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OPEN ABSORPTION SYSTEM FOR COOLING AND AIR CONDITIONING USING MEMBRANE CONTACTORS

2006 Annual Report

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SUMMARY

The *MemProDEC Project* has attained the stage of construction of the first prototype (a laboratory prototype) with the manufacture of its various components. This follows a careful selection and testing of materials, and of the components manufacturing processes.

The mechanical design implements a concept of compact and modular construction of the main components, in particular of the membrane contactors. The modularity of the contactors means that each contactor is built out of elements that are themselves functional contactors. Assembling takes place by stacking together several identical elements. This allows a very high flexibility in terms of capacity of each component, that may be attained using the same size of contactor element.

The thermal design of the components for the various possible Air Handling Unit (AHU) configurations has been formalized in the design of the first prototype. The various steps of the thermal design are described succinctly in this report.

Project Objectives

General Objectives

In the *MemProDEC Project,* it is envisaged to develop, build and test experimentally in the laboratory a conceptual design of a new type of air handling unit (AHU), operating with a liquid desiccant. The AHU shall be autonomous, i.e. shall not require additional mechanical refrigeration. It shall be thermally driven at temperatures below 80 °C. Waste heat sources, solar thermal collectors, district heating plants and cogeneration systems are able to provide thermal energy at this temperature level. The use of district heating in Summer is especially advantageous since the network loads are, in general, well bellow their nominal capacity. District heating plants burning urban waste, on the other hand, have to dissipate generated heat through cooling towers in Summer, particularly since they must continue to burn waste, even without demand from the network.

The AHU shall operate as an open absorption system (atmospheric pressure), although no direct contact takes place between the air and the liquid desiccant. Air and desiccant are contacted through adequate membranes, thus avoiding desiccant aerosols and solving the attending corrosion and potential health problems. Furthermore, confining the desiccant also permits a reduction of the amount of desiccant required in relation to common open systems. A reduction of the quantity of desiccant, besides reducing costs, reduces the start-up times as well. This is also an important aspect to consider when the system has to cycle at part-load.

This type of AHU shall reduce electric energy demand for air conditioning and may contribute to improve the economics of district heating networks by providing new customers for the excess heat available in Summer. On the other hand, solar thermal energy becomes a real alternative, since the driving energy is required at a level well bellow that of traditional, closed, absorption systems.

Development of membrane contactor technology for air-conditioning processes

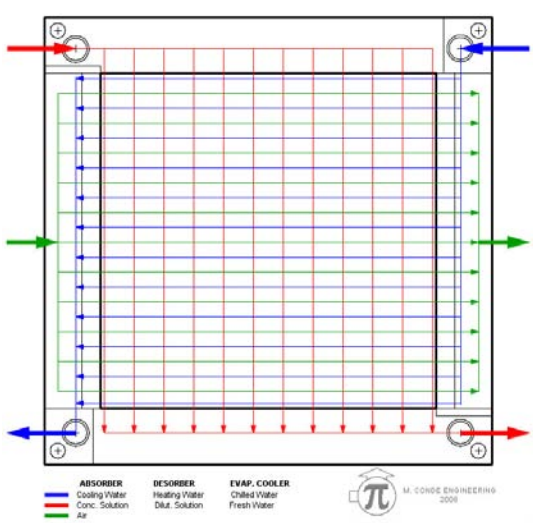

Figure 1 *– Schematic representation of a three-stream crossflow membrane contactor.*

Membrane contactors for air-conditioning processes considered in this project contact either a desiccant solution or, water with air, through a membrane. Suitable membranes for these liquid-air contactors are hydrophobic, microporous, polymeric, membranes. In this case, and provided that the liquid penetration pressure is not exceeded, only water vapour crosses the membrane. The processes are vapour pressure (concentration) driven: Either the vapour crosses from the liquid phase to the air (air hydration, as in an evaporative cooler, or desiccant regenerator) or, from the air to the liquid phase (air dehydration either by cold water[1] or by a desiccant solution (absorber)). For the *MemProDEC Project,* four types of membrane contactors are in development: an absorber, a desorber, and two evaporative coolers (direct and indirect). Prototypes of all contactors have been designed, and shall be described in detail in the following sections of this report.

The development concentrated on solving the problem of the corrosion risk, already discussed in last year's Annual Report, on the selection of materials that are cheap and easy to handle and process, and on providing for modularity with easily assembled elements.

The idea is to design stackable elements allowing for variable configuration of the contactors, whose capacities may be set in a relatively large range. Figure 1 shows schematically the concept of a structured plate-based membrane contactor element (three stream, crossflow heat & mass exchanger, as absorber, desorber, or indirect evaporative cooler). Two stream membrane contactors as evaporative

[1] Air dehydration by cold water across a membrane may cause humidity condensation on the air side of the membrane, which is undesirable.

coolers have also been designed for internal cooling of the AHU, although they shall not be used in the first prototype in the laboratory.

