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Eidgenössisches Departement für
Umwelt, Verkehr, Energie und Kommunikation UVEK

Bundesamt für Energie BFE

OPEN ABSORPTION SYSTEM FOR COOLING AND AIR CONDITIONING USING MEMBRANE CONTACTORS

Final Report

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Impressum

Datum: 8. Juli 2008

Im Auftrag des Bundesamt für Energie, Forschungsprogramm Energie in Gebäuden

Mühlestrasse 4, CH-3063 Ittigen

Postadresse: CH-3003 Bern

www.bfe.admin.ch

Projektnummer: 10131

Bezugsort der Publikation: www.energieforschung.ch

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Summary

Air conditioning systems based upon the open absorption principle, essentially an absorption device operating at atmospheric pressure, have been proposed and investigated at many instances in the past eighty or so years. Their potential for improving energy efficiency is clearly recognized in the earliest research reports. By the mid 1950,s, solar thermal energy was being applied to drive open absorption-based air conditioning systems. For several reasons, however, the open absorption technology was not mature enough to take place in the mainstream. In the past two decades, vigorous efforts have been undertaken to reverse this situation, but success continued to elude, despite the fact that the main problems, such as corrosion, aerosols in the supply air, etc., have been identified.

This report details the work and the main results from the MemProDEC Project. In this project innovative solutions were proposed, and successfully investigated, for the corrosion problem and the improvement of efficiency of the absorption process, in particular a new method to cool a very compact absorber. The practically uniform flow distribution for all three streams in the absorber (air, water and desiccant) warrants the contact of the air to be dehumidified with the desiccant over the whole surface of exchange (across a porous membrane). This, together with the cooling with water in counter flow to the air, are the key factors for the excellent effectiveness of the absorber. As the results show, the dehydration effectiveness of the prototype absorber are up to 150 % higher than that previously obtained by others.

The solutions developed for compactness and modularity represent an important step in the way to flexible manufacturing, i.e. using a single element size to assemble autonomous air handling units of various nominal capacities. And although the manufacturing methods of the individual elements require improvement, namely by avoiding adhesive bonding, the choice of materials and the design methods have proved perfectly adapted for the purpose.

Zusammenfassung

In den vergangen achtzig Jahren sind mehrere Klimatisierungssysteme, die nach dem offenen Absorptions-Prinzip funktionieren, vorgeschlagen und untersucht worden. Das Potenzial zur Steigerung der Energieeffizienz wurde schon bei frühen Forschungen in den dreissiger Jahren erkannt. Schon Mitte der fünfziger Jahre wurden Systeme dieser Art gebaut und mit Solarenergie betrieben. Aus verschiedenen Gründen war diese Technologie jedoch noch nicht konkurrenzfähig gegenüber etablierten Technologien. In den letzten zwanzig Jahren sind grosse Anstrengungen unternommen worden um offenen Absorptions-Systemen zum Erfolg zu verhelfen. Diesen Anstrengungen zum Trotz blieb der Erfolg begrenzt, auch wenn die Hauptursachen der Misserfolge identifiziert wurden, wie z.B. Korrosion und Aerosole in der Zuluft.

In diesem Bericht werden Entwicklungen und Hauptresultate des Projekts MemProDEC präsentiert. Im Projekt wurden innovative Lösungen für das Korrosionsproblem (ausschliessliche Verwendung von Kunststoff) und zur Effizienzsteigerung des Absorptionsprozesses (Stabilisierung der Arbeitstemperatur im Absorber) erfolgreich untersucht. Die praktisch uniforme Verteilung aller drei Stoffflüsse (der Luft, des Kühlwassers und des Desiccants) im Absorber ermöglicht der Luft über eine mikroporöse Membrane überall einen guten Kontakt mit dem Desiccant. Diese Faktoren, zusammen mit der Führung des Kühlwassers im Gegenstrom zur Luft, sind für die ausgezeichnete Entfeuchtungseffektivität des Absorbers entscheidend. Wie die Resultate zeigen, ist die Entfeuchtungseffektivität des neuen Absorbers um 150 % grösser im Vergleich zur herkömmlichen Lösungen.

Der kompakte und modulare Aufbau der entwickelten Ab- und Desorber stellen einen wichtigen Schritt auf dem Weg zu einer flexibleren Herstellung dar, d.h. aus einzelnen Elementgrössen können Aggregate mit unterschiedlichen Nominalleistungen hergestellt werden. Die ausgewählten Materialien und die Auslegung des Systems sind zweckmässig. Verbesserungen sind notwendig im Bereich Herstellung, insbesondere sollten die einzelnen Teile geschweisst und nicht mehr geklebt werden.

Resumée

Des systèmes de conditionnement d'air fonctionnant selon le principe de l'absorption ouverte, en effet des systèmes d'absorption opérant à la pression atmosphérique, ont été proposés et étudiés à plusieurs reprises aux cours des dernières 80 années. Son potentiel d'amélioration dur rendement énergétique étant reconnu déjà dans les premiers compte rendus de recherché sur ce sujet. L'énergie solaire thermique actionnait déjà vers 1955 des systèmes à absorption ouverte. En dépit de cela, les systèmes basés sur l'absorption ouverte n'étaient pas encore en mesure de jouer un rôle important dans le marché des équipements de conditionnement d'air. Pendant les vingt dernières années des efforts vigoureux ont été entamés pour renverser cette situation. Ces efforts n'ont pas réussi de grands succès jusqu'à présent, même si les problèmes principaux ont été clairement identifiés, parmi eux la corrosion et des aérosols dans l'air distribué.

Ce compte rendu présents les travaux réalisés et les résultats plus importants obtenus dans le Projet MemProDEC. Aux cours de ce projet des solutions innovatrices ont été proposées et étudiées pour le problème de la corrosiion et pour l'amélioration du rendement du procés d'absorption, tout particulièrement une nouvelle méthode de refroidissement d'un absorbeur très compact. La distribution uniforme des écoulements d'eau de refroidissement, de l'air et du désséchant garant un contact parfait de l'air avec le désséchant sur toute la surface d'exchange à travers d'une membrane microporeuse. Cette distribution uniforme des écoulements, ensemble avec le refroidissement en contrecourrant avec l'air, sont les facteurs clés pour l'excellente effectivité de déssiccation réalisé avec l'absorbeur. Les résultats montrent une effectivité de déssiccation autour de 150 % plus forte que celle rapporté par d'autres jusqu'ici.

Les solutions constructives dévelopées en termes de compacité et de modularité représentent une étape importante vers l'bjectif d'une fabrication fléxible, c'est-à-dire, elle permet l'utilisation d'un élément unique pour assembler des unités de traitement d'air (UTA) ayant des puissances nominales variées. Et même si les méthodes de fabrication des éléments individuels nécessite encore des améliorations, particulièrement pour réduire au minimum, ou éviter complètement l'utilisation des adésives, le choix des materiaux et les méthodes de conception ont prouvé être parfaitement adaptés aux objectives.

1. Project Background

The conditioning of air for comfort, manufacturing or other activities, requires the control of temperature, humidity content, particles, (Volatile Organic Compounds) VOCs, germs and of harmful gases eventually present in atmospheric air. Particle control is mostly done through the use of suitable filters, and their regular maintenance. VOCs and germs may be done with in air washers and, particularly for germs, through UV radiation. Harmful gases may be eliminated by ad/absorption in suitable beds or contactors. Temperature and humidity control, however require the most of the energy used in the conditioning of air. The relative energy intensity for temperature and humidity control depends both on the local climate and on the particular application. The control of humidity content and temperature is the main subject of this project. The control of other variables shall be left either to special technologies out of the scope of this project, or considered as by-products of the developments to be undertaken.

The control of temperature is done through cooling and heating, following the requirements of the particular application considered. There are various possibilities for carrying out both processes. While adiabatic evaporative cooling of the outside air (OA), or a mixture of outside air with return air (RA), may do in the climates such as those of Central Europe, it may not be adequate for the climates of other regions. It may also be problematic in terms of germ control, when the supply air (SA) is cooled by direct evaporative cooling. Controlling the temperature by direct evaporative cooling implies, mostly, no control over the humidity content, leading in many cases to discomfort situations.

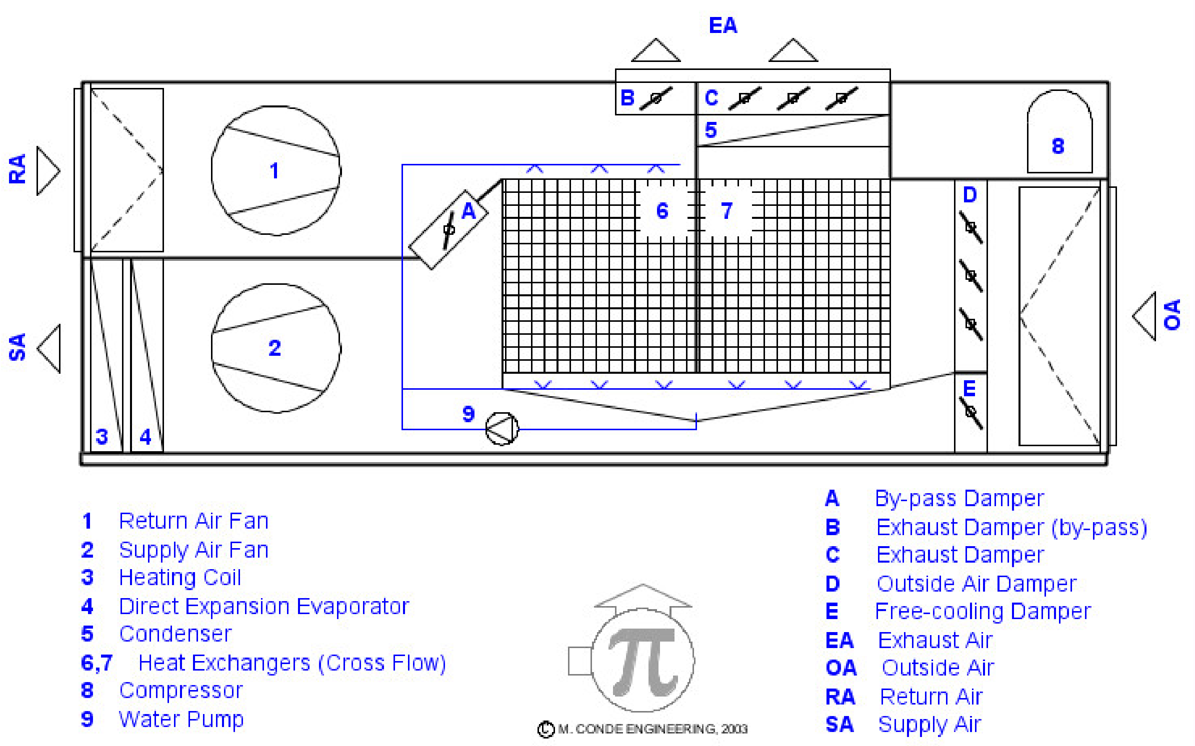

Figure 1 - *Air handling unit featuring mechanical refrigeration assisted indirect evaporative cooling.*

The control of humidity content is improved when indirect evaporative cooling is used, although systems operating along this principle require assistance from mechanical refrigeration to keep comfortable conditions in hot and humid days, or at high internal latent loads, such as in swimming pool halls. The schematic in Figure 1 depicts one such system combining indirect evaporative cooling with mechanical vapour compression.

In those situations where additional cooling is required, both mechanical vapour compression and absorption refrigeration equipment may be used. Anyway, the use of mechanical refrigeration is far more widespread than evaporative cooling, even in climates where the late would represent the most suitable solution from the energy efficiency point of view. Heating may require separate equipment, but in many cases integration with other systems available at the plant or building may allow flexible and efficient solutions to be found. Energy efficiency is improved everywhere by choosing approach temperatures as close as possible to those desired for the air, which implies a careful design of the components.

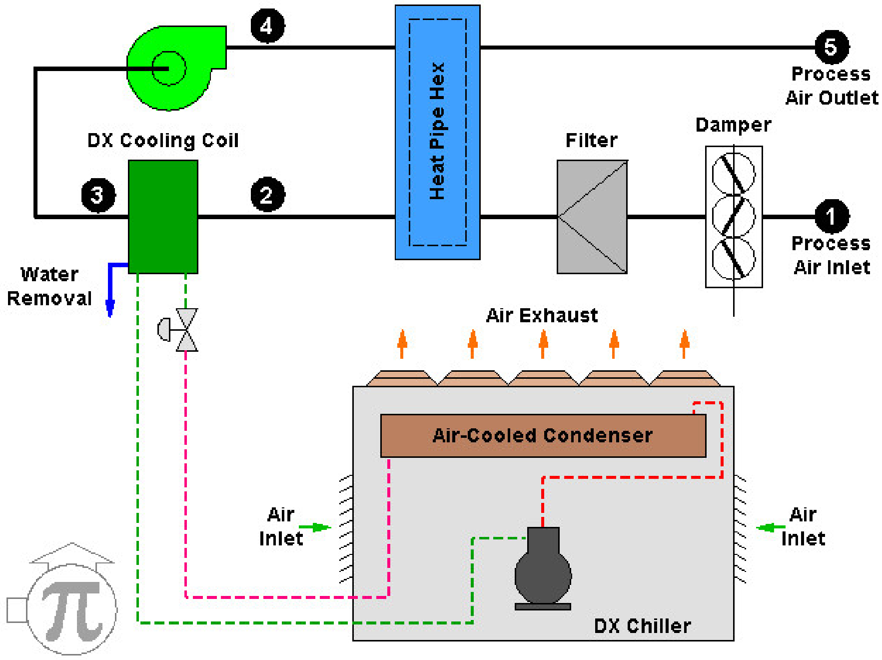

Figure 2 *- Schematic of a typical air conditioning system with a direct expansion chiller.*

In the still most common process used to control humidity content, Figure 2, the air is cooled in contact with a surface at a temperature lower than its dew-point temperature, in order to condense the excess part of that humidity, processes 1&2 in Figure 3.

These processes require mostly a heating step before the air is supplied to the conditioned space. Control of the temperature and humidity content are not independent from each other. On the other hand, there is a double energy loss due to cooling beyond the necessary level and to reheating afterwards, although energy recovery is mostly possible, Figure 3. Despite all losses and other arguments, the well proven and sturdy mechanical vapour compression equipment still continues to be preferred by many for the generation of the necessary cold source.

The replacement of the air dehydration process by active cooling surface contactors (e.g. cooling coils) beyond the dew-point has been the subject of intensive research for many years. Practicable solutions have been found that decouple the control of temperature and humidity and that avoid the most of that double energy loss. For the climates of central Europe, convenient and reasonably satisfactory solutions may be found through the combination of energy recovery and evaporative cooling. Although these processes do not in most cases provide for an accurate control of humidity, they do however provide for acceptable comfort.

In the last thirty or so years serious efforts have been undertaken to diversify the solutions applied to control humidity in air conditioning systems. Some of the ideas involved have been patented long ago [1], but only the perceived need to protect the environment and to minimize the depletion of non-renewable resources, has stimulated the development of new equipments implementing those ideas. On the other hand their lower running costs and high reliability has increased their presence in air conditioning plants. Besides energy recovery, the essential of the systems being developed are characterized by separating the control of temperature (cooling and heating) from the control of humidity content (humidifying and dehumidifying). Most of these *new systems* involve some sort of sorption process, using *desiccants.*

Desiccants are materials with a high affinity for water. Solid Desiccants *adsorb* moisture *onto* the surface of their highly porous structure. Liquid desiccants *absorb* it *into* their mass, Figure 4. In both cases, the enthalpies of condensation and sorption are 'released' in the process. This change of state increases the temperature of the desiccant reducing its capability to take more moisture. Besides the different nature of the sorption process in the solid and liquid desiccants, it is the relative simplicity of cooling the liquid desiccants during the absorption that gives them a great advantage over the solid ones. Both kinds of desiccant have to be regenerated, when operating in a cycle, in order to preserve their dehydration capability. The *regeneration* consists in stripping the water out of the desiccant. This is usually done by heating the desiccant to a point where water vapour may be stripped away, mostly by an air stream. Liquid desiccants are advantageous as they can be heated more efficiently (with liquid media instead of gaseous).

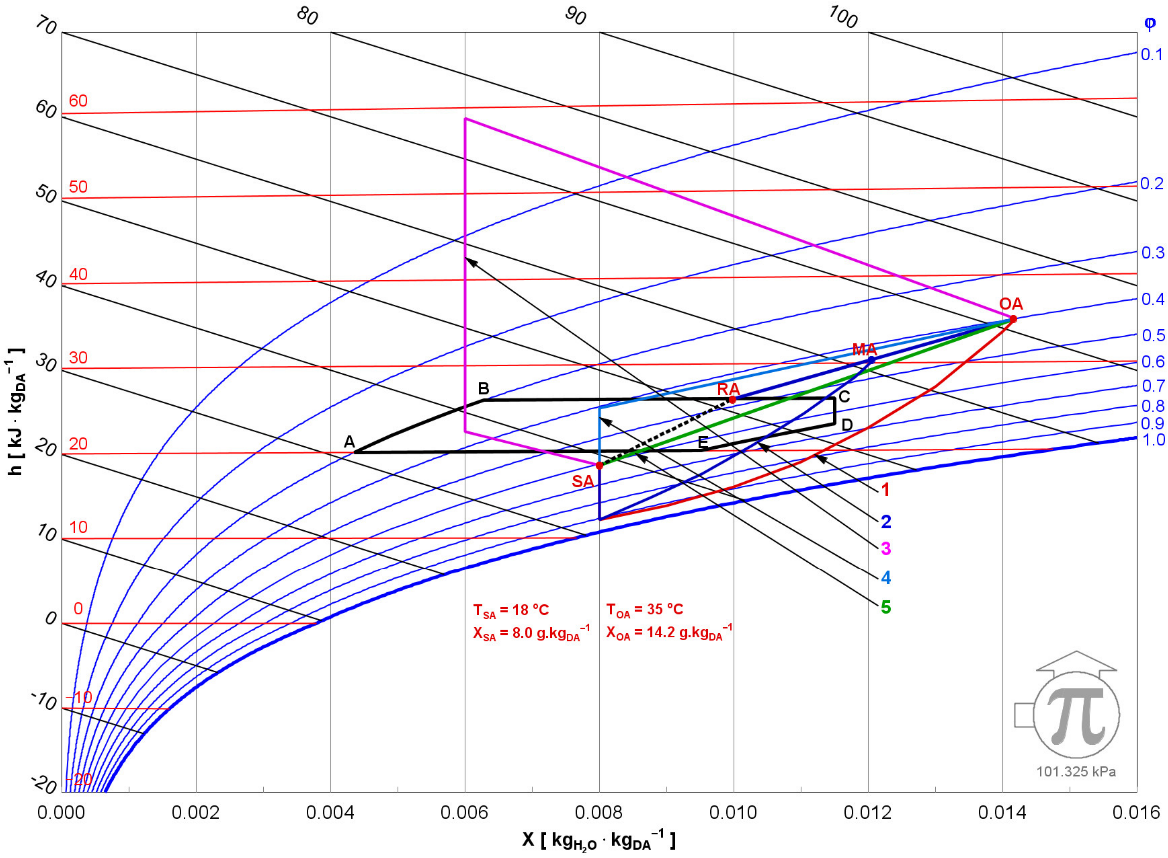

Figure 3 - *Air dehydration processes – Paths from OA to SA: 1&2 – Dehumidification by a surface contactor; 3 – Dehumidification by a solid desiccant & evaporative cooling system (DEC); 4 – Dehumidification by a liquid desiccant system & sensible cooling; 5 – The ideal process line.*

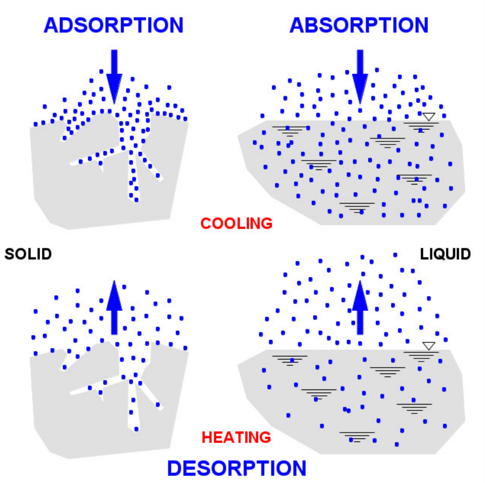

Figure 4 - *Illustration of sorption processes with liquid and solid desiccants.*

Open absorption systems operate with liquid desiccants at atmospheric pressure. The atmosphere also functions as evaporator and condenser, if the system is compared with standard, closed absorption.

