DEVELOPMENT AND EXPERIMENTAL INVESTIGATION OF A MEMBRANE-ABSORPTION COOLING PROCESS

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Abstract: To open the market to small power residential sorption chillers a novel type of absorption cooling process is under development, which is based on membrane-pervaporation and uses Lithiumbromide-Water solution as the working pair. The sorption devices are made of flat sheet porous membranes in an advanced, compact and high efficient stack design to reduce the size and costs of thermally driven chillers. Suitable membrane types have been identified, several designs of the basic membrane modules with integrated cooling plates were developed and tested. The principle feasibility of the membrane sorption process was proven in experimental testing for both absorption and desorption.

Key Words: absorption chiller, pervaporation process, hydrophobic membrane, flat plate module, stack design, Lithium Bromide

1 INTRODUCTION

In most OECD economies buildings account for about 40% of all energy use (Waide 2008). Building supply is the largest single usage sector, exceeding industry or transport. Within residential and commercial buildings the provision of thermal comfort and air quality is the greatest energy use. For this reason efforts to improve energy efficiency have to focus on HVAC equipment and to utilize non-electric energy sources such as solar energy, district heating water or waste heat of small CHP -plants.

In this context a focus is put on small thermally driven heat pumps (i.e. cooling capacity 5-10 kW) which can be used for domestic heating and cooling purposes (Jakob 2007). Especially the Lithium-Bromide/Water absorption cycle, environmentally friendly and traditionally well established in large scale applications, appears to offer great promise as a high-efficient cooling process and can be driven by widely available low temperature heat. It can be used for non-electric driven residential air conditioning (AC), easy to install and to operate, provided a significant reduction in size and weight can be achieved. Utility space in private houses is strictly limited.

A focus of current R&D-work is the size and cost reduction of the main components of an absorption chiller. One promising approach is the introduction of elements from high performance heat and mass transfer principles to the thermodynamic cooling cycle. The bulky conventional falling film heat exchangers for example, could be replaced by a compact membrane pervaporation process with hydrophobic membranes, to improve heat and mass transfer and to reduce the required unit volume.

The investigations presented in this paper were embedded in the research projects “Development of a small scale thermally driven absorption chiller using membrane

technology for residential air conditioning" (FKZ 0327860B) with support from BMWI via its Project Management Organization PTJ.

2 MEMBRANE STACK

The aim of this study was to adapt a membrane process to a sorption cooling process, driven by hot water from solar collectors or waste heat, as shown in Figure 1.

