Textile-based heat exchanger for humidity recovery between spatially separated air flows

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Abstract. Both, sensible heat recovery and the combined heat and humidity recovery are state of the art. Of particular importance is humidity recovery in winter season. The transfer of water vapour from the humidity-laden extract air to the very dry outdoor air is very important for a good room air quality. Enthalpy exchangers potentially reduce the energy requirements of any subsequent air humidification on the supply air side considerably. In the planning phase, the possibility of enthalpy recovery is therefore often used as a weighty argument for dispensing with humidification systems.

However, all systems established on the market require a coupling of supply air and extract air by means of recuperation (e.g. plate heat exchanger) or direct regeneration (rotating storage mass). Nevertheless, enthalpy recovery systems for HVAC-Systems with spatially separated supply air and extract air are not available on the market.

In order to close this gap in the market, ILK Dresden has developed textile-based heat exchangers, which - integrated in closed loop systems - can transfer humidity as well as sensitive heat between spatially separated air flows (e.g. between supply air and exhaust air). The functional principle is based on a liquid sorption process via semipermeable membranes. This is regardless of whether it is a 2-fluid system (air, brine), in which the heat-transferring fluid and the mass-transferring fluid is the same fluid and only one circuit is utilised, or a 3-fluid system (air, brine, water), in which the fluids involved flow in separated circuits. In general, the developed system can be used all year round - thus also for air dehumidification or indirect evaporative cooling processes.

The current state of development is presented. In addition, an outlook is given for which applications the textile heat exchangers could be further developed and which application potentials are offered.

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

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1. Introduction

Research and development on the field of heat transfer applications with membranes lies within the scope of ILK Dresden for more than twelve years. The initial idea was to eliminate or improve air conditioning processes in HVAC systems, with direct contact between water and air, in order to improve hygienic conditions. The reason for this is that - whether air humidification or air dehumidification by condensation - the availability of water is a precondition for any undesired organic growth.

The second objective is the application of renewable energy sources or available waste heat as energy source for air humidification or dehumidification in order to increase both the energy efficiency and the sustainability of air conditioning.

Initial investigations showed that both liquid sorption-based air humidification and dehumidification using semi-permeable membranes work quite well [1, 2]. Contrary to sorption processes with direct contact between brine and air, corrosion damage can also be avoided [3, 4]. In the course of the development process several technical issues were solved e.g. how to fix the membranes in the air flow or how to implement them in a sufficiently pressure-stable construction [5].

In addition, an ongoing research project focuses on improved applications with long-term stable materials. Using the example of humidity recovery between spatially separated air flows, this paper gives an overview of the current state of development of membrane heat exchangers as well as its application potential in future air conditioning technology.

2. Development emphases

2.1 Pre-discussion on humidification

The air-conditioning industry is becoming increasingly aware of the importance of relative humidity for health-related well-being [6]. Complaints such as dry eyes or dry mucous membranes in the mouth, nose and throat can be caused by excessively dry indoor air. According to [6, 7, 8, 9], in general, the risk of spreading viral infections or bacterial diseases is lowest in the range between 40 and 60 % RH, which is perceived as thermally comfortable. Excessively dry air (< 30 % RH), on the other hand, increases the risk of respiratory infections [10]. From a health/medical point of view and due to the current corona virus pandemic, the argumentation pro air humidification systems or even pro establishing a minimum air humidity of 40 % is considerably supported.

The most important counter-argument against the use of humidification systems is the energy requirement. Due to the high specific evaporation enthalpy of water (approx. 2260 kJ/kg), an isothermal humidification of a fixed air volume by $\Delta x = 4.0$ g/kg requires a heat input of 9.04 kJ/kg dry air. With the same energy input, however, the same air volume could also be warmed up by 9.0 K without changing the moisture content. This is considerable and shows the conflict between energy saving vs. medically based advises.

