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NEW IDEAS FOR ENERGY UTILISATION IN COMBINED HEAT AND POWER WITH COOLING: I. PRINCIPLES

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Abstract—New ideas are needed to reduce installed cooling capacities and growing ventilation costs and to improve control in the various zones of CHP plants with cooling. Above all the thermal energy available in summer from electricity cogeneration must be exploited. Unconventional cooling systems, such as evaporative or chemical dehumidification, allow one to achieve some of the objectives. Chemical dehumidification, both by adsorption and absorption, particularly permits new plant lay-outs, leading to the complete elimination of traditional cooling equipment with direct air treatment and very high potential energy savings. Copyright © 1997 Elsevier Science Ltd.

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INTRODUCTION

The design of a modern heating, ventilating and air-conditioning (HVAC) plant must take into account the fact that many important modifications have taken place in the various elements that influence the design choices, particularly in Italy. It would be a serious error for the technician not to consider them for a plant whose useful life will extend far into the next century.

First of all the structure of the electricity tariff must be carefully accounted; second, natural gas fare tariffs are difficult to predict, even as far as their increase is concerned.

The engagement of electric power is strongly penalising above all for the conventional HVAC plants, since they are often responsible for the peaks of electricity demand; these peaks usually last a short time.

As far as the electricity supply is concerned a significant innovation must be considered in Italy, i.e. the Act 9/1991, that allows the self generation of electric energy without difficulties and above all permits the producers to sell the energy surplus at a reasonable price to the Electric National Board (ENEL).

As far as the users are concerned, the novelties are less but not at all negligible.

An increasing demand for better air quality is apparent, which means among other things an increasing number of air changes. At the same time the improvement of the building quality reduces losses/gains toward/from the outside. From the above the relative importance of the ventilation demand is obvious.

The request for better quality applies also to finer control of the various zones or even of the single room, both in terms of temperature and of humidity; at the same time another need is presented that seems contradictory: to reduce the operating costs and above all the energy costs.

The survey of the novelties in the air-conditioning in commercial or recreational centres, hotels, hospitals, etc., outlines some tendencies which entail further difficult choices to be faced.

A traditional plant design, i.e. based on the so-called design loads, very near to peak-loads, is prevented by the cost structure. Otherwise this choice can be very expensive. In fact plant sizing on the basis of design loads gives at least two unpleasant consequences: a high cost for higher-capacity equipment and a lower efficiency in normal operation at partial load. Storage systems must be provided to shave the peaks (not only to eliminate the peak rates).

Alternative systems to alleviate the conventional equipment engagement should be studied. Two simple examples, strangely neglected by specifiers, are the already cited evaporative cooling and chemical dehumidification.

A growing tendency toward cogeneration is evident. This is already consolidated in a country like Japan, whose energy structure is similar to the Italian one; actually more than 50% of the large buildings in Tokyo are equipped with a CHP plant. This tendency, which was at last recognised by the above mentioned Act 9, must not be considered a new idea, as is the use of storage. They are already mature technologies with relatively few applications due to uncertainties in legislation and in price structures, perhaps also to design habits. As mature technologies, they will not be dealt with here.

A CHP plant does not give as such a sufficient guarantee of good operating results. These can be obtained only with careful plant operation, well planned to buy the shortfall in electric energy from the utility with the least disadvantages and to sell the surplus with the highest profit. In this planning an important role is assigned to the cogenerated thermal energy, which should always find suitable utilisation and rarely be dissipated.

This condition is difficult to fulfill in summer, when the thermal energy demand is strongly reduced and there is the availability of low-level energy from the condenser of the cooling machines.

Summarizing the free reasoning of this introduction, new ideas are welcome: to exploit thermal energy available in summer; to limit the installed capacity of conventional cooling equipment; to reduce the growing ventilation cost; to improve the control of the single-conditioned zones.

THE USE OF ABSORPTION MACHINES

As is well known, the available thermal levels from cogeneration are related to the type of plant. Higher capacity plants can utilise either gas turbines or big reciprocating i.c. engines. Modern high-efficiency gas turbines operate with pressure ratios higher than some years ago; a ratio around 15 is not unusual and the tendency is toward increasing values [1]. This implies, besides a high thermal efficiency, end of compression temperatures comparable with the exhaust so that regenerative cycles are not practicable.

The exhaust at temperatures as high as 450–550°C can be exploited when necessary in steam generation. For sizes over 15–20 MW the possibility of combined cycles with steam turbines and very high efficiencies should be considered.

In recent years even the reciprocating i.c. engine has reached very high thermal efficiencies. Conversion efficiency values as high as 42% are claimed for an electric power of 6 MW. Lower capacity engines can approach those values. The heat recovery can be at 300–400°C from the exhaust and at 85–90°C from the engine jacket cooling. The former is a level suitable for steam generation; the latter gives hot water for different heating purposes.

Steam can drive absorption equipment of the lithium bromide–water type, even double-effect types with appreciable COP values (1.0–1.1). Hot water at 85–90°C can drive single-effect machines designed for solar cooling applications with COPs of between 0.6 and 0.7 and capacities as low as some tens of kilowatts [2].

Many operating plants testify surely to the technical feasibility. The most difficult obstacle to this utilisation of heat recovery is economics.

Absorption equipment, particularly of the lithium bromide–water type, is expensive and its utilisation for a few months a year is seldom justifiable, particularly when the contribution is supplementing, and not a substitution of, conventional cooling equipment.

In other words, if the cogenerated electricity does not drive conventional compression cooling machines, but is produced for other purposes, it can be worthwhile to envisage a cooling plant completely based on absorption. If, however, the electricity is mainly produced to drive the cooling equipment, a composite plant (cogenerator, compression and absorption cooling equipment) can be economically prohibitive with respect to other possibilities (ice storage, directly fired absorption equipment, and so on).

Summarizing, the possible use of absorption machines must be carefully evaluated; the technique is widely practised. The evaluation will often not be economically satisfactory, particularly when the cooling demand is limited to the summer.