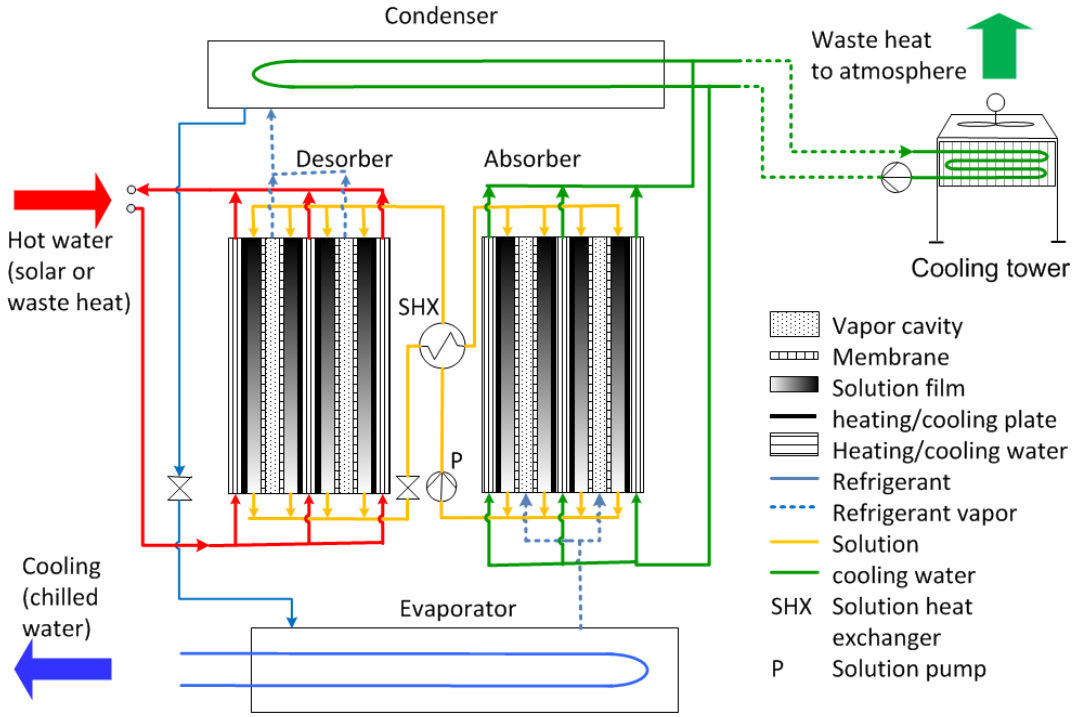


Figure 1: Process diagram of a Membrane-Absorption-Chiller

Hydrophobic membranes could force the liquid working media (aqueous Lithiumbromide solution) to flow in a very thin solution film while the semipermeable material allows fast transmission and ab- or desorption of the refrigerant vapor (water), as illustrated in Figure 2. In ultrathin films heat and mass transfer rates are significantly increased due to reduced concentration polarization and improved heat conductivity.

As a start, the absorber and the desorber could be built as compact flat plate stacks, but in principle also the other components such as the evaporator, the condenser and the solution heat exchanger could be designed as modular thin film stacks.

Hydrophobic membranes are widely used in various separation or mass exchange processes and market available in a large variety. Based on identification and characterization of suitable membrane, several products were chosen for further testing in the Lithiumbromide/water process.

For experimental validation of previous simulations (Ali 2009) a membrane contactor was developed (Figure 3). Basically designed as flat plate modules for about 180 x 240 mm of active area the contactor allows mass and heat transfer between refrigerant and solution. With an integrated heating/cooling function it represents the key component to build up a full size absorber stack (Figure 4). The pervaporation process was experimentally investigated with the single or double membrane module to determine the key parameters of the process.

While gaining practical experience from the lab tests, the flexible module concept was modified several times.