Structured polymer plates available on the market (used in general for packaging, sound and thermal insulation in cars, or for billboard construction) have been selected as basic construction material for the contactors. This material is frequently used in the manufacture of heat recovery heat exchangers, particularly where corrosion is a problem, as in swimming pool ventilation, as well as for other low temperature (< 90 °C) systems.

The membranes are also a product already available on the market, mostly used in the production of electric batteries and accumulators, and for water purification purposes. For the further development of contactor technology for air conditioning applications (next phase of the project) a modification of the mechanical support of the membrane is envisaged, for which the manufacturer has already manifested interest to cooperate with us.

Development of autonomous open-absorption AHU configurations

Autonomous (no mechanical refrigeration needed) Air Handling Units (AHU,s) operating on the open absorption principle may be tailor designed to provide cold water and dry air simultaneously, or just one of both. The AHU producing cold water and dry air is then the general case, from which the other two are particular cases in terms of design. All components are static components, with the exception of fans and pumps. And all components, with the exception of fans and pumps, may be built out of structured plates as described above.

As shall be explained in more detail further down, the AHU components (absorber, desorber, evaporative coolers and heat exchangers), are all built elementwise. This shall allow for a flexible construction of a range of AHU capacities out of a set of standard contactor elements.

For the purpose of demonstrating the principles, as required in this phase of the project, the prototype to be tested is much simpler. The processes in absorber and desorber shall be demonstrated, but no membrane contactor-based evaporative cooler shall be built or used. This follows from the extremely tight budget of this phase of the project.

Work Performed and Results

The work performed in 2006 has centered essentially on the design of the components and on the experimentation with membrane contactor manufacturing methods, and partly on simulation model development. The results of these activities shall be presented and discussed in the following.

1. Design of an AHU and its components

For the design of an AHU and of its components we started from the conditions defining a typical Summer case air conditioning problem, with specified thermal loads and local settings:

Table 1 *– Design conditions for a Summer case air-conditioning point.*

Process Air Data for the Design Case						
		OA(1)	SA(2)	RA(3)	EA(4)	Units
Dry-Bulb Temperature	T_{DB}	32.0	18.0	26.0		°C
Relative Humidity	φ	40.0	55.0	40.0		%
Humidity Ratio	ω	11.958	7.076	8.403		$g.kg_{DA}^{-1}$
Barometric Pressure	P	101.325	101.325	101.325	101.325	kPa

(1) Outside Air; (2) Supply Air; (3) Return Air; (4) Exhaust Air.

The desiccant solution is assumed to operate between the salt mass fractions of 0.40 and 0.42. The design capacity of the prototype to be tested is 1.0 kW.

The thermal design of an AHU is carried out in three steps:

1. Calculation of the air process, with assumptions regarding driving force potentials and component effectivenesses (heat and mass transfer);
2. Thermal design of the individual components, based on the results of step 1;
3. Overall equipment thermal design.

Although this process may be iterated upon, a simulation program for this purpose has not been developed as yet. Its development shall be part of the next phase of the project. Calculations are currently being done with a *MathCad*® calculation sheet.

1.1 Calculation of the air processes

The laboratory prototype is based on an *all air AHU* designed for the above conditions. Figure 2 depicts a schematic representation of the kind of unit considered, although the prototype to be tested is reduced to the main components 3, 5, 6, 7, besides ventilators, pumps, valves and measurement sensors.