2.2 Humidity recovery between spatially separated air streams

Heat recovery systems with humidity transfer between the outside air and exhaust air cannot completely resolve the discussion about the pros and cons of air humidification. They can only "recover" a proportion of the humidity mass (water vapour) previously introduced into the balance scope from a humidity source. The humidity input by people is by far not sufficient to realise room air humidity ≥ 40 % RH permanently (i.e. also in winter) [11]. Nevertheless, so-called enthalpy exchangers have established themselves on the market. They supplement humidity conditioning by humidifiers and, in this constellation, they significantly reduce the energy requirement of air humidification.

However, all heat recovery systems with built-in humidity recovery require that the supply and extract air streams cross within the unit (plate heat exchanger) or that a rotating mass storage is moved through both air streams while both airstreams mounted in a directly adjacent arrangement.

Enthalpy recovery systems for system concepts with spatially separation of supply and extract air - for example in the form of closed-loop systems - are not yet available on the market. Closing this gap in the market is interesting for all ventilation and air-conditioning tasks (office, work, residential buildings) up to process air technology. Centralised or decentralised air handling concepts with separated supply and extract air units or air handling systems with contaminated extract air (workshops, laboratories,...) would benefit particularly.

2.3 Liquid desiccant process using membranes

In a R&D project, the ILK Dresden has developed textile heat and mass transfer units equipped with semi-permeable membranes, which - integrated into a circulation system - are flowed through by a liquid desiccant and thus enable mass transfer between spatially separated air flows (**Fig. 1**):

While the liquid desiccant binds water vapour from the air on the exhaust side (absorption) according to the driving forces in the liquid desiccant process (water vapour partial pressure differences), it releases the water vapour to the dry outdoor air flow (desorption). At the same time, the sorbent absorbs sensible heat on the exhaust air side and releases it on the outside air side.

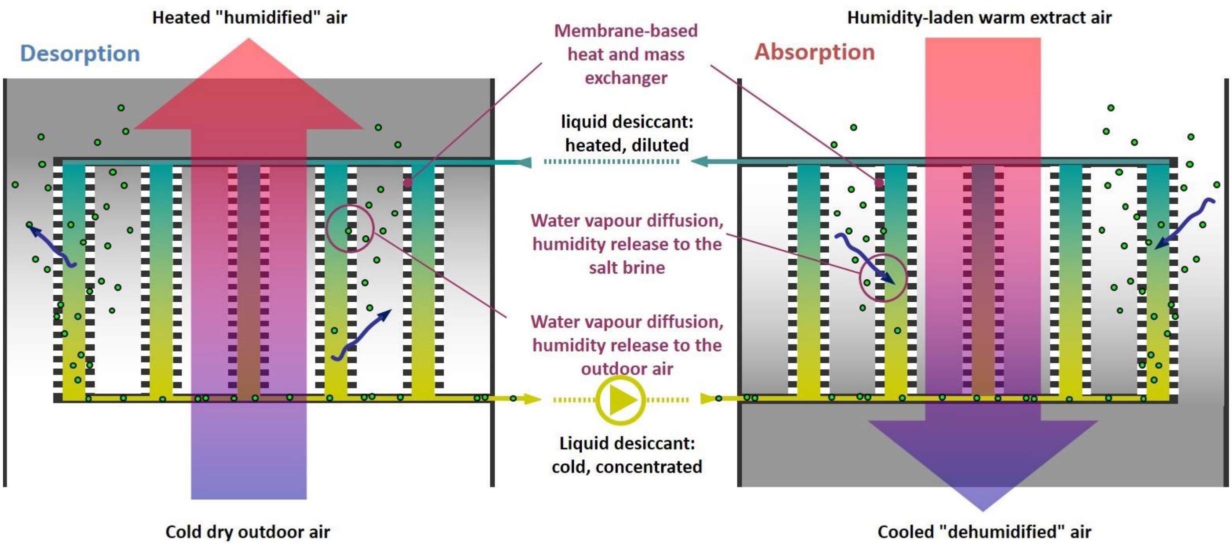

Fig. 1 - Schematic of enthalpy recovery using two membrane heat exchangers and a liquid sorption circuit.

