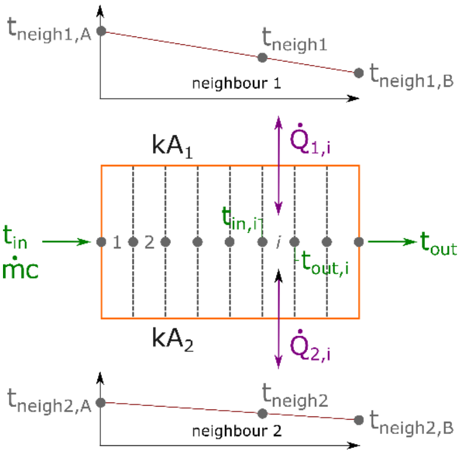

Fig. 3 – Heat transfer between unit cell and heat transfer to neighbour cells, division of the unit cell into single sections

The objective of this numerical model is the calculation of

- transient heat and mass transfer,
- fluids in parallel-, cross- and counter-flow regime
- temperature- and pressure-dependent material data
- dilution enthalpies, condensation- and evaporation enthalpies.

The temperature- and pressure-dependent material properties of humid air and LiCl-brines are calculated by means of Conde [9] and Conde [10], respectively.

2.2 Calculation of mould-growth risk

Currently, several models for mould-growth exist. All these models have different advantages and disadvantages and were compared by several authors, e.g Vereecken et al. [11]. One of the most common models is the updated VTT (uVTT) model as described by Ojanen et al. [12]. Based on the calculation method developed by Hukka and Viitanen [13] the calculation was extended from wood to other materials. The risk of mould-growth is described by the mould-index M. This index correlates to the description according to Tab. 2. The parameters of influencing are

- the relative humidity,
- the temperature and
- the substrate.

A second well-established model (WuFi) was developed by Sedlbauer [14]. Instead of calculating a risk as in the uVTT-model, this model calculates the mycelium growth and sperm germination depending upon the specimen of the fungi.

Tab. 1 – Description of the mould-index M

M	Description
0	no growth
1	Small amounts of mould on surface (microscope), initial stages of local growth
2	Several local mould growth colonies on surface (microscope)
3	Visual findings of mould on surface, < 10% coverage, or < 50% coverage of mould (microscope)
4	Visual findings of mould on surface, 10%–50% coverage, or > 50% coverage of mould (microscope)
5	Plenty of growth on surface, > 50% coverage (visual)
6	Heavy and tight growth, coverage about 100%

Within this project the uVTT-model is used for mould-growth calculation due to the consideration of ambient conditions, where mould is not growing or even reduces. Contrary to the WuFi-model, a reduction of mould on a surface is considered in the uVVT-model.

Nevertheless, a correlation of the results (M-index and growth rate) of both models (uVTT and WuFi) is suggested by Viitanen et al. [15]. Cabrera et al. [16] applied a combination of both methods in order to calculate the mould-growth risk for future climate conditions.

The calculation is based on the change rate of the M-index according to eqs. (1) - (5) and the parameters as provided in Tab. 2. Herein t represents the time in hours, RH the relative humidity in %, T the temperature in $°C$, W the timber species, SQ the surface quality (if the substrate is not wood, then $W, Sq = 0$) and c_{mat} the decline coefficient.

$$\frac{\partial M}{\partial t} = \begin{cases} (7e^{k_0})^{-1} k_1 k_2 & RH \geq RH_{crit} \\ -0.00133\, c_{mat} & \begin{array}{r} RH < RH_{crit} \\ t - t_1 \leq 6 \end{array} \\ 0\, c_{mat} & \begin{array}{r} RH < RH_{crit} \\ 6 < t - t_1 \leq 24 \end{array} \\ -0.000667\, c_{mat} & \begin{array}{r} RH < RH_{crit} \\ t - t_1 > 24 \end{array} \end{cases} \tag{1}$$

$$k_0 = -0.68 \ln T - 13.9 \ln RH + 0.14\, W - 0.33\, SQ + 66.02 \tag{2}$$

$$k_2 = \max\left[1 - e^{2.3(M - M_{max})}, 0\right] \tag{3}$$

$$M_{max} = 1 + A \frac{RH_{crit} - RH}{RH_{crit} - 100} - B \left(\frac{RH_{crit} - RH}{RH_{crit} - 100}\right)^2 \tag{4}$$

$$RH_{crit} = \begin{cases} -0.00267\, T^3 + 0.16T^2 - 3.13T + 100 & T \leq 20 \\ RH_{min} & T > 20 \end{cases} \tag{5}$$

Tab. 2 – Description of the mould-index M

	K1		M_{max}			RH_{min}	c_{mat}
	M<1	M≥1	A	B	C	%	
vs	1.000	2.000	1.0	7	2.0	80	1.00
s	0.578	0.386	0.3	6	1.0	80	0.50
mr	0.072	0.097	0.0	5	1.5	85	0.25
r	0.033	0.014	0.0	3	1.0	85	0.10

3. Setup of the investigated heat exchanger

3.1 Experimental setup

The analysis was performed with a closed-loop heat exchanger as illustrated in Fig. 4. This system comprises two heat exchangers connected with a water circuit for cooling the outdoor/supply air (ODA/SUP) of an air handling unit by means of indirect evaporative cooling at a second heat exchanger at the extraction air (ETA) – exhaust air (EHA) section of this air handling unit. A membrane heat exchanger as described by Rosenbaum and Franzke [17], [18] comprising three different fluids (air, water, water for evaporation) with a semi-permeable membrane between air and evaporating water was used for cooling water from inflow to outflow of the respective water. The semipermeable membrane enables the mass transfer of gaseous water between air flow and water flow.

