SOLAR ENERGY FOR COOLING AND REFRIGERATION

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ABSTRACT

Solar refrigeration may have applications in both developed and developing countries. Applications in developing countries such as vaccine storage or large scale food preservation have been the subject of much research. In developed countries the main area of interest is air conditioning. Previous work on photo-voltaic and solar thermal systems is reviewed. Research at Warwick is underway on carbon - ammonia refrigerators driven by the heat of steam condensing in a thermosyphon heat pipe. The heat source can be solar energy, biomass, or some combination of the two. A new area of interest is the use of desiccant wheel technology for solar powered air conditioning. The basic principles are described and past experience assessed.

KEYWORDS

Refrigeration, solar, biomass, carbon, ammonia, adsorption, heat transfer

APPLICATIONS IN DEVELOPING COUNTRIES

There is a demand for cooling in many parts of the world where there is no firm electricity supply and conventional fuels are difficult or expensive to obtain. Requirements tend to be either for medical uses where a high capital cost per kW of cooling is acceptable, or for food (especially fish) preservation where the cooling power required is much greater and the acceptable cost per kW may be lower.

Vaccine storage refrigerators have been sold at a cost of £60-170 /W cooling [1], the lower cost being for a solar thermal system sold by the French company BLM and the larger for a typical photovoltaic system. These high costs are considered acceptable since the application is related to medical provision. Harvey [2] has shown that in the case of a fish storage ice-maker for Zambia, the required capital cost was £8.5/W and he concluded that a 1 tonne ice/day solar thermal refrigerator could be built to this price. There is little possibility that the higher costs per watt of the smaller units could be justified in larger plant.

Possible refrigeration cycles

There are five classes of cycle that can be used for renewable powered refrigeration systems. (Desiccant wheel technology for air conditioning is dealt with later)

1. A standard mechanical vapour compression cycle, requiring an electrical input to a hermetically sealed compressor. The electricity is generated by photovoltaic panels. This has the advantage of using off-the-shelf technology, but the disadvantages of high cost and the probable need for an electricity storage sub-system.

2. Intermittent adsorption cycles.
   Adsorption refrigeration cycles rely on the adsorption of a refrigerant gas into an adsorbent at low pressure and subsequent desorption by heating. The adsorbent acts as a 'chemical compressor' driven by heat. In its simplest form an adsorption refrigerator consists of two linked vessels, one of which contains adsorbent and both of which contain refrigerant as shown in Fig. 1 below.