2.4 Membrane-based textile laminates

The development and composition of the basic textile structure (multi-layer laminates comprising membrane, backing structure and flow-throughable spacer textile) were realised in cooperation with the Sächsisches Textilforschungsinstitut, Germany (STFI). Based on a huge number of test series, the most suitable material and processing parameters for the technical and physical requirements were worked out. The following properties were considered (the achieved target values of the laminate are listed in brackets): Water vapour permeability (> 5000 g/m²d), pressure stability (> 1.0 bar gauge pressure), flow resistance (< 100 mbar/m), free volume (< 0.5 l/m²), adhesive strength, adhesive quantity, adhesive type, application method (hotmelt), textile face structure and membrane material (ePTFE/PU).

2.5 Technical design of the membrane-based heat and mass exchanger

The development of the technical design of the textile heat exchangers is based on the experience the ILK Dresden has accumulated in the field of liquid sorption via membranes over a period of more than 10 years. Water vapour permeable membranes and non-woven fabric layers are laminated onto the cover surfaces of multi-dimensional spacer textiles (material thickness < 1.0 mm). Cut-to-size multilayer laminates with sealed edges and fluid connections are used to create membrane elements. Several membrane elements are assembled in parallel to form a simple (2-fluid) membrane heat exchanger. (**Fig. 2**)

Construction designs in which heat and humidity recovery are functionally separated from each other by adding exclusively water-flowed heat exchanging surfaces (3-fluid heat exchangers) were also developed and analysed. This includes, for example, the use of capillary tube mats or spacer textiles with integrated thin tubes. (**Fig. 3** and **Fig. 4**)

If the membrane-based textile heat exchanger is to operate on the counter flow principle, one of the greatest challenges is the uniform supply of the liquid desiccant to the membrane elements, which are stacked at close intervals of ≤ 4 mm. In the absence of available precision-fit micro manifolds which allows an incident flow of 50 membrane elements with a centre-to-centre spacing of 4.0 mm, these had to be developed. As a result, the single fluid connections of the membrane elements can be integrated into their edge seal.

Textile-physical material characteristics of the membrane-based textile laminates as well as air-sided flow properties are the basis for the dimensioning of the textile membrane heat exchangers.

2.6 Experimental setup

For the measurement analyses of the heat and humidity recovery, one membrane heat exchanger at the outside air side and one membrane heat exchanger at the extract air side were connected to each other on the liquid side. According to the design of the respective pair of membrane heat exchangers, both a 2-fluid and a 3-fluid heat and humidity recovery system were created. The configurations are shown in **Tab. 1**. The 3-fluid system is depicted in **Fig. 5** and **Fig. 6**.

In addition to the flow rates of each fluid flowing through each heat and mass exchanger, the most important measured variables were the following parameters on each inlet and outlet side: Air temperature and humidity, desiccant temperature and conductivity (mass concentration) as well as water temperatures and the mass flows of the respective fluids. Flow resistances had been recorded too.

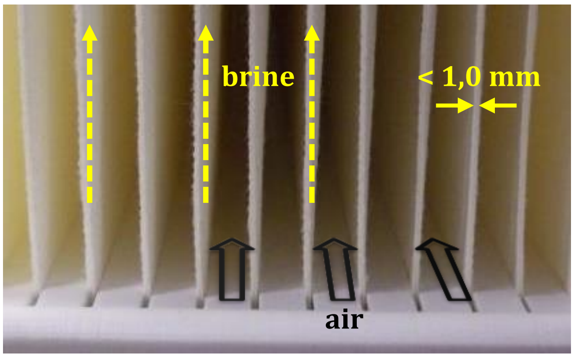

Fig. 2 – Stack of membrane elements with brine flowed through them (thickness < 1.0 mm each) assembled as a cross-flow heat exchanger (2-fluid)

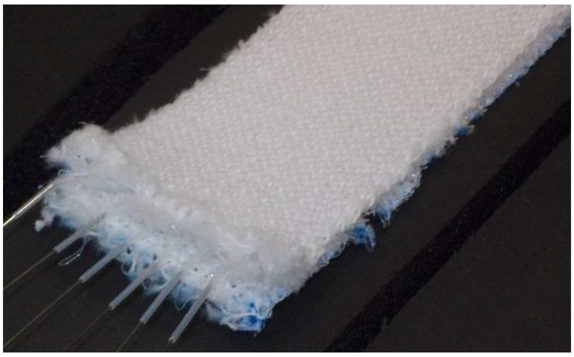

Fig. 3 – Flow-throughable spacer fabric (brine-side) with mechanically incorporated capillary tubes (waterside) for 3-fluid heat exchangers