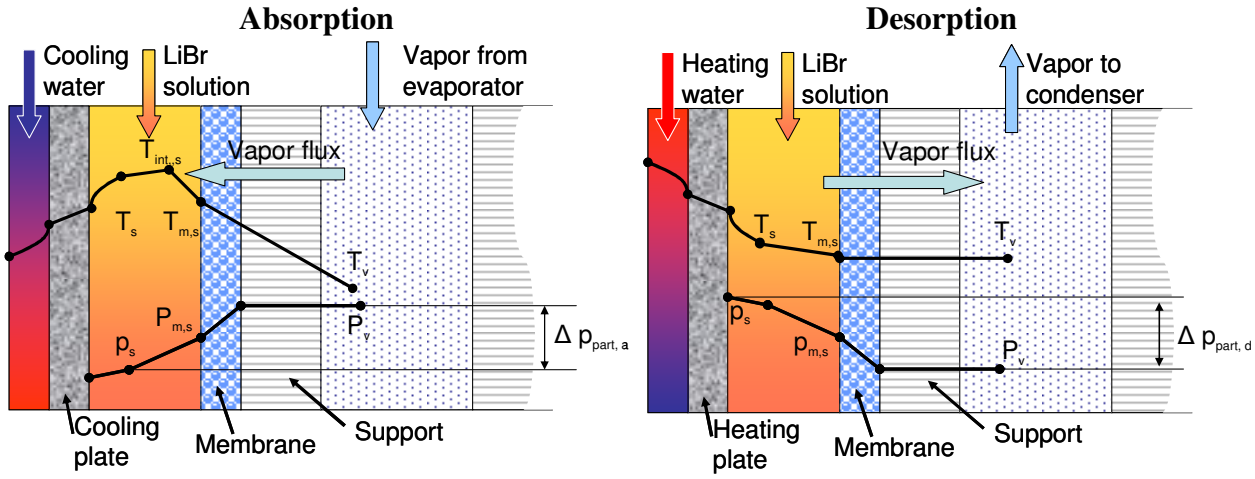
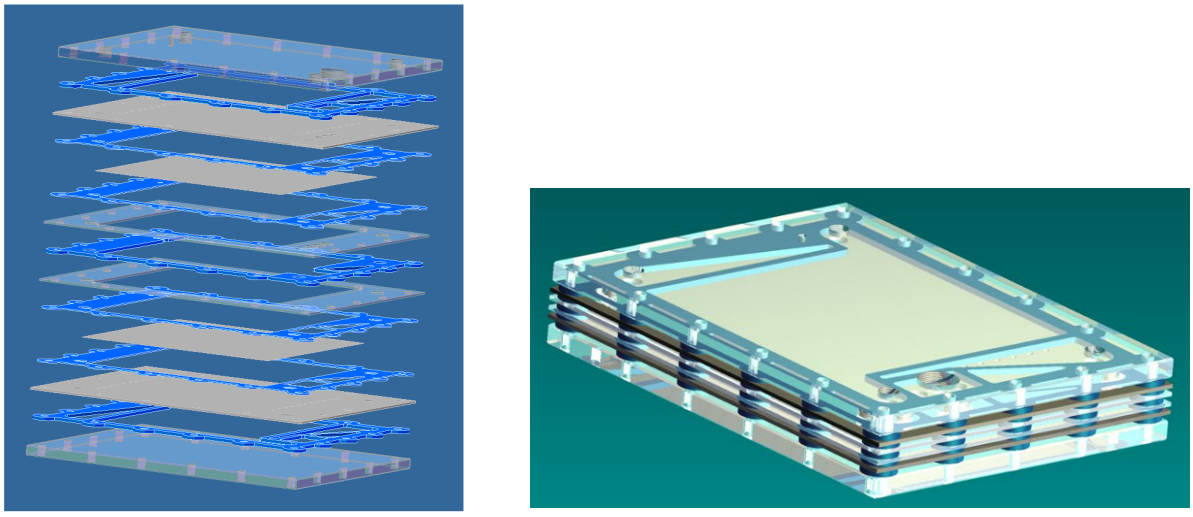


Figure 2: Refrigerant partial pressure and temperatures of membrane pervaporation

After function testing of basic single-membrane-units a membrane sorption module with two active membranes, one cooling module and several improved features was built and tested.

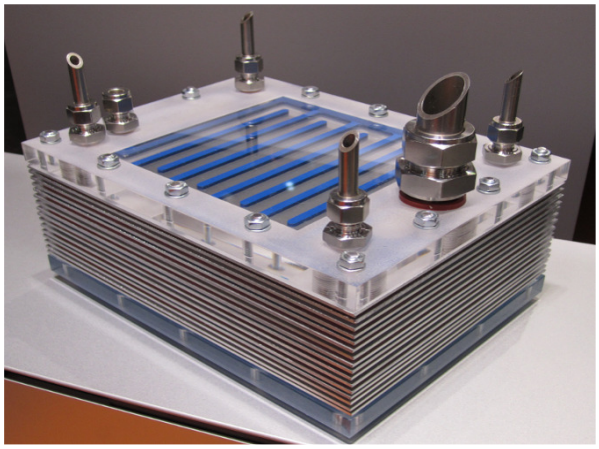
The most challenging requirement was to keep stability and tightness of the module, which is facing a vacuum pressure on the process side and above atmospheric pressure on the cooling water side, just separated by a thin metal sheet. Design strategies to keep a force of >8 kN from damaging the thin film channels included: draw bolts around the module/ support points in membrane area, stabilizing the cooling plate against inside pressure by draw bolts, soldering, welding. For the experimental tests bonding with a hot-setting adhesive has proven to be a reliable method to fabricate a stable thermo-plate sandwich (Figure 4b).