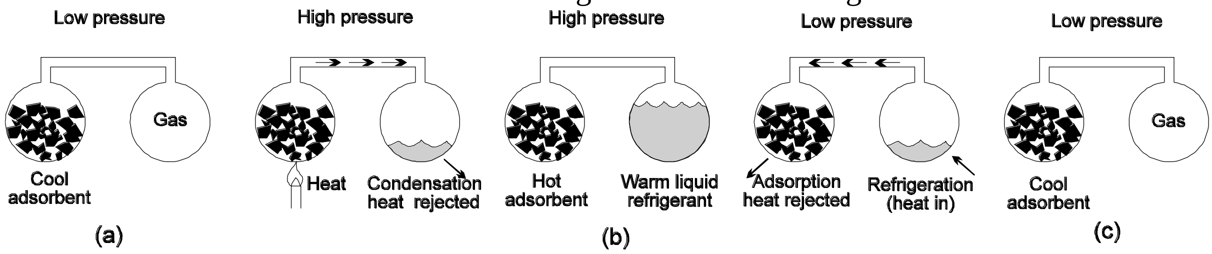

Figure 1

   Initially the whole assembly is at low pressure and temperature, the adsorbent contains a large concentration of refrigerant within it and the other vessel contains refrigerant gas (a). The adsorbent vessel (generator) is then heated, driving out the refrigerant and raising the system pressure. The desorbed refrigerant condenses as a liquid in the second vessel, rejecting heat (b). Finally the generator is cooled back to ambient temperature, readsorbing the refrigerant and reducing the pressure. Because the liquid in the second vessel is depressurised and boils, it takes in heat and produces the required refrigeration effect. The cycle is discontinuous since useful cooling only occurs for one half of the cycle. Two such systems can be operated out of phase to provide continuous cooling. Such an arrangement has a comparatively low Coefficient of Performance (COP = Cooling / Heat Input). Also, the thermal conductivity of the bed is generally poor so the time taken for a cycle could be an hour or more and the cooling power per mass of adsorbent could be as low as 10 W/kg. This is not a problem with solar powered vaccine refrigerators which produce a few kg of ice each day and operate on a diurnal cycle (Critoph [3]). However, a refrigerator producing one tonne of ice in a diurnal cycle would need 5 tonnes of carbon and contain 1.5 tonnes of ammonia. When contemplating larger icemakers it is obviously necessary to use a much faster acting cycle in order to reduce the mass of adsorbent and the cost of the system. Two beds, similar to the one shown above, can be heated and cooled out of phase to provide continuous cooling Good heat transfer is required to reduce the cycle time to a few minutes and thereby increase the power density of the adsorbent to the order of 1 kW/kg. We can also achieve a higher COP by maximising the quantity of heat regenerated. The heat rejected by one bed when adsorbing can provide a large part of the heat required for desorbing in other bed. This also requires good heat transfer.

3. Intermittent absorption cycles
   These are thermodynamically identical to adsorption systems but use liquid absorbents rather than solid adsorbents. Typically the pair used is ammonia-water, but ammonia-NaSCN, methanol-LiBr and other pairs have been used experimentally.

4. A continuous absorption cycle with an electrically driven feed pump eliminates the problems of bulk, but if electricity is available to drive a solution feed pump then it could be argued that it would be better to use a conventional vapour compression cycle. The use of a small amount of photovoltaic electricity to drive a feed pump might be justified.

5. The Platen-Munters diffusion absorption cycle is continuous and does not use a mechanical pump. It is used successfully in small gas or kerosene refrigerators and freezers but has proved difficult to adapt to larger sizes and to irregular heat sources such as solar energy.

Energy Efficiency

No mention of Coefficient of Performance (COP), the ratio of cooling to energy input has been made in the above discussion. This is partly because of the difficulty of comparing systems under different conditions, but also to avoid the inference that COP is the most important parameter. Commercialisation will depend on the total cost of capital equipment, maintenance and fuel over the lifetime of the plant. In a solar thermal system where the collectors probably dominate the capital cost, and the fuel cost is zero, it can be argued that a high COP reduces collector area and thus the total cost. However, if the consequences of a high COP are complexity and unreliability then other costs may rise. As a rough guide one may say that internal COP (cooling / heat to generator) of thermal systems can range from 0.1 (typical) to 0.5 (best) for a Platen-Munters machine, 0.2 to 0.5 for intermittent sorption systems and up to 0.7 for intermittent regenerative cycles. Vapour compression machines with an electricity input would have typical COP’s of 1.0 to 1.5.

Past Experience of Renewable Energy Refrigeration Systems

Photovoltaic vapour compression systems have predominated in the area of small medical refrigerators since their high cost can be justified in these applications. Initial field testing showed them to be unreliable [4], suffering from simple faults which were difficult to rectify under field conditions. However there are now many companies manufacturing them and the reliability problems would appear to have been overcome.

There have been several solar thermal icemakers marketed. The Danish company Kaptan ApS produced an intermittent adsorption refrigerator based on the ammonia - calcium chloride pair investigated by Worsøe-Schmidt [5]. The French company BLM produced and sold a series of intermittent adsorption refrigerators using the active carbon - methanol pair [6,7]. Both of these concepts were technically successful but neither are produced now. The BLM range was discontinued after a company take-over. More recently, Dornier have tested solar icemakers using the strontium chloride - ammonia pair. A field trial in Delhi was partially successful but needs further development [8]. Iloeje [9] has succeeded in building and testing an experimental ammonia - calcium chloride system in Nigeria but it is not manufactured commercially.