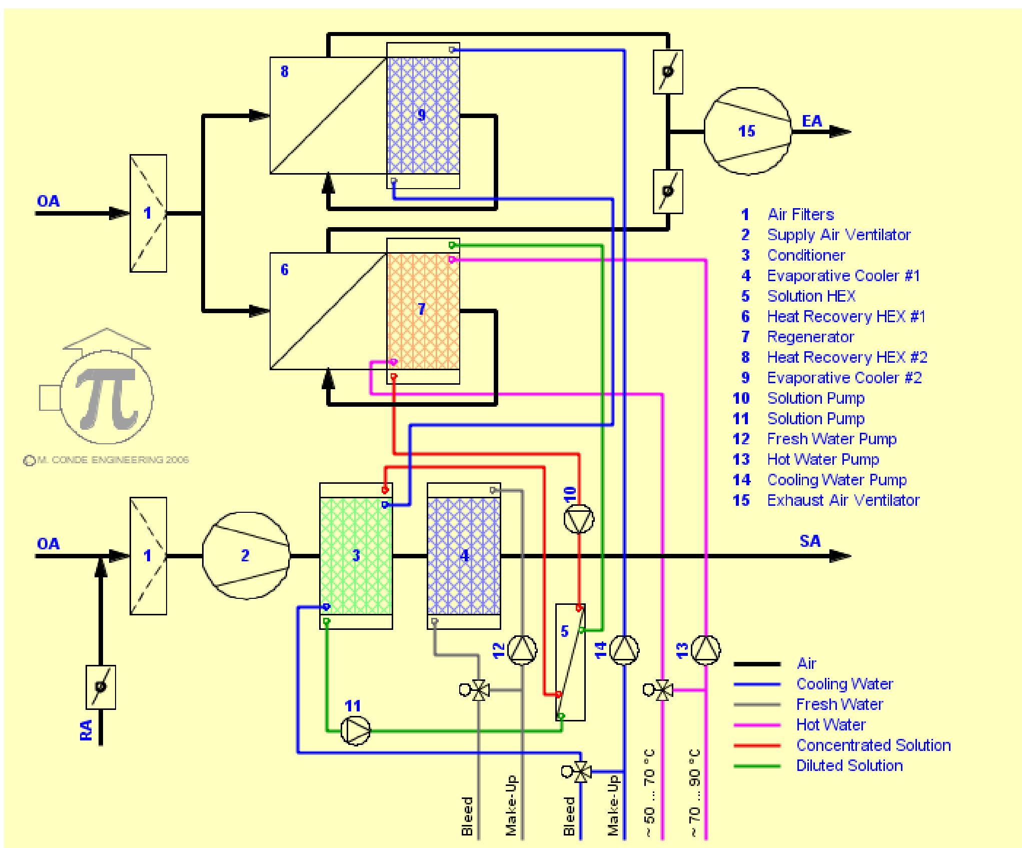

Figure 2 *– Schematic representation of an AHU for an all-air system. The main components of the unit are the membrane contactors 3, 4, 7 and 9, and the heat exchangers 5, 6 and 8.*

The results of the calculations of the air processes are represented graphically on *the Mollier h-x diagram* of Figure 3. The air processes represented in Figure 3, take place in the components shown in Figure 2, according to Table 1.

It is interesting to observe that the air actually exhausted (EA) is at approximately the same temperature as the outside air (OA), albeit at a higher humidity content. This has the important advantage of avoiding the so-called 'heat islands' found in the vicinity of buildings using air-cooled chillers (rooftop units in particular).

Table 2 – Processes and components where they take place.

Process	Component
2 – 3	Absorber (conditioner) 3
3 – 4	Evaporative cooler 4
1 – 8 & 9 – EA1	Heat exchanger 6
8 – 9	Desorber (regenerator) 7
1 – 6 & 7 – EA2	Heat exchanger 8
6 – 7	Evaporative cooler 9

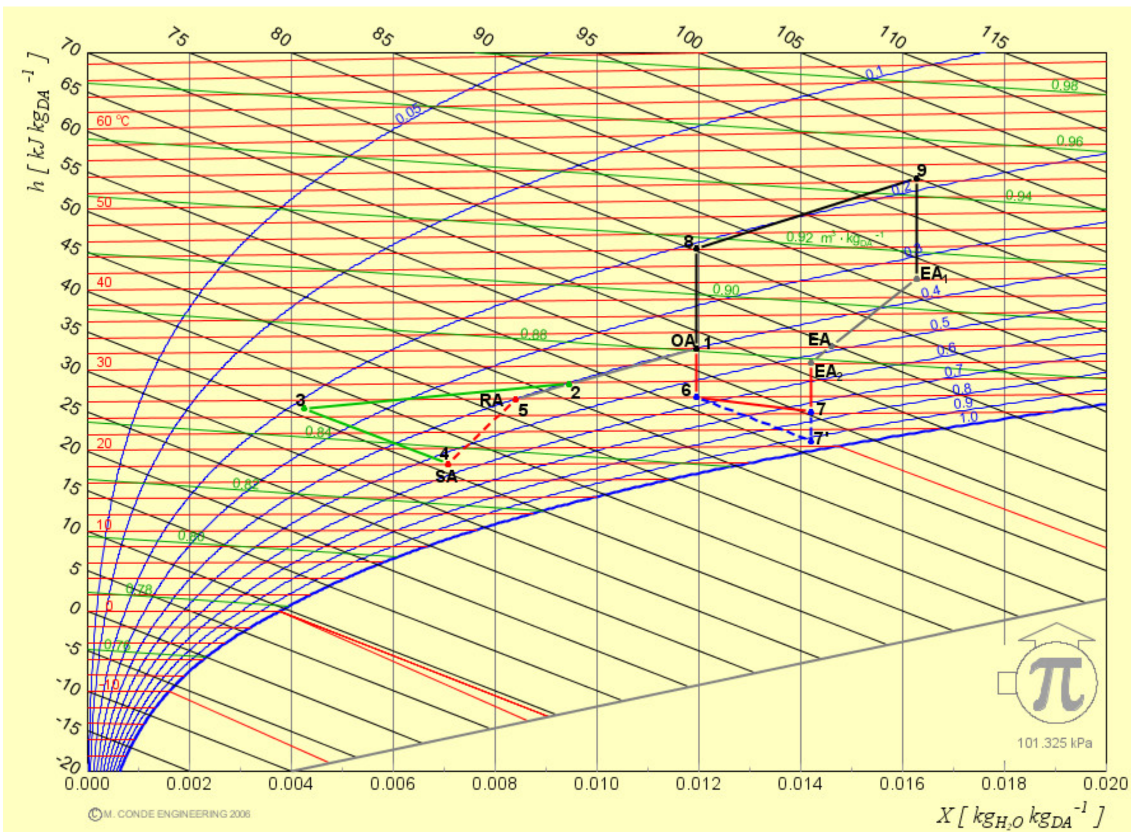

Figure 3 – Representation of the air processes on a Mollier h-x diagram for an all air AHU.