The technologies adopted initially for open absorption systems were the same as those used for closed ones, or in the process industry: direct contact gas-liquid packed columns, tube bundles and direct sprays. Two problems emerged from these choices:

It is almost impossible to maintain a regular contacting surface, particularly at part load;

The air contacting the desiccant transports aerosols loaded with corrosive salt solution. These aerosols not only corrode the plant downstream of the unit, but are also dangerous for people and other living organisms.

The corrosion effects of liquid desiccant aerosols are well illustrated in Figure 5, for a system operating with aqueous LiBr, [28]. Although corrosion may be well controlled in closed absorption systems, in the open ones, with conventional gas-liquid contactors, this is practically impossible due to the presence of oxygen.

Figure 5 - *Corrosion in open absorption systems: Left, in the condenser; Right, in the supply air channel. Adapted from [28].*

The system studied in [28] used a reboiler as regenerator and a condenser to recover energy from the vapour produced.

The study of the properties of aqueous solutions of alkali halides has shown that it is possible to operate open absorption systems at relatively low driving temperatures. Temperatures in the range of 50 to 80 °C are sufficient to drive these systems efficiently. This range of temperatures can be easily attained with flat solar collectors, are available from district heating networks, are common in cogeneration systems, and as effluents in many industrial processes.

New concepts for the various components of open absortion systems may contribute to overcome the remaining obstacles for their more extensive application.

A review of some equipment already market and of the latest research on sorption-based air conditioning is presented in Annex 1, with emphasis on liquid desiccant systems.

2. Project Objectives

2.1 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.

Liquid desiccant-based AHUs operate as open absorption systems (atmospheric pressure), with two operating fluids: The liquid desiccant itself, running in an open circuit in contact with atmospheric air (dry air + water vapour), which constitutes the second operating fluid. Open absorption systems consist of at least two contactors. In the absorber the operating desiccant dehydrates the air, while being itself dehydrated in desorber. These two operations need not be simultaneous. There are mostly heat recovery heat exchangers both on the air and on the desiccant sides.

In the development undertaken in this project there is no direct contact 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, and thus may be provided by conventional thermal solar collectors.

2.2 DEVELOPMENT OF MEMBRANE CONTACTOR TECHNOLOGY FOR AIR-CONDITIONING PROCESSES

Microporous, hydrophobic membranes have the particularity of being permeable to air and water vapour while blocking the flow of water, or other liquid for that matter, if its pressure does not exceed the penetration pressure. The flow of vapour across the membrane is controlled by the gradient of the water vapour partial pressure. Figure 6 depicts a general process using a membrane contactor and defines the process nomenclature.

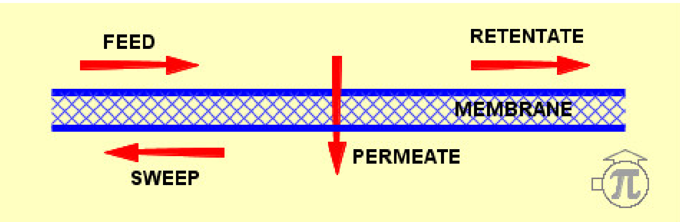

Figure 6 - *Generic membrane operating principle.*

Air dehydration using a membrane contactor is realized by a process known as ***Vapour Permeation (VP)*** and hydration is realized by a process known as ***Membrane Distillation (MD),*** in the terminology of membrane technology. The processes and membrane terminology as applied to air conditioning are explained in Table 1 for the cases where the solution contacts air through the membrane.

Table 1 - Description of membrane and process fluxes.

Membrane		Process / Fluid	Membrane		Process / Fluid
Membrane Distillation (MD)	→	Solution Regeneration	Vapour Permeation (VP)	→	Air Dehydration
Feed	=	Diluted Solution	Feed	=	Moist Air
Permeate	=	Water Vapour	Permeate	=	Water Vapour
Retentate	=	Concentrated Solution	Retentate	=	Dry Air
Sweep	=	Air	Sweep	=	Concentrated Solution
The solution must bring up the regeneration energy (enthalpy of vaporization + enthalpy of dilution). It will be cooled in the process.			The solution will take away the dehydration energy (enthalpy of vaporization + enthalpy of dilution). It will be heated in the process.		

Membrane contactors for air-conditioning processes developed 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[a] or by a desiccant solution (absorber)).

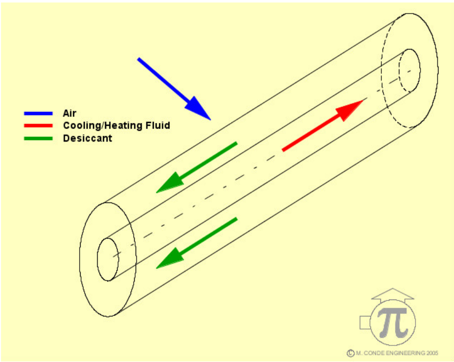

Figure 7 *- Schematic illustration of a three stream membrane contactor.*

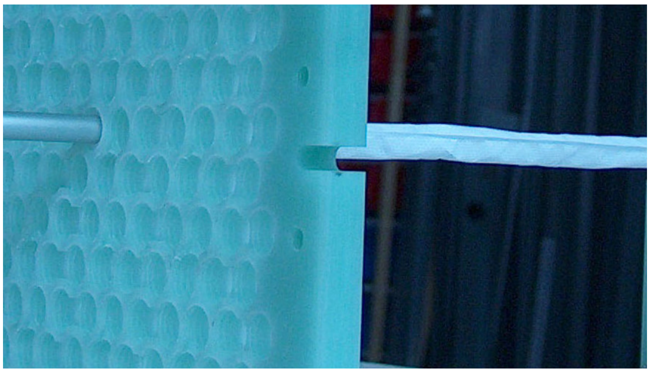

Figure 8 *- Partial view of a membrane tube, built in the first contactor prototype. The seam of the membrane tube is clearly observable.*

The first, and preliminary, approach to the design of the contactors considered a coaxial construction, with a metallic tube in the center, and an annulus defined by a membrane tube, as shown schematically in Figure 7. Membrane tubes in the range of diameters required are not available on the market, except for high cost medicinal products (used in heart surgery, for example). Membrane tubes were thus manufactured out of membrane film by welding (sealing process) at the *Empa Protection and Physiology Laboratory.* Although the seams produced by this process, Figure 8, were rather resistant, the tubes so manufactured could hardly be fitted in the contactor without damage. In the experiments, the stability of the membrane tubes manufactured by this process could not be warranted.

A redesigned contactor frame, Figure 9, that would facilitate the mounting and removal of membrane tube assemblies, presented similar problems.

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

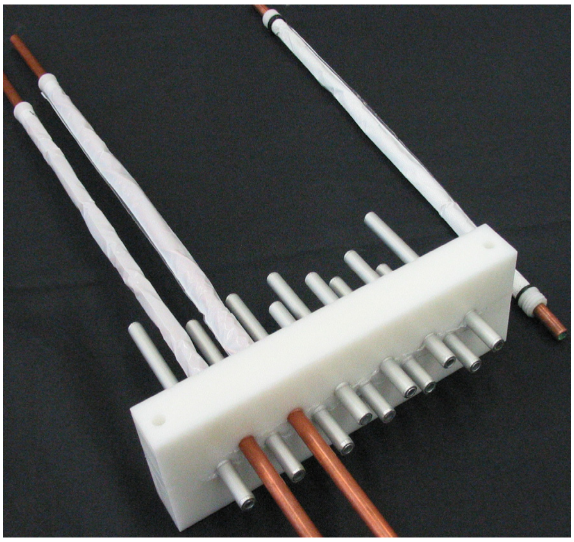

Figure 9 *- Details of a redesigned membrane contactor frame that facilitates mounting and removal of the membrane tube assemblies.*

As shall be explained under methods, metallic tubes, even ‚corrosion resistant' copper-nickel alloy ones, are strongly corroded by the liquid desiccant solution. This has lead to consider other materials (polymers) and to the design of new forms of contactors.

The idea behind this new design is illustrated in Figure 10, and a picture of one such new designed contactor element is shown in Figure 11. These are stackable elements, in themselves fully functional two or three-stream contactors, that may be assembled in variable numbers to produce a contactor of a given capacity.

Four types of membrane contactors were considered for the *MemProDEC Project*: an absorber, a desorber, and two evaporative coolers (direct and indirect). Prototypes of all contactors have been designed, and shall be described in the following sections of this report. The development concentrated as well on solving the problem of the corrosion risk, already discussed in the first Annual Report (2005), on the selection of materials that are cheap, and easy to handle and process, and on providing for modularity with easily assembled elements.

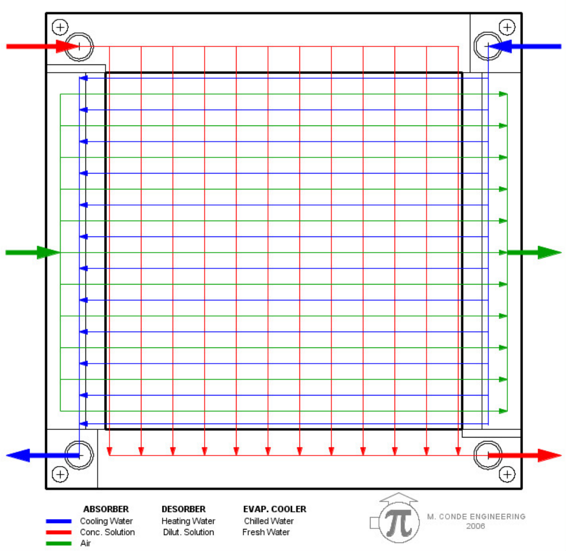

Figure 10 *– Schematic representation of a three-stream cross flow membrane contactor.*

Figure 11 *- Picture of a three-stream membrane contactor element.*

Twin-wall 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 (< 80 °C) systems.

The membranes, also a product already available on the market, are 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, or its replacement by another type of membrane, is envisaged.

2.3 DEVELOPMENT OF AUTONOMOUS OPEN-ABSORPTION AHU CONCEPTS AND 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. An AHU producing cold water and dry air, Figure 12, 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 twin-wall structured plates as described above.

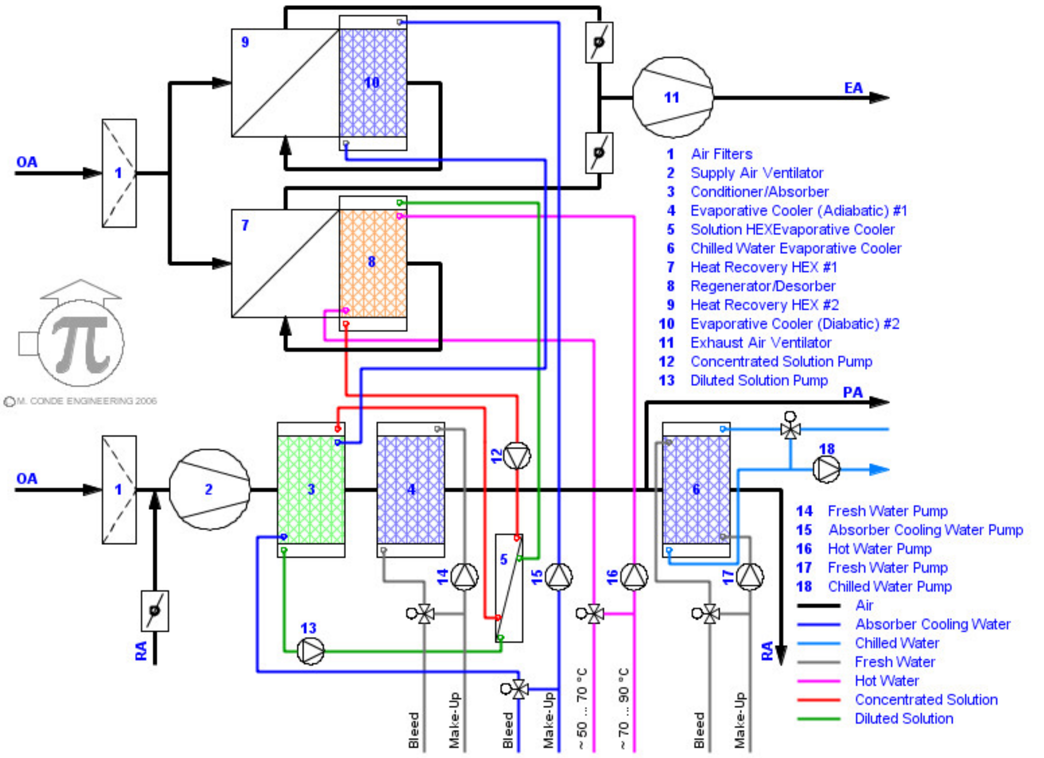

Figure 12 - *Schematic illustration of an AHU generating dry air and cold water.*

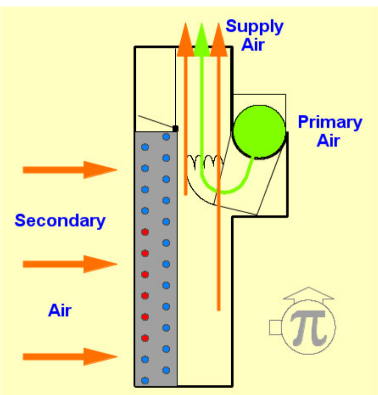

Figure 13 - *Schematic of an induction unit.*

The AHU components (absorber, desorber, evaporative coolers and heat exchangers) are all built element-wise. This shall allow for a flexible construction of a range of AHU capacities out of a set of standard contactor elements.

This generic AHU is particularly suitable for use in conjunction with terminal units of the induction type. Induction units, Figure 13, require a small amount of fresh air (hygienic minimum) at a relatively high pressure, together with hot and cold water to condition the air locally.

The high velocity of the primary air at the *induction* nozzle, generates a secondary air stream across the heat exchanger of the order of three to six times the primary air flow rate (Supply Air ~ 4 ÷ 7 x Primary Air).

On the other hand, *All Air* AHUs, Figure 14, just provide cold, dry air, and are simpler to control and build. Flexibility may be obtained using decentralized conditioners operating together with a common regenerator, including common solution storage.

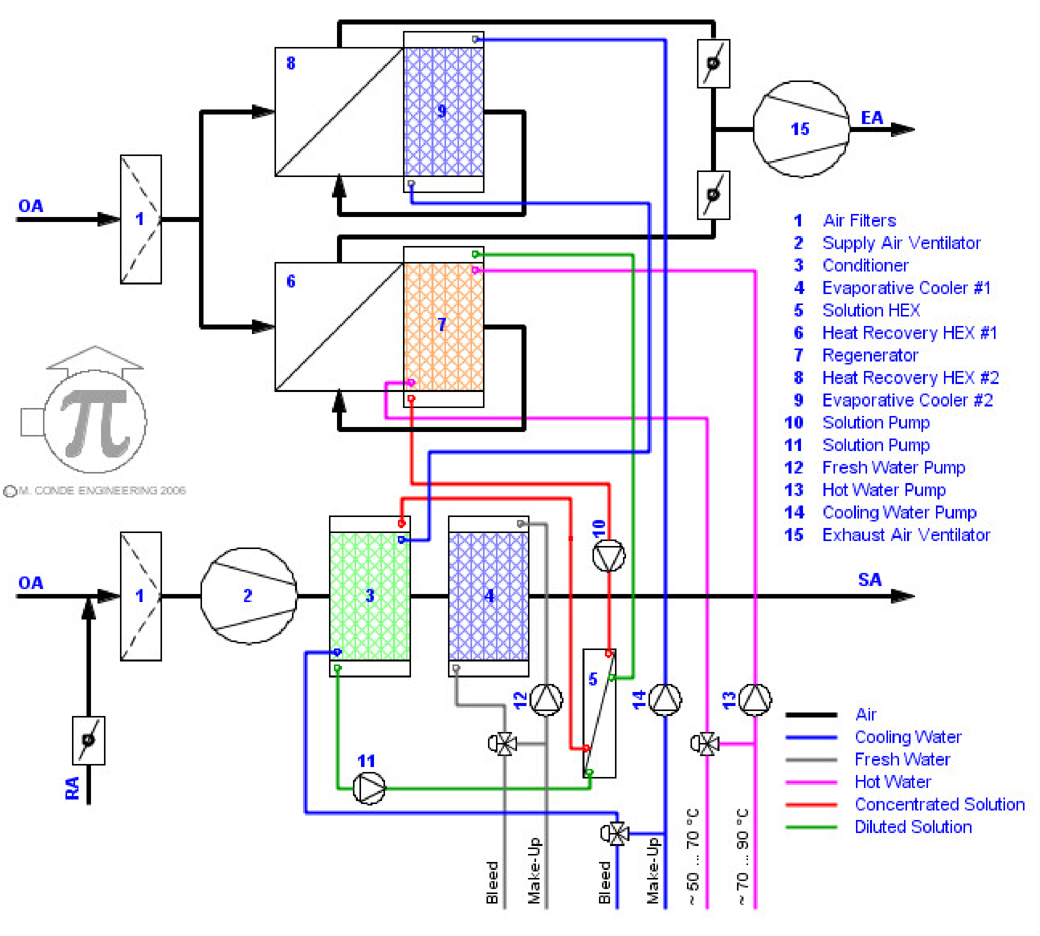

***Figure 14** - Schematic representation of an **All Air** AHU.*

In general, given the fact that one of the operating fluids is air, and that at least two heat recovery loops on the air side will be present, it is to expect that a complete AHU will be bulkier than conventional AHUs. To this we shall add the eventual presence of desiccant storage (concentrated solution). On the other hand, there is no need for a separate chiller and the eventual cooling tower. The system may be conceived both as a packaged unit, or decentralized, with various absorbers operating in conjunction with a single desorber and storage. When using desiccant storage, regeneration and air handling need not take place simultaneously. Units driven by solar energy, or other only periodically available driving energy sources, can take advantage of energy storage in the form of concentrated (and diluted) desiccant solution.

For the purpose of demonstrating the principles of operation, and of the membrane contactor technology for air conditioning, as required in this phase of the project, considering the budgetary limitations, the prototype tested is much simpler, Figure 15. The demonstration concentrated on the processes in the absorber and desorber built as membrane contactors, but no membrane contactor-based evaporative cooler was built or used. A standard (cellulose pad) direct contact evaporative cooler has been used just to test functionality. This followed from the extremely tight budget and time frame of this phase of the project. In fact, the two iterations made on testing materials and the manufacturing of the prototype contactors have demanded significantly more manpower than we have ever expected.