The closed loop system was equipped with several measurement probes. At each inlet and outlet the average temperature was calculated from five temperature probes. Additionally to the five temperature probes, two probes for the relative humidity were installed. All water temperatures where measured with one probe at each connection of the heat exchangers. Furthermore, the mass flows were saved in a measurement file. The files were updated every 30 seconds. The measurement period lasted from 2020/07/07 to 2020/12/18.

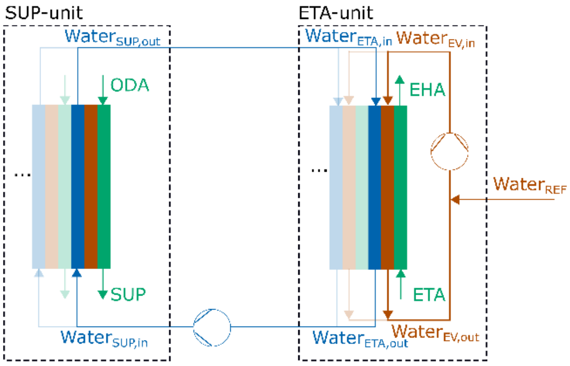

Fig. 4 – Schematical drawing of the closed-loop system used in this investigation

3.2 Numerical setup

For the first calculations, only the ETA-unit of the closed-loop system was considered. The heat exchanger has a numerical resolution of 450 cells. This value was proven to be reasonably feasible by a convergence study, for which the results are printed in Fig. 5.

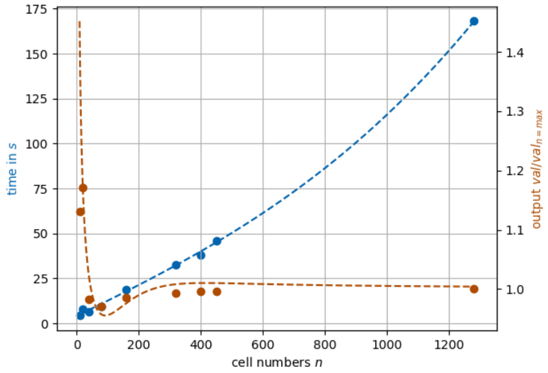

Fig. 5 – Results of the convergence study with different cell numbers at x-axis, time for full iteration of the heat exchanger at the left y-axis and the resulting output at the right y-axis, performed at an I7-7600 @ 2.8 GHz

For the further calculation of the heat exchanger thermodynamics, the values recorded by the measurement were averaged in one-hour time slots and the calculation was performed for the first 1054 hours. The numerical inlet conditions of the heat exchanger were set to these measured values (ETA, $\text{Water}_{\text{EV,in}}$, $\text{Water}_{\text{ETA,in}}$) in order to calculate the outlet conditions by predefined thermodynamic parameter settings of the heat exchanger as thermal conductivity, mass transfer coefficient, active surface and permeability.

The mould-calculation was performed using the described code and was applied to the temperature and the humidity at EHA. The sensitivity of the substrate to the mould was set after 62.5 days from ‘mr’ to ‘s’ and after additional 62.5 days to ‘vs’. Such an increase in sensitivity may be caused by a gathering of biological non-inert matter at the surface of the textile heat exchanger.

For mould-calculation, the processing of 664,311 data points took about 78 s at an I7-7600 @ 2.8 GHz. The heat exchanger is operated continuously for about 158 days, followed by a dry-out phase.

4. Results

The results of the calculation of the outlet conditions of air, water and evaporation water in comparison with the measured data are provided in Fig. 6. The measured inlet conditions are represented by a solid line whilst the measured outlet are represented in a dashed line style. The calculated outlet conditions are printed as dots. There is a slight deviation between measurement and calculation.