1.2 Thermal design of components

Four types of membrane contactors and two kinds of heat exchangers are required to build a complete AHU operating along the principles considered in this project:

1. Absorber (conditioner) is a three stream contactor, with heat and mass exchange between the air and desiccant solution across a membrane, and simultaneous heat exchange (cooling) of the solution with water (3 in Figure 2);
2. Desorber (regenerator) is a three stream contactor, with heat and mass exchange between the air and desiccant solution across a membrane, and simultaneous heat exchange (heating) of the solution with water (7 in Figure 2);
3. Indirect evaporative cooler (not present in Figure 2) is a three stream contactor, with heat and mass exchange between the air and fresh water across a membrane, and simultaneous heat exchange with cold water (to be cooled in the process);

4. Direct evaporative cooler is a two stream contactor, with heat and mass exchange between the air and cold water (to be cooled in the process) that is used for the internal cooling of the absorber (4 and 9 in Figure 2);

5. Solution heat exchanger is an internal energy recovery device between the concentrated and diluted desiccant solutions (5 in Figure 2);

6. Air-to-air heat exchangers as energy recovery devices before the desorber (6 in Figure 2) and the absorber cooling evaporative cooler (8 in Figure 2).

Absorber and desorber are similar devices with reversed driving potentials for both heat and mass transfer. The indirect evaporative cooler can be assimilated to these, considering a desiccant solution at null salt concentration. The direct evaporative cooler is a different kind of device. The heat exchangers are compact (high heat transfer area density) either in cross, or countercurrent flow arrangement.

1.2.1 Three stream membrane contactors

Figure 4 shows schematically a three stream contactor and a pictographic impedance model of the energy fluxes in such a contactor.

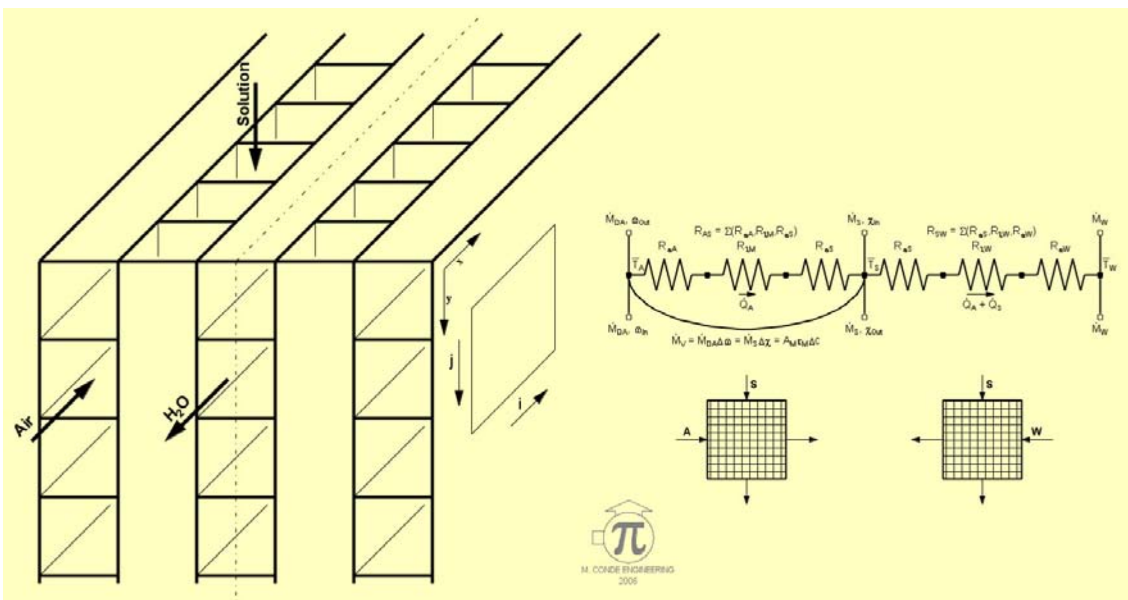

Figure 4- *Schematic of a three stream contactor indicating flow arrangement as applied to an absorber or desorber in the project. To the right a pictographic impedance model of the energy fluxes.*

An element of contactor, as depicted in Figure 4, is built out of five structured plates that may be of equal or different size (cross section), where the membrane constitutes the interface between the air channels and the solution channels. From the thermal point of view it has two equal symmetrical parts, with the water plate being common to both parts. As shall be explained below, such a contactor element is also an individual mechanical unit that may be stacked together with other equal elements to build a contactor. The capacity (mass and energy transfer) of the contactor being proportional to the number of elements stacked together. Mass and energy transfer intensities are naturally coupled through the driving potentials, the concentration and temperature gradients across the interfaces.

Although the structured plates are manufactured from polymeric materials (low thermal conductivity), their influence upon the heat transfer process is insignificant: The heat transfer is essentially controlled by the convective transport in the liquid and gas phases. The thickness of the channel walls varies between 0.1 and 0.3 mm.