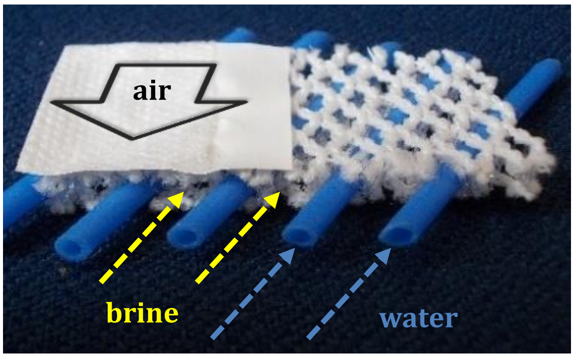

Fig. 4 – View of a sample conducted as a 3-fluid membrane element

Tab. 1 – Membrane-based heat and mass exchanger

one exchanger in each air stream	2-fluid crossflow	3-fluid counterflow
System design	1…2 people	3…4 people
Airflow	50 m³/h	100 m³/h
Duct size	20 x 30 cm	20 x 44 cm
Active surface (tex. Multilayer)	15 m² (7.5 m²)	20 m² (10 m²)
Membrane-elements	50	50
Initial brine concentration	25…35 %	25…35 %
Water mass flow	-	25…30 kg/h
Desiccant mass flow	20…65 kg/h	30…40 kg/h
Membrane material	ePTFE/PU	ePTFE/PU

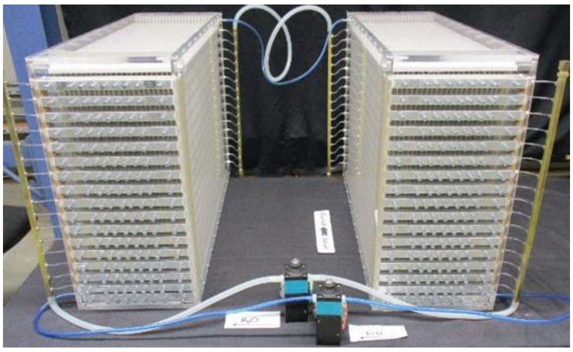

Fig. 5 – 3-fluid membrane-based heat exchanger before mounting into the experimental setup

Fig. 6 – experimental setup of the 3-fluid closed-loop system for temperature and humidity recovery

3. Measurements

3.1 enthalpy recovery rates

In a first measurement session on the 2-fluid system, the enthalpy, humidity and the sensible heat recovery rates were determined (**Fig. 7**). This was done at fixed air conditions but variable desiccant flow rates. (t_{ODA} = 8.0 ± 0.5 °C; x_{ODA} = 3.0…4.5 g/kg; t_{ETA} = 27 ± 0.5 °C; x_{ETA} = 15…17.5 g/kg)

The results confirm a significant heat and mass transfer between the spatially separated air flows. With a desiccant/air heat capacity flow ratio of 1.1, the sensible heat recovery rate (relation of the temperature differences SUP-ODA and ETA-ODA) is just about 0.5. To increase the heat recovery rate to 0.6, it is necessary to double the desiccant flow rate.