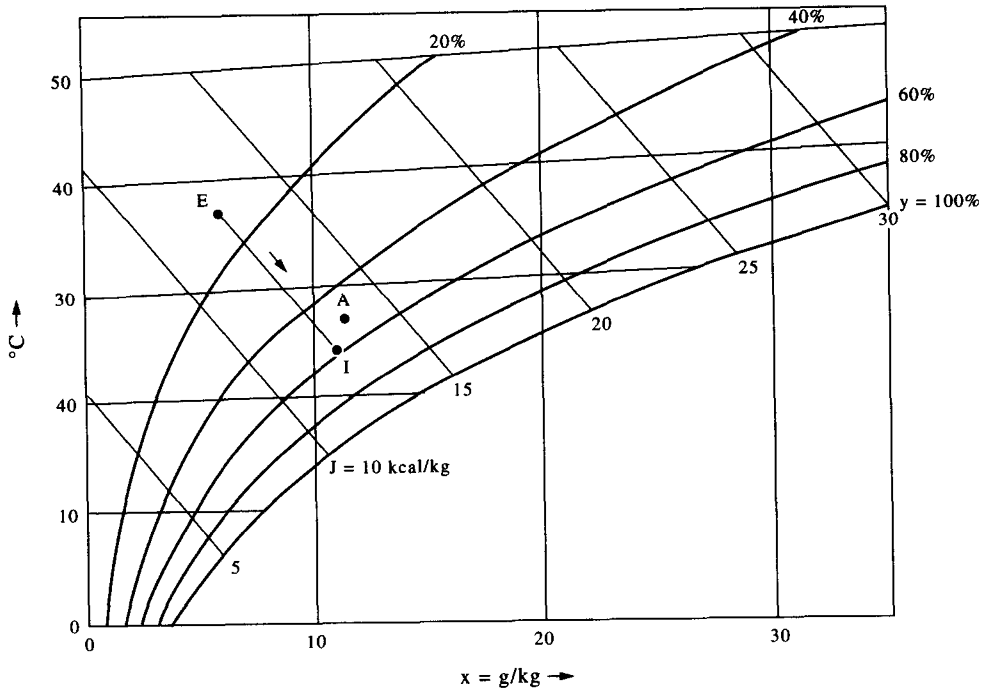

Fig. 1. Evaporative cooling in an adiabatic washer represented in a psychrometric chart.

EVAPORATIVE COOLING

As is well known, if unsaturated air is humidified by an adiabatic washer or by passage through wetted media, its temperature drops towards wet bulb temperature (Fig. 1). It is wrongly assumed that this cooling method is useful only in a hot and arid climate (Fig. 2), whereas it is not advisable

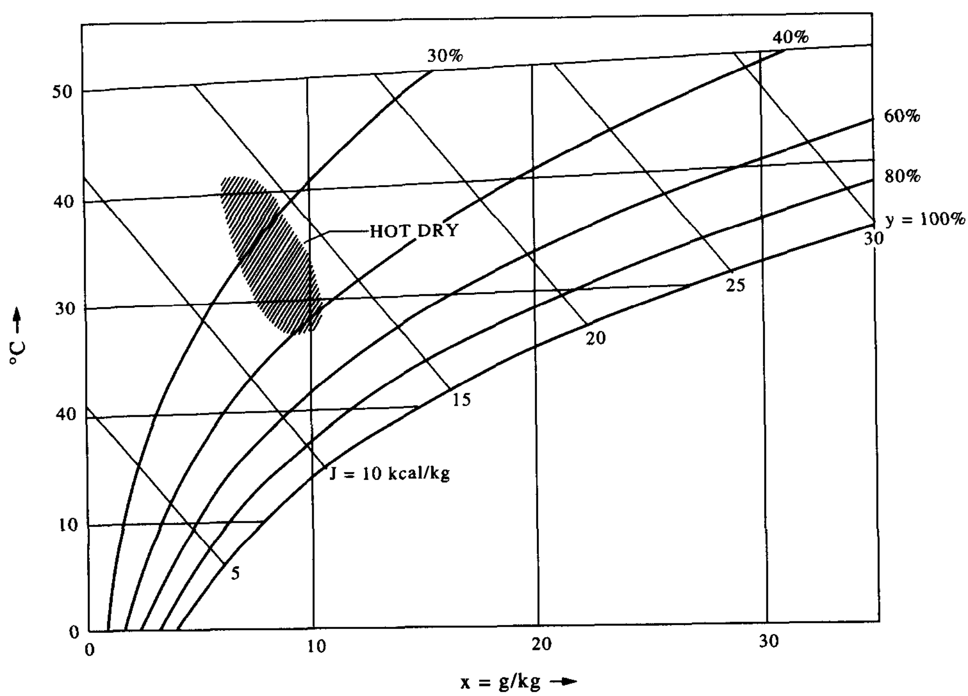

Fig. 2. Psychrometric conditions of a hot arid climate.

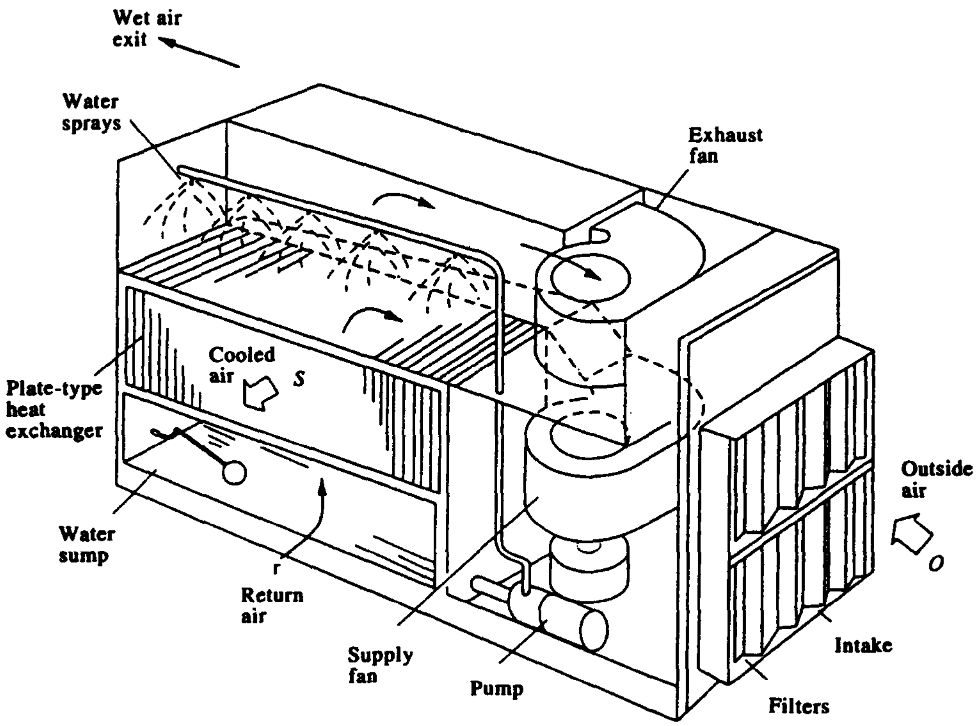

Fig. 3. Schematic diagram of an indirect evaporative cooler.

in temperate climates, where, instead, air dehumidification is usually necessary both for the internal latent loads and for the higher humidity ratio of the outside air.

Evaporative cooling should be equally considered, here the treated air is cooled only sensibly through heat exchange with air cooled by humidification [3]. The device can be very simple with operation similar to a cooling tower, but more compact and effective. A possible scheme is represented in Fig. 3, where the core of the system is the plate cross-flow heat exchanger, made of plastic plates of only 0.25 mm thickness, spaced about 2 mm. The very small plate thickness ensures a modest thermal resistance. The air to be treated flows horizontally, whereas the humidified water sprayed air flows vertically.