There are fewer examples of larger icemakers and they are experimental prototypes rather than commercial products. A 100 kg/day ice-maker was built in Thailand by Exell and Kornsakoo [10]. This was a 25 m^2 collector ammonia - water refrigerator working on a diurnal cycle. This did not produce its full yield due to problems with the evaporator design but was otherwise successful.

Saunier and Reddy [11] tested a similar but biomass fuelled device in Thailand. Neither system was developed commercially. Harvey [2] investigated a regenerative version of the same cycle with approximately twice the COP and costed a 1 tonne / day machine for use in Zambia. He concluded that this technology, whilst more energy efficient, is limited by its bulk and the possible need for maintenance of moving parts.

Imam Osman Ahmed *et al* [12] tested a continuous ammonia - water refrigeration system in the Sudan. The feed pump was electrically driven. The project was beset by technical difficulties which prevented successful operation.

Various authors have suggested the use of the Platen-Munters ammonia - water - hydrogen continuous diffusion absorption cycle for solar refrigeration. It is of course already used in kerosene or LPG powered refrigerators. Various attempts, e.g. Upal [13], Guttierez [14] to adapt existing equipment from its normal generating temperature of 200°C down to temperatures more suited to solar collectors (140°C or less) have proved unsuccessful in terms of overall efficiency and general utility. However, Persson and Svensson [15] and Svensson and Hansson [16] have carried out theoretical studies showing that good efficiency is feasible with purpose built designs.

Hinotani [17] built and tested a purpose designed solar diffusion absorption refrigerator. The generaator design was successful in that the solution pumping rate was near the optimum over the full range of generating temperatures. However, difficulties with the hydrogen flow rate were encountered, giving poor evaporation of the generated ammonia and an overall (solar) COP of less than 0.05. Platen-Munters systems are normally restricted to low power since the mass flows within them are limited by the weak buoyancy forces that drive the gas round. However, Stierlin and Fergusson [18] reported on a 3 kW heat pump / 1kW refrigerator built by SIBIR. This machine was 2m high in order to provide sufficient buoyancy to pump gas at the required rate. The main difficulty in adapting the Platen-Munters cycle to solar operation is in designing it to cope with the large range of input powers that are experienced in practice.

ADSORPTION REFRIGERATION RESEARCH FOR DEVELOPING COUNTRY APPLICATIONS AT WARWICK UNIVERSITY

The most expensive part of all solar refrigeration systems is the collector array. If the system is to be economic then ways must be found to minimise the cost. The total area of collector can be reduced by utilising a back-up energy source during periods of low insolation. The source can be a renewable one such as the combustion of agricultural waste i.e. bagasse, rice husks, etc. In some locations there may be enough biomass to dispense with the solar input completely and use a biomass source. If collectors are used in what are bound to be large arrays, there is a case for using an intermediate heating fluid in order to reduce the cost. Many thermally driven refrigeration cycles use ammonia as the working fluid and the cost of constructing solar collectors which heat the fluid at pressures of up to 25 bar could be prohibitive. Other types of machine use water or methanol as refrigerants but in these cases the collectors suffer from the problems of having to be hermetically sealed against air ingress. Any inward leakage of air can stop the system working. The solution preferred here is to use collectors which will boil water in a thermosyphon heat pipe arrangement which does not require a pump and yet provides excellent heat transfer between the collector and refrigeration unit. Such a heating arrangement is also ideally suited to the use of burning biomass as a heat source, whether as a back-up or as sole source. Our research is concentrating on the use of adsorption cooling systems which receive heat either from a thermosyphon heat pipe or from a pumped thermal fluid. The former is probably more suited to remote applications.

