

## SOLARPOWERED/GASHYBRIDAIRCONDITIONING

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### ABSTRACT

Theairconditioningindustryhas, inrecentyears, comeundersustainedattackfromarangeof economic, environmentalandregulatorypressures. Globalenvironmentalconcerns, improving standardsofventilation andincreasingconcernsaboutindoorairqualityhaveallcontributed toachangeindesignthinking. Professionalguidanceisincreasinglysteeringclientsand consultantsawayfromfullairconditioningtonaturalventilationandmixed -modesolutionsin newandrefurbishmentprojects. Neverthelessinefficientlighting, increasesincomputing equipmentandarchitecturalfashionmeanthatoverheatingisthepredominantdesign considerationfornewofficesintheUK.

Thisituationislikelytoworsenifglobalwarmingsscenariosareaccurate. <sup>1</sup>Henceitisvitaly importantthatthebuildingindustryseeksinnovativemethodsofmaintainingandimproving thequalityoftheindoorenvironment, underpotentiallymoredemandingperformancecriteria, withoutincreasingenvironmentalimpact. Theoccurrenceofcoolingpowerinphasewith coolingloadsuggestsacompellingargumentinfavourofconsiderationofairconditioning poweredbythesundisplacingpeakloadelectricityinsummer.

Desiccantcoolingisapotentallybenigntechnologywhichcanbeusedtoconditionthe internalenvironmentofbuildings. Unlikeconventionalairconditioningsystemswhichrelyon electricalenergytodrivethecoolingcycle, desiccantcoolingisoneofanumberofemerging heat drivencycles. Byusinggas -solarhybriddesiccantcoolinganddehumidification technologyitmaybepossibletoofferabenignsolutiontocoolingofbuildings, innewand refurbishmentsituations, reducedependenceonharmfulrefrigerantsandsignificantlyreduce greenhousegasemissionswhichresultfromairconditioningdemands.

Thispaperisadevelopmentofanearlierstudy, andusesrealmeteorologicaldatatoevaluate thefeasibilityofusingsolarenergytodrivethedesiccantcoolingcycleina UnitedKingdom application. Throughtheuseofparametricstudies, thepaperinvestigatestheenergy consumptionandcostsassociatedwithsolardesiccantcooling. Asteadystatedesiccantmodel hasbeendevelopedwhichinitiallyinvestigatedthesolarcontributiontothecoolingloadfora rangeofventilationratesandregenerationtemperatures. Amodelwasthendevlopedto predicttheheatavailablefordesiccantregenerationforanygivensetofmeteorologicaldata, solarcollectoralgorithmandorientation. Earlyindicationsarethatasignificantamountofthe coolingloadcanbeprovidedfromthesolarenergy(50%)withsavingsinrunningcostand reductioninCO<sub>2</sub>emissions.

## 1.0 THE CONTEXT

If we are to seek development strategies compatible with the economic and environmental sustainability then we must seek to design systems which are largely self-sustaining and do not involve excessive operational complexity. Passive systems and renewable technologies are the ones to which we must aspire if we are to create a truly sustainable built environment. In an ideal world mechanical systems would act as efficient supplements to natural systems rather than as complete replacements for them.

In the UK there is an abundance of climatically inappropriate buildings. For reasons of assumed architectural merit, perceived commercial efficiency or even environmental protection (from polluted outdoor spaces) buildings have evolved energy intensive forms and fabrics. Inefficient lighting, increases in computing equipment, occupant expectations and architectural fashion mean that overheating is the predominant design consideration for new offices in the UK. Older buildings often constrain natural solutions. Ironically there is significant concern about rising temperatures; both as a global phenomenon and due to local urban heat island effects, which is likely to impact upon design margins if global warming scenarios are accurate.<sup>2</sup>

According to government sources: -

It is unlikely that an expansion in the amount of air conditioning used in the UK can be resisted.<sup>3</sup>

The driving force towards an increased reliance on air conditioning are seen as: -

The continuing deterioration of the quality of air in cities and the increasing level of noise due to traffic growth.<sup>4</sup>