The behaviour of the device is expressed by the indirect evaporative cooler effectiveness (performance factor), i.e. the ratio between the temperature drop in the air to be cooled and the difference between the inlet air temperature $T_{a,i}$ and the temperature of the saturated air of the cooling flow $T_{s,a}$:

$$\varepsilon = \frac{T_{a,i} - T_{a,u}}{T_{a,i} - T_{s,a}}.$$

The last temperature can be evaluated to be about 1°C higher than the wet bulb temperature of the air to be humidified. The performance factor can be as high as 0.7–0.8 with a the pressure drop for both flows of about 100–300 Pa.

The possible usefulness of such devices in the temperate Italian climate can be suggested by examining the dry and wet bulb design temperatures in some Italian cities: Florence (35 and 21.2°C); Milan or Rome (34 and 23°C). This means that operating with outside air at design conditions, air at 28°C can be cooled respectively to 23°C or to 25°C. Away from the design point, the performance can be even more favourable. Also it is not necessary to operate with outside air. It is often more profitable to work with exhausted air whose wet bulb temperature can be lower than 20°C, so that very effective pre-cooling of the fresh air is possible. This is practicable even in humid climates.

No matter how it is operated, two positive results are obtained at a low cost: (i) a cooling effect at a very low energy cost, accounting for the energy cost of the fans, the EER (energy efficiency ratio, the ratio between the cooling effect and the energy to be supplied) is about 15 w/w, that is a value 4–5 times higher than for usual cooling equipment; (ii) a reduction in the design capacity needed by the cooling machines, even a 20% reduction can be effective both as regards the electric power engaged, the first cost of the machines and their seasonal performances.

The price to be paid is the water consumption. However it is not particularly high, it can be evaluated using the ratio between the cooling effect and the heat of vaporisation of the water (about 2450 kJ/kg), plus a further 50% for the necessary blowdown to limit the salt concentration in the sump.

Dealing with such a simple and low-energy-cost device could appear out of context when considering cooling CHP plants. It is, however, a first clue to what is possible with direct treatment of the air. Besides the process opposite to humidification, dehumidification, is the one usually operated in HVAC plants with relevant energy costs, without exploiting the large opportunities for savings offered by the process.

CHEMICAL DEHUMIDIFICATION

In air-conditioning the latent load is frequently important. It is due mainly to the building occupants or to particular activities, such as cooking or drying. During periods when the outside air humidity ratio is higher than in the conditioned space, as frequently happens, it is necessary to reduce the water vapour content by treating the ventilation air.

This is usually done by cooling and condensation (Fig. 4). The air is cooled below the wet bulb temperature, so that a fraction of the water vapour condenses. The wet bulb temperature depends on the air conditions and it can be very low if a low relative humidity in the conditioned space is requested, as happens, for example, in ice arenas or supermarkets with ample refrigerated cabinets.

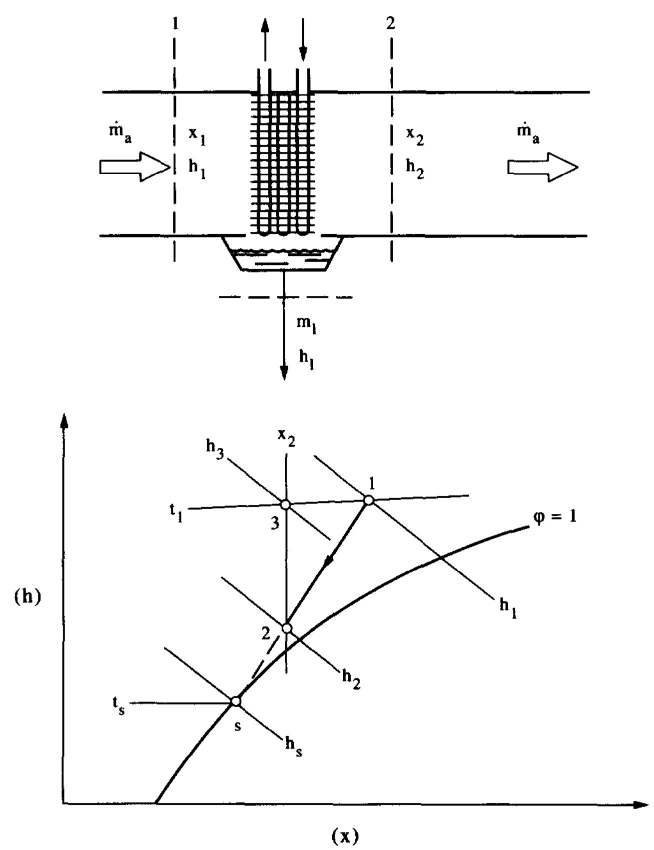

Fig. 4. Cooling and condensation: schematic diagram and the process on the psychrometric chart.

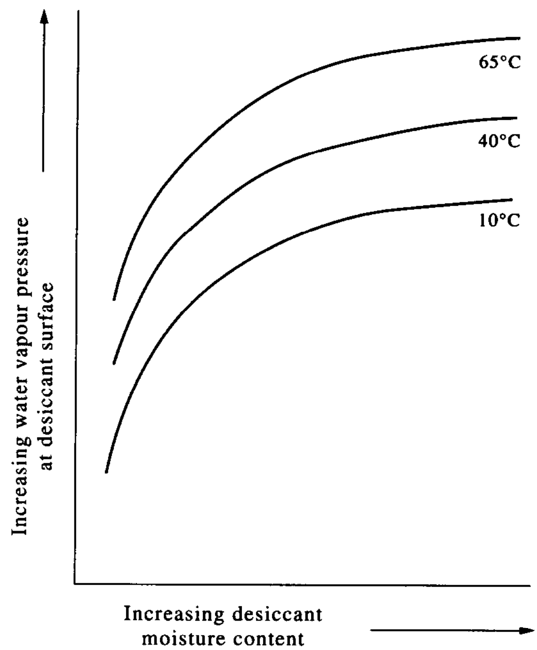

Fig. 5. Desiccant water vapour pressure as a function of desiccant moisture content and temperature.

The process of cooling and condensation gives rise to some disadvantages and these are not adequately considered in favour of the standardization of the process and the thorough knowledge of it by the technicians. First of all, it is necessary to cool the air well below the needs of the conditioned ambient. Air cooled to 18–20°C would normally be enough; instead the cooling is usually 10 or so degrees below that. Thus the cooling equipment operates at COPs lower than normal.

Such cold air cannot be sent as such into the rooms for obvious reasons of comfort and it must be postheated with a process which is twice disadvantageous: first, thermal energy has to be supplied (although this is not particularly expensive, as it can be obtained free, for example by cooling of the cooling machine condenser); second, this thermal energy is a further input to the cooling load (and this means both a higher capacity required for the cooling machines and higher energy costs).

Most people do not consider an alternative procedure for air dehumidification: the treatment of the air by desiccants [4–6].

Desiccants are characterised by the property of attracting and holding moisture. Such a behaviour is not difficult to be surveyed. Natural and synthetic fibres, clays, human hair, cooking salt, all exhibit this ability to a greater or lesser extent.