Early attempts to improve adsorbent bed heat transfer by using finned heat exchangers within them [19] were only of limited success. Attention turned to the use of composite adsorbents with either graphite flakes or metal foams to improve conductivity [20,21]. These do allow higher power densities but the problem of obtaining a high regeneration effectiveness between beds is still comparatively complex. The U.S. company Wave Air patented a ‘Thermal Wave’ cycle [22,23] in which a thermal fluid is pumped through a special heat exchanger in each bed. This sets up heating and cooling waves in each bed in a similar way to those produced in normal heat recovery regenerators and gives good COP’s. This idea is also being evaluated by European groups [24].

The UK company, Sutcliffe Speakman Carbons, has developed processes for making solid blocks of almost any type of carbon in a wide variety of shapes. The details are confidential but may be summarised

by saying that the powdered carbon is either compressed with an organic binder to make briquettes or extruded through a die. The 'green' material is then fired in a furnace. The initial application that prompted this development was the storage of methane as a vehicle fuel, but it is equally useful in refrigeration applications. Monoliths up to 100 mm in diameter have been made. The ammonia adsorption properties of the monoliths have been measured by Critoph (25) and it has been shown that they offer greater storage density for ammonia than conventional granular beds of carbon. The thermal conductivity of the material is three times that of a granular bed. Whilst this is a large improvement, if power densities of 1 kW/kg are to be achieved small conduction path lengths are still needed. Turner (26) and Davies (27) have used finite difference modelling to show that a path length of approximately 3 mm is appropriate.
Sutcliffe Speakman Carbons donated monolithic discs of 208C carbon, 100 mm in diameter and 15 mm thick, with a 25 mm central hole. An experimental generator was designed around the disc dimensions. The discs were machined down slightly to improve the surface finish. This is necessary to ensure a good heat transfer coefficient between the disc and metal heat transfer surface. In order to maximise the intensity of heat transfer, thermosyphon heat pipes were used both to heat the carbon in the desorption phase and to cool it in the adsorption phase. Fins were used to enhance heat transfer within the bed.

Experimental rig

The layout of the experimental rig is shown in Fig. 2 The main components are the generator, the boiler, the condensers (two) and the receiver-evaporator.