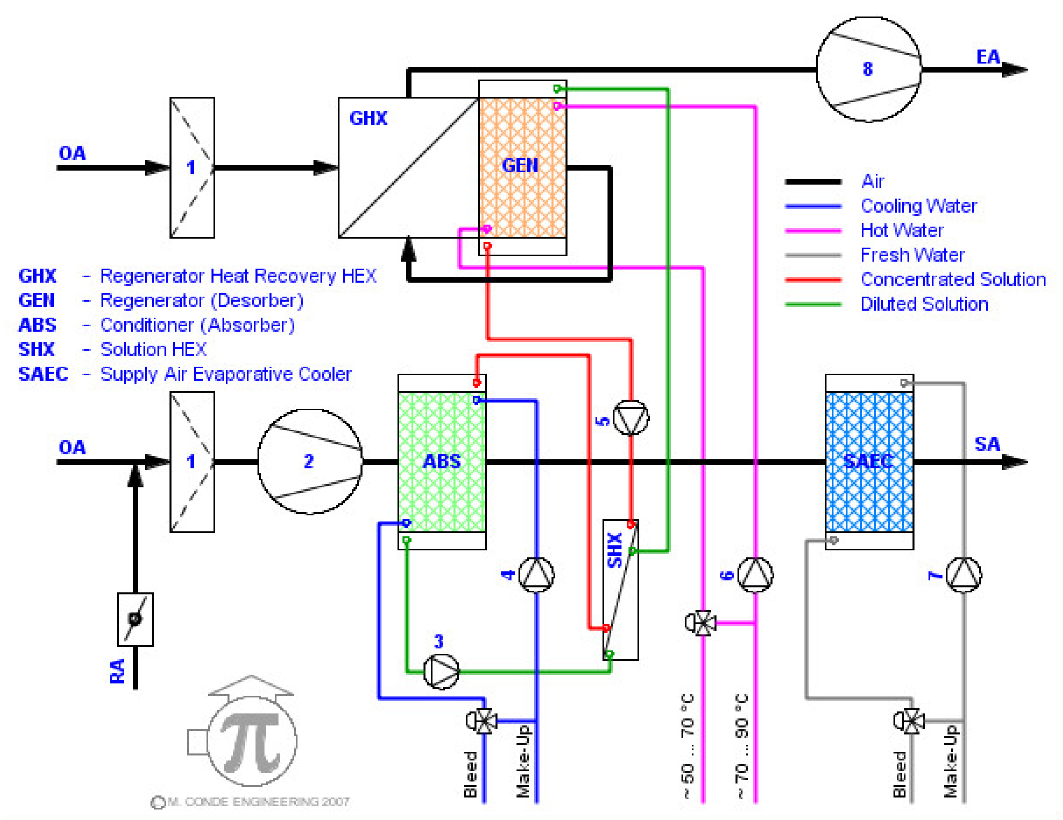

Figure 15 – Simplified schematic diagram of the tested prototype.

3. Methods

3.1 SELECTION OF MATERIALS

Well before the start of this project, an evaluation of several liquid desiccant solutions, in particular of thermodynamic and transport properties data available in the open literature, was carried out resulting in the formulation of a coherent set of equations covering the ranges of interest in the calculation and design of open absorption systems [14]. It has been found that lithium chloride solutions offer the most interesting properties for this application, despite their incompatibility with most metals. TEG (triethyleneglycol) would have posed less problems from the corrosion and crystallization risk points of view, but its much higher vapour pressure makes it unsuitable for use in air conditioners, even using membranes.

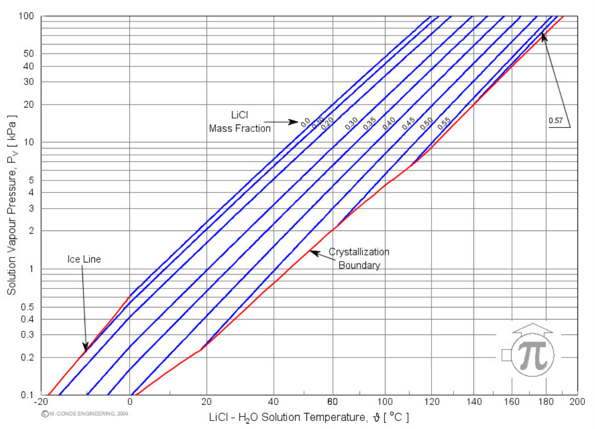

Figure 16 - *Vapour pressure of aqueous solutions of LiCl.*

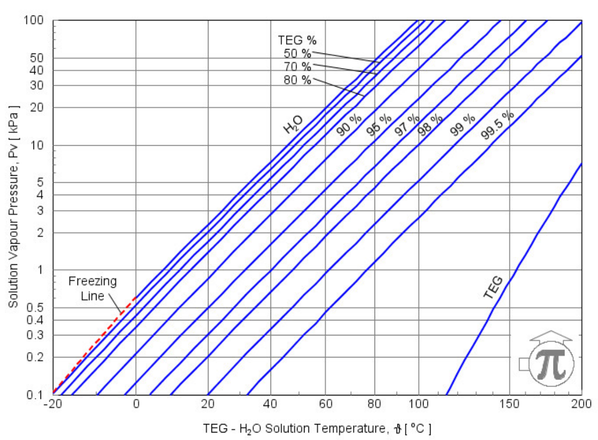

Figure 17 - *Vapour pressure of aqueous solutions of TEG.*

On the other hand, the testing carried out on the effects of the liquid desiccant solution on metallic tubes, of several different copper-nickel alloys, in the presence of oxygen, has shown that even high nickel content alloys would be significantly corroded under the expected operating conditions, Figure 18.

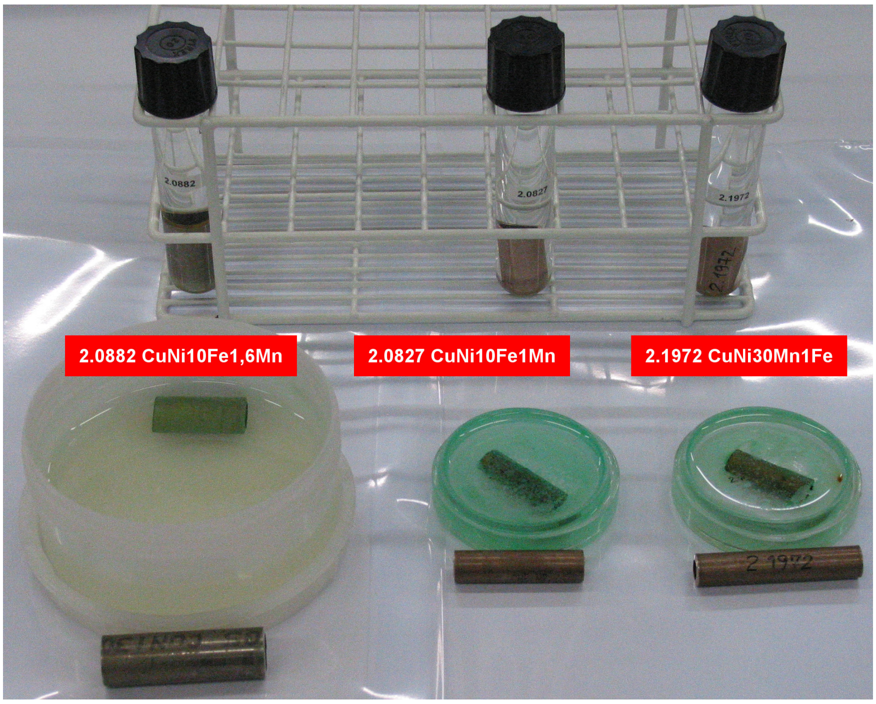

Figure 18 - Corrosion tests on 'corrosion resistant' tubes of three different copper-nickel alloys.

The testing has been carried out at room temperature, with the desiccant solution in equilibrium with the environment (22 °C, 50% RH). Note that the samples immersed in desiccant, in the absence of oxygen (closed vial), are not corroded (back row), while those exposed in Petri dishes (middle row), all show signs of corrosion, after an exposition of just about 120 hours.

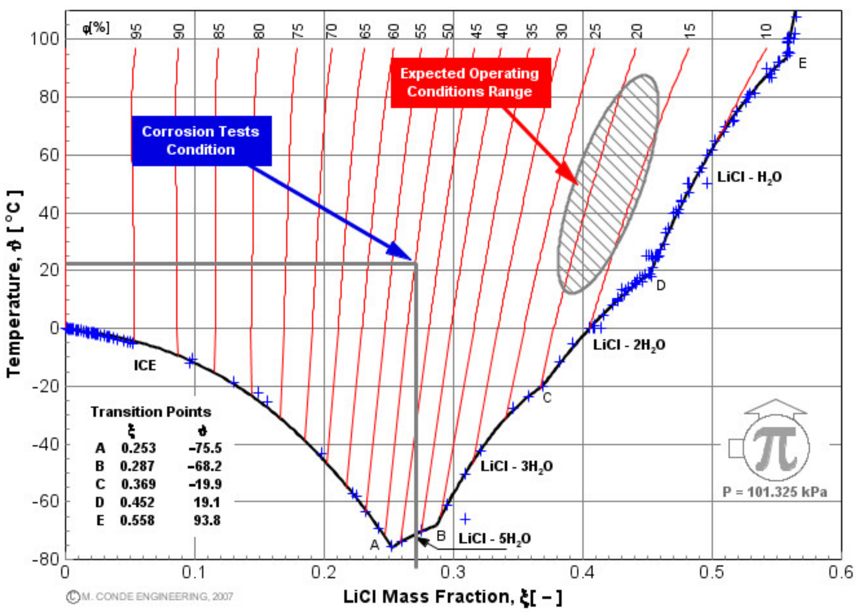

Figure 19 - Corrosion test condition and region of operation of the liquid desiccant solution.

At the normal operating conditions of the desiccant solution in the unit or prototype significantly more intensive corrosion is to be expected. Figure 19 shows the test condition, and the region of operation in a chart representing equilibrium properties between humid air and desiccant solution, at sea level atmospheric pressure (phase diagram). This result has lead to the search for other kinds of materials, that avoid the risks of corrosion, permit constructive geometries other than concentric annulus for three stream contactors, and are in general significantly cheaper and easier to work with than the high nickel content alloys. Polymers are very advantageous from this point of view, although, as we have learned later in the development, some of their other properties may make the design more difficult. The polymer materials used are readily available on the market, though with characteristics optimized for their current main application, which are not necessarily the ones needed in the construction of liquid desiccant equipment.

A number of characteristic properties of the polymeric materials used have to be carefully considered when designing this type of equipment, namely:

Glass transition temperature, T_G

Melting point temperature, T_M

Onset of melting temperature, T_O

Vicat softening temperature, T_V

Coefficient of linear thermal expansion, β

Surface energy, γ.

The polymeric materials used in the construction of the prototype are POM, (polyoxymethylene), and PP, (polypropylene). The most important properties of commercial brands of PP and POM are summarized in Table 2 below.

Table 2 - *Generic properties of commercial brands of PP and POM.*

Property	Unit	PP	POM
T_G	[°C]	~ −10 (DSC)	~ −60
T_M	[°C]	~ 165 (DSC)	~ 168
T_O	[°C]	~ 95 (DSC)	~ 110
T_V	[°C]	~ 150 (ISO 306)	~ 150
β	[K^{-1}]	6.5×10^{-5} @ −30 ÷ 0 °C 10.5×10^{-5} @ 0 ÷ 30 °C 14.5×10^{-5} @ 30 ÷ 60 °C	$6.5 \times 10^{-5} \div 14.5 \times 10^{-5}$ @ −40 °C ÷ 150 °C
γ	[$mN.m^{-1}$]	30.1 @ 20 °C	36
C_P	[$kJ.kg^{-1}.K^{-1}$]	2.0 @ 40 °C (DSC)	0.35 @ −18 ÷ 100 °C
λ	[$W.m^{-1}.K^{-1}$]	0.22 (ASTM C-518)	0.36 (ASTM C-177)
Maximum continuous use temperature	[°C]	~ 85	~ 85

T_G – Glass transition temperature

T_M – Melting point temperature

T_O – Approximate end of the rubbery plateau

T_V – Vicat softening temperature

β – Coefficient of linear expansion

γ – Surface energy

DSC (Differential Scanning Calorimetry) tests, Figure 20 [16], of a common commercial brand of PP confirm approximately the data summarized in Table 2, particularly the temperature range of the rubbery plateau. POM as a thermoplastic presents very interesting properties, particularly a much lower glass transition temperature, for a still higher melting point.

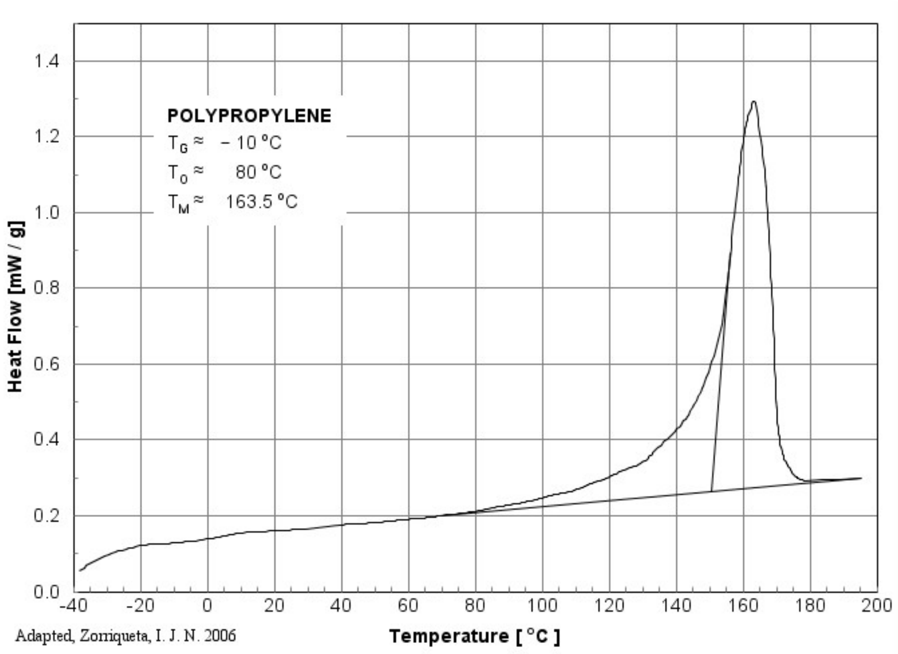

Figure 20 - *DSC thermogram of a commercial PP brand.*

The microporous membranes used in the construction of the contactor prototypes are PP membranes, which show the structure depicted in Figure 21 (left) under the Scanning Electron Microscope (SEM) with a magnification of 20 000x. The structure depicted to the right in Figure 21 is manufactured from another polymer and by a different process.

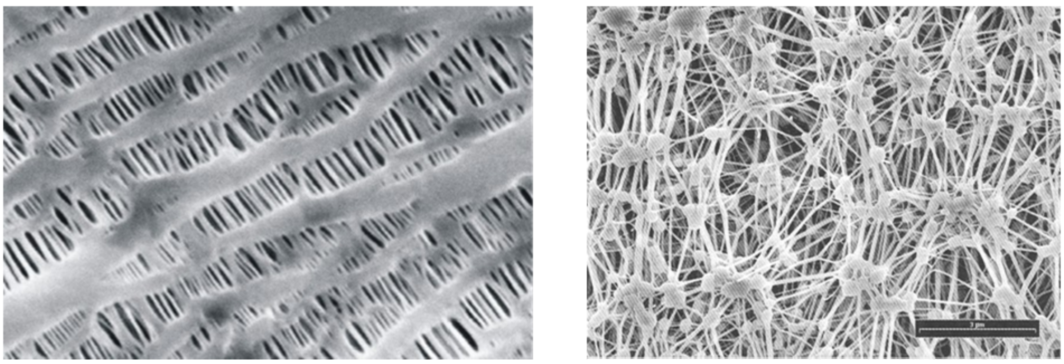

Figure 21 - *SEM pictures of microporous membranes: Left unidirectionally stretched; Right bidirectionally stretched.*

The three-dimensional structure of the membranes can be very well recognized from the SEM images in Figure 21. This three-dimensional structure is, in general, characterized by the the tortuosity parameter τ, which relates the actual average path length of the permeate to the membrane thickness. τ cannot be measured directly. It has to be determined empirically.

Another important parameter for the transport process is, naturally, the porosity of the membrane. Porosity is a three dimensional characteristic that may be estimated by means of air permeance and air resistance test according to ISO 5636-5:2003 (Gurley method). While the porosity of the membrane is an important characteristic regarding the vapour transport across the membrane, the shape and size of the pore openings at the membrane faces determine, together with material wetability, the resistance of the membrane to inundation (penetration) by liquids, which in fact determines the suitability of any given membrane for the manufacture of membrane contactors for air conditioning applications (or any other requiring contacting a liquid with a gas or vapour).

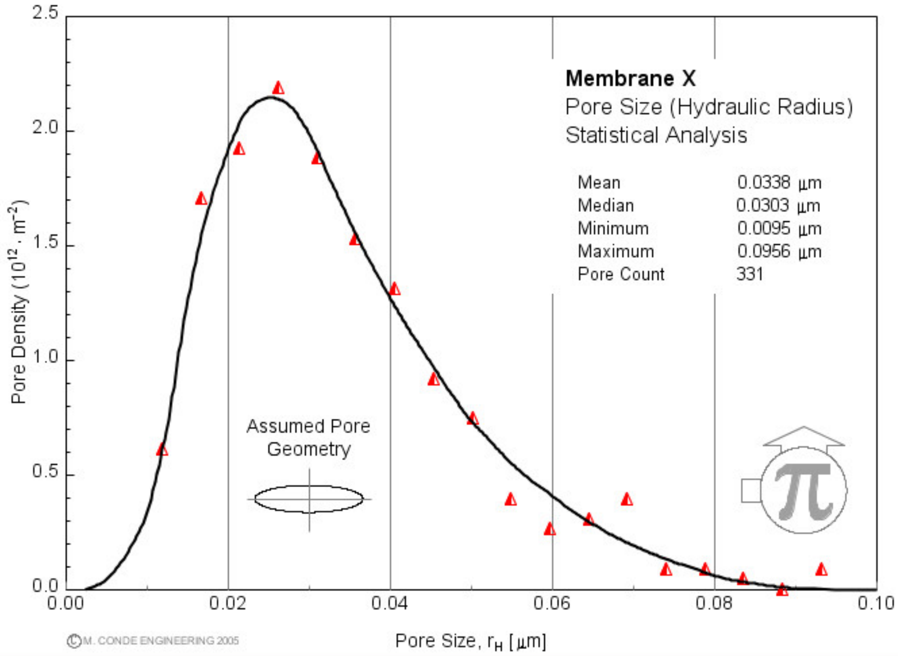

Figure 22 *- Pore entrance size distribution obtained from the analysis of SEM images.*

SEM images (provided by the manufacturer) of the membranes selected for the project were analysed to determine the pore entrance size and fibril diameter distributions. The results of these analyses confirm the average indications of the manufacturer, but reveal, on the other hand, pore entrance sizes significantly larger than the predominant values, Figure 22.

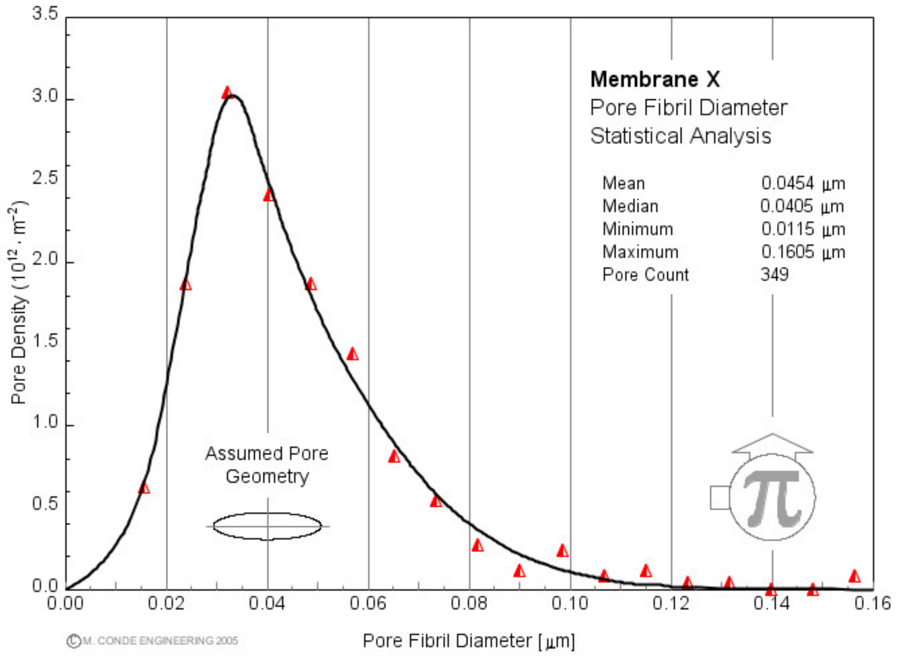

Figure 23 *- Distribution of pore fibril diameters as determined from the analysis of SEM images.*

The distribution of the diameters of the fibrils defining the 3-D structure of the pores was analysed as well from what can be seen in an SEM image. This distribution is shown graphically in Figure 23.

3.2 DESIGN OF THE EXPERIMENTAL PROTOTYPE

The design of the experimental prototype is based on calculations for one point defining a typical Summer case air conditioning problem, Table 3.