True desiccants are materials able to attract and hold moisture many times their dry weight, like a sponge. The property can derive from the capacity of a material with a wide internal surface to attract and hold the water molecules within its capillaries; the process is called adsorption, the material is usually a solid and no chemical reaction takes place. The most common adsorbents are natural zeolites (aluminosilicate minerals), silica gels and synthetic zeolites (also called molecular sieves).

The property can also be due to a chemical process, as happens with the solution of water and salt; the process is called absorption and it frequently involves liquids. The most common liquid absorbents are triethylene glycol and aqueous solutions of salts like LiCl, LiBr and $CaCl_2$. Of course dry salt operates as a solid absorbent.

Both in absorption and in adsorption, the driving force of the process can be identified in the pressure difference between the water vapour partial pressure in the treated air and the partial pressure within the desiccant. This latter pressure is clearly lower at the ordinary temperatures of the treated air and it grows with temperature and the desiccant moisture content (Fig. 5). It then follows that the dehumidification capacity, once given the desiccant, finds two limits, respectively, in the increasing moisture content and in the progressive heating of the desiccant. The heating is due to the absorbed water vapour, which amounts to the heat of condensation increased by between 5 and 25% by the heat of absorption.

Thus desiccants must be regenerated and cooled before or during the dehumidification process. This operation will be considered later in the different devices. The regeneration is achieved by heating the desiccant to temperatures which usually increase as a function of increasing dehumidification ability.

In other words, the desiccant operates in a three-stage cycle (Fig. 6): water sorption, desiccant regeneration by heating and desiccant cooling before new water sorption.

After the process the amount of air dehumidification depends upon the desiccant, the flow rates and the amount of cooling. If no cooling is provided in the process, the air leaves with the same enthalpy as at the inlet, turning some of the latent enthalpy content into sensible heat. Thus the outlet air temperature is higher than the inlet; this is not necessarily penalizing, since sensible cooling can be cheaply provided, for example by tower water. The devices employed are different according to the type of desiccants, solid or liquid [7].

For solid desiccants the simplest possibility is to let the air pass through a bed of desiccant in granular form, whose depth is between 10 and 30 cm. Periodically, the substance must be reactivated by passing hot air through the bed, in order to obtain a continuous process, it is then necessary to provide two beds in parallel (Fig. 7).

Air to be dehumidified is admitted in the first bed A, whereas the reactivating hot air flow passes through the second bed B. When the adsorbent of the first bed is too weak, the processes are alternated with simple on–off valves. The resulting plant is cumbersome, but very simple; its main defect is that it does not give uniform conditions to the air at the outlet. This is well illustrated in Fig. 8, where the wet bulb temperature at the outlet is pictured as a function of time for a given flow rate of treated air, admitted at constant conditions, together with the dry bulb temperature and the moisture content. Starting from a rather high value of the dry bulb temperature, a rapid decrease is apparent, as long as the dehumidifying ability becomes weaker. When the dehumidification is not sufficient, the reactivation phase starts with hot air, which becomes very humid at the outlet, as is evidenced by the wet bulb temperature.

In order to complete the reactivation, the dry bulb temperature at the outlet must be higher than the highest outlet temperature during the adsorption phase.

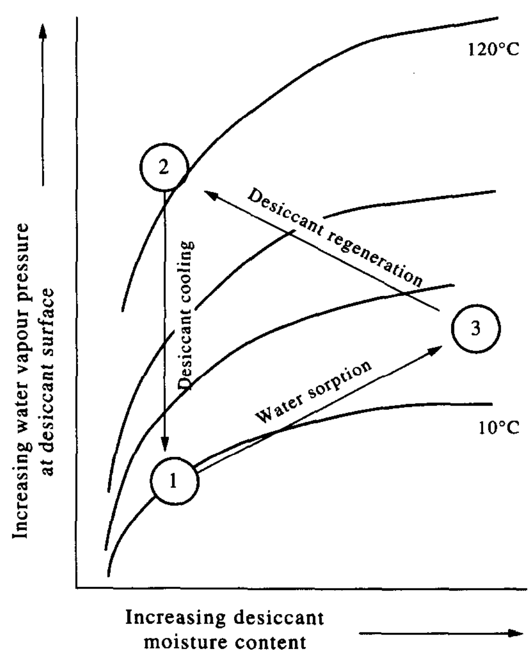

Fig. 6. The desiccant cycle.

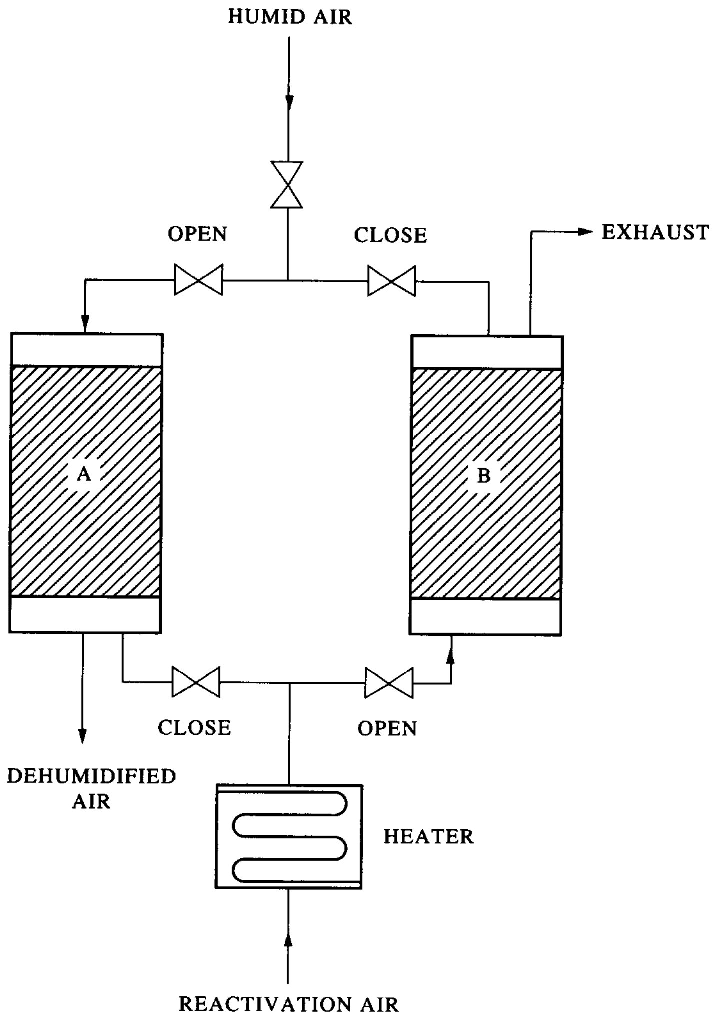

Fig. 7. Scheme of a dehumidifier with double adsorption bed.