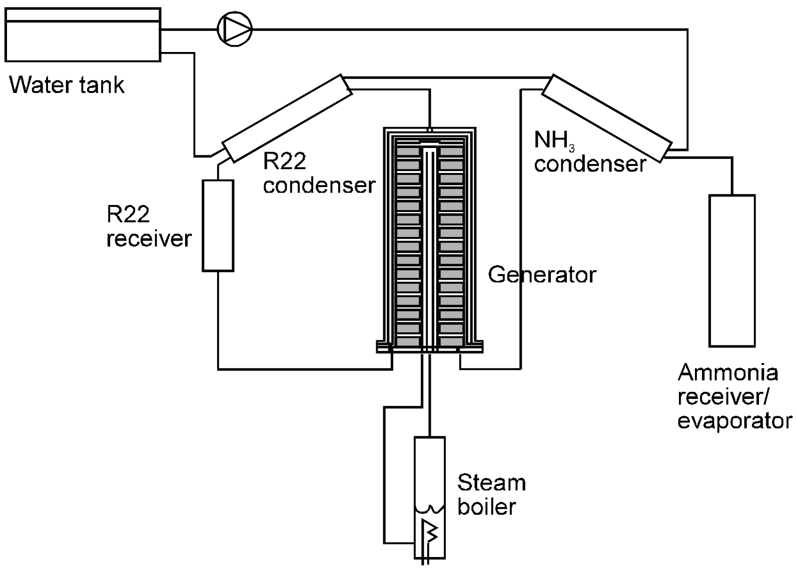

Figure 2: Schematic of heat transfer test rig

The generator (Fig. 3) is made of aluminium and contains three enclosed cylindrical volumes. It is formed by a hollowed inner shell (outside diameter of 25 mm with a thickness of 6 mm) and two outer vessels. The outside surface of the inner shell has fins between which are placed 15 monolithic carbon discs. The fins are approximately 5 mm thick, 32 mm long, 18 mm apart and 90 mm in diameter. They have slots to allow the distribution of ammonia between all the carbon discs in the generator. Each disc is cut radially in two equal parts before being inserting between two fins. The total mass of carbon is about 800 g. During the operating cycle, each of the three volumes contains a different working fluid. These fluids are steam, ammonia and R22 respectively. In the heating phase the carbon is heated by steam supplied to the centre hollow, whilst in the cooling phase the carbon is cooled by boiling refrigerant R22 in the outer shell.

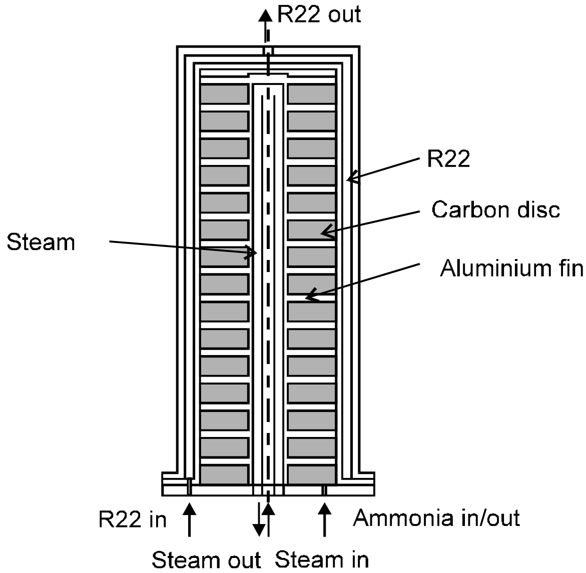

Figure 3: Cross section through generator

The steam boiler is made out of copper tube. An electrical heating coil, which is inserted at the base the boiler, can produce steam ranging from 100º C to 150º C. The steam circuit has a pressure gauge and a pressure release valve to relieve any excess pressure. The heating power is controlled by a variable supply unit and its maximum value is 2 kW.
The ammonia condenser is a concentric tube counter-flow type. The water (coolant) flows in the annulus of the condenser whilst ammonia condenses in the tube part. The outer tube is made out of copper whilst stainless steel is used for the inner tube which contains the ammonia.
The R22 condenser, used when cooling the generator is of similar type but both tubes are copper with R22 condensing in the inner tube. For convenience and to limit the water used, the two condensers (ammonia and R22) use the same network of cooling water. The cooling water is stored in a tank that is temperature controlled by means of an immersion heater with a thermostat. A small pump is used to circulate the water.
The receiver - evaporator made out of stainless steel is a vessel of 300 ml capacity. It collects the condensed refrigerant at up to 20 bar (50º C). A capacity probe is fitted to measure the amount of ammonia liquid collected. After the heating phase the receiver is inserted inside an ice bucket that contains water and that is well insulated. The ammonia cools and freezes water as it evaporates during the cooling phase of the system.
The temperature-time profile at a point within the bed is measured by stainless sheathed K-type thermocouple with a diameter of 1 mm. The steam and ice temperature profiles are measured with three thermocouples of the same type. Two pressure transducers are used to measure the ammonia pressure profiles respectively inside the bed and the receiver.

Experimental results

Experiments have been carried out in which the generator has been heated by steam condensing at 120º C and a heating time of 10 minutes. The experimental results are compared with a numerical simulation in Fig. 4. These tests correspond to cycles having a comparatively low COP of 0.10 because the carbon temperature is only raised to 110ºC. Later experiments will heat the carbon to 130º C, with expected COP’s nearer to 0.3. The heat input to the carbon averaged 300 W/kg, but this could be increased by a factor of at least two if higher temperature steam were used. The carbon disc dimensions were not optimised for this application and so whilst the experiment has confirmed our heat transfer modelling assumptions it was not expected to reach much higher power densities.