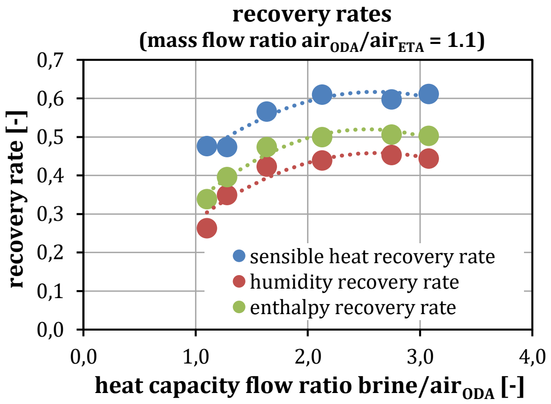

Fig. 7 – Recovery rates depending on heat capacity flow ratio

3.2 long-time monitoring

A further measurement session on the 2-fluid system with statically defined inlet parameters was provided in order to analyse the performance of the recovery rates at different temperatures but constant humidity differences between the outdoor air and the extract air. The measurement results show that the sensible heat recovery rate decreases with decreasing temperature difference, while the humidity recovery rate increases at the same time. If both air streams have the same temperature, the highest level of humidity recovery is measured with η_x = 0.60. On the other hand, the enthalpy recovery rate constantly remains at η_h = 0.51 ± 0.02 independently of temperature.

The liquid sorption process always wants to reach a sorption equilibrium. Depending on the driving forces (temperature differences and water vapour partial pressure difference between air and desiccant), the brine concentration level mainly depends on the weather but hardly on room air conditions. Due to the transport of water molecules between the outdoor air and the extract air this concentration level varies slightly by one to two percentage points.

For a long-term measurement of the dynamic operating performance of the new two-fluid heat and humidity recovery system (two membrane-based heat exchangers in a circulating system), the air flow rate of 50 m^3/h each and the heat capacity flow ratio between desiccant and air of 2.0 were kept constant, while the inlet conditions on the air side changed dynamically.

The measurement results, illustrated in **Fig. 8**, show a permanently constant enthalpy recovery (η_h = 0.55), the inverse trend in the temperature and humidity recovery depending on the temperature difference between the extract air and the outdoor air, and the weather-dependent variation in the concentration level of the desiccant (28...33 %). Drier outdoor air conditions characterised by temperature peaks cause an increase in concentration level, while more humid days cause a decrease in the concentration level.