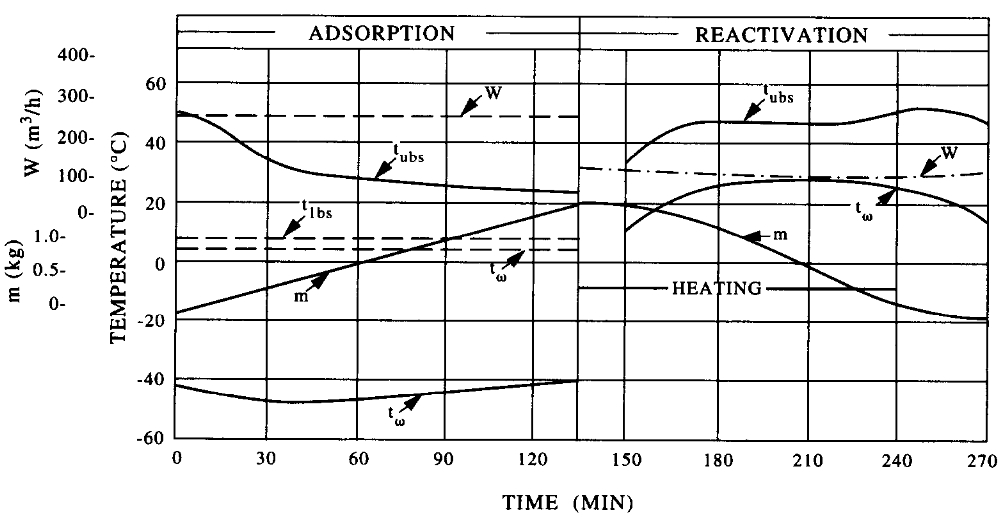

Fig. 8. Time history of some variables in adsorption–reactivation of an adsorption bed: W, air flow rate; $t_{i,bs}$, $t_{u,bs}$, $t_{i,r}$, $t_{u,r}$, inlet (i) and outlet (u) dry (bs) and wet (r) bulb temperatures; m, moisture content.

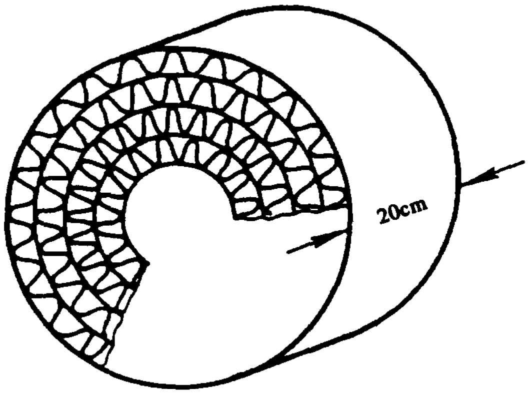

Fig. 9. Desiccant wheel.

A rotating system can allow one to realise a more compact device with more uniform air conditions at the outlet; it is made of a wheel formed of concentric support structures of sheets impregnated with desiccant (Fig. 9), either absorbents such as lithium chloride, or an adsorbent such as silica gel [8].

The air passes through the corrugated sheets; the air to be treated passing through part of the wheel, the other section taking the reactivation air. A fixed partition separates the two parts as in a regenerative heat exchanger (Fig. 10). The wheel turns slowly (from 0.5 to 6 revolutions per hour).

Typical performances for a desiccant wheel are represented in Fig. 11, where one can easily recognise the superior capability at a lower air temperature and the temperature increase through the wheel (outlet temperature on the right via the auxiliary hatched curves). The performance improvement increases when the variation of the humidity between the inlet and outlet widens.

As the air passes through the desiccant structure, it becomes drier and hotter so that the sorption is less effective. Simultaneous cooling of the desiccant can assure good sorption ability. This can be obtained by a cross-flow structure (Fig. 12); corrugated sheets of silica gel are superimposed within a plastic matrix. The air to be dehumidified is admitted from one side, whereas a cross-flow of cooling air enters from another (outside air or inside exhausted air). The elements must be periodically reactivated.

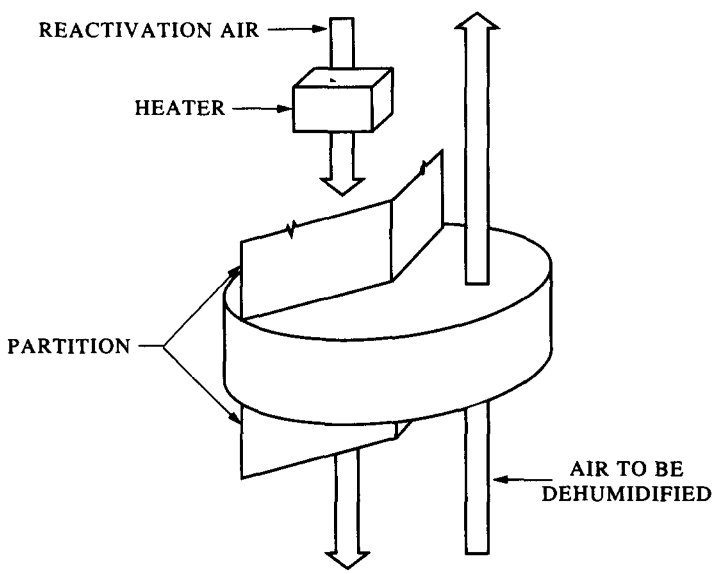

Fig. 10. Typical rotary dehumidification wheel.

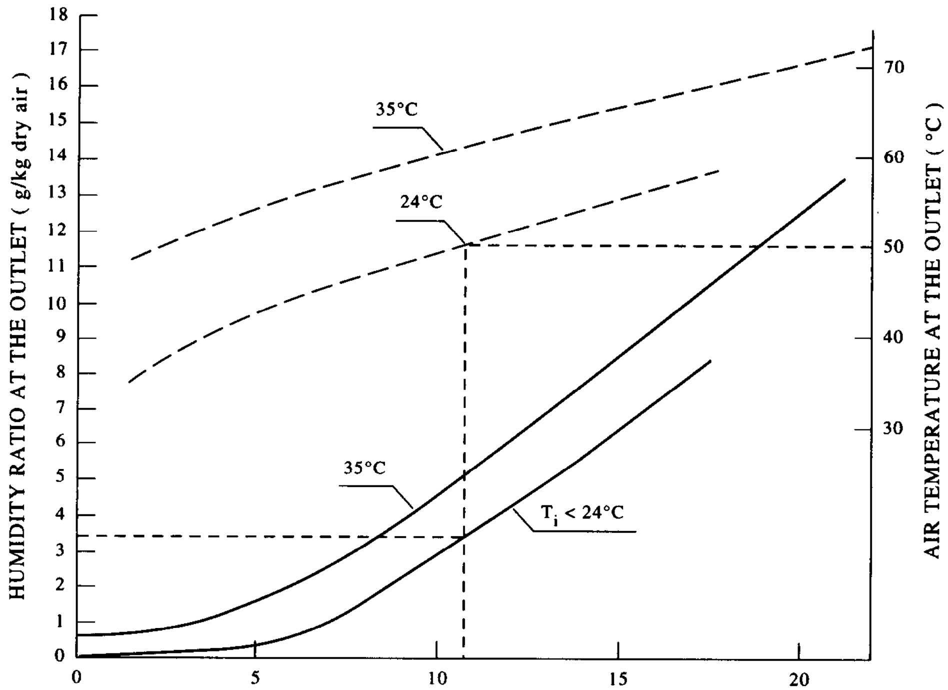

Fig. 11. Typical performance data for a desiccant wheel.