Table 3 *– 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	12.709	7.516	8.927		$g.kg_{DA}^{-1}$
Barometric Pressure	P	95.461	95.461	95.461	95.461	kPa

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

The desiccant solution is considered to operate between the mass fractions of 0.40 and 0.42. An estimated total cooling capacity of 1.0 kW at these conditions was assumed.

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

Calculation of the air process, with assumptions regarding driving force potentials and component effectivenesses (heat and mass transfer);

Thermal design of the individual components, based on the results of step 1;

Overal equipment thermal design.

Although this process may be iterated upon, a simulation program for this purpose has not been created in this first phase of the development. Work on this simulation program shall be part of the next phase of the project. Calculations are currently being done with a *MathCad*® calculation sheet, involving the calculation of the thermophysical properties of humid air, pure water and desiccant solution, besides the design methods of the individual components.

The design calculations have been done for a complete *All air AHU,* as illustrated in Figure 14. A simplified configuration, as illustrated in Figure 15, has been used as prototype for the demonstration in the laboratory. For the design calculations all components have been considered as stacks of elements built out of twin-wall PP structured plates, which is the basic material used in the development of the prototype. The design method for the components, after air process calculations, has been to choose a certain face velocity and an inlet face form factor, corrected for an integral number of elements (width defined by a multiple of the width of a component element). The actual calculations were then carried out for one single element of contactor or component, its length being defined by the actual contacting area required for the element. There has been no optimization done on the calculations, although an iterative calculation procedure is required for most components.

The calculations yielded the composition and dimensions for the experimental setup components shown in Table 4.

Table 4 - Summary of the component dimensions of the experimental setup.

Component	# Elements	Height [mm]	Length [mm]	Width [mm]
ABS – Absorber	29	440.0	520.0	490.1
GEN – Desorber	34	440.0	520.0	574.6
GHX – Desorber Heat Exchanger	85	390.0	350.0	612.0
SAEC – SA Evaporative Cooler	34	390.0	200.0	493.0

3.3 DESIGN AND MANUFACTURING OF THE COMPONENTS

The membrane contactors are built as stacks of equal *contactor elements,* themselves fully functional membrane contactors. The assembling of the membrane contactor elements was made by adhesive bonding. Each contactor element consists of five twin-wall structured plates, offering two solution-air interfaces through one membrane film at each interface, with a water-cooled plate in the center, Figure 24.

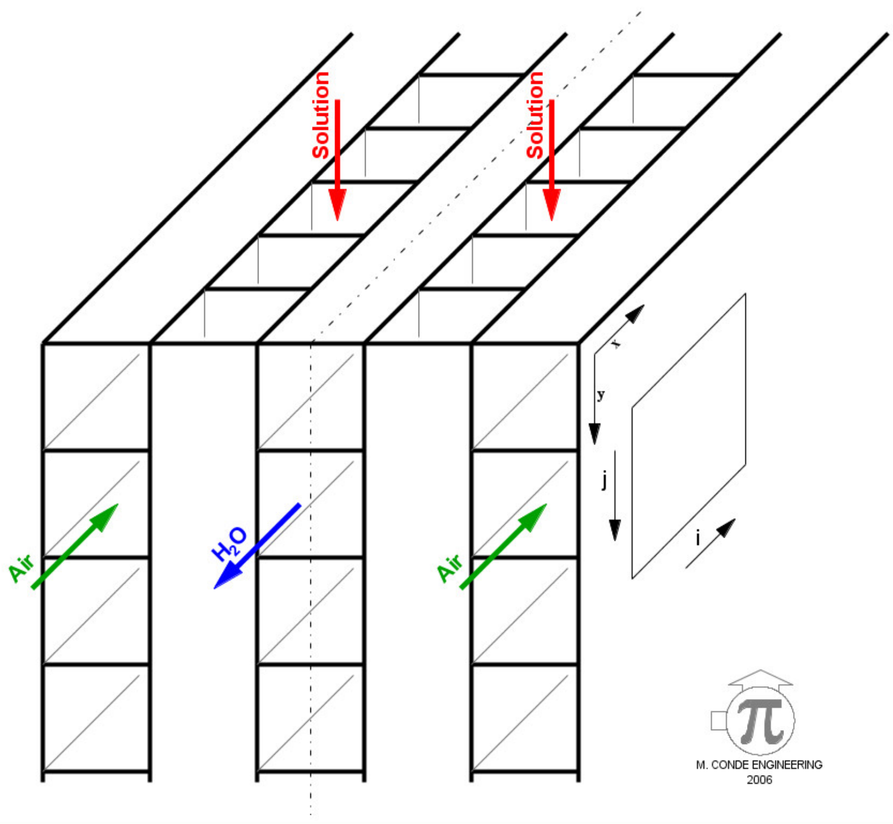

***Figure 24** – Streams in a 3 stream membrane contactor element.*

The selection of the most appropriate adhesive has been an involved procedure, particularly due to the low surface energy of the polymers used. After testing adhesive samples of various manufacturers, the membrane contactors elements were bonded using 3M products[b]. The fact that the bonded components are not subjected to strong pulling forces reduces the risks of peeling. On the other hand, the coefficient of linear thermal expansion of the polymers used in the manufacture of the components is up to twenty times larger than that of construction steel. This

[b] The cooperation of the technical department of 3M (Schweiz) AG is gratefully acknowledged.

means that components subjected to large temperature variations during operation require particular attention, and assembly methods that take this fact into account. The membrane contactors are kept together mechanically by lateral steel plates. Due to the larger temperature variation, the desorber requires higher degrees of freedom than the absorber, Figure 25.

This modular method of construction has a number of advantages:

— Within a given capacity range, membrane contactors of different capacities may be assembled using the same membrane contactor element;

— Theoretically at least, it should be possible to repair a membrane contactor by replacing failed individual contactor elements;

— Manufacturing of both the contactor elements and of the contactor itself can be easily automated.

Figure 25 - *Assembled membrane contactors: Left the absorber, right the desorber (Photos Empa).*

3.4 ASSEMBLY OF THE EXPERIMENTAL LABORATORY SETUP

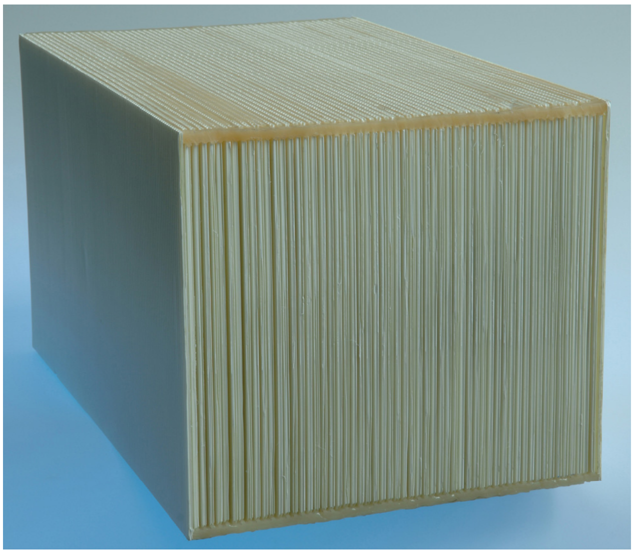

Figure 26 - *The desorber heat recovery heat exchanger, GHX (Photo Empa).*

The components of the experimental laboratory setup were designed following the procedure described above: An absorber (ABS), a desorber (GEN), and an evaporative cooler (SAEC) were designed as membrane contactors. The desorber heat recovery heat exchanger (GHX) was supplied by one of the industrial partners accompanying the project, following specifications resulting from the setup calculations. The GHX, shown in Figure 26, is a cross flow heat exchanger manufactured out of PP twin-wall structured plates.

Soon, the limitations of the financial means available imposed one first revision of this already stripped down configuration of the AHU as it was first intended: The evaporative cooler, SAEC, had to be replaced by some construction other than a membrane contactor. A cellulose pad has been used instead, Figure 27.

A second revision was further necessary, on the same grounds, after testing for tightness, at room temperature, all the manufactured membrane contactor elements. About 50% of them were leaky and no financial means were available to undertake their replacement. It is necessary to recall that the constructive solution adopted is already a second iteration on the geometry and materials of the contactors.

The experimental setup was downsized accordingly, with the absorber sized down to 14 elements, and the desorber sized down to 17 elements (approximately 50 % of the design capacity). The setup was assembled inside a climatic chamber at EMPA, as depicted in Figure 28. The absorber cooling water and the desiccant solution preparation and supply systems are not shown in the picture. The various components are interconnected by adaptors manufactured out of clear acrylic plate in order to allow for inspection and the observation of component behaviour.

Figure 27 *– Details of a structured cellulose pad as used for the SAEC (Munters Europe AB).*

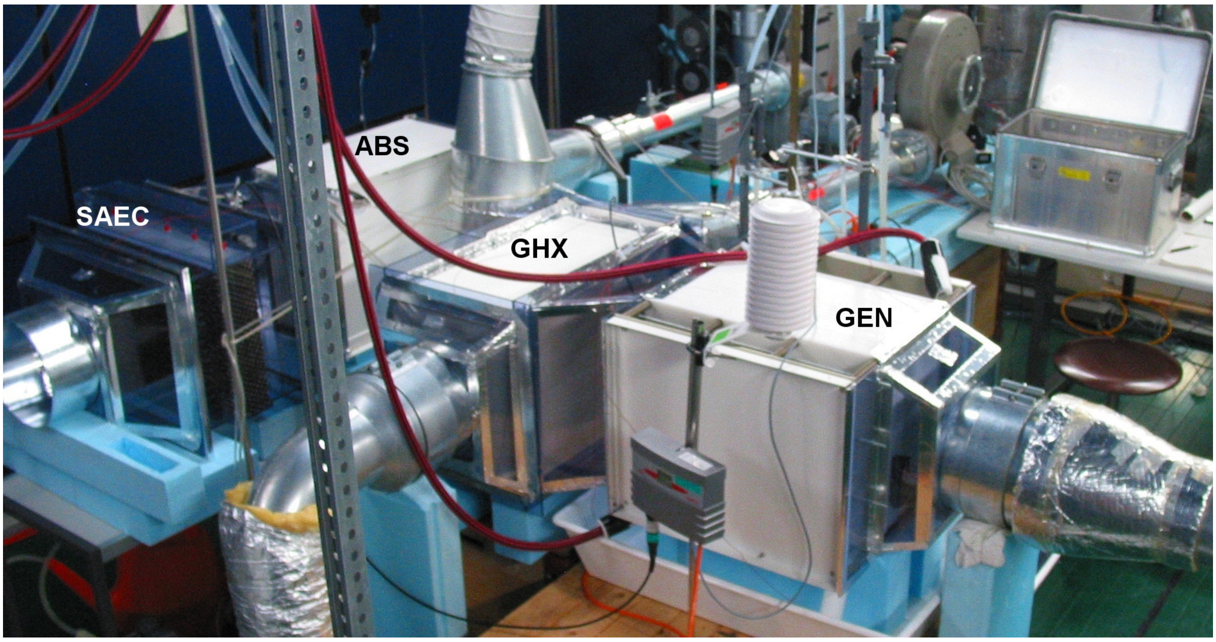

Figure 28 *- View of the experimental setup as assembled in the climatic chamber at EMPA (Photo Empa).*

The instrumentation is only partially visible in the picture of Figure 27. It is schematically shown in the *P & I diagram* of Figure 29, which follows the actual layout in the climatic chamber.

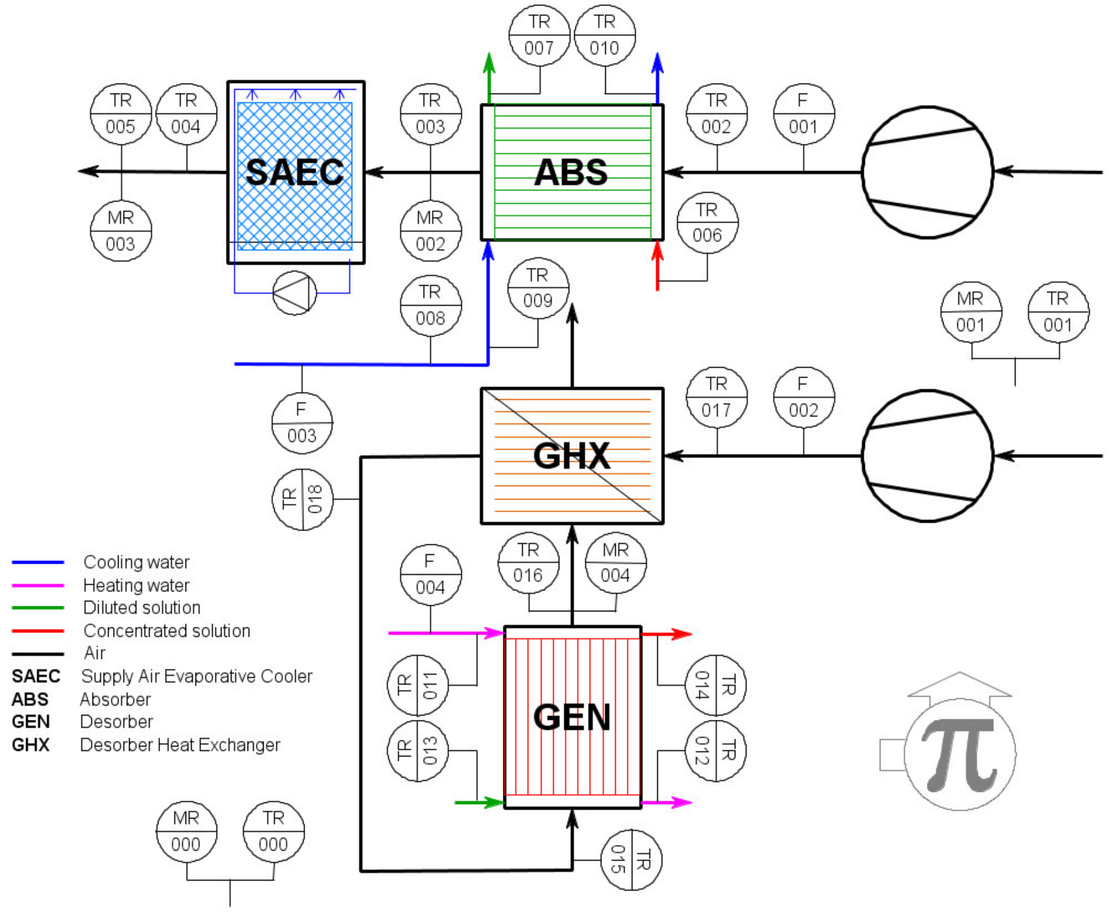

Figure 29 - *P & I diagram of the experimental setup.*

Table A.1 in the Appendix gives details of the types and precision of the instruments used. During testing the temperature and the relative humidity sensors were scanned once per minute and the values were registered by a computer.

4. Results

4.1 DESIGN METHODS

Design methods were established for all components required in the construction of two types of air handling units, one type generating cold, dry air ***(All-Air AHU)***, and the other cold, dry air and cold water ***(Air+Water AHU).*** The models and calculation procedures are used in a *(MathCad®)* calculation sheet. The results of the calculations were used to draft the construction drawings of the various components.

4.2 CONSTRUCTION OF THE COMPONENTS

The manufacture and construction of the components of the experimental prototype produced some important results, in particular regarding solutions for a future commercial product. As already mentioned above, the elements of membrane contactors were assembled by adhesive bonding the various parts. Some of these parts were manufactured by milling away sections of twin-wall structured plates under frozen conditions, Figure 30. This process, although elegant in its conception, is too expensive (and time consuming) for use in the manufacture of a commercial product.

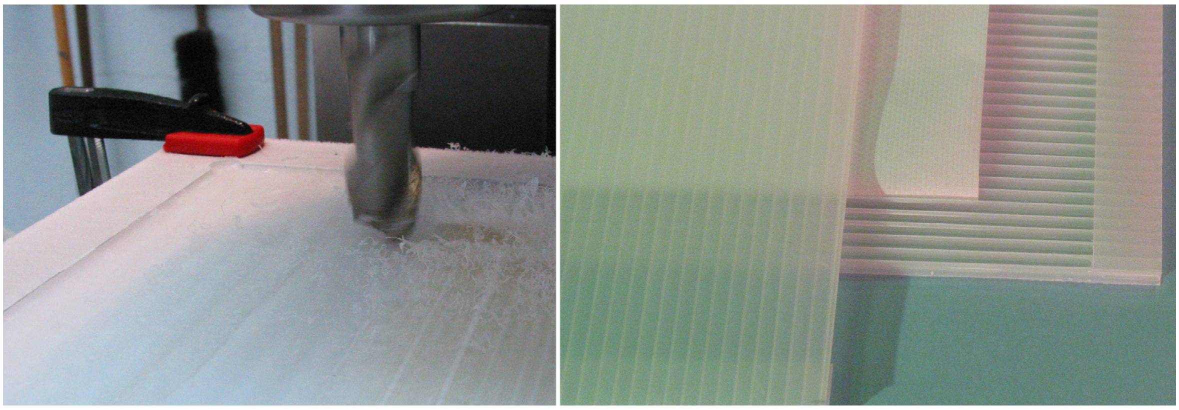

Figure 30 - *Processing twin-wall structured plates: Left, milling the top wall; Right, plates after processing (Photos Empa).*

This constructive solution required various kinds of adhesives, depending on the surface to be bonded. All the adhesives used were supposed to be absolutely compatible with the polymers they should bond, and testing with small samples did not contracdict that assumption. However, the largest surface to be bonded showed a very different behaviour. After applying the adhesive, in spray form, and assembling all the parts of an element of contactor this would remain stable for about a week, but showed significative swelling after this period. Since this concerned the central plate of the contactor, all distributor parts for desiccant and water were displaced, in some cases so much so that the connections and the distribution channels were leaky. After an extremely time intensive repair effort, about fifty percent of the manufactured contactors could be considered tight, after testing under pressure, and ready for the assembling of the individual contactors. The transfer area absorber is ~4.64 m^2, for an area density of ~117.65 m^2/m^3. For the desorber these values are ~5.63 m^2 and ~142.86 m^2/m^3, respectively.

Unfortunately, this would not be the last surprise resulting from the adhesive bonding construction. As the experimental setup was assembled in place and the first test run started, the desorber was heated with hot water at a temperature that would be running between 60 °C and 80 °C. The adhesive bonded water distribution channels would not stand it, and leaked abundantly. The regeneration loop of the experimental setup had to be shutdown. From here on the experiments were concentrated upon the absorber loop, which behaved as expected. One could naturally argue about the adopted bonding methods as was the case during design, construction and pressure testing of the contactor elements. There were however no financial means to test or even seek alternative construction methods, such as welding.

4.3 TESTING CONDITIONS OF THE EXPERIMENTAL SETUP

The testing conditions for the experimental evaluation of the prototype are defined on the basis of 'outside air conditions', that is, air conditions at the inlet to the absorber. These conditions were created inside the climatic chamber used for the experiments at EMPA. Although the specification called for constant relative humidity (45 %) at inlet, the climatic chamber could not stabilize this variable, as illustrated in Figure 31. The inlet temperature of the cooling water was specified as the wet bulb temperature of the inlet air, actually the limiting case of using a cooling tower, or other evaporative cooling device, to produce the cooling water, as conceived in the design of a complete ***All-Air AHU.*** The actual cooling water inlet temperature deviates only slightly from this ideal condition (in parentheses in Table 5).

The actual testing conditions are given in Table 5.

Table 5 - *Testing conditions of the experimental setup.*

Air inlet conditions			Cooling water inlet
Temperature °C	Relative humidity %	Water vapour content g/kg_{DA}	Temperature °C
34.1	43.0	15.27	24.6 (23.7)
32.7	51.4	16.96	23.5 (24.4)
30.5	46.9	13.59	21.0 (21.7)
27.5	45.2	10.96	18.6 (18.9)
26.0	49.0	10.88	17.6 (18.4)
24.5	39.3	7.94	15.9 (15.5)

The testing conditions of the desorber loop (GEN + GHX), are set by the ‚outside air' conditions on one hand, and by the inlet temperature of the GEN heating water, on the other. The GEN heating water inlet temperature shall vary between 60 °C and 80 °C, and was set to 80 °C on the first test run. The evaporative cooler (SAEC) was left to self regulation in the experimental tests. The water temperature would converge to approximately the wet-bulb temperature of the air leaving the absorber, but this was not monitored in the experiments.