Nonetheless the air conditioning industry is under economic, environmental and regulatory pressures. Global environmental concerns, improving standards of ventilation and increasing concerns about indoor air quality have contributed to a change in design thinking. Professional guidance is steering clients and consultants away from full air conditioning to natural ventilation and mixed mode solutions in new and refurbishment projects. The research project described in this paper has therefore been undertaken in the context of reducing the demand for air conditioning through the use of passive measures (attention to building mass, improved shading, minimising indoor gains, and good control) and low energy cooling strategies but with the knowledge that there are perceived limitations to the use of natural ventilation strategies. In addition recommendations of best practice approaches for the research have been identified.<sup>5,6</sup>

An important concept in passive/mixed mode building design, is that of a variable indoor air condition. Traditionally, building designers have used air conditioning to produce a rigid indoor environmental condition (e.g. 21 °C and 50% relative humidity), often resulting in unnecessarily high energy consumption. By contrast the passive/low energy approach is to allow indoor air conditions to float between acceptable limits (i.e. higher indoor air temperatures in summer, and lower indoor temperatures in winter). Consequently, the studies described in this paper assume a variable indoor air condition. They have been designed to test whether or not acceptable room air conditions are achievable for a variety of outside air conditions. Also, it should be noted that the work described in this paper is a feasibility study,

and not the formulation of a formal operating and control strategy for a desiccant cooling system.

## 2.0 THE STUDY

This paper investigates the potential in the UK for exploiting solar energy to drive desiccant cooling systems. The parametric energy studies reported in this paper were carried out using a solar desiccant computer model developed at the University of Leeds, and follow on from previous work by Halliday and Beggs<sup>7</sup> and Beggs and Warwicker<sup>8</sup>.

In a typical desiccant cooling system a desiccant wheel is coupled to a thermal wheel in a single air handling unit (AHU), Figure 1, to produce a system which is capable of heating, cooling, and dehumidifying air, with little or no need for refrigeration.<sup>9</sup> The system is an open heat drive cycle in which the heat required to drive off the moisture absorbed by the desiccant surface, is provided by a low temperature hot water (LTHW) regeneration coil located before the desiccant wheel in the exhaust air stream. Being a heat drive cycle, it has the potential to reduce both energy costs and environmental pollution, when compared with conventional vapour compression based systems.

Figure 1. Desiccant Cooling System

Figure 2. Psychrometric Process

The cooling/dehumidification process is illustrated by the psychrometric chart shown in Figure 2. During the summer time warm moist air at for example 26 °C and 10.7 g/kg moisture content is drawn through the desiccant wheel leaving at say, 39 °C and 7.3 g/kg moisture content. The psychrometric process line for the air passing through the desiccant wheel on the supply side, has a gradient approximately equal to that of a winter time room ratio line of 0.6 on the psychrometric chart. The supply air stream then passes through the thermal wheel where it is sensibly cooled to say, 23 °C. The air then passes through a small direct expansion (DX) or chilled water cooling coil and is sensibly cooled to the supply condition of say, 17 °C and 7.3 g/kg moisture content. It should be noted that if humidity control is not required in the space, then the cooling coil can be replaced by an evaporative cooler with an adiabatic efficiency of approximately 85%. In which case, air may be supplied to the room space at say, 16.2 °C and 10.2 g/kg moisture content.

On the return air side, air from the rooms at for example, 22 °C and 8.6 g/kg moisture content is first passed through an evaporative cooler so that it enters the thermal wheel at approximately 16.7 °C and 10.8 g/kg moisture content. As the return air stream passes through the thermal wheel, it is sensibly heated to approximately 33 °C. The air stream is then heated up to approximately 55 °C in order to regenerate the desiccant coil. It should be noted that in order to save energy approximately 20% of the return air flow by-passes the regenerating coil and the desiccant wheel.<sup>10</sup>