Operating with liquid absorbents the possible devices are basically four [9]:

1. The wetted-wall tower is simply a vertical pipe where a thin film of liquid runs down the wall with gas flowing either co-currently or countercurrently. It is a very simple device, but its efficiency is poor.

2. A tray tower is sketched in Fig. 13. The liquid is admitted at the top and flows downwards by gravity across each tray or plate to the outlet. The air enters at the bottom and passes upwards through openings in the trays, then bubbles through the liquid, forming a froth. Passing from one

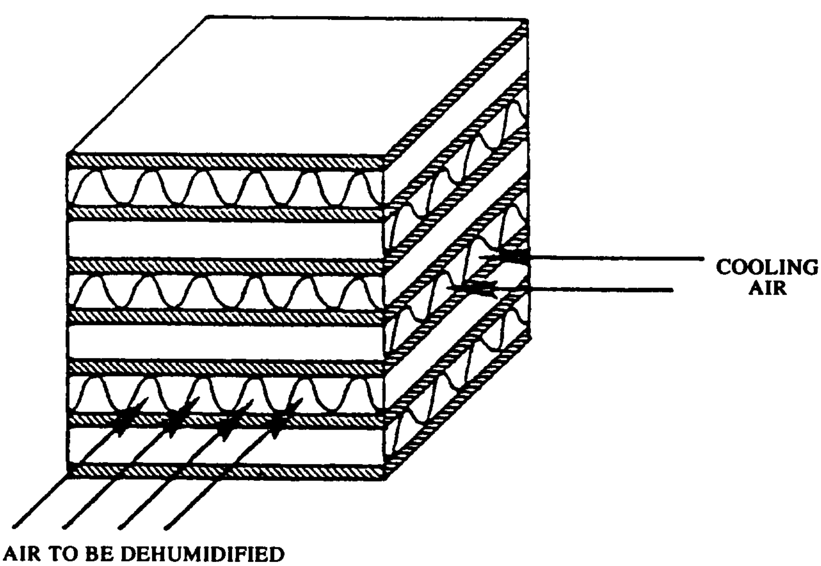

Fig. 12. Cross-flow dehumidifier.

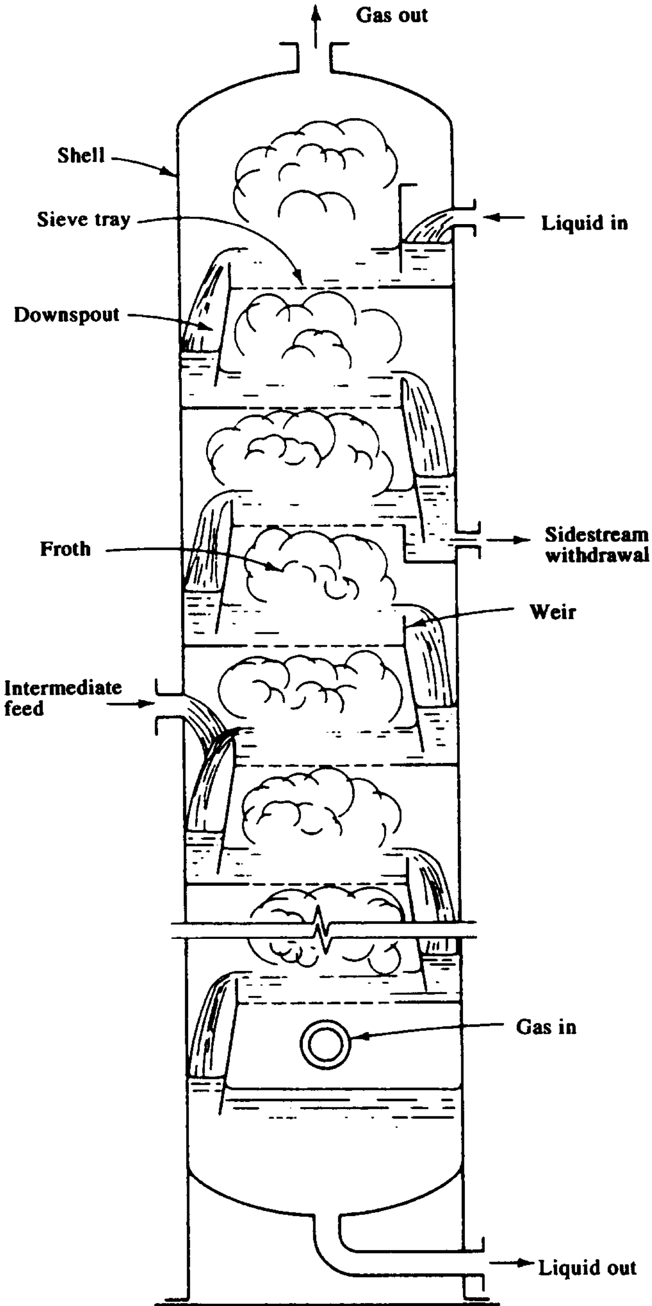

Fig. 13. A tray tower.

tray to the next the air arrives at the outlet. A correct choice of the parameters of a tray tower is provided by a difficult compromise, based on much experience, of the various parameters.

3. The spray chamber is basically a device where the air is admitted from the bottom and the desiccant is finely sprayed at the top through atomising nozzles (Fig. 14). The device has the advantage of small pressure drops for the air, but also some disadvantages which should not be underrated. First of all there is a high pumping cost for the liquid, owing to the high-pressure drop through the nozzles. Secondly the liquid is carried away by the air, so that very effective mist eliminators must be provided. Moreover, unless the diameter-to-length ratio of the chamber is very low, the air is practically wholly mixed with the spray and counterflow mass transfer cannot be achieved. Nonetheless, the diameter-to-length ratio cannot be reduced too much, otherwise the