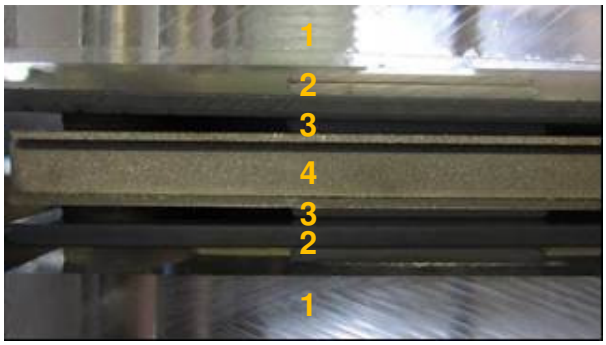


a) basic elements of a membrane module

b) Membrane module, assembled -2 membranes and end plates

Figure 3: CAD design of double cell membrane module III





1 Cover plates
2 Vapor channels
3 Solution film channel
4 Cooling plate (bonded sandwich structure)

a) Stack with 10 membranes (design study) **b) Test unit with bonded cooling plate**

Figure 4: Flat plate membrane contactors

3 EXPERIMENTAL INVESTIGATION

The performance of the membrane sorption process was experimentally investigated with different test modules, with single or double membranes, connected to a reversible refrigerant evaporator / condenser and supply systems for solution, cooling or heating water and vacuum.

All entering and leaving enthalpy flows of the sorption process (Figure 5) are summarized in the energy balance of Eq. 1, also regarding the heat exchange with the environment (Eg. 2).

The internal or external measured or derived heat flows directly indicate the performance of the particular membrane process. In the experiments the heating or cooling load carried by the external water circuit was taken as the main indicator for the process capacity.

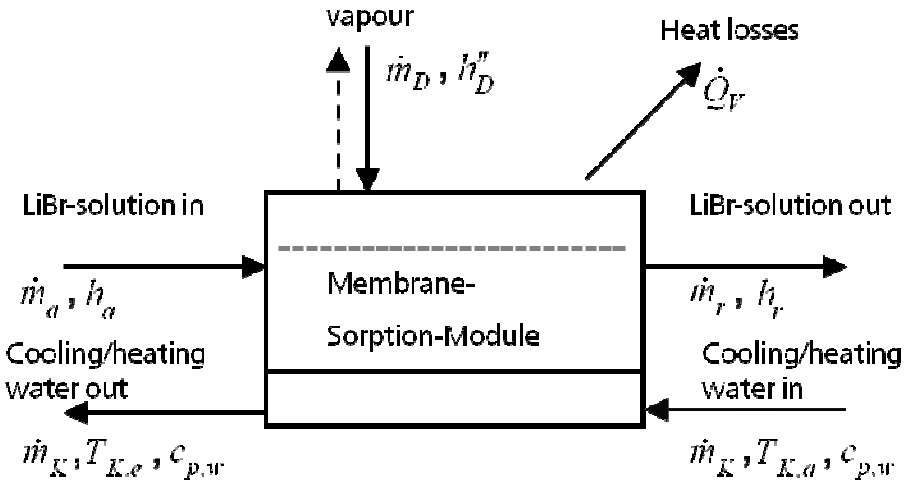


Figure 5: Energy balance at membrane-module for both absorption and desorption

$$\dot{Q}_D + \dot{Q}_a + \dot{Q}_{K,e} = \dot{Q}_r + \dot{Q}_{K,a} + \dot{Q}_V \,. \qquad (1)$$

$$\dot{Q}_v = \dot{m}_D \cdot h''_D + \dot{m}_a \cdot h_a - \dot{m}_r \cdot h_r - \dot{m}_K \cdot c_{p,w} \cdot (T_{K,a} - T_{K,e}) \quad (2)$$

From the exchanged heat of absorption the specific value $\dot{q}_D$ is derived, representing the actual heat flow per membrane area:

$$\dot{q}_D = \frac{\dot{Q}_D}{A_{M,ges}} \quad (3)$$

Experimental testing was performed with realistic conditions of the external temperatures: $T_{\text{cold water}}$: 9-17°C, $T_{\text{cooling water}}$ 28-32°C, $T_{\text{heating water}}$ 50-60°C. These external media flows were supplied by two laboratory thermostats (Figure 6.). The fresh LiBr-solution was fed from a supply tank to the module by a gear pump, via a filter and a solution heat exchanger (SHX). The SHX was supplied with circulating water from a thermostat bath to adjust the solution module entrance temperature to the level of a real process. The concentration of the LiBr solution was in a range of 53 to 56 %.