## 3.0 SOLAR APPLICATION

Any heat driven cycle affords an opportunity to utilise heat which might otherwise be wasted. It can therefore be coupled to solar collector to produce a cooling system. However, the use of solar energy puts constraints on the application of desiccant cooling. Assuming a ratio of solar collector to building floor area of 1:10, gives available heat (in the UK) to power the cycle of  $25 \text{ W/m}^2$  to  $50 \text{ W/m}^2$ , depending on the climate, type and orientation of the solar collector. If this heat is to be harnessed effectively, the desiccant cooling system must be applied in the correct fashion. The desiccant cooling cycle is essentially an open cycle, which rejects moisture at a high temperature, which is unsuitable for recirculation. Consequently, the greater the air volume flow rates supplied, the greater the fan power required and heat energy consumed. If desiccant cooling is used in an all air application, the parasitic losses will be large and the regeneration heat load is going to be many times greater than the available solar energy. However, if the bulk of the sensible cooling within a space is carried out using a water based system such as a chilled ceiling, with the desiccant AHU dehumidifying and tempering the incoming fresh air, then the air volume handled will be much less and solar energy may make a significant contribution.

This is confirmed by theoretical work by Beggs and Warwicker<sup>11</sup> which showed that desiccant cooling is a best applied to installations in which the bulk of the sensible cooling is performed by a water based system, such as a chilled ceiling. The desiccant cooling system treats only the incoming ventilation air. A chilled ceiling is designed to have a dew point of approximately  $17^\circ \text{C}$ , it is possible to use low grade chilled water which can be produced for much of the year using only evaporative cooling towers. This may avoid the need to install any vapour compression refrigeration machinery. This should reduce energy costs and improve the energy utilisation of any vapour compression refrigeration machinery that is installed.

In an initial theoretical study, Halliday and Beggs<sup>12</sup> demonstrated the potential opportunity for harnessing solar energy to drive desiccant systems in northern Europe. This study yielded some good results, and demonstrated that for much of the cooling season most of the regeneration heat required could be provided by solar energy. However, the study had the weakness of being based solely on theoretical meteorological data. Consequently, it was decided to repeat the original study, in a modified form, using real UK meteorological data (London 1994) in order to verify the original theoretical results. The model used to determine available solar energy is described by Halliday and Muneer.<sup>13</sup>

#### 4.0 THE SOLAR DESICCANT MODEL

In order to investigate the potential for coupling desiccant system to solar collectors, a solar desiccant computer model was developed. In the model, solar collectors were indirectly coupled to a desiccant system via a water storage tank as shown in and a solar regeneration coil was inserted in the exhaust air stream. The model simulated the psychrometric and thermodynamic processes associated with desiccant cooling, and made the following assumptions:

- ò The desiccant cooling system was employed solely to dehumidify the incoming fresh air supply, and to provide, when required, supplementary sensible cooling. It was assumed that the bulk of the sensible cooling would be performed by a separate water based system.

- ò The desiccant cooling system did not contain a cooling coil. The required degree of sensible cooling being achieved through the use of an evaporative cooler.

ò The desiccant cooling system contained a solar heating coil located directly before the regeneration coil.

ò The desiccant cooling system incorporated a 20% bypass on both the solar heating and regeneration coils.

ò The regeneration and supply air temperatures were specified, and the room condition was allowed to float.

ò The solar desiccant cooling model considered only the primary and delivered energy consumption associated with the thermal aspects of the desiccant cooling cycle. The associated fan energy consumption was ignored.

The overall objective of the study was to investigate the feasibility of using solar power to drive a desiccant cooling system in a UK application. Consequently, the study used regenerative air temperatures which were achievable using solar power as the principle energy source. In the study the regeneration temperature was fixed, and the acceptability of the resulting room air condition was observed. Although a fixed regenerating temperature may not be used in practice (i.e. in an operating control strategy), it was used in the study to simplify the analysis. It should also be noted that the room air condition was allowed to float, in keeping with the environmental control strategy adopted in many passive/mixed-mode low energy buildings.