The design of the contactor departs from the air processes that state its performance requirements, Table 1. Once the basic assumptions are made (e. g. air face velocity) the geometrical configuration of the contactor may be defined and transfer areas calculated, establishing the number and geometrical size of the contactor (or one element). This is an iteration intensive process, be it done by global or detailed calculations.

The sizing of the contactor involves extensive use of transport and thermodynamic property calculation methods for water, desiccant solution and humid air. All calculation methods and the respective programs have been developed prior to the start of the project [1], [2], [3].

1.2.2 Two stream membrane contactors

A two stream membrane contactor is in principle a direct evaporative cooler, where the contact air-water takes place across a membrane. Figure 5 depicts a schematic of a two stream contactor element and a pictographic impedance model of its energy fluxes. It may as well be used as an absorber or desorber, if cooling or heating, respectively, are done outside of the contactor, and desiccant solution replaces water in the schematic of Figure 5. This is not the method proposed in this project, however.

This contactor element is also a symmetrical component, with two central water frames and two lateral air frames. As an evaporative cooler, it offers the very interesting advantage of contacting air and water through the membrane, thus eliminating any risk of contamination with dangerous germs eventually present in the water, e. g. *legionella pneumophila*. Contactor elements are stackable as in the three stream contactor described in 1.2.1. The design process is also similar albeit simpler.

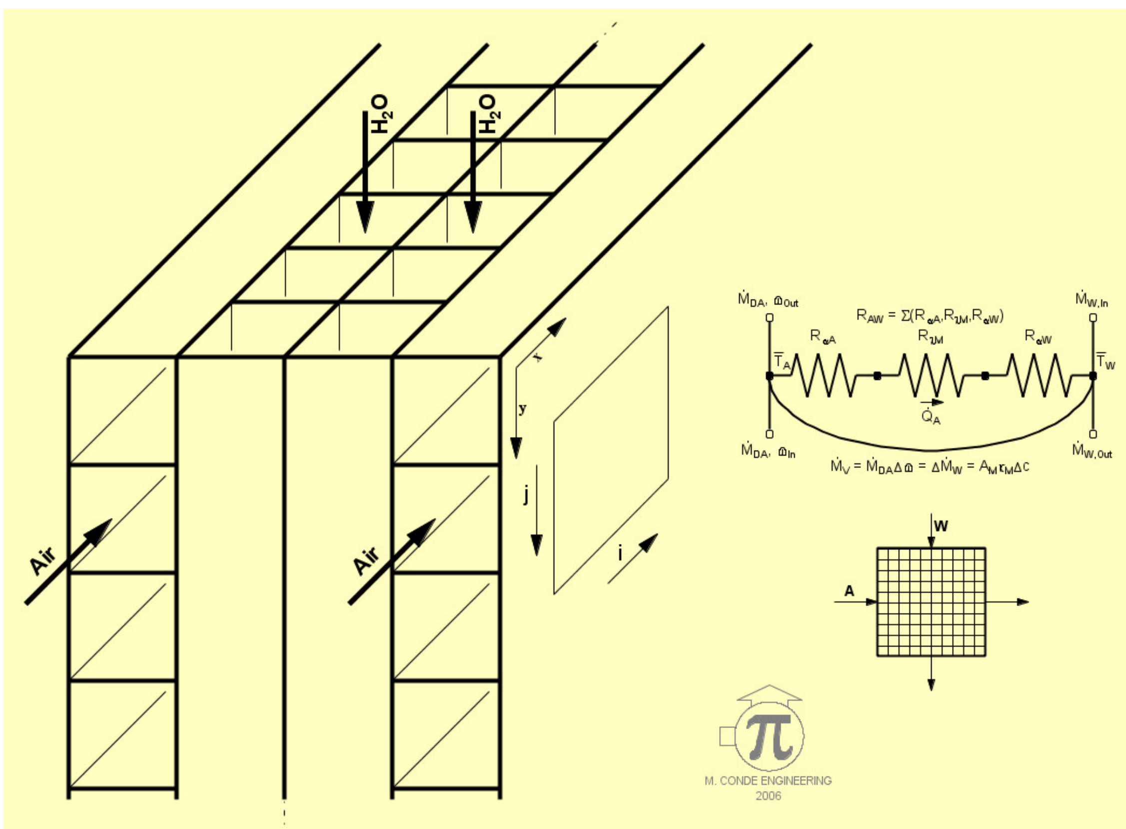

Figure 5 *– Schematic of a two stream membrane contactor element and pictographic impedance model.*

1.2.3 Structured plate heat exchangers

These are compact heat exchangers in the sense of Kays and London [4], with surface area densities of the order of 200 m^2/m^3 and higher. Two such heat exchangers have been provided by the industrial partners and shall be used in the laboratory prototype, Figure 6. Heat exchangers of this type have been designed for the process and are an integral part of the AHU design. The exchanger to the right in Figure 6 has been built, according to our calculations, by the techniques of one of the industrial partners. That to the left proceeds from the product line of the other industrial partner.