4.4 EXPERIMENTAL MEASUREMENTS

The analysis of the measurements shall concentrate on the absorber loop, since, as reported above, it was not possible to operate the desorber.

The following values were set for the experiments, and kept sensibly constant all along:

- Cooling water flow rate 140 litres/hour at a supply pressure of 0.3 bar;
- Desiccant solution flow rate ~35 litre/hour at a supply pressure of 190 mmca, and an inlet LiCl mass fraction of 0.405;
- Air flow rate ~143 m^3/hour.

One testing session, covering a total of about seven (7) hours, was carried out with all measured variables recorded every minute. Figure 31 depicts the registered values of the pertinent sensors during this test run.

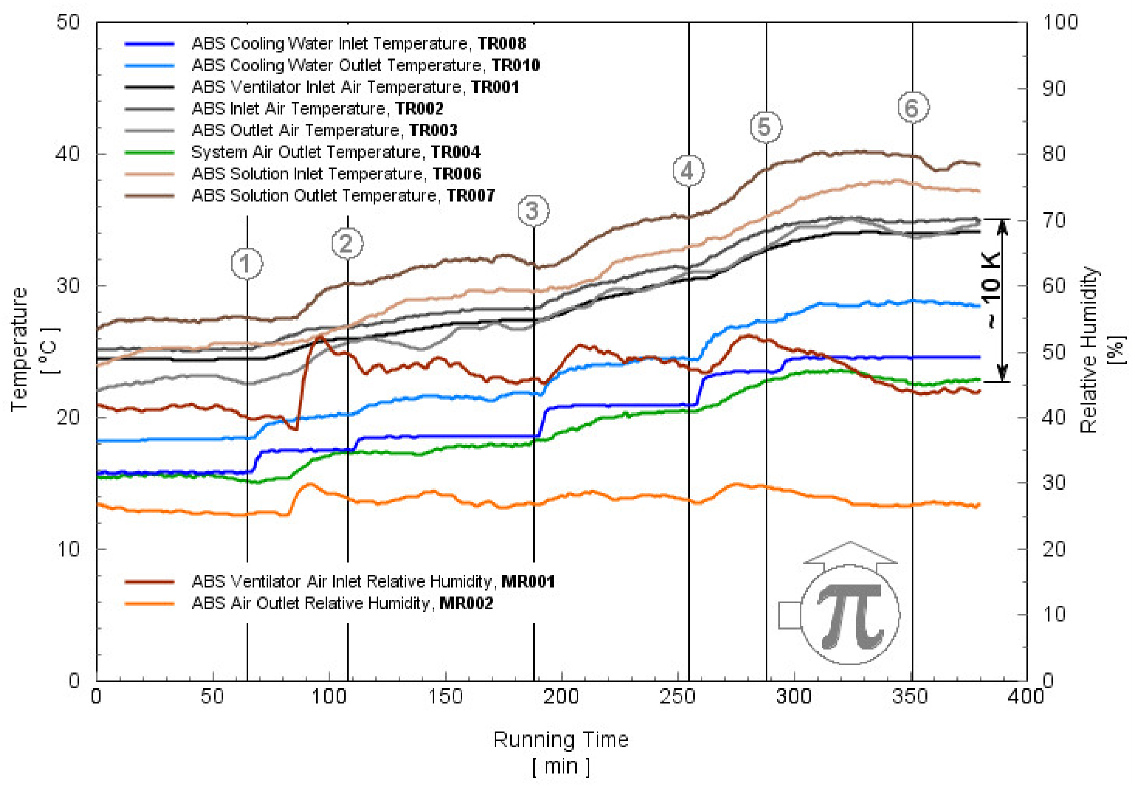

Figure 31 - *Time evolution of the measured variables on the absorber loop of the experimental setup. Numbers identify points retained for analysis.*

The first impression from Figure 31 is the extreme variability of the relative humidity of the air at the inlet to the absorber. This variability is also at the origin of the behaviour of the absorber outlet air temperature, and the desiccant solution outlet temperature. On the other hand, the dampenning effect of the absorber upon these humidity variations is readily apparent. Under these conditions, identifying a stable operating point for analysis has been difficult. The criterion used was to select operating points near the end of each step of the most stable variable (black lines), in this case the cooling water temperature. This does not mean the selected point to be a steady-state point, but the nearest condition to the desired steady state.

The most interesting observation is, perhaps, that the absorber loop provided a constant cooling of the air of about 10 K, including fan energy effects, at all conditions.

4.5 ANALYSIS OF THE MEASUREMENTS

The first analysis made on the experimental results was done for coherence of the measured values, namely through an energy balance of the absorber.

This balance is described for a ‚black box' as represented in Figure 32 by the equation:

$$\dot{M}_{da}\left(h_{a,o}-h_{a,i}\right)+\dot{M}_{s,o}\,Cp_{s,o}\,T_{s,o}-\dot{M}_{s,i}\,Cp_{s,i}\,T_{s,i}+\dot{M}_{w}\left(Cp_{w,o}\,T_{w,o}-Cp_{w,i}\,T_{w,i}\right)=0$$

Where the variation of the desiccant solution flow rate is given by the dehydration rate of the air:

$$\dot{M}_{s,o}-\dot{M}_{s,i}=\dot{M}_{da}\,\Delta\omega$$

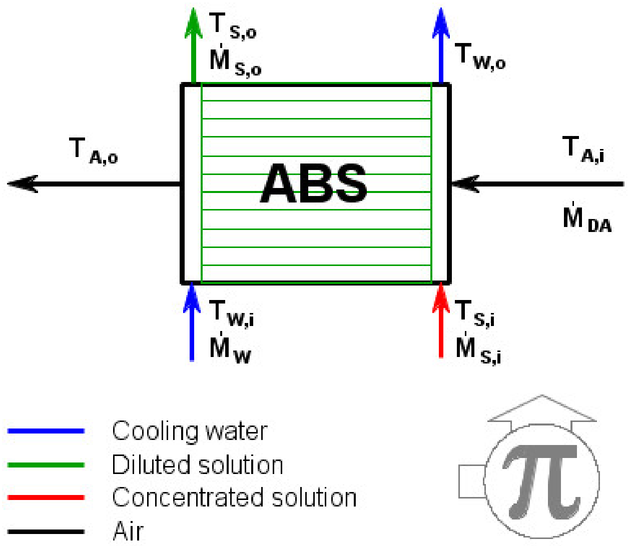

***Figure 32 -** Schematic of the absorber.*

The results of this analysis show that the calculations from the measurements are within ±13% of the balanced capacity[c] of the absorber, Figure 33.

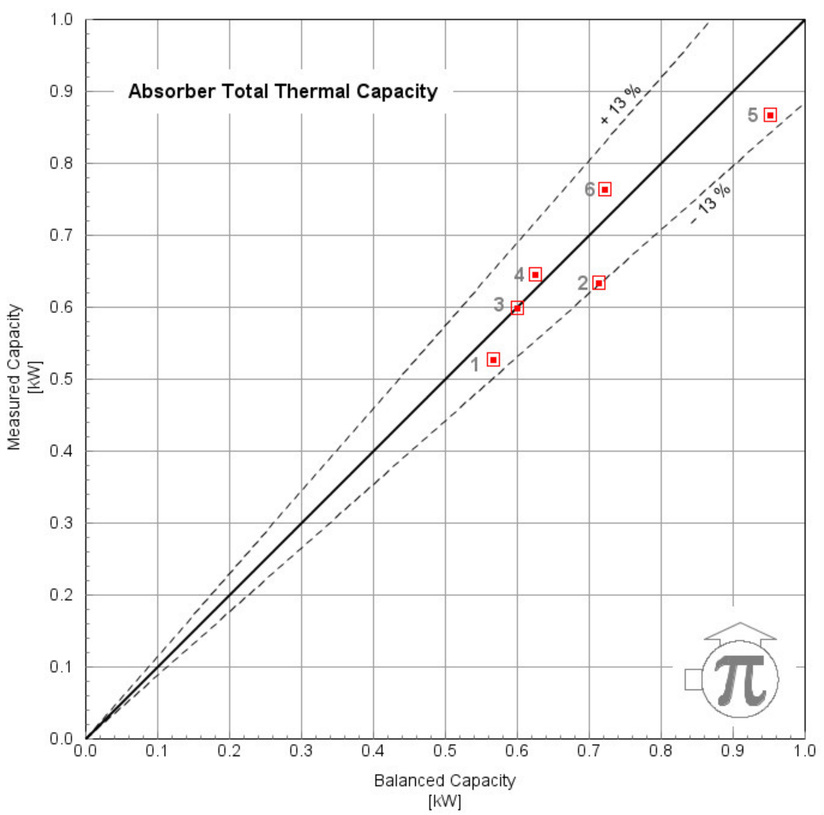

***Figure 33 -** Comparison of the measured and balanced capacities of the absorber. The numbers by the data points refer to Figure 45.*

[c] The balanced capacity of the absorber is determined from the measurements by adding a Δ of capacity determined from the energy balance equation.

The comparison of the graph of Figure 33 with that of Figure 31 shows that the largest deviations, at points 2 and 5, occur for the two shortest runs at a given setting. Although there are strong variations of the inlet relative humidity within these runs, these deviations are an indication of the slow response of the system to setting variations.

A measure of the performance of the absorber is given, in general, by the *‚dehydration effectiveness'* ε_{ω} defined as the ratio of the actual dehydration to the maximum possible dehydration of the air (infinitely large absorber):

$$\varepsilon_{\omega} = \frac{\omega_i - \omega_o}{\omega_i - \omega_{eq}}$$

Where ω_{eq} is the water vapour content of the humid air in equilibrium with the desiccant solution at the inlet to the absorber. Figure 34 shows the equilibrium states for the six points analysed here in a phase diagram of the desiccant solution – humid air system.

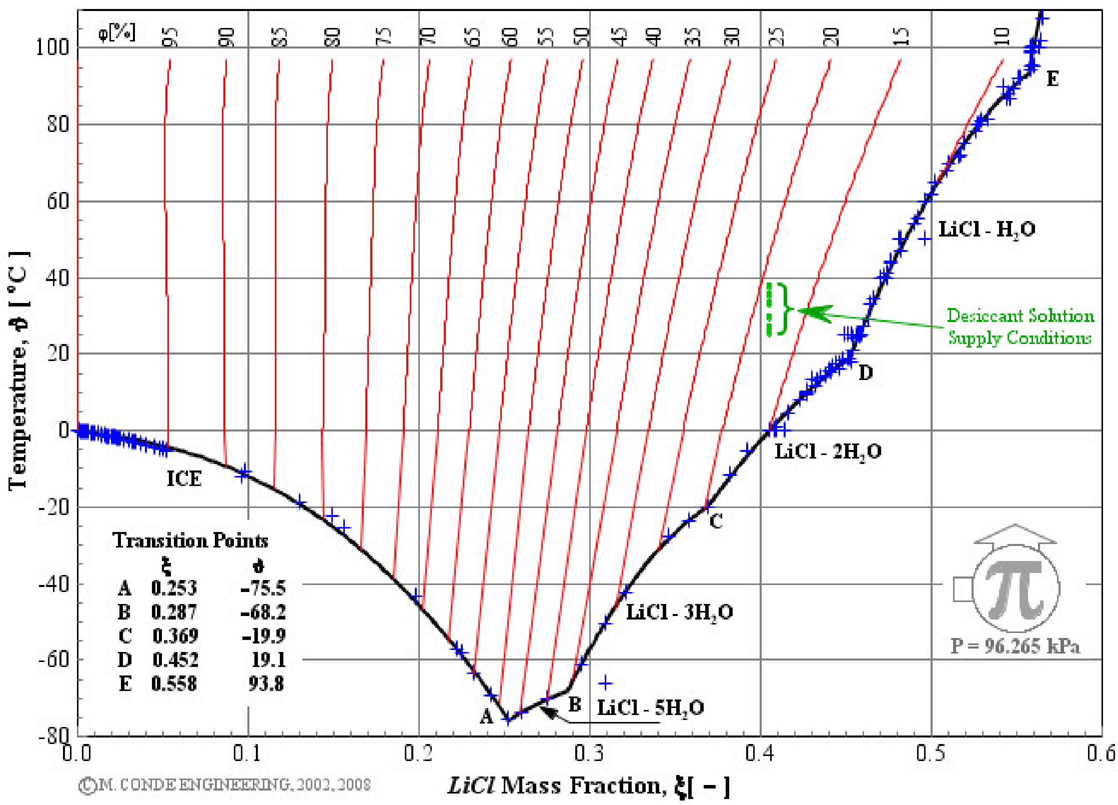

Figure 34 *- Equilibrium conditions of the humid air with the desiccant solution at inlet to the absorber.*

The values obtained in the set of measurements analysed for the *‚dehydration effectiveness'* ε_{ω}, as well as other important results are summarized in Table 6.

Table 6 - Summary of absorber performance results.

Magnitude	**Average**	**Range**	**Unit**
Dehydration effectiveness	0.79	0.74 ... 0.88	[-]
Total thermal power	671.5	526.5 ... 865.5	W
Power density	144.83	113.54 ... 186.67	W/m^2
Mass transfer density	0.186	0.124 ... 0.246	$kg/h.m^2$
Global mass transfer coefficient	6.78	6.37 ... 7.55	mm/s
Air to solution mass flow ratio	3.468	3.414 ... 3.527	[-]

5. Discussion

In this project we set about to develop a prototype of air handling unit (AHU) with the aim to reduce energy consumption in the process of air conditioning on one hand, and to be able to drive the whole process with thermal energy in temperature range between 50 °C and 90 °C. This level of temperatures can be provided by conventional flat plate solar collectors, by effluents of many industrial processes, by district heating networks, by co-generation systems, etc.

This approach to conditioning the air has been attempted in many instances since the early years of the twentieth century. Sometimes the designs would be poor, sometimes the materials unsuitable, and mostly concurrent technologies more successful on the market. Nevertheless, air conditioning based on open absorption has remained a promising principle, being applied there where conventional approaches would not do, e.g. fine control of air humidity. There is however no fundamental reason for this to remain so, as the results of this project, and those of other recent developments show.

While the materials used, particularly in view of corrosion problems, mostly decide the question of capital costs, running costs are essentially dependent upon energy efficiency, and in minor part upon maintenance costs. The use of cheap, readily available materials, such as the polymeric ones used in this project, contributes to tackle the capital costs while solving the corrosion problems. The manufacturing costs contribution requires careful attention: The manufacturing costs are typically high in the first prototypes, but can usually be systematically reduced as the development continues.

In order to situate the progress made in the project, the results obtained for the absorber shall be discussed by comparing them to six other variants of contactor technology and using other desiccants, through experimental results reported in the literature.

The most common contactor technology is that used in the chemical industry, the contacting tower. Contacting towers are built as spray, random packing (Raschig rings, Berl saddles, Intalox saddles, etc.) and structured packing towers (cellulose pads, etc.).

Representative of the conventional contacting tower, are the results reported by Lazzarin et al. [17]. The random packings in the contacting tower were 25 mm Pall Rings, and the tower was 725 mm high, with a diameter of 400 mm, constructed in stainless steel. The desiccant used in this plant was an aqueous solution of LiBr, and the experiments were carried out at inlet salt mass fractions ranging from 0.53 to 0.56. Figure 35 shows a picture and a schematic of the experimental plant, built at Padua University, in Italy. The air flow rate was set at 220 m^3/h, with the temperature varying between 23.6 °C and 35.4 °C, while the humidity ratio varied between 10.4 g/kg_{DA} and 18.7 g/kg_{DA}. The desiccant temperature at inlet varied between 16.1 °C and 34.1 °C.

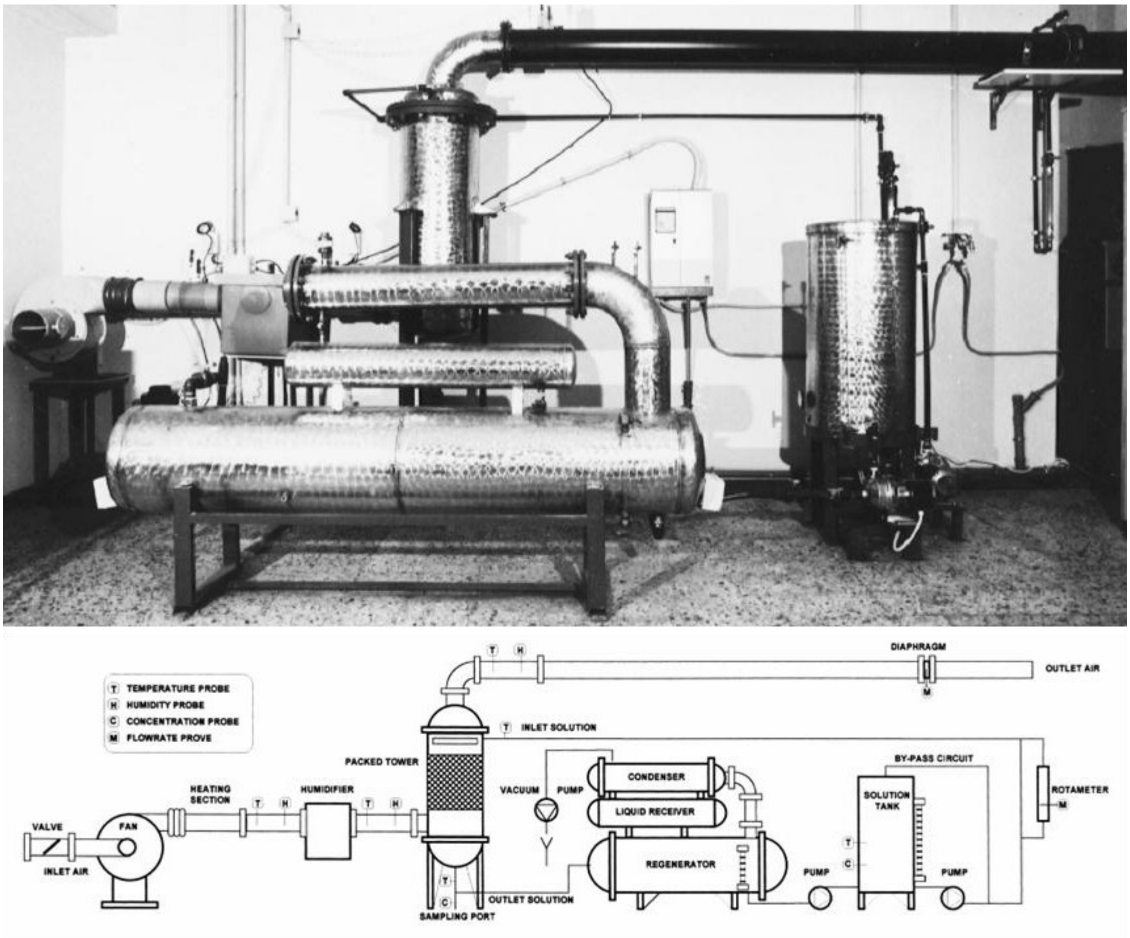

Figure 35 - *Picture and schematic of the desiccant cooling plant reported by Lazzarin et al. (2000). Adapted from [17].*

The second set of experimental data considered for comparison, refers to a system that is already on the market, and that is described in Annex 1, Figure A1.12. The data considered here were obtained during the development of the absorber of that system [18]. Figure 36 shows details of the absorber (right) and operating concept (left).