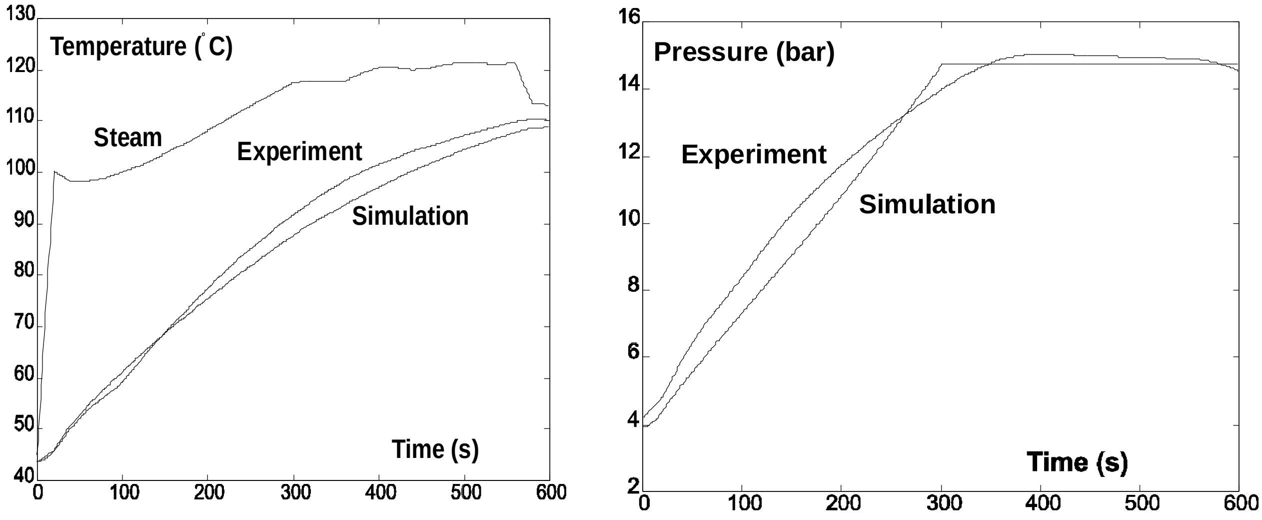

Figure 4: Experimental and simulated generator conditions

Current developments

We have concluded that the best way to exploit the potential of the material is to experiment with the possibility of forming the carbon blocks integrally with the heat transfer surface or fin. In granular beds the gas space between the metal surface and adjoining grains has a high thermal resistance. Since grain packing near a wall is less dense than within the bed the effective bed conductivity is reduced near the wall. This is normally modelled by assuming a low heat transfer coefficient (or high thermal resistance) between wall and bed. The use of a monolithic block of carbon reduces the thickness of the gas space, but its thermal resistance still limits the heat transfer. If the monolith is actually formed around the heat transfer surface, the contact resistance between carbon and metal should become negligible. If consolidation of the bed around fins or tubes proves to be not feasible or uneconomic there are alternatives that will still reduce the gas space resistance significantly. A number of design concepts exist. We are evaluating a thermosyphon heat pipe in a tubular design as shown in Figure 5. We have measured the effect of manufacturing process options on material properties, modeled the heat and mass transfer in a number of design options, and are constructing a 3 kW cooling generator. The estimated power density of the adsorption generator is close to 1 kW cooling / kg carbon which it is hoped will lead to final designs that are compact and have low manufacturing costs.