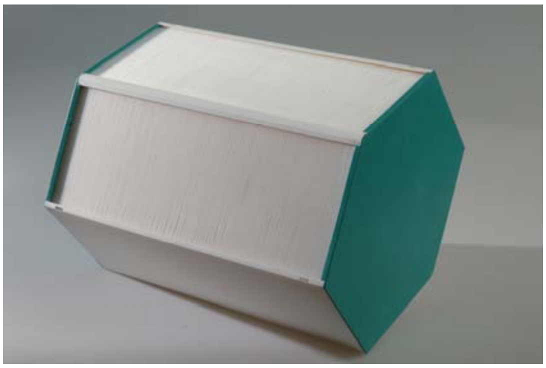

Figure 6 *– Air-to-air heat recovery heat exchangers to be used in the prototype, 6 and 8 in Figure 2. The exchanger to the right corresponds sensibly to that sized in the calculations (photos Empa).*

Figure 7 *– Shell-and-tube type solution heat exchanger (Polytetra GmbH).*

The solution heat exchanger (5 in Figure 2) has also been designed as a structured plate heat exchanger in the project. For this first prototype, however, a heat exchanger shall be acquired on the market. It is a countercurrent type of exchanger built as a single-pass shell-and-tube heat exchanger, out of polymer materials. Figure 7 shows a picture of a typical heat exchanger of this type: Tube bundle, shell, heads and connections are all made out of polymer materials (PP in this case).

2. Membrane Contactor manufacturing methods

The use of polymer materials readily available on the market facilitates the process of manufacturing the membrane contactors for the prototype. On the other hand, in order to contact the desiccant solution and air streams (or water and air streams in an evaporative cooler) the structured plates must be modified by milling, after having been cut to the right size.

As mentioned before, the wall thicknesses of the structured plates are in the range of 0.1 to 0.3 mm, thus making milling a delicate operation. This problem has been mastered by Empa with excellent results, as shall be explained in the following.

The technique consists of: filling the structured plates with water and freeze them on top of a good thermal conducting metallic plate. This metallic plate, especially manufactured for the purpose, is placed rigidly on the table of the milling machine, before freezing and milling, Figure 8. The frozen structured plates may then be milled according to need, Figure 9.

To accelerate the manufacturing process, defreezing of the structured plates may be speeded up by gently warming the metallic plate below them, Figure 10. To manufacture the structured plates required for the prototype, the process so engineered at Empa shall now be applied by an external workshop.

As may be observed from the pictures in Figures 11 and 12, only one wall has to be milled away, just where the membrane is to be inserted between two plates.

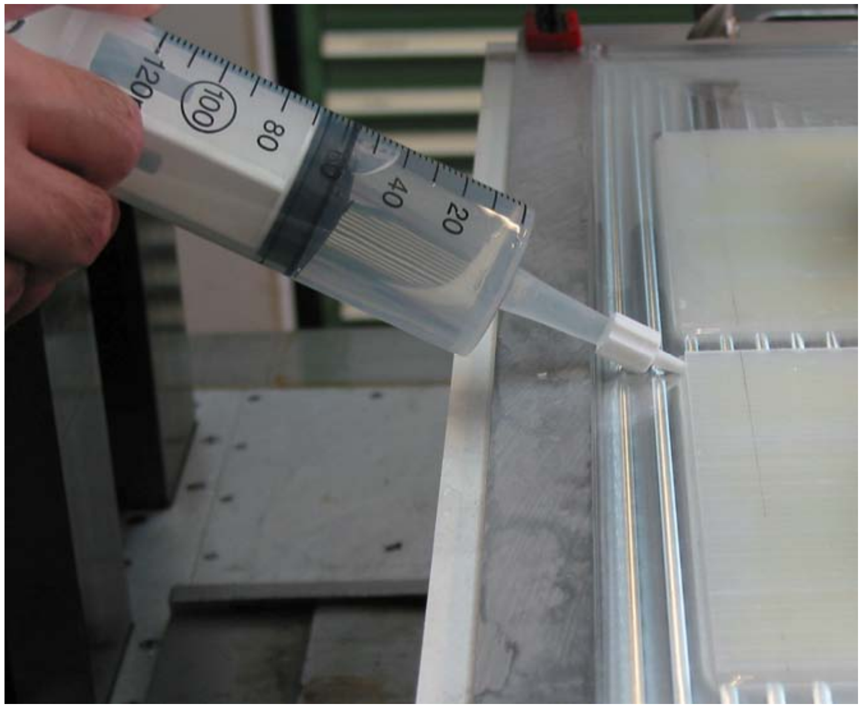

Figure 8 *– Filling the structured plates with water before freezing (photo Empa).*