#### 4.1 METHODOLOGY

The system was analysed in cooling mode only, under the part-load conditions generated by the solar model, shown in Table 1. These data were generated by the solar model for the input conditions shown in Table 2, represented by the temperature profiles in Figure 3. The study assumes a constant latent heat gain to the room space of  $7\text{W/m}^2$ , based on work by Arnold. 14

Loading Date & Time	Sensible Heat Gain ( $\text{W/m}^2$ )	Latent Heat Gain ( $\text{W/m}^2$ )	Outside DB. Temp ( $^{\circ}\text{C}$ )	Outside WB. Temp ( $^{\circ}\text{C}$ )	Outside Air Moist. Cont. ( $\text{g/kg}$ )	Flow Water Temp. ( $^{\circ}\text{C}$ )	Return Water Temp. ( $^{\circ}\text{C}$ )
Peak 3.8.1994 (3pm)	50	7	28.9	19.2	9.8	61.0	48.6
Mid 6.6.1994 (3pm)	40	7	20.4	16.1	9.6	54.9	43.5
Low 12.9.1994 (3pm)	30	7	16.1	12.1	7.1	41.1	n/a

Table 1. Part-load data used in Parametric Study

Table 2. Sample of Input Data

Figure 3. Regeneration Temperature Profiles - Model Output based on London Met Data 1994

The study focused solely on the energy consumption of the desiccant fresh air system. In the study the energy consumption of the chilled ceiling was ignored. The maximum sensible cooling output of the chilled ceiling was assumed to be  $40\text{W/m}^2$ .

Figure 4. An office building with chilled ceiling & with fresh air introduced at high level

It was assumed that under peak load condition the desiccant cooling system would make up the 10 W/m<sup>2</sup> shortfall in sensible cooling. However, under part load the desiccant system would supply air to the space at room temperature. If the outside conditions were such that dehumidification was not required, then the system would push through untreated outside air. Under these conditions the chilled ceiling output would decrease to compensate for the free cooling provided by the ventilation system. It should be noted that the mid-load condition of 20.4°C (db) and 16.1°C (wb), was considered to have an unacceptably high relative humidity (i.e. 62% RH), and therefore dehumidification was deemed to be necessary.

It was assumed that the solar regeneration coil had a U value of 35 W/m<sup>2</sup>K and an area of 0.06 m<sup>2</sup> per m<sup>2</sup> of floor area. It was assumed that the solar collectors were of an evacuated tube type and that the water flow rate to the solar regeneration coil was 0.0005 kg/s per m<sup>2</sup> of floor area; equating to a solar collector to floor area ratio of 1:10. In the study the water flow temperature varied as shown above, and return temperature was assumed to be a constant 30°C. It was also assumed that a 1°C temperature rise in the air stream would occur across both the supply and exhaust fans.

The operating data for the study is shown in Table 3. It should be noted that the degree of sensible cooling achieved by the desiccant cooling system is governed by the degree of dehumidification achieved by the desiccant wheel, and that this in turn is governed by the regeneration air temperature. In short, the greater the regeneration air temperature, the lower the supply air temperature achievable to the room space. In order to determine the impact of varying the regeneration air temperature on the energy consumption of the cycle, the peak load conditions simulation was carried out twice; once with a regeneration temperature of 55°C, and once with a regeneration temperature of 65°C which enabled the supply air moisture content to be reduced to 8.5 g/kg.

Loading	Supply Air Volume Flow Rate (l/s m <sup>2</sup> )	Regen Air Temp. (°C)	Moisture Cont. Leaving Desic. Wheel Output (g/kg)	Ceiling Cooling (W/m <sup>2</sup> )	Sensible Cooling From Desiccant Cooling System (W/m <sup>2</sup> )	Supply Air Condition Peak (°C & g/kg)
Peak	1.8	55	6.7	40.0	10.0	20, 9.3
Peak	1.8	65	5.6	40.0	10.0	20, 8.5
Mid	1.8	55	5.2	40.0	0.0	21, 5.6
Low	1.8	na	n.a	21.6	8.4	17.1, 7.1

Table 3. Operating data for the various loadings

## 4.2 RESULTS

The results of the study are shown in Table 4.