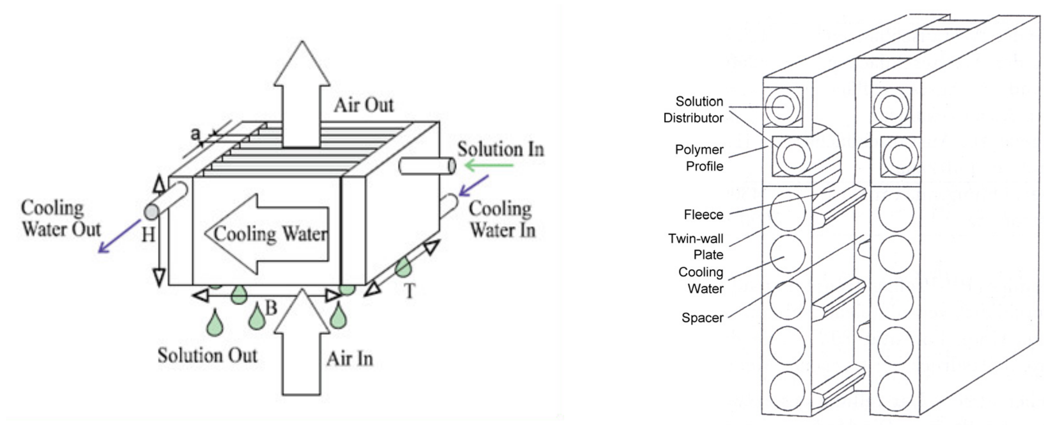

Figure 36 - *Details of the absorber of the L-DCS system. Adapted from [18].*

The *L-DCS* considered in this second data set runs on aqueous LiCl as desiccant, with an inlet salt mass fraction of 0.40 in the experiments considered. The air mass flow rate of 1100 kg/h, the humidity ratio of 14.5 g/kg$_{DA}$, and an inlet temperature of 24 °C, were held approximately constant during the measurements. The mass flow rate of the cooling water was ~3700 kg/h also at approximately 24 °C at inlet. The ratio of the flow rates between the desiccant and air is very low in these experiments, implying a large variation of the desiccant solution concentration.

The main dimensions of this absorber are:

Description	Value	Units
Width of the transfer surface	1000	mm
Length of the transfer surface	960	mm
Width of the channels	8	mm
Total area of the transfer surface	56	m^2
Net area of the transfer surface	41.7	m^2
Total number of channels	29	-

The third set of experimental data [19] are from the monitoring of a *L-DCS* system installed in jazz club in Munich - Germany, combining desiccant solution storage with indirect evaporative cooling to deliver cold water to the terminal units (fan coils). Basic geometry of the absorber contactor is the same as that described above. The absorber was designed to handle an air flow rate of 4000 m3/h producing cold water at 15 °C to dissipate a cooling load of 16 kW.

The fourth set of experimental data includes the data reported by Vestrelli [20] in 2006 for a membrane contactor-based air dehumidifier (see Figure A1.17). The experiments were carried out under atypical air conditioning conditions, serving only to study dehumidification performance. The desiccant was aqueous solution of LiCl entering the contactor at 21 °C and 0.44 mass fraction of salt. The inlet conditions of the air were 18 °C and 36 % relative humidity. The flow rate of solution was held constant at 400 kg/h, while that of the air varied between 200 and 540 m^3/h. The actual geometry of the absorber is not reported in detail.

The fifth set of data results from work undertaken at Essen University [21]. In its conception it is a system very similar to the *L-DCS* system considered above. Data are reported for two different desiccants, but for compactness only a set of three runs using aqueous calcium chloride $CaCl_2$ – H_2O shall be considered here. As in the *L-DCS* case, a rather low solution to air flow rate ratio is considered. The inlet mass fraction of salt was held constant at 0.40. The experimental absorber consisted of five elements with four air channels, as depicted on the right in Figure 37. Desiccant and air flowed in counter current, while the cooling water flowed in cross-co-current with the air. The data depicted for this case in Figure 39, were recalculated from the original data to harmonize the definition of dehydration effectiveness, which the author in [21] defined differently. Figure 37 shows a schematic of the test plant on the left, and a functional view of the absorber in this system on the right.

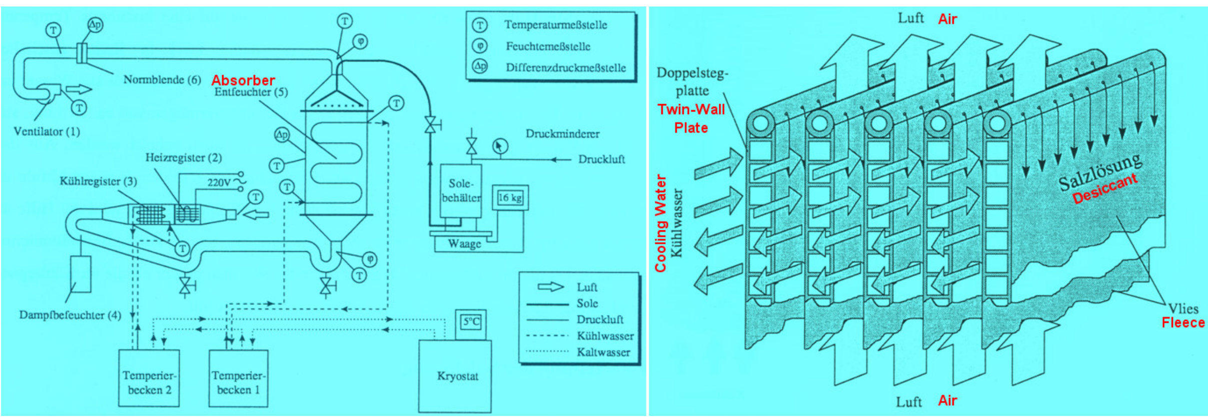

Figure 37 - *Schematic of the test plant (left) and functional view of the absorber of the system. Adapted from [21].*

The sixth set of data is from a system using an aqueous TEG (Triethylene Glycol) solution as desiccant. This is work inspired by the suggestion of Löf [24] that aqueous TEG might be an adequate desiccant for air conditioning applications. In fact, TEG has a much too high vapour pressure for this purpose. Nevertheless, it is interesting to include these results in this comparison. The test plant used for this study [25], [26], is depicted schematically in Figure 38.

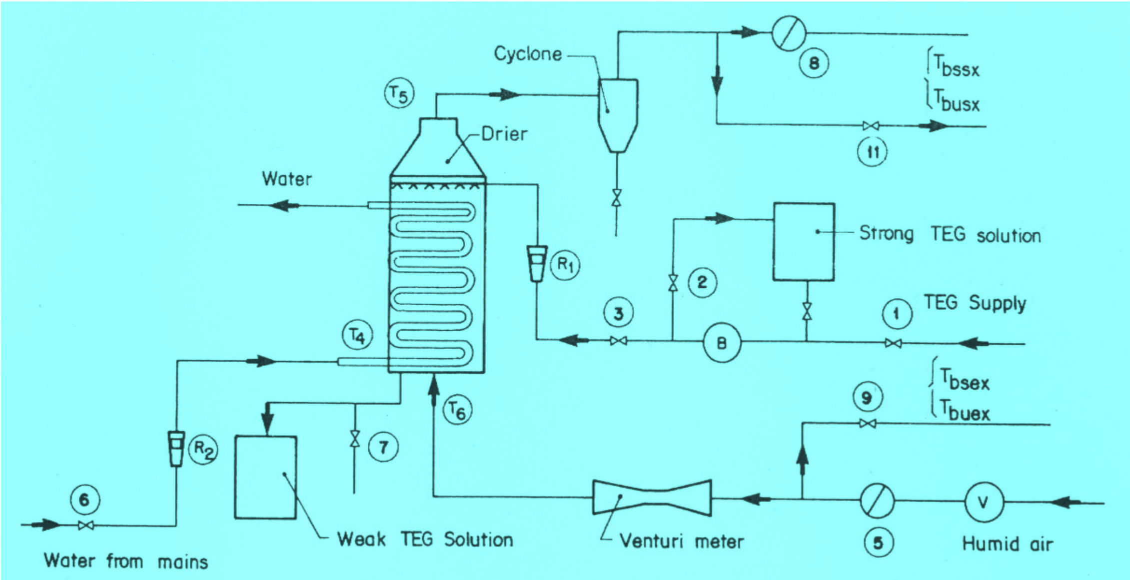

Figure 38 *- Schematic of the test rig used by Azevedo [25]. Adapted from [26].*

The absorber is built as a vertical tube bundle. Cooling water is circulated inside the tubes in cross co-current with air, while the desiccant solution is sprayed on their top. Air is supplied at the bottom and flows in counter current to the desiccant solution.

Figure 39 compares graphically the *dehydration effectiveness* from these five data sets with the absorber results of this project.

As can be appreciated from Figure 39, if the *dehydration effectiveness* is taken as the best indication of absorber performance, the results obtained for the absorber developed in the project are excellent. They are due to a couple of essential features of the absorber developed in the project:

Warranted full surface contact of the air with the desiccant at all conditions;

Cooling water flowing in counter flow to the air;

Very well defined distribution of the air, the desiccant solution and of the cooling water;

Uniform micro-rugosity on the membrane side to the desiccant solution.

In fact the observations reported by Kessling [18] and Laevemann et al. [19] during their experiments, indicate that large patches of the fleece, used to improve desiccant to air contact, were dry, even when using special hydrophylizing techniques to improve wetability.

From random packing contactors it is known that full wetting can only be ensured in a narrow range of liquid to gas flow rates in the column, although from the data available this optimum flow ratio point seems not have been attained. On the other hand this tower absorber was not internally cooled.

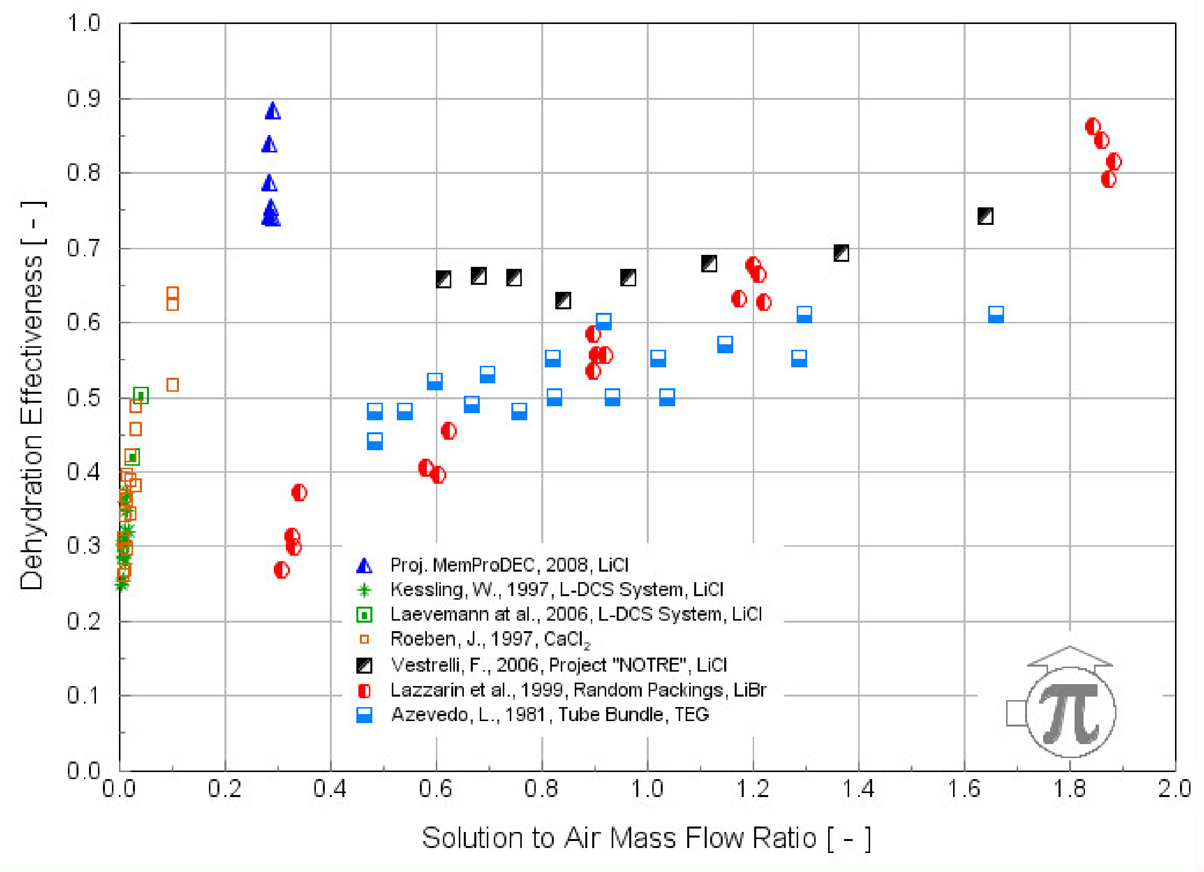

Figure 39 - *Graphical comparison of experimental data sets for various absorber systems with the results obtained in this project.*

6. Conclusions and Outlook

From the discussion above, it is to conclude that the components designed, manufactured and tested represent a great potential for performance improvement of open absorption air conditioning systems. It has been demonstrated that the design solutions adopted are superior to those known from both R&D and Market.

Most R&D in the field of open absorption air conditioning systems have concentrated on the *‚performance defining'* component, the absorber. In this project it was also proposed and tried to include the *‚economics defining'* component, the desorber. Unfortunately, as reported, the desorber failed during the tests, due to unsuitable bonding adhesives used in its manufacture, and the financial constraints of the project, more than 2/3 self financing, did not leave any allowance for recovery of the setback when testing the desorber.

Nonetheless, the results obtained are highly promising from the design down to the choice of materials. In particular the cooling method of the absorber, which is the fundamental reason for the high *‚dehydration effectiveness',* allows the operation with a small salt mass fraction spread. This, on the other hand, permits compromises on the desorber side between size and the regeneration driving temperature.

Manufacturing must be done otherwise, minimizing as much as possible the use of machine tools and adhesive bonding. The polymer parts, which form the essence of all components, shall be injection moulded, or produced by any other advanced method, and whenever parts need to be assembled, welding them shall be the preferred method.

The further developments of the technology require at least one more R&D step to refine and test the manufacturing methods as outlined. This next R&D step should still be, preferably, pre-competitive. The objectives shall be:

to refine design techniques through simulation, by further development of the existing design methods;

to refine manufacturing methods, including moulding and welding of components;

to manufacture and test experimentally a polymer membrane-based desorber able to stand the required desiccant regeneration temperatures;

to test, and evaluate extensively in the laboratory, complete air handling units in their most general configuration, under a variety of typical climatic conditions.

It is foreseeable that at the end of that development step, one, or more, industry partners shall be in a position to enter the market with low temperature (50 .. 80 °C) driven, autonomous air handling units able to compete successfully with conventional technologies.

Symbols

Latin Symbols

Cp	Specific thermal capacity
h	Enthalpy
$\dot{M}$	Mass flow rate
T	Temperature

Greek Symbols

ε	Effectiveness
ω	Humidity ratio
Δ	Variation, Difference

Subscripts

a	Air
da	Dry Air
eq	Equilibrium
i	Inlet
o	Outlet
s	Desiccant Solution
w	Water

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Annexes

ANNEX 1 – A REVIEW OF SORPTION-BASED AIR CONDITIONING SYSTEMS

In conventional sorption-based systems, the sorption part handles in general only the latent load (dehydration) while the *chiller* (vapour compression or absorption system) handles the sensible load. This has the remarkable advantage of significantly improving the performance of the vapour compression system, since it is not any more necessary to operate the cooling equipment at temperatures below the dew point of the air to be treated. Regeneration of the desiccant involved in the sorption process may however require temperatures higher than those available at the condenser of the vapour compression system, particularly when solid desiccants are used. Combinations with solar thermal collectors have been proposed and tested in the past, but in general it was found that they increase significantly the capital costs.

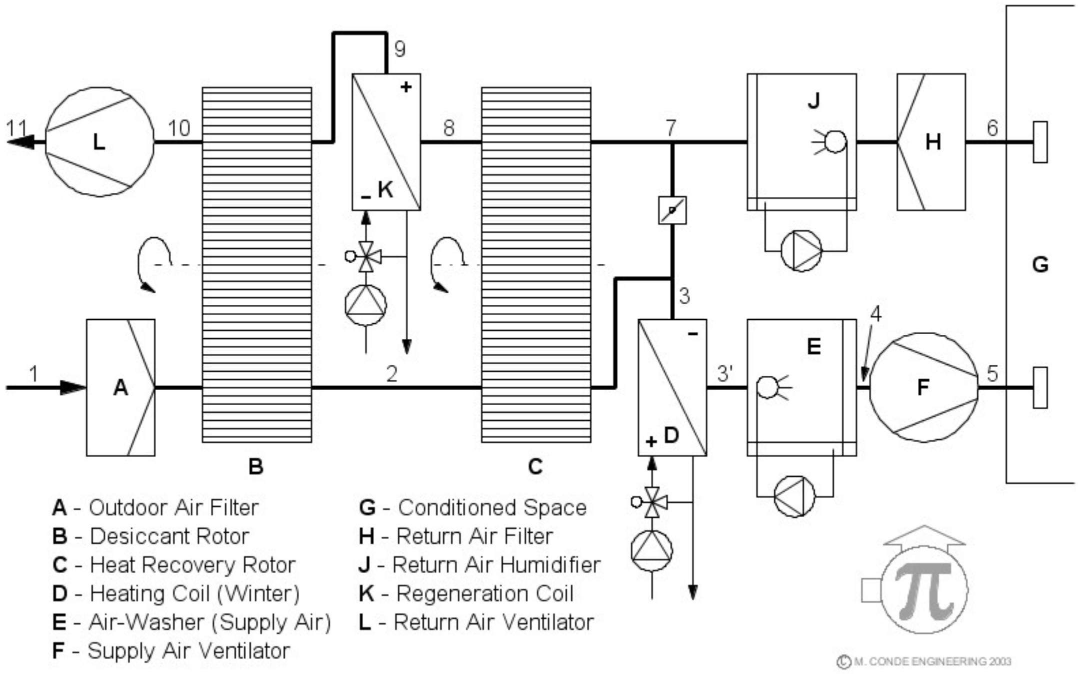


Figure A1.1 - *Schematic of a solid desiccant & evaporative cooling DEC air handling unit.*

Figure A1.1 depicts a schematic of an AHU operating with a solid desiccant rotor in combination with direct evaporative cooling (DEC System), and Figure A1.2 shows the cycle of operation of one such AHU for Summer conditions, the *Pennington Cycle.*

Where sorption systems are used, either in combination with evaporative cooling (DEC Systems) or with refrigeration units, of the vapour compression or absorption types, they may rely either on solid or on liquid desiccants. In the US, the GRI (Gas Research Institute) [2] in cooperation with NREL (National Renewable Energies Laboratory) [3] have been pushing the development and application of the technology of desiccants in view of increasing the share of natural gas driven systems in applications to air conditioning. This is in reality an effort to increase natural gas demand in Summer, which is traditionally much lower than in Winter.

Systems with solid desiccants are relatively well established[d], despite their almost insignificant market share [4].

[d] The technology, particularly with desiccant wheels, is relatively well known and tested. Some niche markets are developing fast.