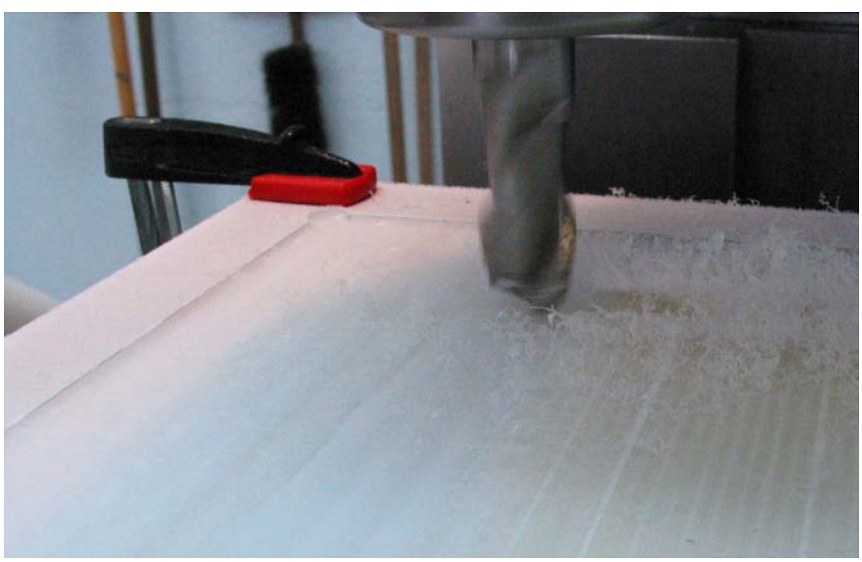

Figure 9 *– Milling the structured plates (photo Empa).*

Figure 10 *– Defreezing structured plates after milling (photo Empa).*

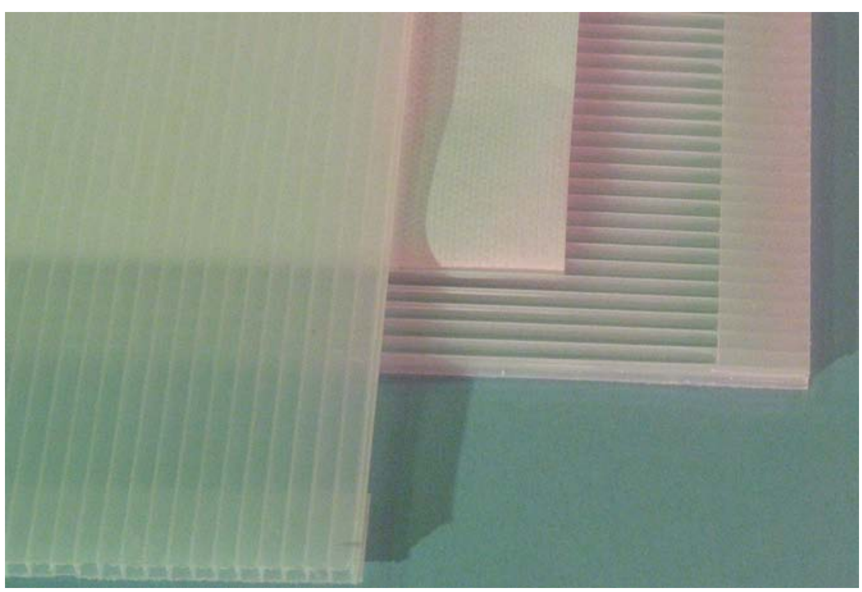

Figure 11 *– Detail of the milled structured plates with a sample membrane between them. The internal structure of the plates is clearly visible here (photo Empa).*

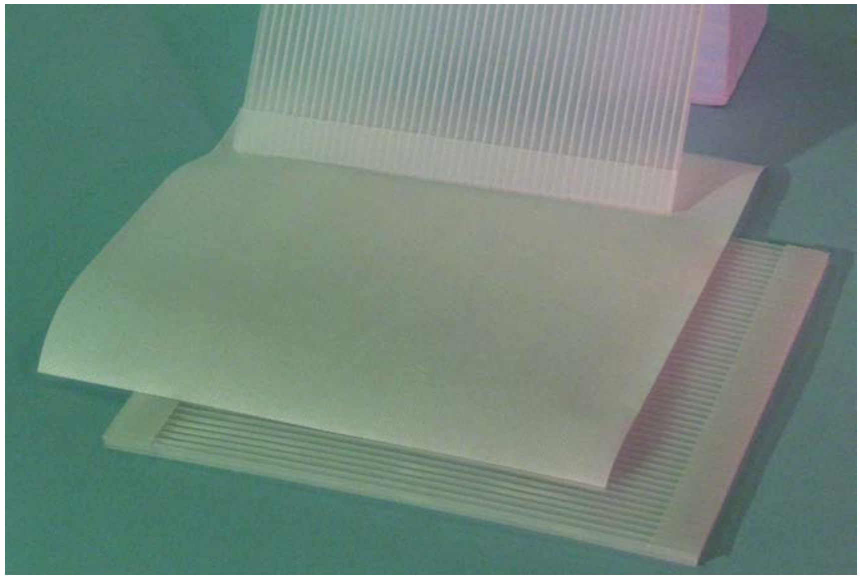

Figure 12 – Detailed view of milled structured plate samples with membrane (photo Empa).