To cover both absorption and desorption conditions the operation parameters were varied in a wide range: starting from favorable absorption conditions the partial pressure difference was stepwise reduced and then inverted by increasing the solution and reducing the refrigerant temperature.

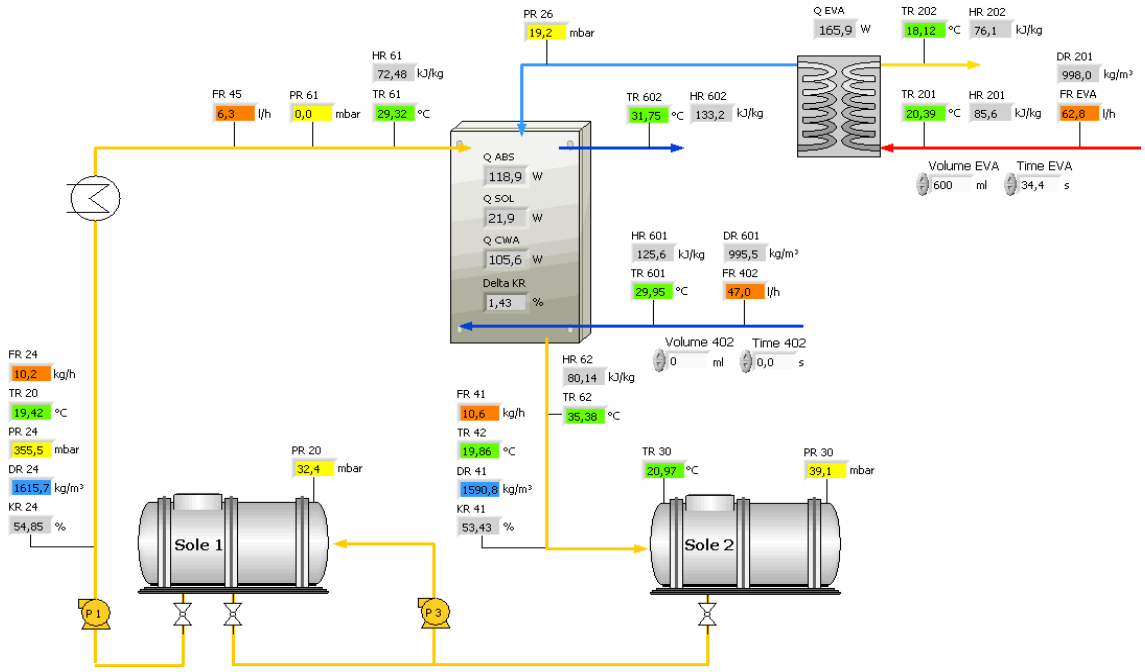


Figure 6: LavView front panel for online process data visualization of sorption performance tests

A typical test procedure with stepwise parameter variation without interrupting the process is shown in Figure 7. To measure the dependency of the membrane process performance from the driving partial pressure difference, the outer process media parameters are varied from

absorption (heating the water heat exchanger -acting as evaporator- and cooling the sorption module, to desorption (heating the sorption module and cooling the water heat exchanger -acting as condenser).