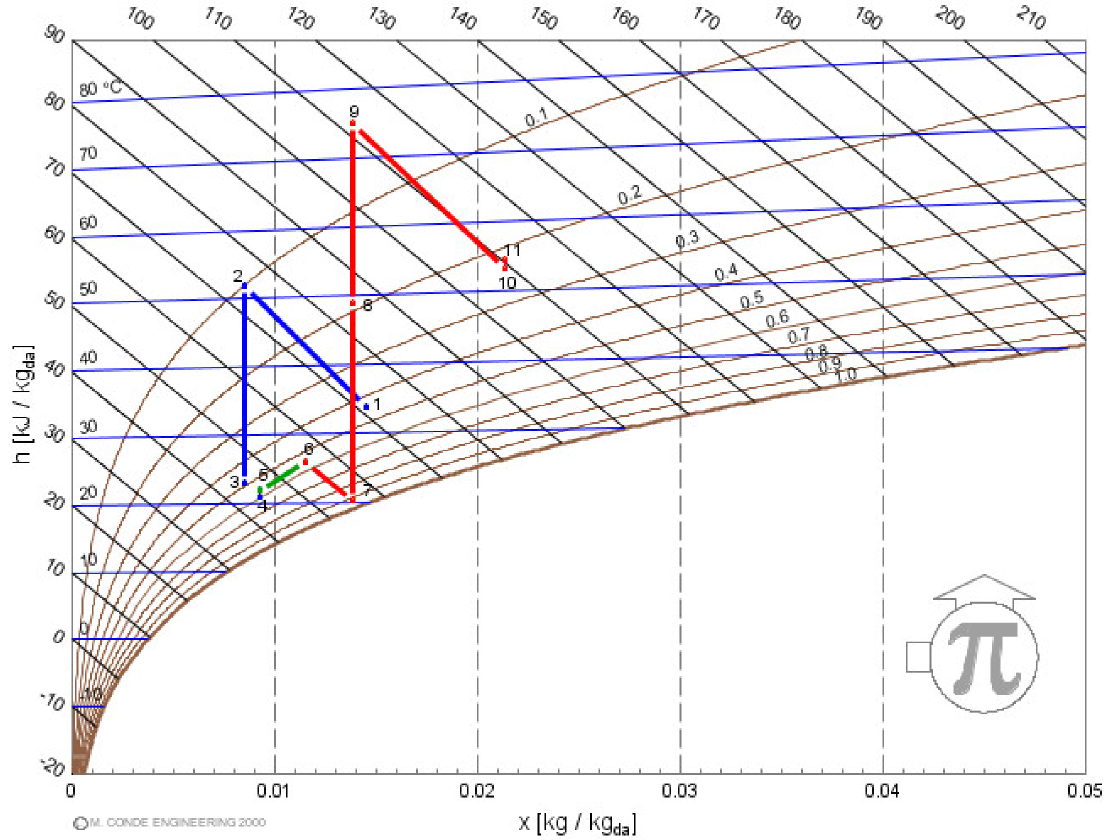


Figure A1.2 *- The Pennington cycle for Summer conditions (the numbers correspond to the positions indicated in Figure A1.1).*

Systems with liquid desiccants seem not to have yet attained the necessary maturity to get widespread application. The first system of this type was probably that proposed by Bichowsky and Kelley [5] in 1935, Figure A1.3.

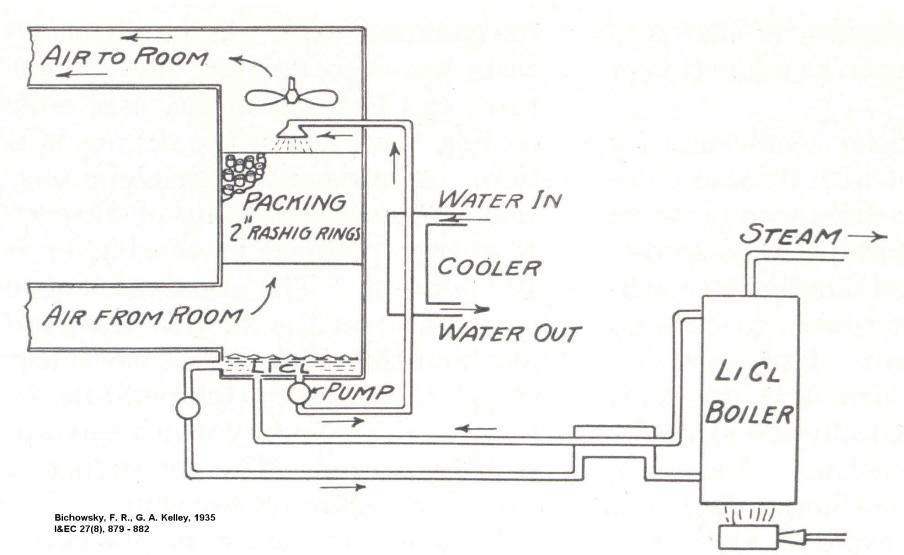


Figure A1.3 *- Schematic of the liquid desiccant system proposed in 1935 by Bichowsky and Kelley for the dehydration of air.*

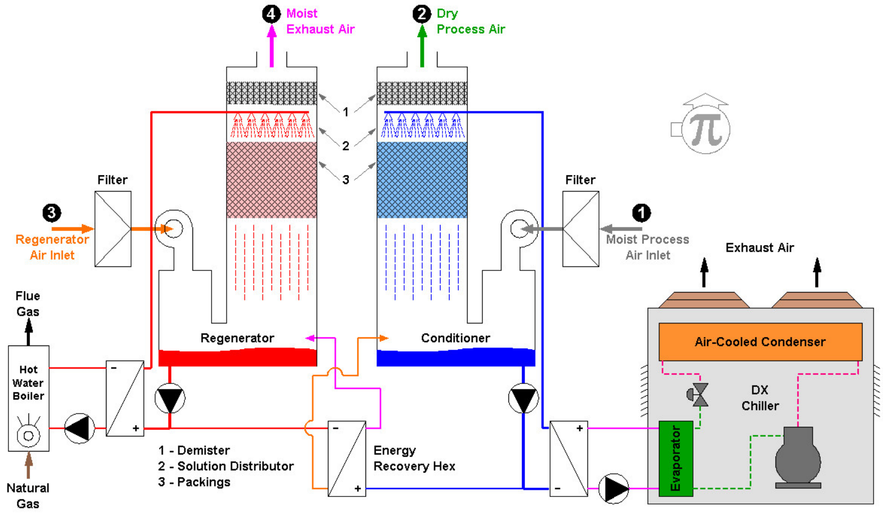


Figure A1.4 *- Schematic representation of the Kathabar liquid desiccant air dehydration system (adapted with permission of Kathabar®, Inc.).*

This system was further developed later, and become known as the Kathabar® System. The technology involved derives from the process industry. Two packed column contactors are used as the conditioner (absorber) and as the regenerator (desorber), Figure A1.4.

Several developments have been undertaken in the last twenty years, particularly in combination with solar energy as driving energy source. In some developments with solar energy, solutions are proposed that are absolutely hopeless, such as open solar collectors as regenerators.

A recent development combines a conventional vapour compression heat pump with an open absorption system. It has been developed, and commercialized by Drykor® Ltd., of Atlit - Israel[e], Figure A1.5.

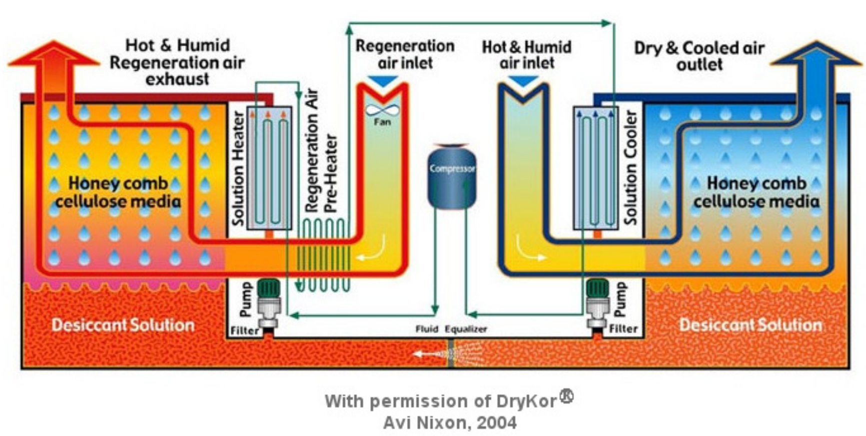


Figure A1.5 *- Schematic illustration of the principle of operation of the Drykor® liquid desiccant air dehydration system.*

Other systems are currently being field tested for the market, such as the AHU depicted schematically in Figure A1.6. In this system, cooling is provided exclusively by indirect evaporative cooling. The conditioner (absorber) and the regenerator (desorber) are built as compact packed

[e] Equipment corrosion problems among other liabilities, have forced this manufacturer out of the market in 2006.

columns inside a conventional unit box. Particularly at high air to desiccant flow ratios, surface wetting is impaired in this unit due to the particular kind of compact construction chosen that uses cross flow in the packed columns. The combination of evaporative cooling with air dehydration as depicted, reduces significantly the electric energy required. The unit may be driven by a thermal solar collector array.

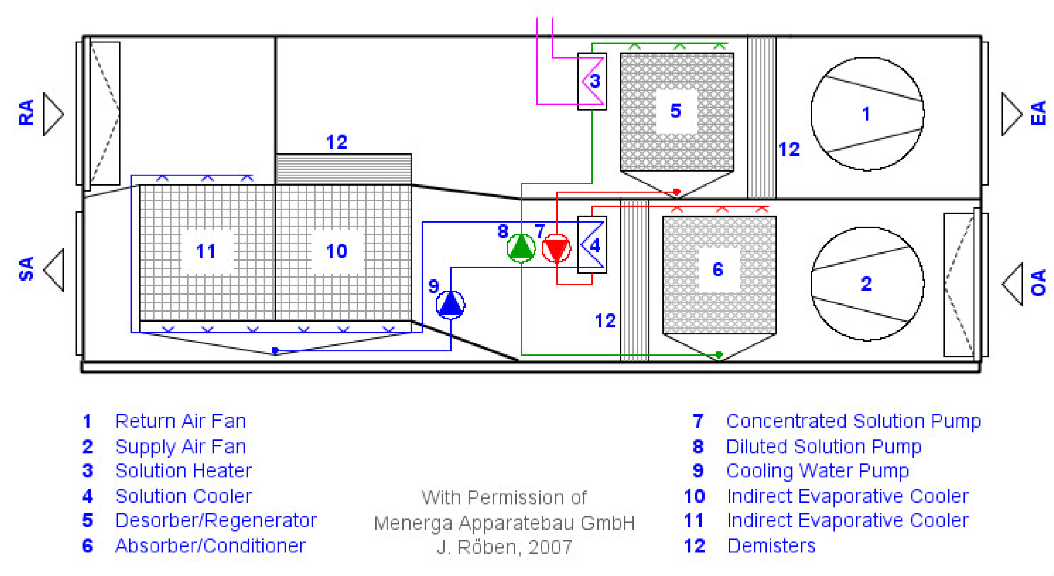


Figure A1.6 *- Schematic of an AHU combining indirect evaporative cooling with direct contact, crossflow, liquid desiccant contactors.*

A further system, using indirect evaporative cooling, has been studied in the framework of the *EUREKA Project E!2098 EuroEnviron SOLDEC - Solar Desiccative and Evaporative Cooling in Buildings* at the 'École d'Ingénieurs du Canton de Vaud - Yverdon-les-Bains' [6]. This system is based upon the patents WO 22 497, 1996 and EP 959 307, 1998, Figure A1.7.

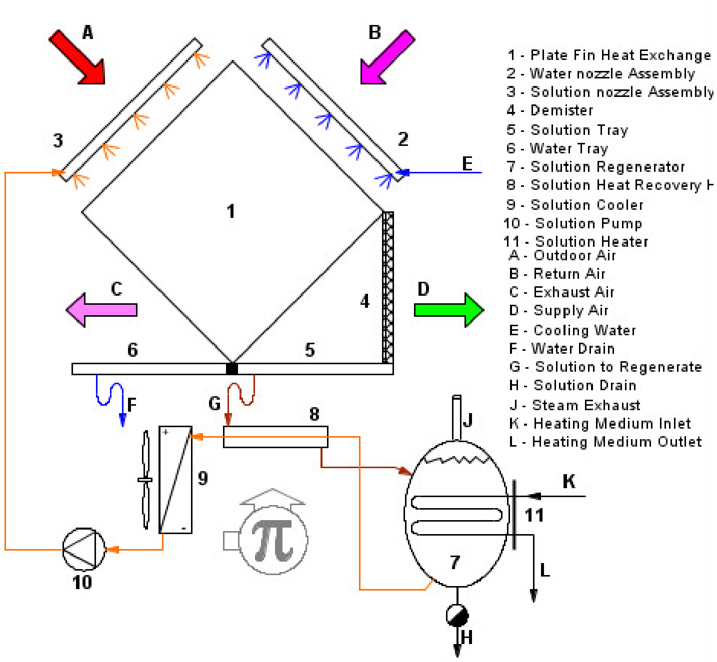


Figure A1.7 *- Schematic illustrating the principle of operation studied in the EUREKA SolDec project.*

The already mentioned work at the GRI and NREL resulted, after an evolution along more than 10 years, in a product currently manufactured by AIL Research, Inc., in the US, Figure A1.8. This long maturing period is documented both in the open literature [7], [8], [9] and in several patent applications [10]. A schematic of this unit is depicted in Figure A1.9.

Figure A1.6 - *Image of the AIL Research Liquid desiccant Unit.*

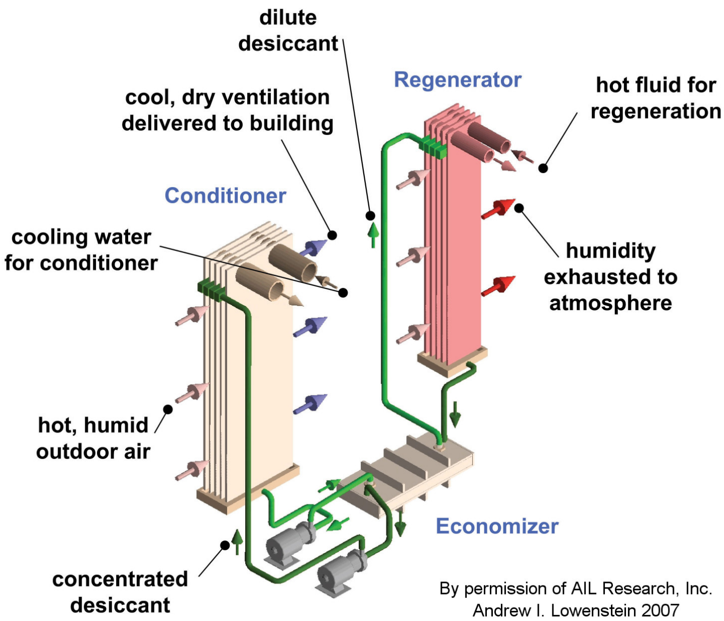


Figure A1.9 - *3-D schematic of an AIL Research liquid desiccant dehumidifier.*

The unit is intended to handle the latent load only (dehumidifier) and to operate upstream of the evaporator of a conventional cooling system, although it might as well deliver supply air directly in some cases. Since both absorber and desorber operate in direct contact with air, it is questionable whether, with ageing of the contactors surfaces, the carryover problem is definitely solved.

Another development with very interesting features has been carried out by Ficom, Pty., of Australia. In the *DICER-D* system[f], Figure A1.10, Ficom combines air dehydration with indirect evaporative cooling in a single unit, with regeneration taking place separately Figure A1.11. This concept allows for distributed air handling, with its inherent flexibility, and centralized desiccant regeneration.

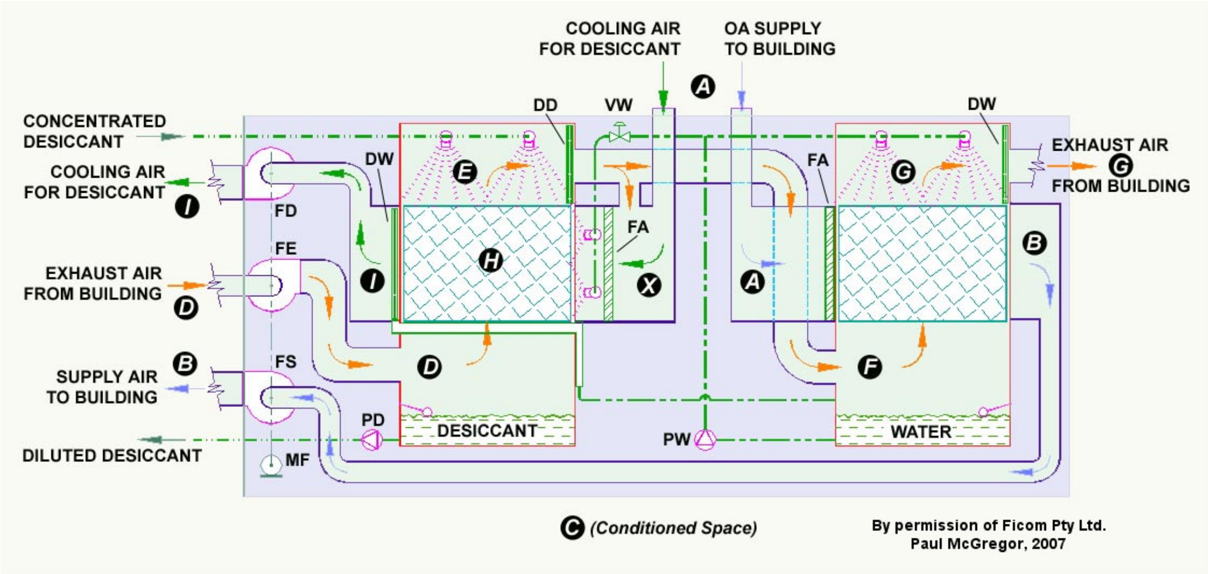


Figure A1.10 **-** *Illustration of the DICER-D liquid desiccant-based air conditioning system.*

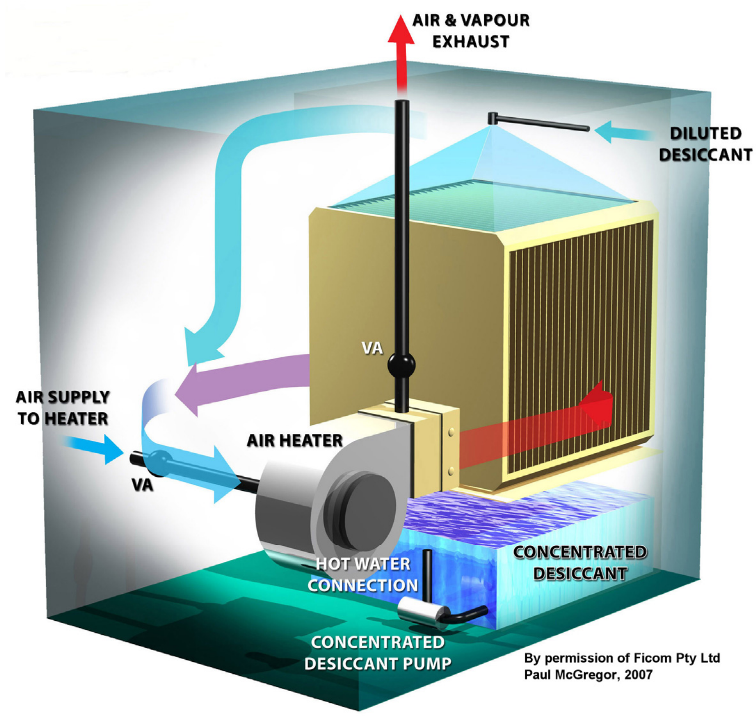


Figure A1.11 **-** *Regenerator (desorber) part of the DICER-D system.*

[f] Dual Indirect Cycle Energy Recovery.

Demand management, particularly when the system is solar energy-driven, is done by storing concentrated desiccant solution. The exhaust process air is dehumidified in one first contactor and cooled by re-humidification to provide evaporative cooling to the supply air. This air washing step warrants that no aerosols come out of the AHU, the supply air never contacting water or the desiccant solution. On the other hand, this air handling method forfeits the potential benefit of the bacteriostaticity of the desiccant solution, and does not really control the humidity of the supply air, since indirect evaporative cooling, as used in the unit, is not able to control both temperature and humidity simultaneously.

A further development resulting from work carried out at the Bavarian Center for Applied Energy Research (ZAE Bayern) is currently being marketed by *L-DCS GmbH*. This system consists of on purpose designed equipment, combining decentralized air handling (dehydration + evaporative air cooling) with central regeneration and desiccant storage, Figure A1.12.

The air-desiccant contactors use a patented desiccant distributor [11] for micro-quantities of liquid, to ensure a good wetting of the contacting surfaces. The absorber is internally cooled by water, and the desorber internally heated by water at a temperature in the range 60 – 80 °C. The direct contact of process air with the desiccant solution warrants the benefits of the bacteriostaticity of the desiccant, although the production of desiccant containing aerosols is also probable. No reports are as yet available on this respect though.