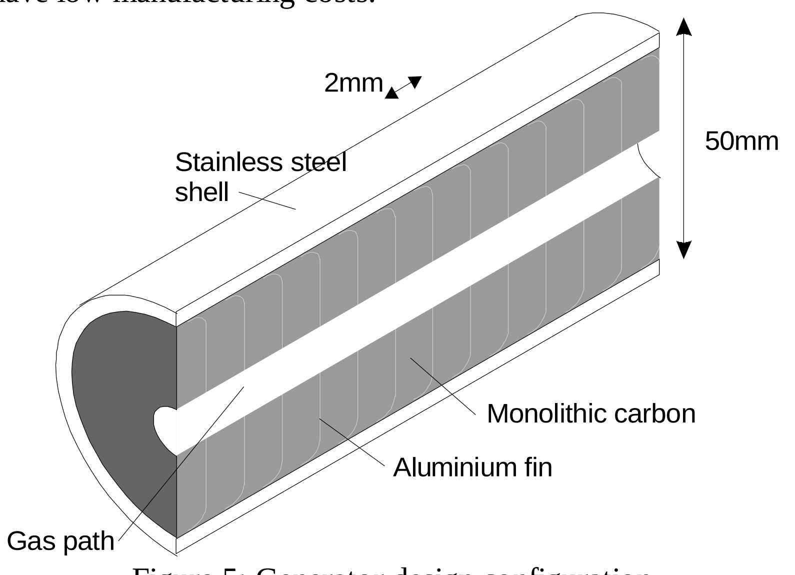

Figure 5: Generator design configuration

APPLICATIONS IN DEVELOPED COUNTRIES

In developed industrialised countries where there is grid electricity, there is no cost effective application for solar powered refrigeration of food, medicines etc. However, there may still be the possibility of cost-effective solar air conditioning. The target cost per unit of cooling must be competitive with conventional systems, perhaps around £1 / Watt. None of the above mentioned systems are likely to achieve this figure. A few photovoltaic powered air conditioning systems have been built experimentally, but they are prohibitively expensive. Evacuated tube solar collectors have been used in conjunction with conventional Lithium Bromide - Water absorption air conditioners but are still far too costly and complex. The best possibility for cost effective solar powered air conditioning appears to be desiccant cooling.

Desiccant cooling has been known and available for many years but has become popular in recent years due to two factors. The first is that the damage to the ozone layer by conventional chlorofluorocarbon refrigerants has necessitated the search for alternatives to vapour compression refrigeration. Secondly, the need to replace the peak load demand for electricity for air conditioning applications coupled with the desire of gas utilities to balance their heating loads with a summer alternative has lead to the development of heat powered refrigeration cycles. The result has been research into improved desiccant materials and cycles to both improve performance and reduce costs.

Desiccants are substances that have a strong affinity for water and, because of this, can absorb moisture from an air stream. Desiccants can be solids such as lithium chloride, silica gel or molecular sieves, or liquids such as glycol, sulphuric acid or lithium bromide solution. There is a partial pressure of water vapour than can exist in equilibrium with a desiccant at a particular temperature. If the actual vapour pressure is above the equilibium value, moisture will be absorbed, but if it is lower then moisture will evaporate from the desiccant. The process is therefore reversible.

The most common arrangement of desiccant system is the desiccant rotor. A desiccant rotor consists of a honeycomb support which has been impregnated with a finely divided desiccant. As air flows axially through the narrow honeycomb channels, moisture is absorbed by the desiccant. The design of the rotor gives a large surface area of contact between air and desiccant. As the air stream passes through the rotor, moisture is absorbed and the heat of absorption, almost equal to the latent heat of condensation, is released. The resulting air stream is therefore warmer but drier. The latent enthalpy contained in the moisture vapour is effectively exchanged for sensible enthalpy in the temperature of the resulting air.

It is arranged that the rotor rotates slowly so that desiccant that has been exposed to moist process air moves into a separate sector. Here warm air, in which the vapour pressure is less than the equilibrium vapour pressure, carries away moisture that evaporates from the desiccant on the rotor

A schematic of a desiccant cooling system is shown in Figure 6. Latent heat contained in the fresh air (1) drawn into the building is exchanged on the desiccant rotor for sensible and the air temperature rises. This warm dry air (2) is then passed through a heat wheel. The heat sink for the heat wheel is extract air (5) from the building that has been cooled by evaporative cooling (6). The resulting air stream (3) is therefore cool and dry. If moisture is added to this air stream, evaporative cooling takes place and cool air (4) is supplied to the building.