System	Regen. Air Temp.	Supply Air Condition	Room Air Condition	Regen. Coil Duty	Delivered gas (Wh/h/m <sup>2</sup> )	Cost per hour	CO <sub>2</sub> produced (kg/h/m <sup>2</sup> )
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	(°C)	°C&g/kg	°C&g/kg (W/m <sup>2</sup> )		(p/h/m <sup>2</sup> )		
Non-solar(Peak)	55	20&9.3	24.6&10.6	35	50	0.08	0.011
Solar(Peak)	55	20 &9.3	24.6 &10.6	9	13	0.02	0.003
Non-solar(Peak)	65	20 &8.5	24.6 &9.9	48	68	0.10	0.014
Solar(Peak)	65	20 &8.5	24.6 &9.9	25	35	0.05	0.007
Non-solar(Mid.)	55	21 &5.5	21.0 &6.9	42	60	0.09	0.013
Solar(Mid.)	55	21 &5.5	21.0 &6.9	18	26	0.04	0.005
Non-solar(Low)	n.a.	17.1&7.1	21.0&8.5	0	0	0.00	0.000
Solar(Low)	n.a.	17.1&7.1	21.0&8.5	0	0	0.00	0.000

Table 4. Analysis results (system incorporating evaporative cooler)

It can be seen from the results presented in Table 4 that coupling the desiccant cooling system to solar collectors produces significant savings in both running cost and CO<sub>2</sub> emissions. It is noticeable that the greatest savings were achieved at peak load when the system was operating with a regeneration temperature of 55 °C. This is because;

- the flow water from the solar collection system was at a high temperature;
- and
- the return air leaving the thermal wheel was at a high temperature.

It should be noted that at the peak load condition, if the regeneration temperature is 55 °C, then the room air condition is 24.6 °C and 10.6 g/kg moisture content; a condition which might lead to condensation problems if a chilled ceiling is installed. Consequently, it may be advisable to raise the regeneration temperature to 65 °C, which results in a more acceptable room air condition of 24.6 °C and 9.9 g/kg moisture content.

It is noticeable that for all the outside air conditions, an acceptable room condition was achieved without resorting to the use of a supplementary cooling coil in the supply airstream. It was found however, that the contribution of the evaporative cooler on the supply side was minimal. Under peak load conditions with a regeneration temperature of 65 °C, the evaporative cooler provided approximately 7 °C of sensible cooling (assuming a 1 °C temperature rise across the supply fan). However, at the mid-load condition the evaporative cooler provided a mere 1 °C of sensible cooling. This implies that for much of the cooling season the evaporative cooler would be working at very low efficiencies, and might therefore be difficult to control.

### 4.3 EVAPORATIVE COOLING\_A DISCUSSION

With a desiccant system it is possible to avoid the use of a cooling coil, by installing an evaporative cooler in the supply airstream, to provide the required sensible cooling. However, this strategy has been shown to have three major drawbacks:

- The air supplied to the room space is humid. Consequently, although the system might achieve the required degree of sensible cooling, it may not be able to provide adequate latent cooling, with the result that the occupants may find the environment humid and uncomfortable. In addition, the resulting high humidity in the room may lead to condensation problems.

- In order to achieve the required degree of sensible cooling, it is often necessary to perform a large amount of dehumidification on the desiccant wheel. Such a high level

of dehumidification necessitates a high regeneration temperature, with the consequence that energy consumption is increased dramatically.

Evaporative coolers are difficult to control accurately. They can be turned on quickly, but cannot be turned off instantly since they contain a damp wetted surface which requires a long period of time to dry out.

The above drawbacks are significant and as a result most desiccant cooling systems incorporate some form of supplementary cooling coil. Whilst the installation of a supplementary cooling coil might result in an overall energy saving, this introduces refrigerants into the system. However the size of this cooling coil will be considerably less than that which would be incorporated into a conventional fresh air dehumidification system.

#### 4.4 FRESH AIR VOLUME FLOW RATE

In the study outlined above it was assumed that the fresh air volume flow rates supplied to the room space was constant at 1.8 l/s per m<sup>2</sup> of floor area, which equated to 18 l/s per person. In most applications this value would be considered to be high. So in order to investigate further the impact of supply air volume flow rate on the room condition, a short parametric study was undertaken. The study considered only the peak load condition and assumed a regeneration temperature of 65 °C, for a variety of supply air volume flow rates. The results of this study are shown in Table 5.