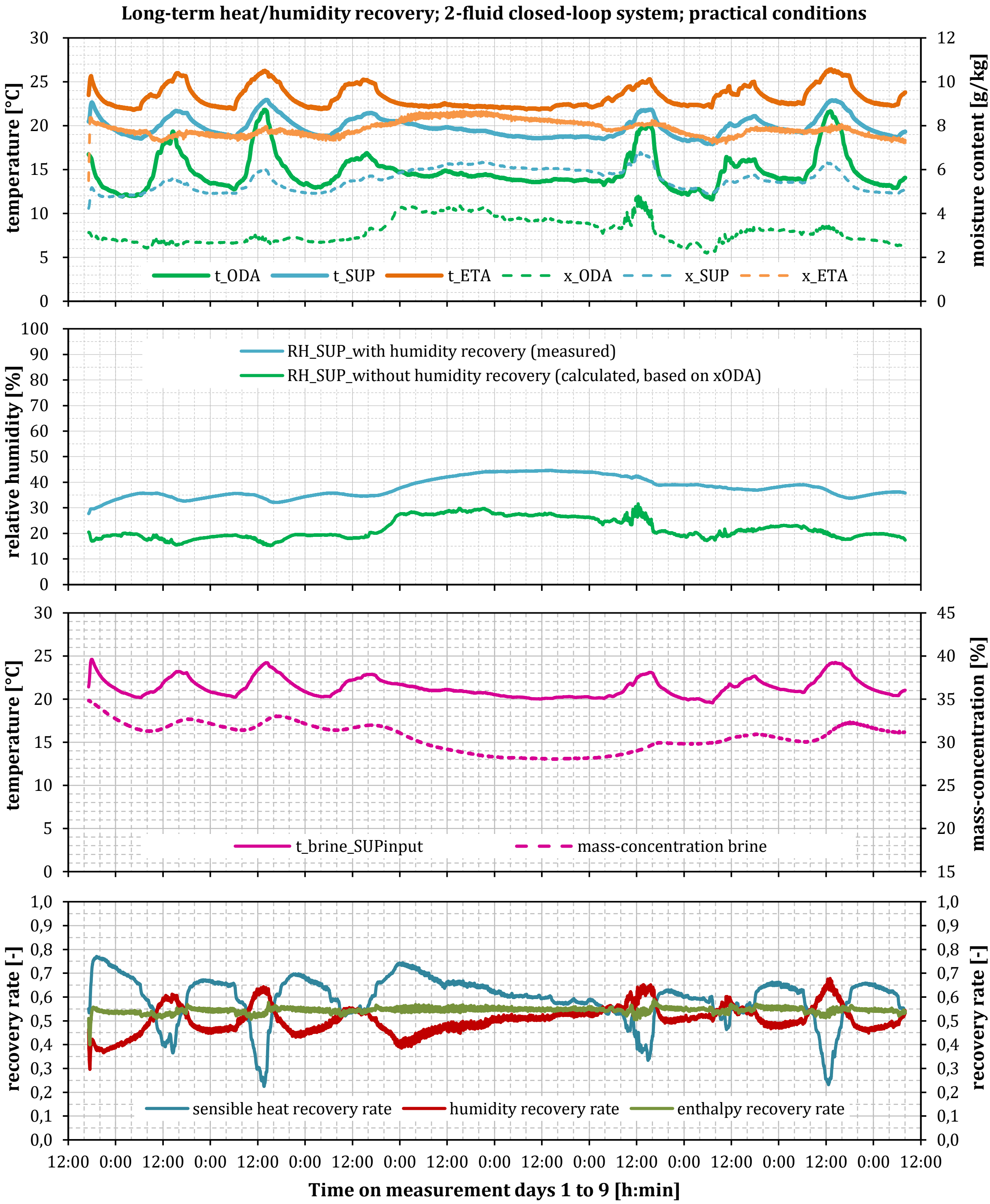

Fig. 8 – long-term measurement of the dynamic operating performance of the 2-fluid heat and humidity recovery system

3.3 Additional thermal functions

The particular advantage of closed-loop systems in general is the possibility of coupling heat into or out from the heat transfer fluid. In this way, the outdoor air flow can already be tempered to the setpoint of the supply air temperature via the heat exchangers of the closed-loop system.

To test this multi-functional utilisation on the innovative 2-fluid system with humidity recovery via textile heat exchangers, desiccant-sided a plate heat exchanger was installed directly upstream to the outdoor air membrane heat exchanger. A heating water circuit with a speed-controlled metering pump and a motor-controlled 3-way valve regulate the heat input into the desiccant circuit and consequently the temperature of the supply air.

With the aim of testing the automatic supply air temperature control by coupling heat into the desiccant circuit, another long-term measurement was performed. In terms of practice-related test conditions, temperature variations between 5 and 20 °C (without regulation of the humidity) were simulated at the outdoor air side. On the extract air side, temperature variations of the environment around the experimental setup (21...27 °C) were used and the moisture content was set to approx. 8.0 g/kg. The supply air temperature setpoint of 23.0 °C and the volume flow rates (50 m^3/h air, 32 l/h desiccant) were part of the fixed specifications. The control parameters of the valve drive were adjusted for optimisation purposes during the measurement period.

According to the measurement results, heat and humidity recovery with simultaneous supply air temperature control is possible. In contrast to closed-circuit systems without humidity recovery, the membrane-based 2-fluid system can transfer so much humidity from the extract air, even at a controlled supply air temperature, that the supply air humidity is usually above 30 %. Therefore, the risk of the room air being perceived as too dry would decrease.

4. Results

4.1 Optimisation potential

Measurements of the thermal inertia of the system indicate a correlation of the outdoor and supply air temperature trends, whereby the temporal shift roughly corresponds to the circulation rate of the desiccant. The circulation rate itself is significantly influenced by the filling volume of the desiccant circuit (heat exchangers, tubes, tanks) and the desiccant volume flow rate. Reducing the thermal inertia of the system (about 45 min in the above measurements) requires the minimising of the volume of the desiccant circuit to be flowed through.