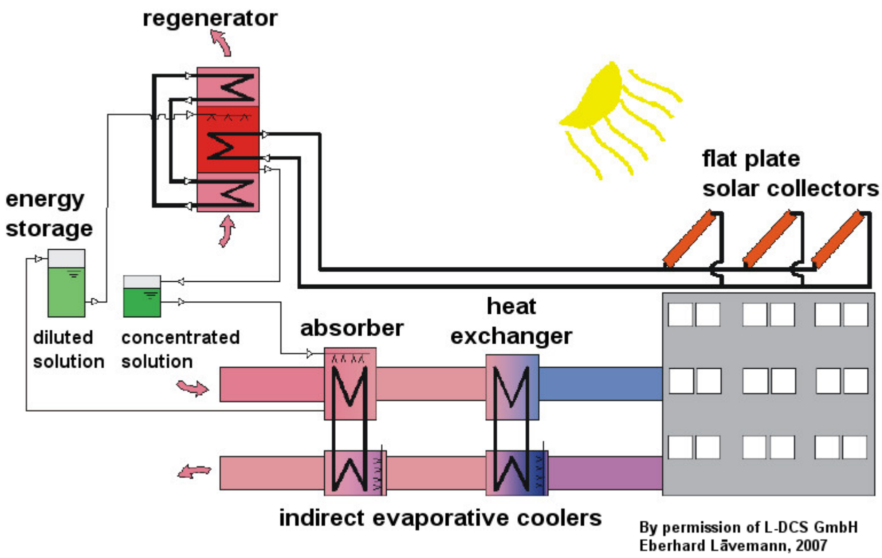
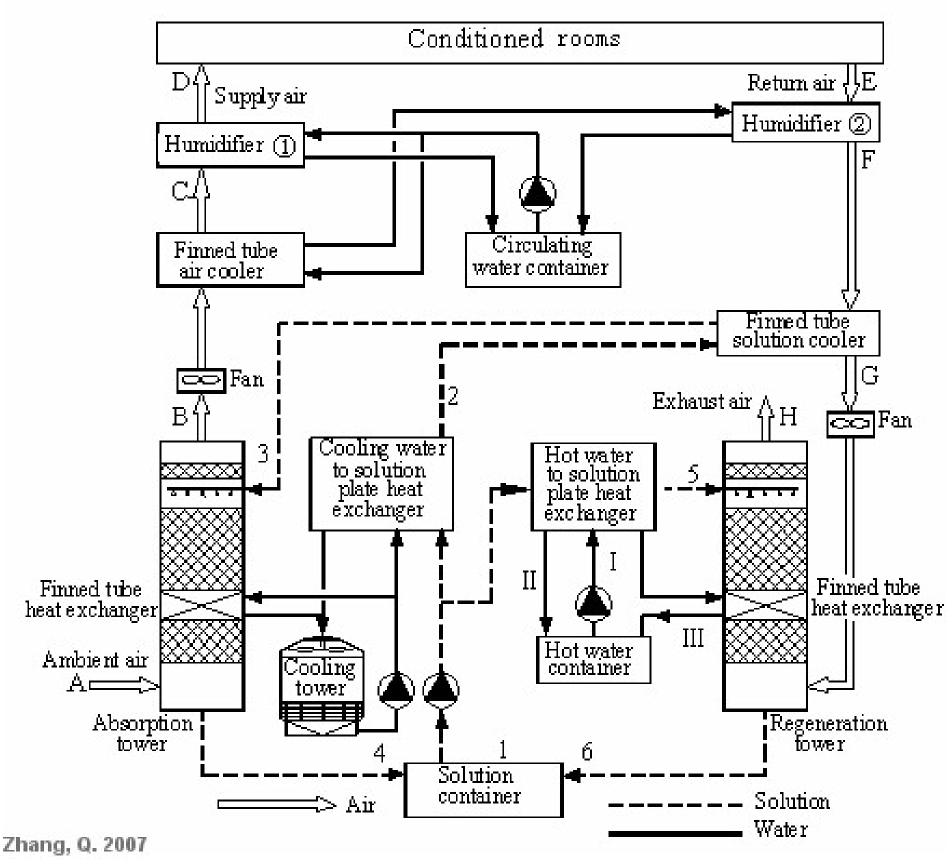


Figure A1.12 - *Schematic representation of a solar-driven L-DCS plant.*

While the pulling force for the development of liquid desiccant air conditioning systems has been until shortly the gas industry in the US, in Europe it is essentially the potential for the use of renewable resources, the SARS crisis has driven the far-East research in recent times, particularly in China. In this case the bacteriostaticity of liquid desiccant solutions is seen as important in the control of the spread of the SARS virus, particularly in large installations.

Figure A1.13 shows a schematic of a system currently under development at the Shanghai University of Science and Technology [12].



Zhang, Q. 2007
University of Science and Technology, Shanghai, P. R. China
Personal Communication

Figure A1.13 - *Schematic of a liquid desiccant-based air conditioning system being studied at the Shanghai University of Science and Technology.*

The use of liquid desiccants implies, in general, the construction of an open absorption system. This in itself presents the non-negligible advantage of avoiding the operation under vacuum, with the concurrent need for heavy and very tight components as well as purging equipment. On the other hand, state-of-the-art open absorption systems suffer from three important drawbacks:

- The need for amounts of desiccant solution larger than in closed systems,
- the contamination of the solution in direct contact with the air, and
- the negative effects of air dissolved into the solution upon the mass transfer process.

It shall also be observed that the eventual formation of aerosols of the desiccant solutions poses risks for both equipment and people, due to their toxicity[g] and corrosion potential. In excess of this, it is well known that direct contacting equipment may be difficult to control[h] at conditions other than design (part load). Still, one main advantage of these systems remains: No surfaces must be cooled to or beyond the dew-point temperature of the air. Cooling equipment may thus operate at higher efficiency, or be dispensed with completely.

[g] When inhaled as aerosols.

[h] Incomplete wetting of the contacting surfaces at low solution flows (trickling) or inundation at high flows, which might block the air flow pathways completely (flooding).

There have been attempts, in the last several years, at confining the desiccant solution, and having it contact the air across *microporous membranes,* partly in response to the problems mentioned above.

One known system brought to the market by American Energy Exchange, Inc. (AEX) and marketed as *'enthalpy pump'* [13]*,* is used to dehumidify the air before the evaporator of conventional chillers, practically eliminating the latent load on it. Several of these absorbers, Figure A1.14, may be associated to a central desorber (regenerator), as was the case with the *'DICER-D'* system described above.

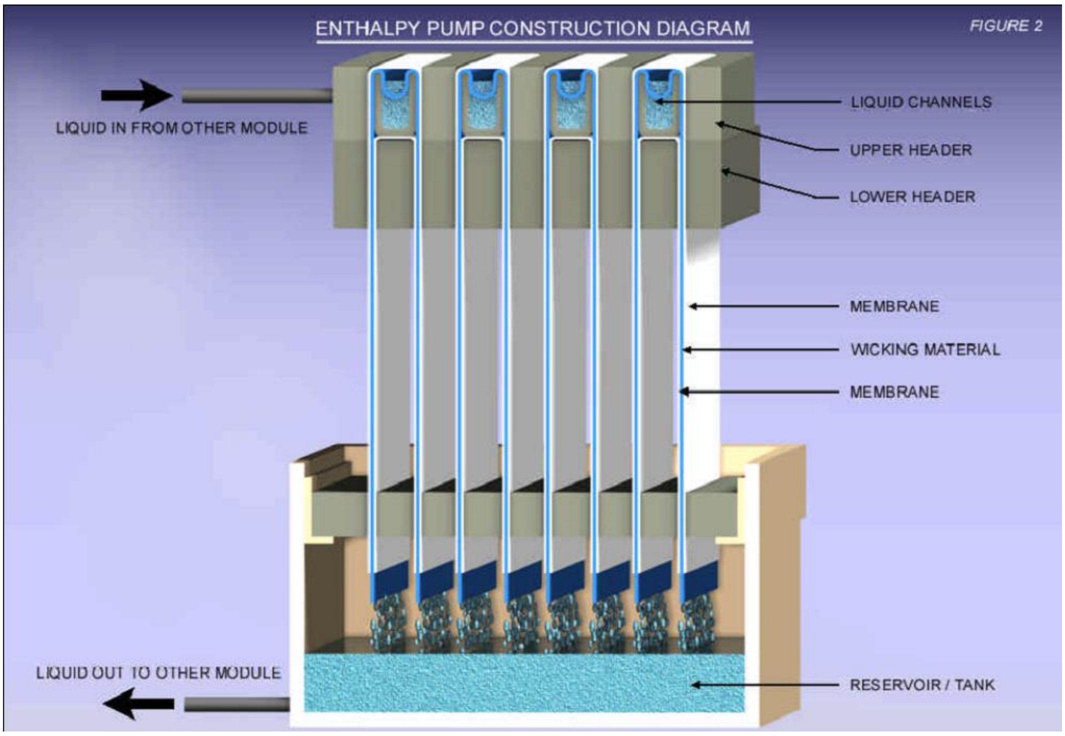


Figure A1.14 - *Artist's illustration of the AEX Enthalpy Pump (Image from the product sheet of AEX, Inc.).*

The system illustrated schematically in Figure A1.15, was the subject of research and development in the *'Drycomfort Project',* financed with ~10 M€ through the *EU FP5 - GROWTH Program,* for a total project cost of ~17 M€. As may be seen from this schematic, the system continues to require mechanical refrigeration, the liquid desiccant being used only to dehydrate the air [27].

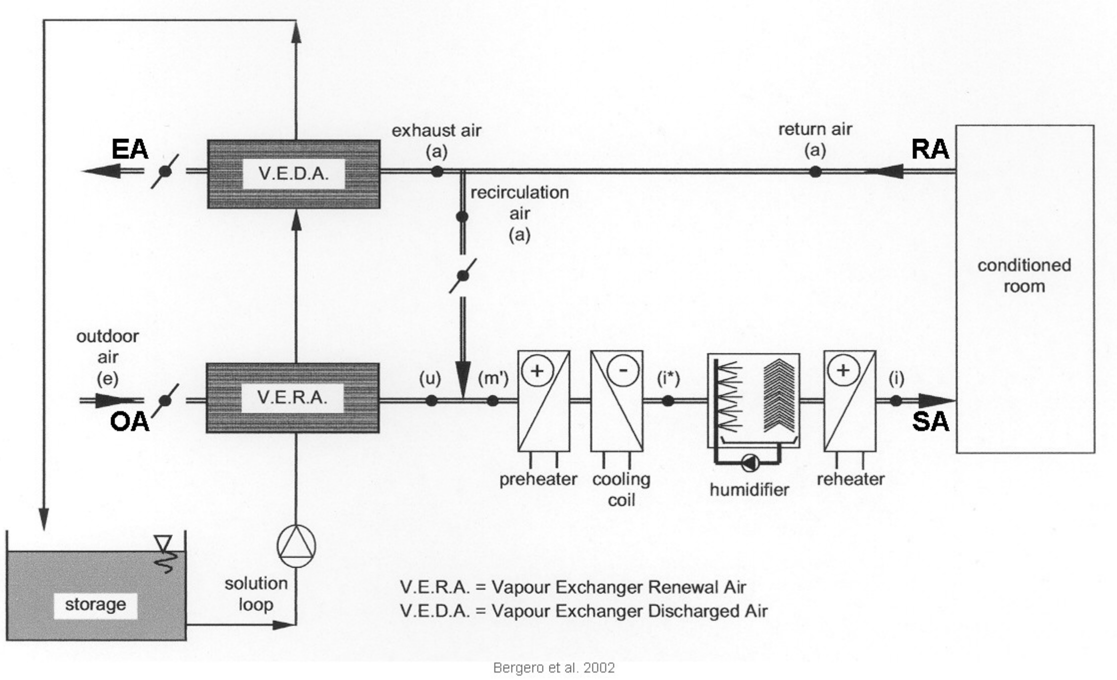


Figure A1.15 *- Schematic of the liquid desiccant system developed in the DryComfort Project 2000 – 2003. Adapted [27].*

The membrane contactors designated VEDA and VERA in Figure A1.15 were designed with the geometry shown in detail in Figure A1.16 [14]. The microporous membranes used in their manufacture are PVDF (polyvinylidenefluoride) membranes, produced at the time by one of the project participants. One of the main conclusions of this project was that the selected contactor geometry was unsuitable due to the very high pressure losses both on the air and the solution sides.

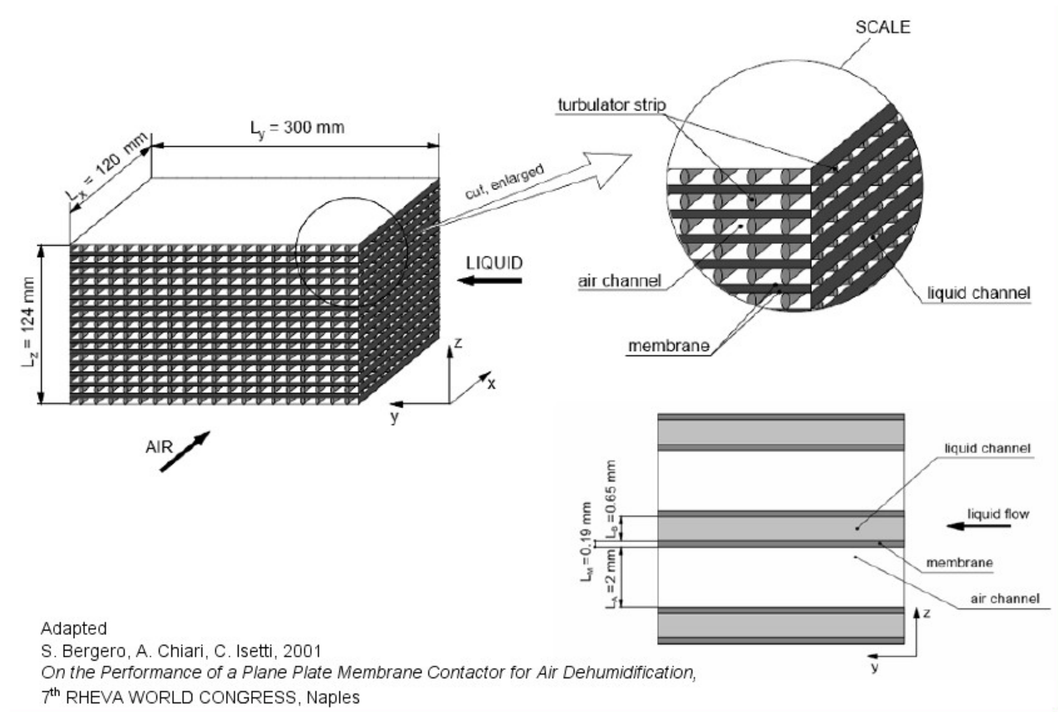


Figure A1.16 *- Structure of the membrane contactors developed in the DryComfort Project. Adapted [14].*

The work of this group was continued in a follow-up project *'NOTRE'*[i], financed with ~0.5 M€ through the *EU – FP6 LIFE program,* for a total project cost of ~1.4 M€. The objective was now to develop membrane contactors suitable for automotive application in order to reduce CO_2 emissions, caused by the air conditioning systems of busses and trucks in particular. Figure A1.17 illustrates the kind of solution adopted in this development that ended in October 2007 after a duration of 24 months.

As shown at the right in Figure A1.17, the membrane contactor is assembled using pre-formed structures that support the membrane, shown olive and green. Between the membranes (gray) is a channel defined by a separator (red). The air channels are delimited by the green and olive plates, and defined by the size of the O-ring (blue). There is no cooling inside this absorber.

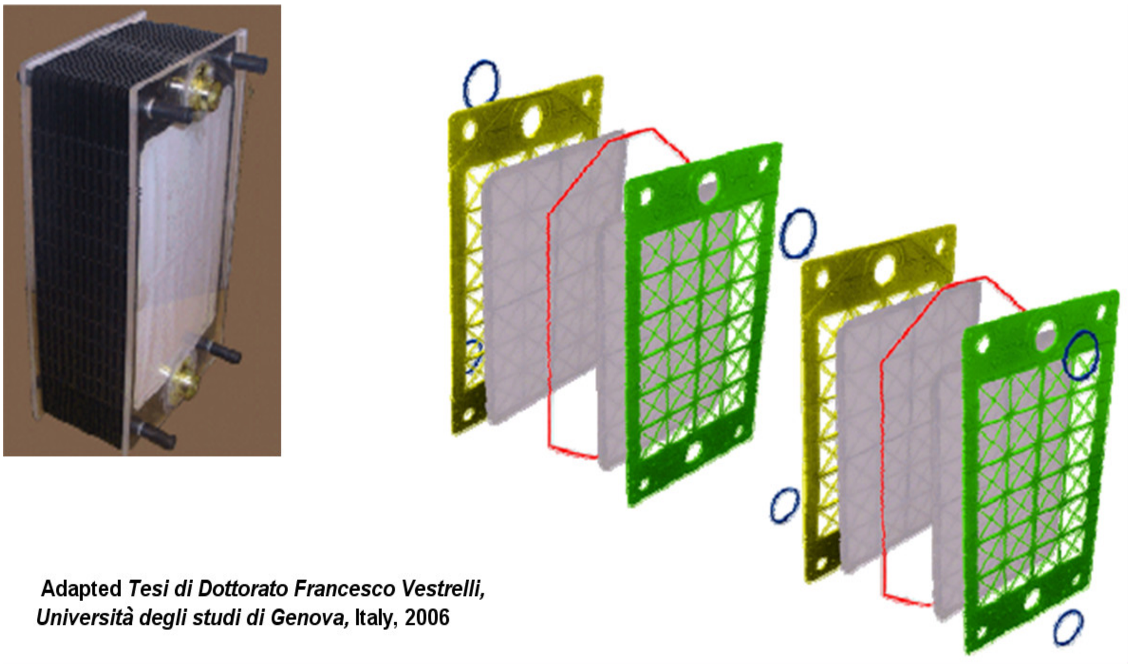


Figure A1.17 - *Assembly and components of the membrane contactors developed by the participants of the NOTRE Project.*

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[i] Reference LIFE05 ENV/IT/000876.

ANNEX 2 – INSTRUMENTATION OF THE EXPERIMENTAL SETUP

Table A2.1 - *Description and characteristics of the mesaurement and monitoring sensors.*

Ref.	Measuring Point	Type	Precision
MR000	Air in the Climatic Chamber	Capacitive	0.05%t[°C]±1.5%
MR001	Air at Inlet to Ventilators	Capacitive	0.05%t[°C]±1.5%
MR002	Air at Absorber Outlet	Capacitive	0.05%t[°C]±1.5%
MR003	Air at Evaporative Cooler Outlet	Capacitive	±0.35[%]
MR004	Air at Desorber Outlet	Capacitive	0.05%t[°C]±1.5%
TR000	Air in the Climatic Chamber	Thermistor	±0.2 K
TR001	Air at Inlet to evaporators	Thermistor	±0.2 K
TR002	Air at Absorber Inlet	Cu/Const TC	±0.2 %
TR003	Air at Absorber Outlet	Thermistor	±0.12 K
TR004	Air at Evaporative Cooler Outlet	Cu/Const TC	±0.2 %
TR005	Air at Evaporative Cooler Outlet	Thermistor	±0.2 K
TR006	Desiccant at Absorber Inlet	Cu/Const TC	±0.2 %
TR007	Desiccant at Absorber Outlet	Cu/Const TC	±0.2 %
TR008	Water at Absorber Inlet	PT100/4w	±0.1t[°C] ±0.2%FS
TR009	Water at Absorber Inlet	Cu/Const TC	±0.2 %
TR010	Water at Absorber Outlet	Cu/Const TC	±0.2 %
TR011	Water at Desorber Inlet	Cu/Const TC	±0.2 %
TR012	Water at Desorber Outlet	Cu/Const TC	±0.2 %
TR013	Desiccant at Desorber Inlet	Cu/Const TC	±0.2 %
TR014	Desiccant at Desorber Outlet	Cu/Const TC	±0.2 %
TR015	Air at Desorber Inlet	Cu/Const TC	±0.2 %
TR016	Air at Desorber Outlet	Thermistor	±0.2 K
TR017	Air at GHX Inlet	Cu/Const TC	±0.2 %
TR018	Air at GHX Outlet	Cu/Const TC	±0.2 %
F001	Air at Absorber Inlet	Trox-Hesco V-Type	±2 m^3/h
F002	Air at GHX Inlet	Trox-Hesco V-Type	±2 m^3/h
F003	Water at Absorber Inlet	Rotameter	±3 %
F004	Water at Desorber Inlet	Rotameter	±3 %