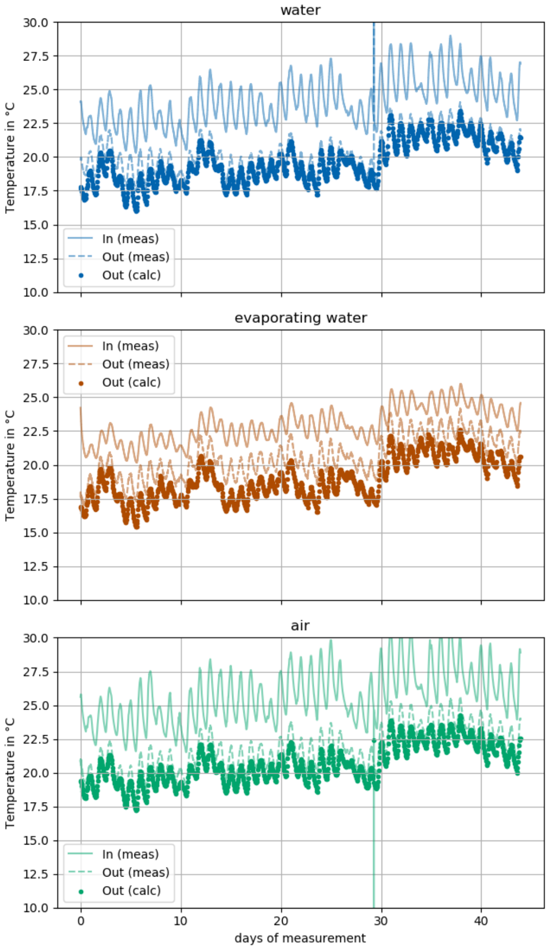

Fig. 6 – Temperature profiles of the measured conditions at the ETA-unit at inlet and outlet (lines) in comparison to the calculated outlet conditions.

The mould-calculation was performed for the whole measurement period and different sensitivities where assumed. The results shown in Fig. 7 provide the course of the M-index for constant sensitivities of the substrate to mould. The profile of the M-index for time-dependent sensitivities from ‘mr’ to ‘s’ is presented in Fig. 8.

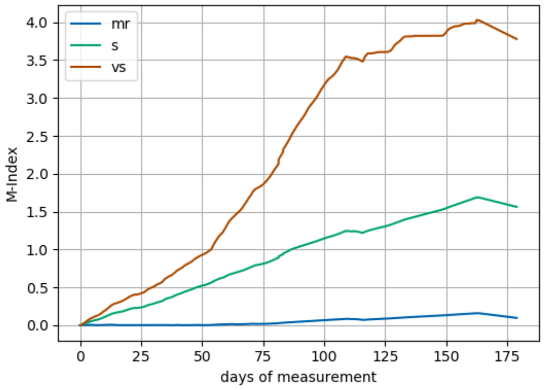

Fig. 7 – Profile of the M-index over the whole measurement period for the sensitivities of 'mr', 's' and 'vs'

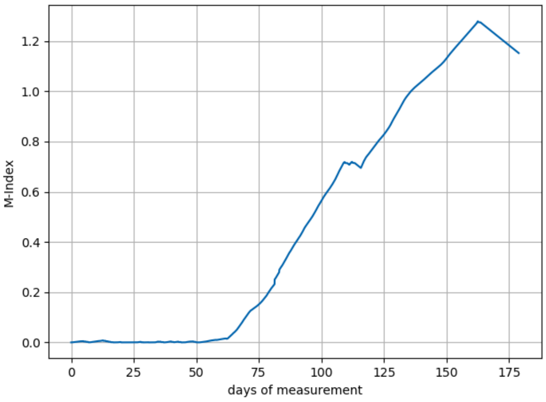

Fig. 8 – Profile of the M-index over the whole measurement period (sensitivity 'mr', 's' and 'vs' at 0, 62.5 and 125 days, respectively)

The formation of mould colonies is strongly dependent on the sensitivity of the heat exchanger material. If the heat exchanger material is tendentiously inert ("mr"), the growth of moulds can only be detected with the help of microscopy, if at all. In cases with higher sensitivity, mould formation is stronger to the point of being visible to the eyes. In the assumed situation of deterioration of the resistance of the surface, mould growth is retarded, but there is a tendency to form a higher risk of mould after the dry-out phase. Here there is still a high sensitivity of the biologically contaminated heat exchanger material to mould growth.

5. Discussion and Conclusions

The measured values of the heat exchanger proof the stable operation of such a textile heat exchangers with three different fluids.

The presented results of the heat exchanger calculations indicate an overall good coincidence with measured values at the outlet. Nevertheless several deviations have been detected. A better adaption of the calculation parameters to the measured data is mandatory. This refers to the inclusion of the currently neglected thermal inertia of the heat exchanger, too.

The calculation established in the numerical heat exchanger analytics is too slow for time resolved investigation (e.g. 30 s for one time step). One of the underlying reasons is based in the air property calculations. We expect an improvement by changing from the scientific calculation to industrial style of the parameters according to the IAPWS formulas.

The coincidence of the calculated mould-growth risk was not verified by separate investigations at the heat exchangers surface. This challenging issue should be topic of further investigations.

For this project, the mould-growth risk was calculated for the outlet conditions (EHA). In future, a risk depending upon the internal calculated conditions might provide better information on the actual state of the hygienic conditions. By applying the analysis only at the outlet (or inlet) conditions, the mould-growth risk might be underestimated.

Caused by the operation of the heat exchanger within a controlled environment, no deviations from the acceptable parameters where recorded, unfortunately. By applying this algorithm at a unit installed within a more practically operated system will provide better data for establishing a machine learning algorithm for fault detection and improper unit operation. This challenge coincidences with the reduction of measurement probes to a very limit.

6. Acknowledgement

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The datasets generated during or analysed during the current study are not publicly available but will be available upon direct request to the authors.

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