Operating scenarios with very warm, humidity-laden extract air and very cold outdoor air cause a local condensation risk inside of the 2-fluid cross-flow heat exchanger especially near the intersection areas of outdoor air and desiccant inlet (ODA-SUP part of the heat exchanger) or extract air and desiccant inlet (ETA-EHA part of the heat exchanger). Membrane-based heat exchangers with countercurrent air and liquid flows could minimize this risk. A risk of crystallization of the liquid desiccant during enthalpy recovery in the 2-fluid system is not expected whilst the mass concentrations of the liquid desiccant is between 25 to 32 %. To play it safe, the liquid desiccant circuit shall be emptied into a system-integrated tank when it is not in use.

There is still an optimisation potential concerning the sensible heat recovery rate. Nonetheless to the already achieved heat recovery rates of more than 50 % higher recovery rates are expected. According to ErP Guidelines (2018) this should be more than 68 % [12, 13].

It is also preferred that the recovery of sensible heat and humidity can be regulated independently from each other. In the two-fluid system, this option is highly limited.

Some of the optimisation approaches have already been implemented in the 3-fluid system.

4.2 Results of the three-fluid system

The measurement results of the 3-fluid system confirm the expected higher enthalpy recovery rate compared to the 2-fluid system. The sensible heat recovery rate increase slightly whereas the humidity recovery rate is a little lower (**Tab. 2**). In both systems, the air-side pressure loss of 5 or 10 Pa is very low.

Tab. 2 – Recovery rates of the closed-loop systems during long-term measurements cf. Tab. 1

twice in each system	2-fluid crossflow	3-fluid counterflow
Enthalpy recovery rate	0.50…0.55	0.57…0.61
Sensible heat recovery rate	0.25…0.70	0.71…0.77
Humidity recovery rate	0.40…0.65	0.38…0.41
air-side pressure loss	5 Pa	12 Pa

5. Conclusions

The functionality of the heat and humidity recovery with textile heat exchangers in a 2-fluid, liquid desiccant closed-loop system was successfully demonstrated. This also applies to the coupling of heat for the supply air temperature control. The thermodynamic and fluidic parameters achieved can also be assessed positively. They can certainly be compared with current normative requirements, e.g. DIN EN 13053.

As a result of the endurance tests under practical conditions, the recovery rates - especially the humidity recovery rate - almost permanently caused relative humidities of the supply air to exceed 30 % RH. In the context of the discussion about the pros and cons of air humidification systems mentioned at the beginning, the membrane heat exchangers developed for humidity recovery between spatially separated air flows make a substantial contribution to energy saving. Without humidity recovery, drier air conditions would have been measured in more than 60% of the measurement period. Maintaining specified humidity standards (>30 % RH) would have required the usage of active humidification and therefore a significant energy demand.

With the application of further thermal functions, especially 3-fluid textile heat and mass exchangers in corresponding closed-loop systems can be expanded into a multifunctional component. Potentially, in addition to heat and humidity recovery, all thermal state changes (heating, cooling, dehumidification, and humidification) can then be realised independently of each other at the outdoor air side as well as at the extract air side. Indirect evaporative cooling can also be realised. Temperature and humidity control can operate independently of each other. Conventional reheating or cooling coils can be omitted.

Potentially, the liquid desiccant process - i.e. sorptive and condensate-free air dehumidification - can also be used for dehumidification [11, 14, 15, 16, 17, 18, 19]. This enables the use of synergy effects all around the year and supports the use of renewable energies and works in a resource-saving and energy-efficient way. That is sustainable.

Back to the pre-discussion: The basis of closing the gap in the market for heat and humidity recovery between spatially separated air flows has been founded. In order to enable economic operation in the long term and to be able to establish itself on the market, the design, manufacture and production must be improved. Particularly necessary are issues regarding the long-term stability of the materials and automated production methods as well as assembly lines for membrane elements, media connections and entire membrane-based heat exchangers.

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The datasets generated and analyzed as part of this study are not publicly available, but can be made available for specific purposes upon request from the authors.

7. Appendix

Tab. 3 – Symbols and indices, used in this paper

t	Temperature
x	Moisture content
h	Enthalpy
η	Recovery rate
ODA	Outdoor air
SUP	Supply air
ETA	Extract air
RH	Relative humidity

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