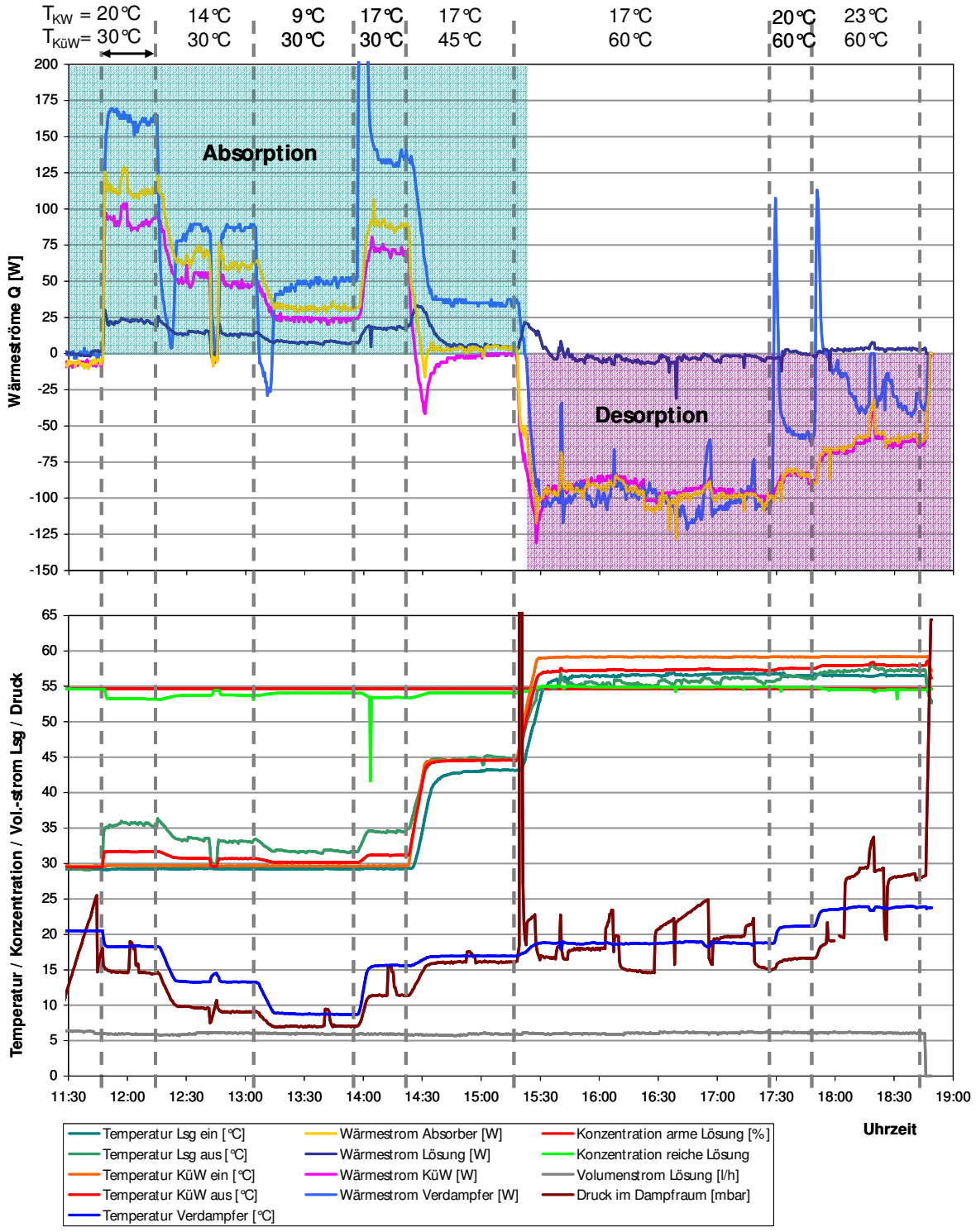


Figure 7: Typical signal trends - process passing from absorption to desorption

Typical results of the membrane process performance of the modules III and IV, expressed as the heat transfer rate vs. the driving partial pressure difference, are summarized in Figure 8. As an example a value of 2 kW/m² at Δp 5 mbar was observed from the experiments, which represents a significant improvement compared to previous designs. But the required driving pressure difference is still relatively large and has to be reduced to avoid a large

membrane area, to allow lower heating water and/or warmer cooling water temperatures. While the first would increase the number of modules, the hydraulic complexity, the stack size and costs, the cooling water restriction could hamper the waste heat rejection on hot days.

In comparison to the conventional falling film sorption process the heat transfer rate of a membrane pervaporation process has more factors influencing the overall performance.