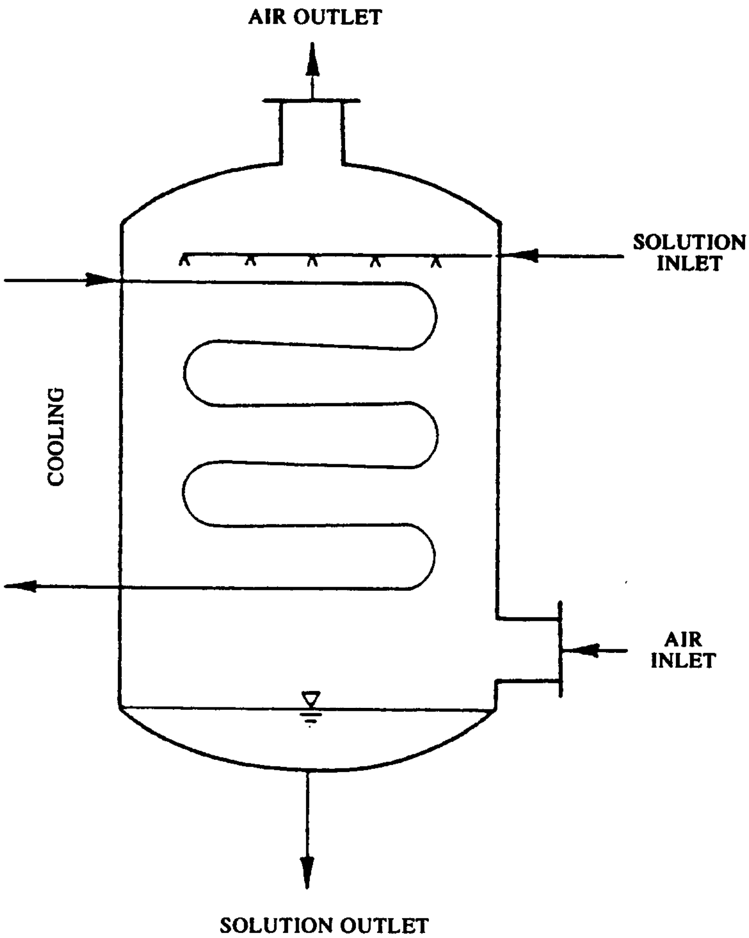

Fig. 14. Scheme of a spray chamber.

spray would soon accumulate on the chamber walls, losing its effectiveness. Finally another unfavourable feature of the spray chamber is the fast efficiency loss as soon as the operation moves outside its design range. A given spray chamber equipped with specific nozzles works well only for a limited range of desiccant and air rates and the efficiency greatly reduces outside that.

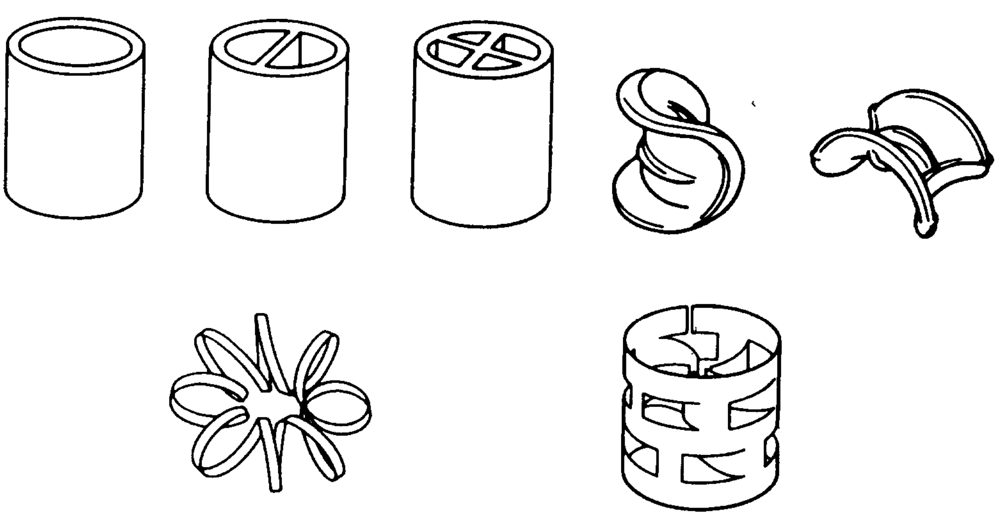

Fig. 15. Some random tower packings.

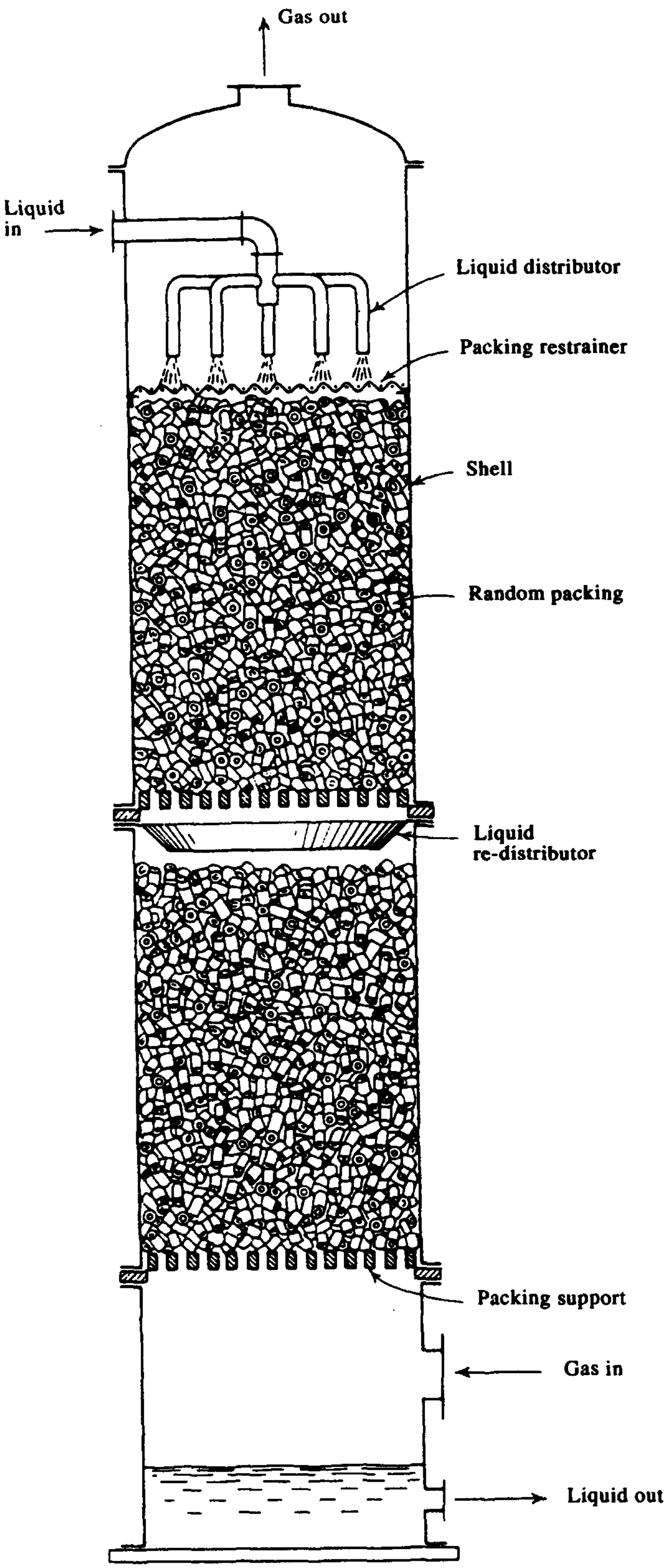

Fig. 16. A packed tower.