The warm moist extract air (6) after the heat wheel is heated further and the hot gas (7) passed through the desiccant rotor. Moisture leaves the rotor and so a warm moist air stream (8) is discharged to outside the building.

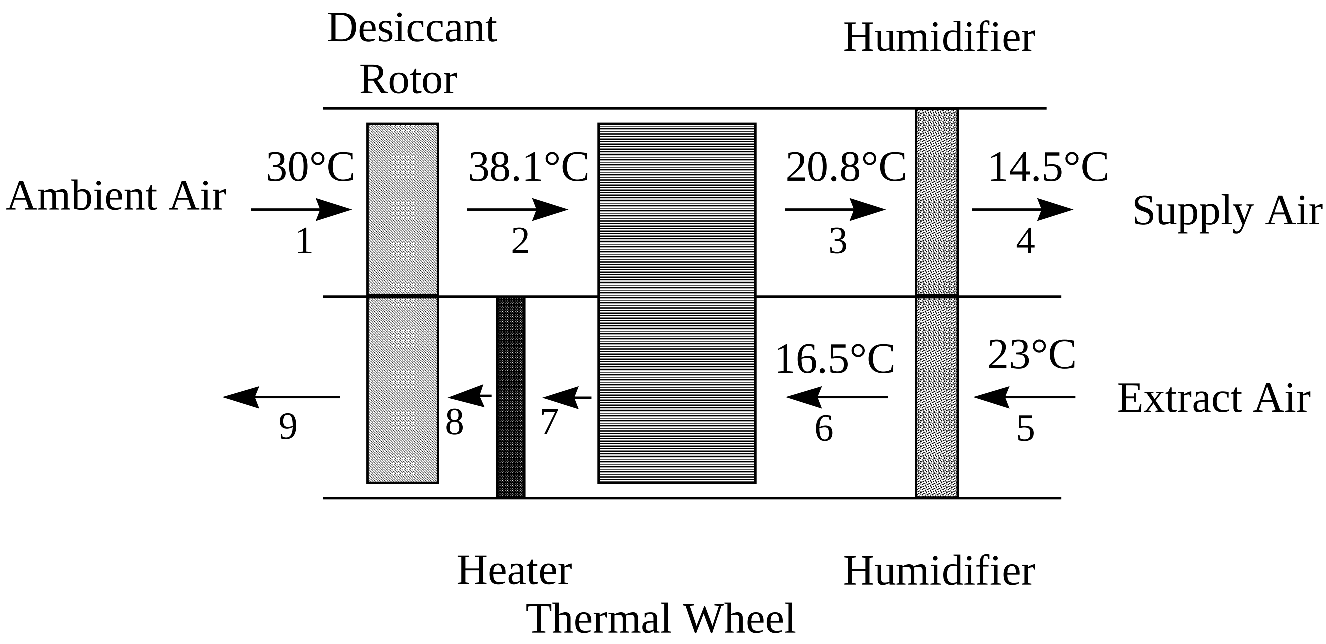

Figure 6: Schematic desiccant cooling system

The benefit of a desiccant cooling system is that the air temperature required for reactivating the desiccant rotor needs only to be in the region of 50° to 80°C. Air in this range can readily be provided from an array of solar heating panels. Also, by the addition of a second heat exchanger in the supply air and by stopping the evaporative cooling, the system can be used to heat the building with excellent recuperation of the heat from the extract air.

A number of solar assisted air conditioning systems using desiccant wheels have been evaluated in Germany [28], Sweden [29] and in the USA where a system has been installed in a Kentucky Fried Chicken Restaurant in Florida [30]. These systems normally use solar energy together with a gas fired heater backup in order to provide a cost-effective solution.

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