Beside the given vapor diffusion resistance of a membrane, another important effect is the concentration polarization, which is mainly the diffusion resistance of the solution film at the membrane surface. It is determined by the particular film parameters, such as thickness, velocity, Reynolds number, flow pattern, spacers etc. Many measures were focusing so far on the improvement of film parameters, especially by testing solution channel spacers from 1 mm down to 0.3 mm and varying the solution flow in a wide range. Reducing the film thickness is the main subject of further R&D work. A substantial enhancement of the refrigerant and heat transfer rates by the factor of 10 is expected with films of less than 0.15 to 0.1 mm (*Yu et.al.* 2012). This requires changing from spacer filled solution channels to microstructures in the cooling plate itself.

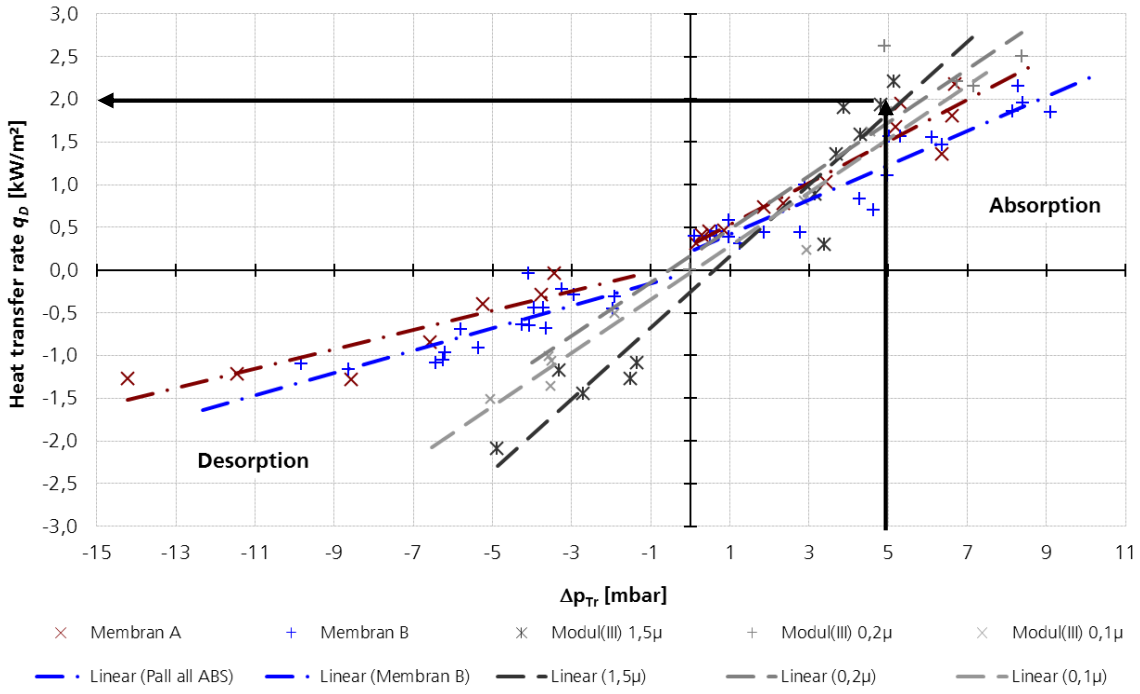


Figure 8: Spec. heat transfer rate vs. refrigerant partial pressure - modules III and IV

Other challenging topics will be to limit the pressure drop of the thin film solution, to achieve an even solution flow field, to control the media flows inside the stack with its parallel modules and to deal with the large pressure difference of external heat transfer fluids and the process media.

CONCLUSION

The membrane pervaporation process, realized in a compact stack design with flat sheet membranes appears as a promising size, weight and cost reducing alternative to conventional falling film absorption and desorption apparatus in small scale chillers. The experiments with the Lithiumbromide/water process and low driving partial pressures resulted in a vapor flux of 2.2 kg/m²/h for the absorber unit. This indicates a specific absorber heat flux of about 1.6 to 2.1 kW/m², which has to be improved significantly to reduce the number of modules and complexity of the stack.

Further R&D work will e.g. cover the use of micro structured surfaces in the cooling plate to significantly enhance the mass transfer rate of the thin film. The basic module design seems promising as a flexible basis for multiplication to achieve a cooling capacity of 5 kW for residential air conditioning.

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