Supply Air Vol. Flow Rate (l/s per m <sup>2</sup> )	Regen. Temp. (°C)	Outside Air Condition	Supply Air Condition	Room Air Condition
0.6	65	28.9°C & 9.8g/kg	20.0°C & 10.6g/kg	33.7°C & 14.6g/kg
1.2	65	28.9°C & 9.8g/kg	20.0°C & 9.1g/kg	26.8°C & 11.1g/kg
1.8	65	28.9°C & 9.8g/kg	20.0°C & 8.5g/kg	24.6°C & 9.9g/kg

Table 5. Results of Fresh Air Volume Flow Study

It can be seen from the results in Table 5 that the 0.0018 m<sup>3</sup>/s supply air volume flow rate is justifiable, since the low rates resulted in unacceptably high room humidities. The high fresh air flow rate appears to be necessary to achieve the required room latent cooling of 7 W/m<sup>2</sup>, since the chilled ceiling system is incapable of performing any latent cooling.

#### 4.5 CONCLUSIONS

The energy study reported in this paper clearly demonstrates that it is feasible to use solar energy to power desiccant cooling systems in UK applications. It also indicates that a net energy saving in excess of 50% should be achievable.

The main conclusions to be derived from the studies are as follows:

- (i) The inclusion of a solar heater into the desiccant cooling cycle can lead to significant savings in primary energy consumption and associated CO<sub>2</sub> emissions.
- (ii) Due to desiccant cooling being an open cycle, solar energy can only be effectively used in applications where the supply air volume flow rate is small. This effectively limits its

application to installations where the bulk of the sensible cooling system is undertaken using a water based system.

- (iii) In applications where the bulk of the sensible cooling is being performed by water based systems, it may be necessary to supply larger than normal fresh air volume flow rates, in order to perform the required degree of latent cooling. Supply volume flow rates in the order of 1.8 l/s per m<sup>2</sup> of floor area should be acceptable for most applications.
- (iv) The regeneration air temperature should be kept as low as is practically possible, in order to minimise fossil fuel energy input.
- (v) Provided that the room air temperature is allowed to float, it is possible in the UK to achieve an acceptable air condition within the room space under most external conditions, without the use of a supplementary cooling coil. Despite this, the benefit to be derived from using an evaporative cooler on the supply air side is questionable, since the inclusion of such a device if not closely controlled, may result in increased energy consumption and unacceptably high air humidities in the room space, especially under conditions of high ambient humidity. Consequently, it may be preferable to include a small refrigerated cooling coil, which is only used under conditions of peak load.

## 5.0 DISCUSSION

There will be an ongoing need for air conditioning systems as a consequence of client perception, architectural fashion and decreasing quality of the urban environment. The threat of global warming may ironically add to the demand for artificial cooling. The technical potential for solar cooling exists and although the research is still at an early stage there appear to be opportunities to significantly reduce the environmental impact of cooling systems through the use of full fresh air systems which are refrigerant and compressor free and which utilise benign desiccants. By using gas/solar hybrid desiccant cooling technology it may be possible to offer a benign solution to cooling of buildings, in new as well as refurbishment situations, and to significantly reduce greenhouse gas emissions.

Desiccant systems are now being sold in the UK but are still very new. They rely upon complex control algorithms, and are often put in place with supplementary cooling. At present very little is known about the performance of these systems in relation to energy consumption, first and running cost, management, parasitic losses (in particular fan power) and scope of delivered indoor climatic conditions. The relationship between large air volumes (with associated energy consumption) and delivery temperature and humidity needs clarification.

Whilst the energy contribution of solar is likely to be significant there is a need to clarify the capital cost and return in the UK climate. The solar collectors can in principle make a contribution to the heating requirement and as such can provide a better year round utilisation and hence return on investment. However there are significant control implications with respect to the overall system design, frost protection etc., if winter use is envisaged. Innovations in solar collection technology need consideration. The potential to utilise other waste heat sources deserves clarification.

It should be acknowledged that the primary opportunities for solar are likely to be outside the UK, in hot humid climates. Also that expansion of the air conditioning market is

predominantly in the field of small units and this is the area in which the greatest technical and financial challenges remain. On the technical side existing small scale technologies may offer opportunities for innovation and aspects such as the opportunity to investigate passive evaporative techniques is of interest. It is important that national development strategies are based on technology appropriate to the risk and that international agreements facilitate responsible action from industry and commerce.

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