As schematically shown in Figure 1, desiccant solution and water are fed to the structured plates by distributors. These distributors are designed to frame the structured plates making up an element of contactor into a mechanically rigid whole. The distributors ensure that no leakage occurs from one stream to the other. In the case of the water distributor, in three stream contactors, they form a convergent reducing the pressure loss of the air at inlet. The various parts of an element are assembled using a suitable adhesive. Figure 13 depicts a horizontal section of the water distributor of an element of a three stream contactor, while Figure 14 shows a vertical section of a solution distributor.

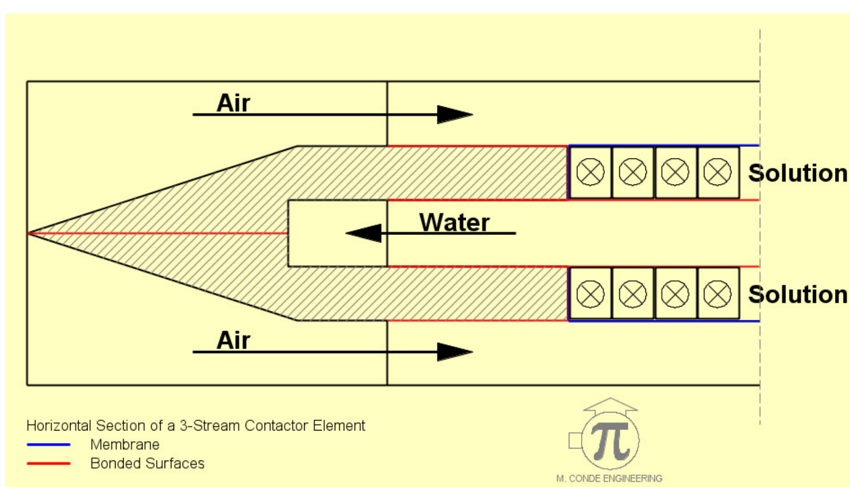

Figure 13 *- Horizontal section on an element of a three stream membrane contactor (water distributor). Notice the relative directions of the flows (crossflow).*

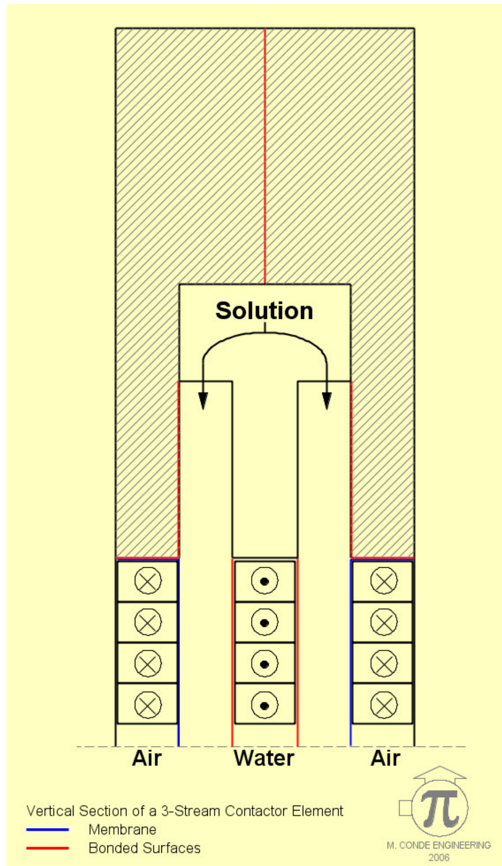

Figure 14 *– Vertical section on an element of a three stream membrane contactor (Solution distributor).*

Cooperation at the national level

This project is being carried out jointly by *M. Conde Engineering* and *Empa*. Two industrial partners *(Soltherm AG and Zehnder Comfosystems AG)* have already made small contributions in terms of components (heat exchangers), and the *Swiss District Heating Association* participates as an observer.

International cooperation

There is no international cooperation in this phase of the project.

Assessment 2006 and outlook 2007

The research on materials and processes carried out in 2005 has been continued in 2006. Although some questions remain open, that shall be answered when testing the first prototype, the search for the most suitable materials is now over. It may eventually be necessary to reassess the structure of the membrane selected for the membrane contactors, particularly in mechanical terms. We shall count with the support and interest of the manufacturer, as has been demonstrated in many discussions during this year.

The thermal design of Air Handling Units (AHUs) using the developed technology, has been formalized and shall be implemented in a design/rating software later in the project (next phase).

The first laboratory prototype is currently under construction (manufacture of the various components) and testing is expected to start during February 2007. This first phase of the project is now scheduled to terminate by end June 2007. The delay in regard to the planned termination by the end of February is essentially due to the need for extended tests with adhesives and the development at Empa of the manufacturing process of the membrane contactors. This manufacturing process has now been demonstrated and transferred to an external workshop.

We expect the first results of testing in early Spring 2007, on the basis of which the further development of the technology shall be decided. This includes decisions regarding intellectual property protection of the developed technology, and on which framework to proceed with the development work.

References

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[4] W. M. Kays, A. L. London: ***Compact heat exchangers,*** 3rd Ed., McGraw-Hill, Inc., 1984.