4. The packed column is a tower filled with packing elements. These are structures whose size is of the order of 1 cm, characterised by large surface area per unit volume. The most common packings (Raschig and Lessing rings, Intalox saddles and pall rings) are represented in Fig. 15. They can be realised in many different materials according to the needs, for example in plastics, ceramics or metal.

A typical shape of the tower is pictured in Fig. 16; the liquid, sprinkled from the top, wets the packing uniformly which gives a large surface area for exchange with the air blown from the bottom.

Very good counterflow is obtained with very low pressure drops for the liquid, relatively higher for the air, but still significantly lower than for the tray tower.

The packed column couples a great building simplicity and a wide operative range. Besides the mass transfer can be huge within a relatively small volume.

The useful life of desiccants depends on the amount and type of polluants in the treated air flow. The useful life can be from 10,000 to 100,000 h, but it is sometimes longer [10, 11]. At the same time the germicide property of desiccants, particularly in liquid form, and the air washing ability must be emphasised.

As long as the air is dehumidified, it can be worthwhile to provide simultaneous cooling within the dehumidification chamber. It is commonly obtained by a coil, wherein tower water flows. The regeneration of the solution can be implemented in an adjacent chamber (Fig. 17), where the desiccant is sprayed into an air flow heated by a coil carrying hot water [12–16].

As the conditioned spaces do not normally require very intense dehumidification, the regeneration temperatures need not be particularly high, usually below 100°C and often even below 80°C. Consider in Fig. 18 the outlet humidity as a function of the desiccant reactivation temperature, starting with an inlet humidity ratio of 8 g/kg (21°C). Good results are achieved (outlet humidity ratios of 5–6 g/kg), even for a reactivation temperature of 60–90°C. The interesting coincidence of these temperatures with even the lower levels of the recovered heat of reciprocating i.c. engines is apparent [17].

The possibility of exploiting thermal energy otherwise dissipated is a favourable feature of chemical dehumidification against the cooling and condensation method. Besides exploiting the available energy, it allows one to reduce appreciably the installed cooling capacity and often even the engaged electric power. It can be sometimes worthwhile to consider this technology even in the absence of a CHP system, using a gas burner instead. This is much the more favourable, as the latent load is higher than the sensible one [18].

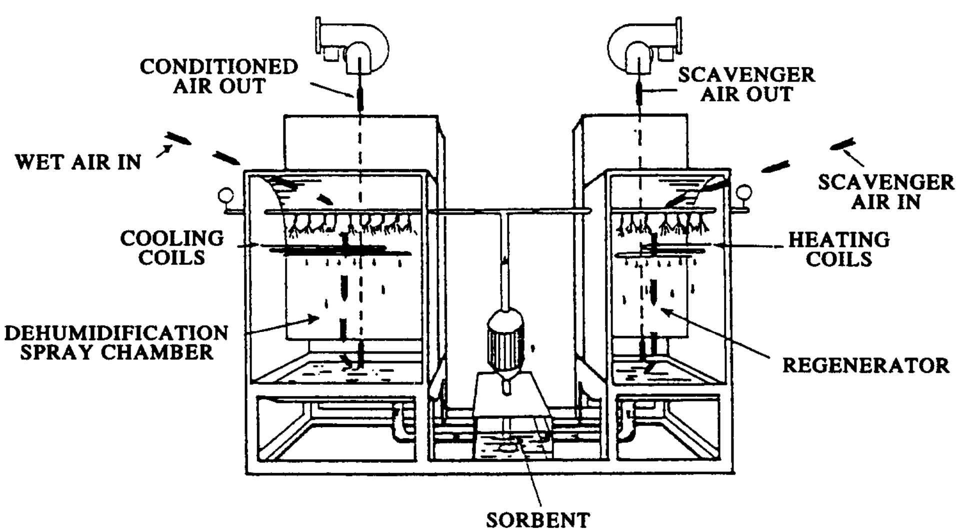

Fig. 17. A liquid absorbent dehumidifer with the reactivation section.

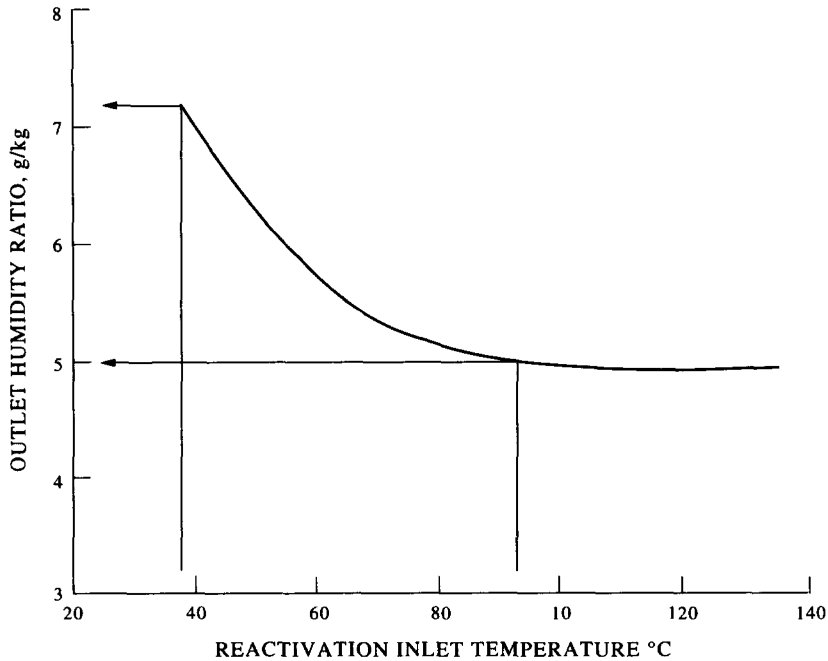

Fig. 18. Effect of changes in reactivation inlet temperature on the dehumidifier outlet moisture condition.

The latent heat in commercial buildings can be estimated to be 20–40% of the total load. In supermarkets it can easily be as high as 65%. In fact the presence of refrigerated cabinets requires careful control of the space humidity to avoid massive condensation on the cold surfaces.

Another typical situation appears in ice arenas, where the ordinary conditions of the space humidity imply strong condensation on the icerink with a great increase of the cooling load and a worsening in the quality of the ice surface. Chemical dehumidification allows one to keep the relative humidity as low as 30% with inside temperatures of 10–15°C, eliminating most of the cited shortcomings [19].

CONCLUSIONS

An alternative procedure for air dehumidification, i.e. treating the air by desiccants, allows one to achieve a better efficiency in air-conditioning as air needs only a moderate cooling, since its temperature can be well in excess of the dew point, avoiding postheating at the same time.

Moreover, the process can often be energised by waste heat recovery, such as the recovered heat of reciprocating i.c. engines. Evaporative cooling is another useful unconventional technique, able to reduce the costs of ventilation air and to improve the performance of chemical dehumidification.

Chemical dehumidification is particularly effective either by desiccant wheels, which resort mainly to adsorbents or by packed columns, which use liquid desiccant.

A better knowledge of chemical dehumidification processes can extend the possible applications, as the examples considered in a later paper will suggest.

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